

PHYSICOCHEMICAL CHARACTERIZATION AND FULGURITIC ORIGIN OF A GLASSY MASS FORMED BELOW AN ELECTRICAL POWER PYLON AT GUEHIEBLY (WESTERN COTE D'IVOIRE)

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ABSTRACT

The occurrence of molten rocks manifested as viscous fluids is a rare but well-documented geological phenomenon. This process can result from extreme events such as lightning strikes or from intense heat generated by the Earth's internal dynamics. These molten materials may cool very rapidly, leading to the formation of glassy materials. Such a phenomenon occurred in the mountainous western region of Côte d'Ivoire, specifically in Guéhiébly, Duékoué Department. At the base of an electrical transmission tower, the surrounding soil and granite underwent partial melting, resulting in the formation of a glassy mass. It is within this context that the present study was conducted at the impacted site, with the aim of elucidating the phenomenon responsible for the extrusion of this mass and determining the nature and physicochemical characteristics of the extruded siliceous material. Field investigations enabled the characterization and description of the molten material. In situ methods, including radiometry and magnetic susceptibility measurements, together with X-ray fluorescence (XRF) analyses, indicate that the material is an anthropogenic fulgurite. Its chemical composition, characterized by high silica content and low potassium content, combined with the absence of volcanic features, leads to the conclusion that the glassy mass resulted from the melting of the substrate (soil and rock) immediately beneath the electrical transmission tower, triggered by a lightning strike. The metal transmission tower conducts the electrical current into the underlying ground. This confined zone undergoes melting, producing a molten mass characterized by upward movements that, together with the resulting pressure, carbonize the base of the tower, ultimately causing its collapse. The formation of viscous fluids resulting from lightning-induced rock melting remains a fascinating phenomenon, despite being brief and highly localized. It demonstrates that atmospheric phenomena can generate intense thermal effects capable of causing the partial melting of rocks at the Earth's surface.

Keywords : Fulgurite, Lightning, Melting, Metal transmission tower

1. INTRODUCTION

Since antiquity, lightning has fascinated humanity. It was often interpreted as a manifestation of divine anger. It was not until the eighteenth century, through the work of the physicist Franklin (1773), that its electrical nature was recognized, marking a major turning point in the scientific understanding of this random and awe-inspiring phenomenon. As stated by the physicist Condon (1946), lightning is one of the greatest mysteries of atmospheric physics, an event that is both random and capable of releasing colossal amounts of energy, far beyond what we currently understand.

The most common source of lightning is the separation of electrical charges within thunderclouds, specifically cumulonimbus clouds (Williams and Latham, 2001). According to Machado *et al.* (2021), lightning occurs through the discharge of excessive static electricity accumulated either between two storm clouds (IC, Intra-Cloud) or between a cloud and the ground (CG, Cloud-to-Ground). Among the different types of lightning, cloud-to-ground (CG) discharges have been particularly studied and are considered the

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most dangerous because they can directly impact infrastructure and endanger living organisms (Elmi *et al.*, 2018). Despite scientific advances, the hazards and unpredictable nature of lightning remain.

It is within this context that a particular incident occurred in Guéhiébly, Duékoué Department, in western Côte d'Ivoire. The site is located barely 1 km from Guéhiébly, along the road leading to Gozon (Fig. 1). At the site, a metal electrical transmission tower collapsed, resulting in a power outage in the locality. A glassy siliceous mass flowed from the cavity left by the fallen metal tower, extending over a radius of approximately 5 m. The surrounding inhabitants, deeply concerned by the sight of this glassy material, hypothesized that it was the result of volcanic activity. Excavation of the ground revealed scoriaceous materials and rock blocks altered by intense heat. This study, conducted in the impacted area, aims to determine the origin of this phenomenon and to characterize the physicochemical nature of the extruded siliceous mass, as well as the scoriaceous and altered earth materials excavated from the site.

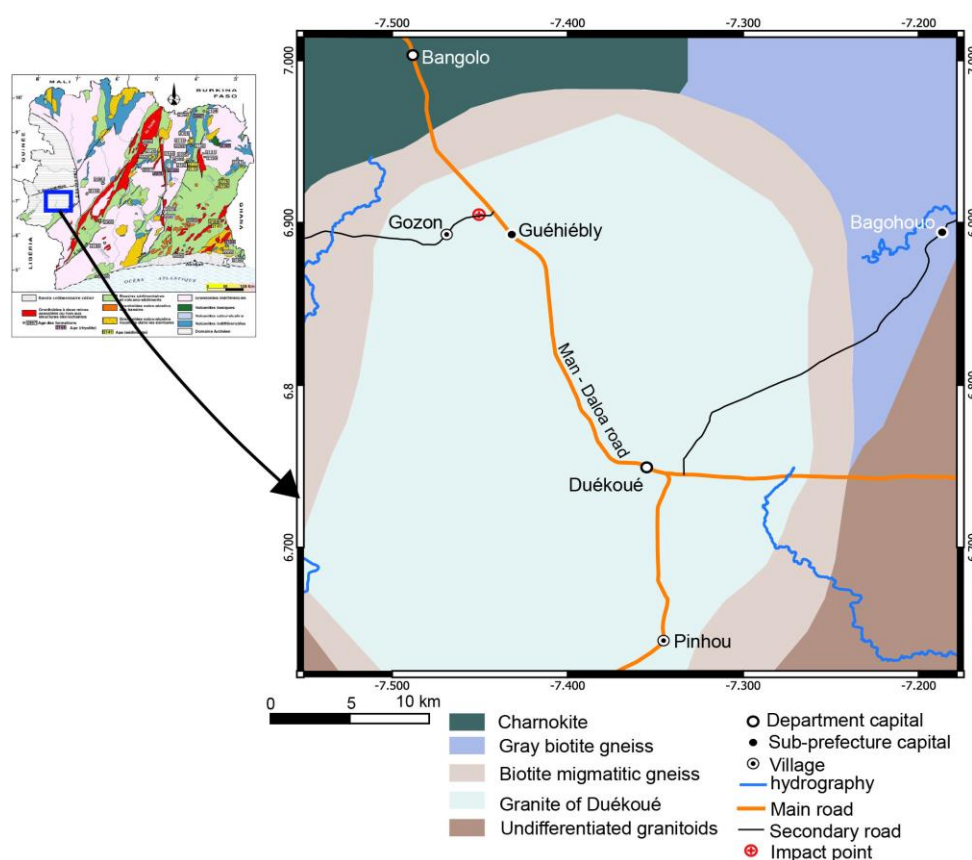


Figure 1 : Geological map of Côte d'Ivoire (modified after Bagarre *et al.*, 1965) and the study area

2. TOPOGRAPHIC SITUATION AND GEOLOGICAL SETTING

The Guéhiébly sub-prefecture is located in the Duékoué Department, specifically along the Duékoué–Man axis, approximately 18 km from Duékoué, within the Montagnes District in western Côte d'Ivoire. The geomorphology of the region is characterized by rugged terrain dominated by undulating plateaus and mountainous massifs, including granitic domes. The soils are predominantly ferrallitic, generally reddish-ochre in color. The climate ranges from warm to humid and is characterized by two rainy seasons alternating with two dry seasons. The vegetation consists mainly of dense forest.

The study area is part of the Ivorian Archean domain, located west of the Sassandra Fault, and consists of ancient geological formations that were structured during two major orogenic cycles, namely the Leonian (3.4–3.0 Ga) and Liberian (2.9–2.7 Ga) orogenies (Tagini, 1971 ; Yacé, 1984 ; Kouamelan, 1996 ; Pitra *et al.*,

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2010). This domain is well documented geologically, having been the subject of several doctoral theses and scientific publications (Camil, 1984 ; Djro, 1998 ; Gouédji, 2014 ; Koffi, 2020 ; Kouamelan, 1996 ; Camil *et al.*, 1983 ; Kouamelan *et al.*, 1997 ; Gouédji *et al.*, 2014 ; Coulibaly *et al.*, 2012 ; Koffi *et al.*, 2020 ; Pitra *et al.*, 2010).

The study area is located precisely beneath a medium-voltage power line, approximately 1 km from the paved road and near the track leading to Gozon, at coordinates 06°54'18.1"N and 07°27'01.8"W (Fig. 1). In this sector, granitoid domes are observed. These outcrops consist of granites whose continuity is thought to correspond to that of the granitic domes in the Duékoué area. According to Papon (1973), the Man domain is abundantly composed of migmatites, common charnockites, ferruginous quartzites, amphibole-pyroxenites to pyroxenites, and porphyritic granites (Fig. 1). This domain mainly consists of biotite-bearing migmatitic gneisses, porphyritic granite (Duékoué granite), charnockites, and gray gneisses (Koffi *et al.*, 2020).

MATERIALS AND METHODS

3. Analytical Method

3.1. Sample Collection and Optical Petrography

The study began with an examination of the morphology of the impacted site. Several rock outcrops are exposed at the site. The lithology corresponds to granite, displaying a weak preferred orientation of minerals in the E–W direction. The outcrops show no evidence of recent fracturing.

After collecting several samples of the glassy mass (Fig. 2A–B), an excavation was carried out using a hydraulic excavator (Fig. 2E). This operation made it possible to investigate the continuity of the damage at depth and to collect samples from the affected zone (Fig. 3B–C). A macroscopic description was performed on all samples collected both at the surface and at depth. This description included assessment of the degree of vitrification, as well as lithology, color, and texture.

In addition, several thin sections were prepared from samples collected at the site and examined using a petrographic microscope.



Figure 2 : Photographs of the extruded mass and the excavation stage. A – Measurement of the gas escaping from the emission vent. B – Photograph of the emission vent of the extruded mass. C–F – Hollow ovoid mass with a 5–7 cm thick shell, displaying vesicles and flow grooves. D – Photograph of the impacted electrical transmission tower and the spectroradiometer. E – Excavation of the effusion source.

3.2. Radiometric Measurements and XRF Chemical Analyses

Radiometric measurements were also carried out directly in the field using a radiometric device and magnetic susceptibility measurements (Table 2, Fig. 2A). X-ray fluorescence (XRF) analyses were also performed. The radiometric measurements were conducted to determine the concentrations of potassium (K),

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uranium (U), and thorium (Th) in the rock, soil, and extruded mass (Table 1, Fig. 2D). The magnetic susceptibility of the samples was measured in the field to assess variations related to thermal effects and the presence of magnetic minerals. A portable XRF analyzer was used to determine the chemical composition of the materials (rock, soil, and extruded mass) directly in the field (Table 3). This technique provided data on the major elements present, which are essential for determining the nature of the protoliths and the chemical transformations undergone by the materials during melting.

4. RESULTS

The lightning-impacted site is located in the Guéhiébly sub-prefecture. It consists of a metal transmission tower belonging to a medium-voltage power line (Fig. 5). The metal tower is positioned on a small mound characterized by granite blocks and slabs. It is noteworthy that the other towers along the power line are made of concrete.

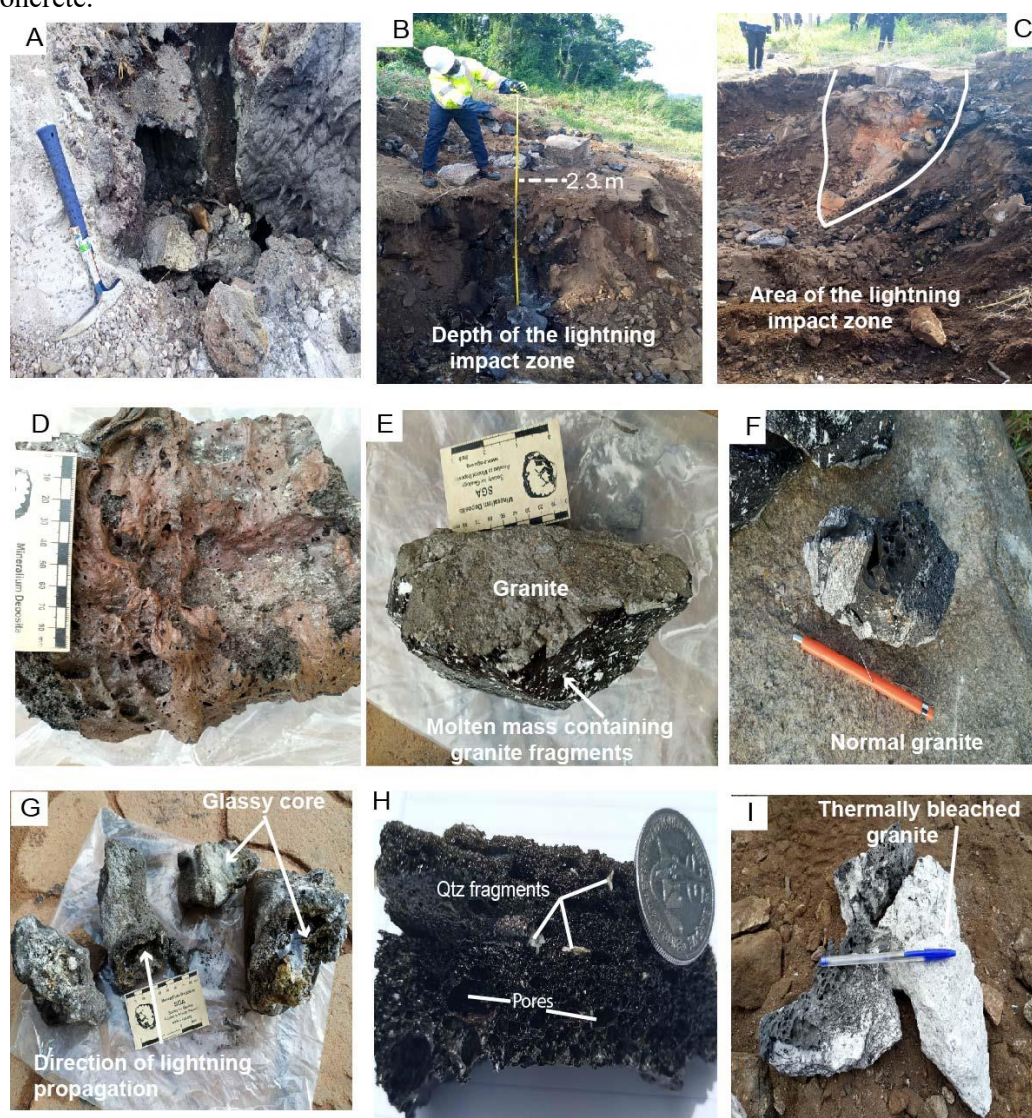


Figure 3 : Photographs of the emission source and the various samples collected. A – Photograph of the emission vent. B–C – Surface of the area affected by lightning-induced melting. D – Reddish sample showing the presence of scoriaceous material. E – Photomicrograph of the molten mass in contact with granite. F – Photograph of unaltered granite and samples of molten material containing fragments of bleached granite. G – Morphology of the vitrified materials (fulgurite). H – Photograph of a sample of the extruded mass displaying numerous pores. I – Photograph of the bleached granite.

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4.1 Petrographic Characteristics of the Extruded Masses and Excavated Materials

4.1.1. Granite

This is the host rock supporting the metal transmission tower struck by lightning. The granite in the study area is leucocratic, medium-grained, and shows no apparent recent fracturing. The main minerals are quartz and feldspar, while ferromagnesian minerals appear to be absent to the naked eye (Fig. 3E–F).

4.1.2. Extruded Masses and Excavated Materials

Extruded Masses

The material exhibits a glassy appearance with a uniform black coloration, indicating rapid cooling. These masses are ovoid at the surface, fragile, and range in size from several tens of centimeters to approximately one meter. Internally, they contain voids forming a shell with an average thickness of 5–7 cm (Fig. 2C, F and 3H). The external surface of the masses is marked by grooves or flow ridges (Fig. 2C–F). Both the internal and external structures are characterized by the presence of thin, millimeter-scale layers (lamellae), giving the material a foliated appearance. These lamellae form numerous small bubbles or cavities (vesicles), some of which are so fine that they render the material slightly translucent (Fig. 3H). A slightly sulfurous odor emanated from the hole left by the pole. This odor became more pronounced under stronger sunlight. The material is friable, leaving a blackish and sharp-edged residue.

Excavated Materials

Excavation of the site provided essential information on the materials present at depth and the effects of the lightning strike on the substrate. Localized areas of carbonization were identified in the excavated soil materials (Fig. 3E–F). The zone located directly beneath the effusion source displays a distinct reddish coloration at a depth of less than one meter (Fig. 3B–C).

The base of the metal transmission tower, buried to a depth of approximately 1.3 m, was found to have been completely consumed and pulverized. The walls of the source cavity bear traces of scoriaceous material displaying magnetic properties (Fig. 3A–D). Granite fragments were also observed, characterized by their texture and composition, with evidence of partial melting and the development of a glassy phase. Calcined zones are also present in some samples.

A dark, dense rocky mass was identified at a depth of approximately 2 m beneath the effusion source, in contact with the granite. It differs from the superficial extruded mass by its significantly higher density and much lower porosity (Fig. 3E–F–I). It contains granite enclaves bleached by the effect of intense heat. This dark mass is less than 1 m in diameter and gradually disappears toward the granitic bedrock, located at a depth of approximately 2.5 m. At this depth, the granite appears thermally bleached and remains hot (Fig. 3I). It regains its normal appearance only a few centimeters beyond the edge of the affected zone.

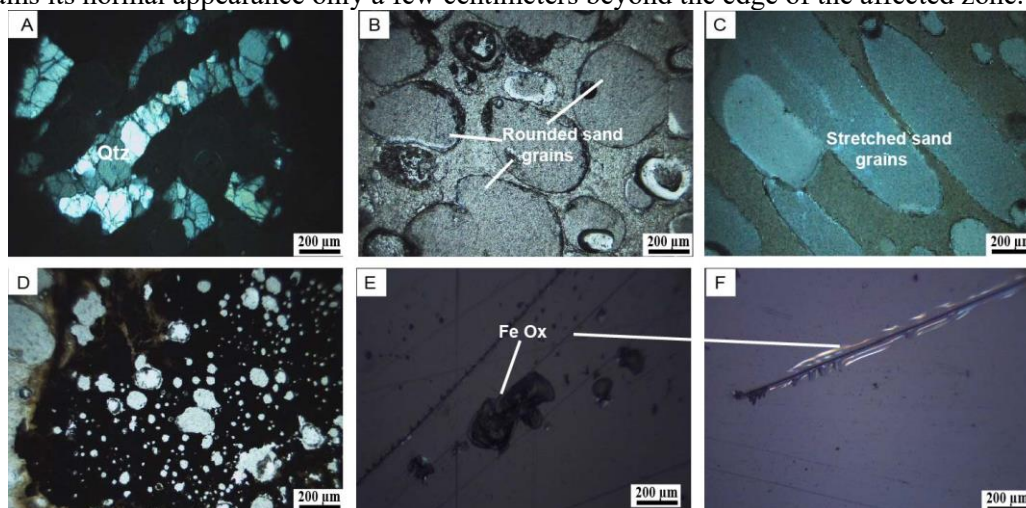


Figure 4 : Photomicrographs of samples from the extruded masses. A – Photomicrograph of sample 1. B – Photomicrograph showing rounded sand grains (ECH 2). C – Photomicrograph showing elongated sand grains (ECH 1). D – Photomicrograph showing an opaque matrix with pores. E–F – Iron oxide resulting from the melting of the metal transmission tower (ECH 1). Qtz: Quartz ; Fe Ox : Iron oxide.

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The emanating fumes subsided after the removal of the black rock. This observation indicates that the removed rock constitutes the main source of the gas emissions. The granitic rock formations surrounding the site show no evidence of recent fracturing.

Polarizing microscope analysis made it possible to characterize the petrographic composition of the extruded siliceous mass, which consists predominantly of amorphous silica and sand grains (quartz). These sand grains display a wide range of shapes and sizes, ranging from rounded to elongated grains (Fig. 4A–D). The mineral assemblage is consistent with that of the granitic soil in the region. Amorphous silica (opaque) is also observed surrounding the unmelted grains (Fig. 4A). Secondary minerals were also identified, notably iron oxide crystals (Fig. 4E–F).

4.2 Radiometric Analyses

Using a portable spectroradiometer, the radioactivity of the granite, soil (collected from different locations), and extruded mass was measured. For each sample, the concentrations of potassium (K), uranium (U), and thorium (Th) were accurately quantified (Table 1). The U and Th contents, which are relatively immobile during weathering processes, show similar ranges of variation among the rock, soil, and extruded mass. Potassium (K), which is more mobile, exhibits slight leaching with increasing distance from the hill.

Table 1. Portable spectroradiometer measurements of granite, soil, and the extruded mass

	Granite	Granite	Soil	Soil	Molten mass	Molten mass	Point	Intermediate point.	Point
	Sample 1	Sample 2	Edge hole	Eastern slope edge	Rim hole	Western	Lower ground eastern side	Soil western side	Lower ground western side
K (%)	1.4	2.9	0.9	1.5	0.6	1.1	0.7	1.8	0.5
U (ppm)	1	1.8	1.6	1.5	1.8	0.9	0.5	1.2	1.7
Th (ppm)	14.3	21.6	12.7	23.2	26.3	15.5	11.7	17.5	16.2

4.3. Magnetic Susceptibility

Measurements of the magnetic susceptibility of the main materials found at the site—granite, soil, concrete, and the extruded mass—were carried out (Table 2). A high magnetic susceptibility was observed in the granite, reaching values of up to 28. In contrast, the soil, concrete, and extruded mass exhibit very low to negligible magnetic susceptibility, with values ranging from 0 to 0.5.

Table 2. Magnetic susceptibility measurements (10^{-3} SI) of granite, soil, and the extruded mass

Granite	Soil	Concrete	Extruded mass
1-28	0-0.5	0.5	0- 0.5

4.4. X-ray Fluorescence (XRF) Analysis

For the chemical composition of the different sampled materials, a portable X-ray fluorescence spectrometer (pXRF) was used. The analytical results are presented in Table 3. The chemical analyses indicate that the extruded mass is mainly composed of SiO₂ (43.61–58.95%), Al₂O₃ (7.54–14.79%), FeO (4.99–13.31%), and CaO (4.42–10.32%). In addition to these major components, trace concentrations of Mg (1.2–2 wt.% MgO), K (1.33–2.18 wt.% K₂O), Ti (0.43–0.69 wt.% TiO₂), Mn (0.06–0.09 wt.% MnO), and P (0.15–0.32 wt.% P₂O₅) were recorded.

The bleached granite also exhibits relatively high concentrations of SiO₂ (44.04–65.05%), Al₂O₃ (4.88–8.97%), FeO (0.92–6.98%), and CaO (1.87–5.93%), but relatively low concentrations of K₂O (0.84–1.81%), TiO₂ (0.16–0.63%), P₂O₅ (0.23%), and MnO (0.07%).

The analytical results show that the unaltered (normal) granite is richer in SiO₂ (73 wt.%) and K₂O (5.81 wt.%) than both the extruded mass and the bleached granite. However, it contains lower concentrations of

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FeO (2.66 wt.%) and CaO (0.73 wt.%) than these materials. The Al₂O₃ content of the unaltered granite (9.19 wt.%) is higher than that of the bleached granite.

Table 3. Chemical composition (wt%) of the granite and various samples of the extruded mass

Samples	SiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	K ₂ O	TiO ₂	P ₂ O ₅	Total
ECH 1	53.59	13.35	9.46	0.09		5.8	1.73	0.56	0.19	84.77
ECH 2	55.53	13.86	9.56	0.08	1.29	5.99	1.9	0.63	0.32	89.16
ECH 3	44.29	9.22	11.36	0.08		5.43	1.33	0.52	0.21	72.44
ECH 4	49.27	11.7	10.73	0.09	1.2	5.29	1.37	0.5	0.21	80.35
ECH 5	49.52	12.35	13.31	0.09	2	10.32	2.18	0.49	1.28	91.55
ECH 6	58.95	14.79	6.81	0.08	1.27	6.47	1.81	0.69	0.24	91.11
ECH 7	43.61	7.54	4.99	0.06		4.42	1.41	0.43	0.15	62.61
Bleached granite	65.05	4.87	0.92			1.87	0.84	0.16		73.71
Bleached granite	44.09	8.97	6.98	0.07		5.93	1.81	0.63	0.23	68.71
Normal Granite	76.66	9.19	0.13			0.73	5.81			92.53

5. DISCUSSION

5.1. Evidence for Fulgurite Formation

The very limited surface area occupied by the extruded material (barely 50 m²), the single effusion vent corresponding to the cavity left by the fallen electrical pole, the nature of the extruded material (glass), the absence of fracturing within the granitic dome, and the physical and chemical measurements conducted indicate that the extruded mass has a superficial origin. There is no evidence of any relationship with magmatism originating from the Earth's interior. Furthermore, no seismic activity associated with magmatic activity was recorded by the monitoring instruments (seismographs) at the Lamto Geophysical Station (SGL).

The morphology of the samples further supports the fulgurite hypothesis. The extruded masses exhibit a glassy appearance, consisting of amorphous silica, alveolar cavities, and a hollow structure. These morphological features have been described by Pasek et al. (2012) as characteristic of fulgurites. The presence of internal porosity indicates rapid melting followed by abrupt cooling and significant degassing, a process involved in fulgurite formation as described by Pasek and Pasek (2018). The observations are also similar to those reported by Knight and Grab (2013) for fulgurites identified in southern Africa. This similarity in textures and structures confirms that the formation process involved a rapid and intense thermal event rather than a slow magmatic process. The grooves and flow ridges observed on the extruded masses at Guéhiébly indicate that the molten material underwent high-velocity circular movements before, during, and after extrusion. The elongated quartz grains observed under the microscope are most likely the result of these intense circular movements.

From a geochemical perspective, pXRF analyses reveal that the extruded masses are enriched in SiO₂, Al₂O₃, FeO, and CaO, while being depleted in K₂O relative to the host rock. This geochemical signature is indicative of lightning-induced thermal transformations. It is consistent with the observations of Çalışkanoğlu et al. (2024), who demonstrated that highly mobile elements such as potassium can be volatilized under the effect of intense heat. This interpretation is further supported by the radiometric analyses, which show relatively stable uranium (U) and thorium (Th) concentrations, whereas potassium (K) displays greater variability. This behavior was documented by Pasek and Pasek (2018), who reported that potassium can escape in gaseous form, whereas heavier elements remain relatively immobile.

The magnetic susceptibility measurements and chemical composition of the materials further confirm mineralogical alteration induced by intense heating. The low magnetic susceptibility values measured in the

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analyzed samples may result from the thermal destabilization and breakdown of ferromagnetic minerals under the effect of lightning. This observation is consistent with the findings of Mayet et al. (2015) and Beard et al. (2009), who established a relationship between lightning strikes and the modification or destruction of the magnetic properties of rocks. The close similarity between the chemical compositions of the fulgurite glass and the host rock (granite) provides additional evidence for their common origin, consistent with the glasses described by Plyashkevich et al. (2016) in the Kolyma fulgurite, which formed from shale affected by lightning.

The records from the Lamto Geophysical Station (SGL) confirm the absence of seismic activity associated with deep-seated magmatism. The extruded mass is confined to a radius of less than 10 m around the location of the collapsed metal transmission tower, while the dark material is observed only to a maximum depth of approximately 2.5 m. The presence of a single effusion vent corresponding to the cavity left by the fallen electrical tower, together with the absence of fracturing within the surrounding granitic dome, further supports the incompatibility of the phenomenon with a deep magmatic process. According to Bonin and Moyon (2011), such a process requires major fractures within the Earth's crust to allow magma to migrate toward the surface.

Lavigne and De Bézilal (2010) reported that extrusive materials associated with active volcanism generally extend over distances of several kilometers, as demonstrated by the pyroclastic flows of Mount Merapi, Indonesia. Furthermore, the geological setting of the site, with the metal tower located on a granitic hill, represents an ideal target for lightning strikes. The thermal alterations observed in the surrounding granite are consistent with the thermal shock effects described by Anderson et al. (2006). The persistence of heat within the granite suggests a continuous input of energy into the rock for several tens of seconds following the lightning strike, potentially through the electrical transmission system. This observation is consistent with the work of Crespo et al. (2009), who reported the persistence of heat in granite for up to 48 h after a lightning strike, attributing it to continuous energy deposition within the rock.

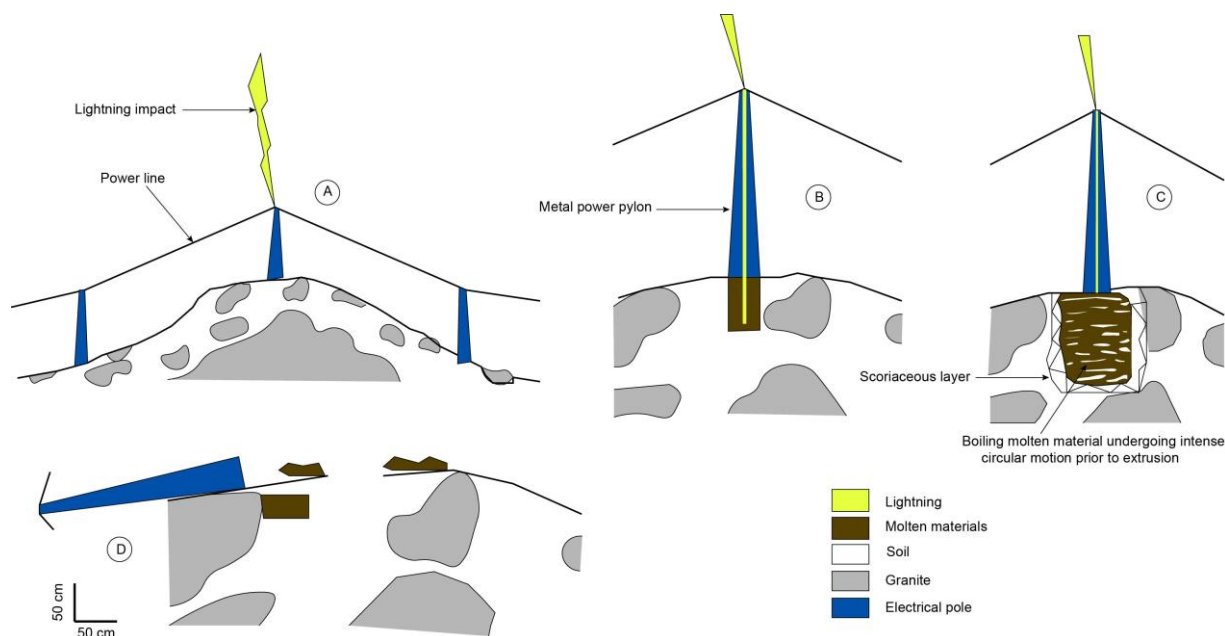


Figure 5 : Formation model of the Guéhiébly fulgurite. A – Metal transmission tower on the hill struck by lightning. B – Electrical discharge of several thousand volts conducted through the metal tower. C – Heat convection and upward movement of the molten material prior to the collapse of the metal tower. D – Extrusion of molten soil at the surface following the collapse of the tower; the remaining molten material solidified at the bottom of the cavity.

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5.2. Possible Scenario for the Formation of the Extruded Mass

Lightning struck the metal transmission tower supporting the medium-voltage power lines (Fig. 5A). Because the tower was located on a small hill, it represented an ideal target for a lightning strike.

The lightning impact caused an electrical current of several thousand volts to flow through the metal tower into the ground (Fig. 5B). In fact, a short circuit occurred on the medium-voltage line at the level of the metal tower, generating a powerful electrical arc that was conducted into the ground through the tower. The electrical discharge, involving several thousand volts, entered the ground through the metal tower and generated temperatures exceeding 1000 °C, which were more than sufficient to melt the soil and other surrounding earth materials (Fig. 5C). The molten mass most likely contained a significant fraction of gas.

The molten material became trapped within a confined environment, with the surface concrete and the metal tower acting as a lid, much like a pressure cooker. The material then began to boil and developed intense upward circular movements (Fig. 5C). As the intensity of the circular movements and gas pressure increased, the lid formed by the surface concrete and metal tower eventually failed, allowing the molten material to extrude (Fig. 5D). The material then cooled and degassed almost instantaneously. The hollow extruded masses, with a vesicular shell, are interpreted as the result of this rapid degassing.

The grooves and flow ridges observed on the extruded masses are interpreted as traces left by the movement of the molten material before complete solidification. The glass formed (amorphous silica) resulted from the extremely rapid cooling of the molten earth materials (soil, rock, and concrete). The presence and high density of vesicles indicate significant degassing during the cooling of the extruded masses. Overall, all the analyses confirm that the extruded material resulted from the melting of the materials present at the site, including the base of the metal transmission tower.

6. CONCLUSION

This study investigated the Guéhiébly event, whose initial manifestations, particularly the extrusion of a glassy siliceous material and the thermal alteration of the substrate, raised questions regarding their origin. Field investigations, complemented by physical and chemical analyses (radiometry, magnetic susceptibility, and XRF), enabled a detailed characterization of the extruded materials and the transformations undergone by the surrounding soil and granite. The results clearly demonstrate that the glassy material originated from the melting of local materials (soil, rock, and concrete), while the thermal alterations observed at depth are consistent with an intense and localized heat source. This substantial heat source was generated by an electrical arc following a short circuit caused by a lightning strike on the metal transmission tower of the medium-voltage power line during a severe thunderstorm.

The absence of fractures in the host rock, together with the restricted and localized impact zone confined to a few meters around the electrical tower, rules out a volcanic origin and instead supports an origin related to a powerful electrical discharge generated by lightning. The glasses formed at Guéhiébly differ from fulgurites commonly observed in natural environments. These findings contribute to a better understanding of the various impacts of lightning on the environment.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Lamto Geophysical Station (SGL) for its financial support. We also thank the members of the SRTM Department for performing the chemical analyses and preparing the thin sections. The authors would also like to express their sincere appreciation to the private company that provided the hydraulic excavator used for the excavation of the study site.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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