

Characteristics of pyroclastic surge deposits in Mount Bamenda (Bambili, Cameroon volcanic Line) and its importance in lithostratigraphy of the volcano

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 between 8 to 35 cm and showing a graded bedding. The layers are matrix-supported and heterolithic, with the lithic fragments consisting of devitrified fiammes, vitrophyres, trachyte, trachytic, and rhyolite, 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 discovery 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 volcano. In fact, after the a trachytic lava flow, a pyroclastic flow deposits permitted the formation of the welded ignimbrites represented by dark gray and whitish units; pulsating hydrostatic and magma pressures have subsequently produced alternating hydromagmatic-phreatomagmatic 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) [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

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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 are found mainly in the central area of the CVL especially within the Mount Bambouto and the Mount Bamenda with respectively 13.5 and 6.3 km³ [3]. Considering both alteration and poor condition of these rock-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].

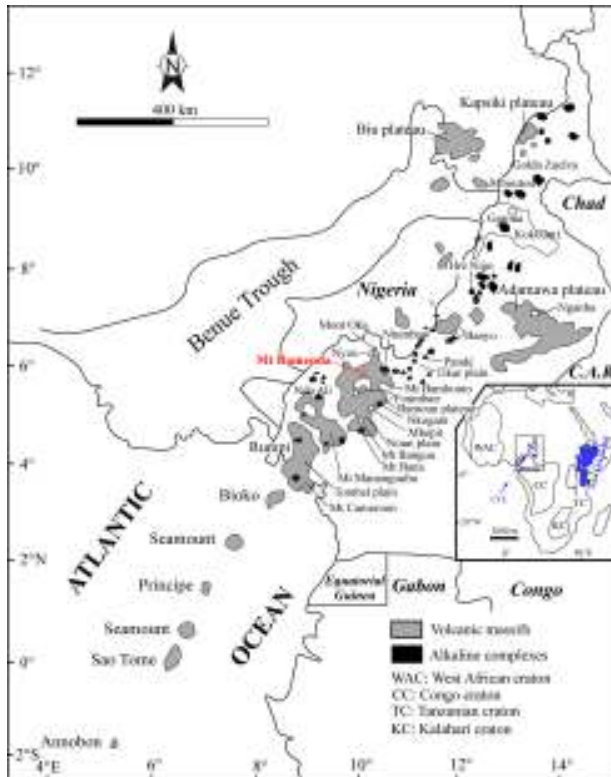


Fig. 1. Map of Cameroon showing the distribution of the Cameroon Volcanic Line (CVL) magmatism. Locations of seamounts are after Burke [2]. C.A.R.: Central African Republic. Inset: location map of CVL in Africa.

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] Wilson and Houghton, 2000) on the earth surface, mainly controlled by gravity [11, 12, 13, 14] (Carey, 1991; Druitt, 1998; Belousov et al., 2002; Burgisser and Bergantz, 2002), and frequently implying a turbulent regime [11, 15, 16, 17] (Fisher, 1990; Carey, 1991; Dellino and La Volpe, 2000; Valentine and Fisher, 2000). Deposits of pyroclastic density currents have

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54 | ~~been~~are generally categorized according to lithology and sedimentary structure, as
55 | ignimbrites, block-and-ash flow deposits and pyroclastic surge deposits [8]. ~~Pyroclastic surge~~
56 | ~~deposits come from turbulent flows, less concentrated or diluted, in which the ashy and~~
57 | ~~gaseous fraction predominates; t~~~~They are generally consist of successive parallel and~~
58 | ~~stratified beds and occasional cross-stratification [8]. The beds are relatively low thickness,~~
59 | ~~well sorted, with or without fine ashy matrix, with abundant presence of parallel stratification~~
60 | ~~and / or cross-stratification [8].~~ Until now, only the deposits of pyroclastic flows represented
61 | by welded and non-welded ignimbrites with their massive lapilli tuff (mLT) and massive lithic
62 | breccias (mLBr) facies have been described in the Mount Bamenda Highlands [3]. In this
63 | work, we highlight the existence of pyroclastic surges deposits in the Bamenda
64 | volcanovolcanic sequence of the area. These surges, deposits are found in remnants
65 | pyroclastic blocks at Bambili locality, situated in the NE of Bamenda town. ~~These They~~
66 | ~~surge deposits~~ are investigated here in detail in order to understand their mode of
67 | deposition origin and to give their importance in the chronostratigraphy of the Bamenda
68 | volcano.

2. GEOLOGICAL SETTING

72 | The Mount Bamenda (600 km²) constitute in volumetric importance the fourth largest
73 | volcano of the CVL after ~~Mount~~ Cameroon, ~~Mount~~ Manengouba and ~~Mount~~ Bambouto. It
74 | constitutes with the Bambouto mountains to the SW and the Oku massif to the NE (Fig. 2),
75 | the three central volcanoes belonging to the volcanic ~~centers~~ of the Western Cameroon
76 | Highlands. Their basement consists of Pan-African granitoids [18, 19, 20]. ~~The~~ Bamenda
77 | volcano, ~~on top of which exists the lake Bambili~~, lies between longitudes 10°00'E and
78 | 10°30'E and latitudes 05°45'N and 06°10'N and culmi nates at 2621 m asl.
79 | The Mount Bamenda is characterized by the presence of two calderas: calderas of Santa-
80 | Mbu (6 x 4 km width) and Lefo (4 x 3 km width) (Fig. 2). They are small ~~sized~~ compare to
81 | neighboring Bambouto caldera and open respectively to the west and ~~south-east~~southeast
82 | [21]. Their floors, located ~~respectively~~ at elevation of 550 m and 400 m respectively, are
83 | mainly composed of trachytic domes, which are also abundant on the external slopes of the
84 | ~~volcano~~. Many craters caused by explosive volcanism, are occupied by lakes generated by
85 | phreatomagmatism like Bambili Lake, Lake Awing and Lake Oku.

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eruptive history of the Oku Vocano and thus to the
chronostratigraphy of the Bamenda volcanic field.



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 the current 0 Ma to 17.4 to 0 Ma 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

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 analysedanalyzed for major elements. These samples were crushed in a steel jaw crusher and reduced to fine powder in agate mortars. Powders were analysedanalyzed 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 precision of 1%.

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

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 are 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 mBr facies (Fig. 5). The pyroclastic surge deposits of Bambili are characterized by stratified ashy layers insert in mBr 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].

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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 mLBr; d) Remnant block of whitish unit of welded mIT. mLBr: 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 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.

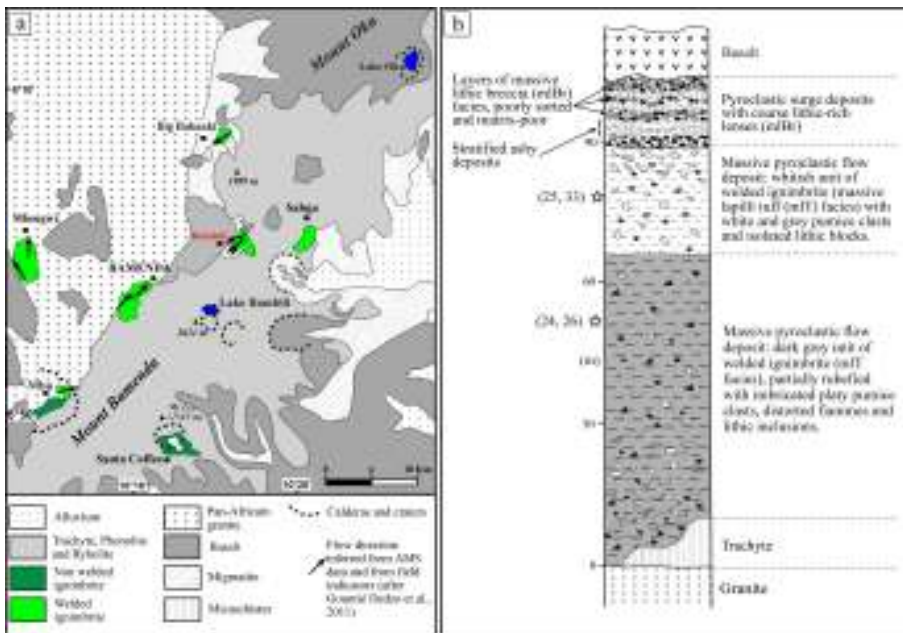


Fig. 5. a) Geological map of mounts Bamenda and surroundings. **b)** Stratigraphic section of Bambili ignimbrites and pyroclastic surge deposits; the numbers 24, 25, 26, 33 represents sampled sites for anisotropy of magnetic susceptibility (AMS) studies (modified after [3]).

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.

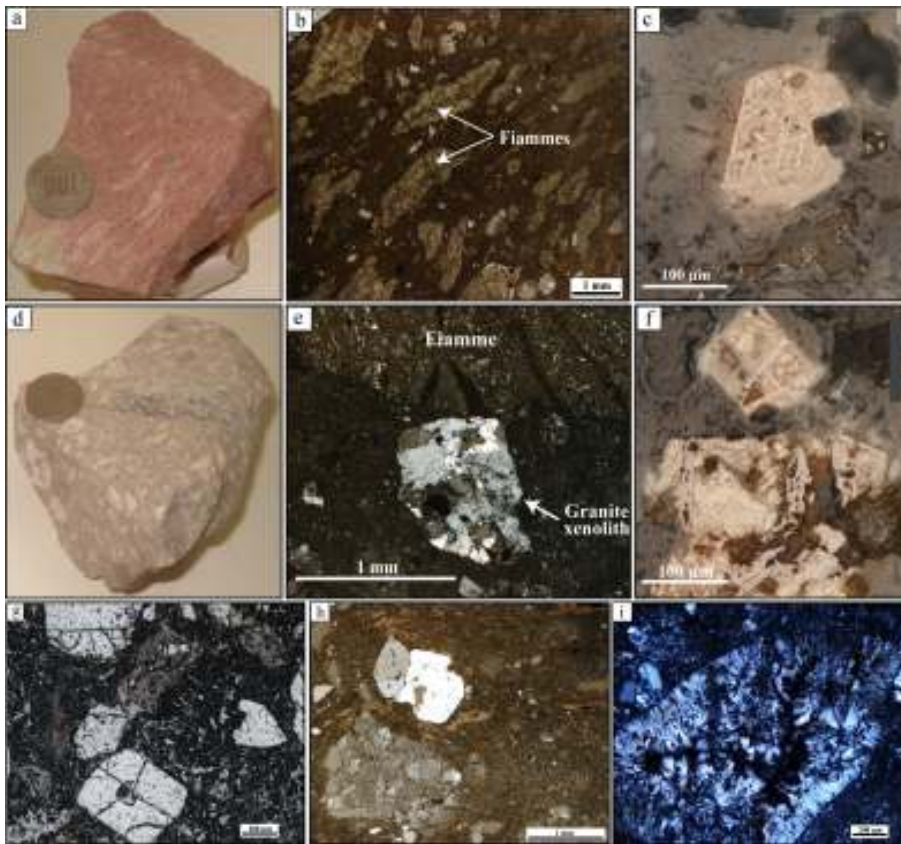


Fig. 6. a) Sample of rubefied dark grey unit (DGU) of mIT and **b)** the corresponding microphotograph showing the eutaxitic texture with imbricated fiammes; **c)** Crystal of titanohematite with thin exsolution lamellae of ilmenorutile in the DGU; **d)** Sample of mIT whitish unit (WU) and **e)** the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

4. 3 The upper unit: mIBr facies

The surface mIBr 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.

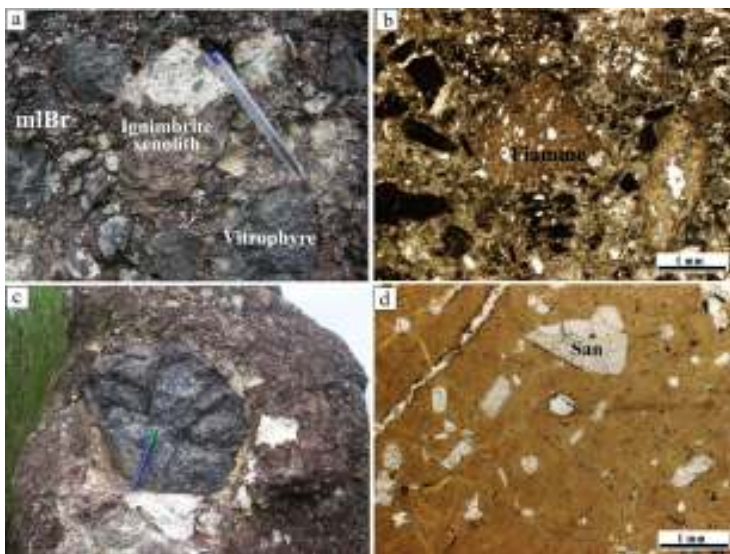


Fig. 8. a) Detail of mIBr facies and **b)** microphotograph of ignimbrite enclave **c)** Enclave of vitrophyre and **d)** the corresponding microphotograph.

Rock fragments 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 fragments than the country rock. Matrix, whitish in color, consists essentially of consolidated volcanic ashes in which are embedded small rocks and minerals fragments.

5. 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, 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 dominance of blocky, poorly vesicular ash particles with hydration cracks, indicates an origin as wet pyroclastic surges of hydromagmatic phreatomagmatic origin [28].

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 mechanisms 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 characteristic 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. 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.

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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 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 phreatomagmatic 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, followed by welded ignimbrites represented by dark gray 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.

AUTHORS' CONTRIBUTIONS

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

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