

Fulgurites in the southern Central Sahara, Republic of Niger and their palaeoenvironmental significance

B. Sponholz*, R. Baumhauer⁺ and P. Felix-Henningsen[°]

(* *Geographisches Institut, Universität Würzburg, Am Hubland, D(W)-8700 Würzburg, Germany*; ⁺ *Fachbereich VI Geographie/Geowissensch., Universität Trier, D(W)-5500 Trier, Germany*; [°] *Institut für Geographie, Universität Münster, Robert-Koch-Str. 26, D(W)-4400 Münster, Germany*)

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Abstract: The mineralogical and chemical characteristics of fulgurites (= natural glasses formed by lightning strikes to the ground) from the southern Central Sahara (Niger) are presented. The fulgurites are indicators of thunderstorms. The northernmost important fulgurite formation in the study area reached up to about 18°N, with decreasing fulgurite concentration from south to north. Their distribution pattern and the relative dating of their formation in relation to landscape history from the Late Pleistocene onwards (e.g., palaeolakes, palaeosols), and to Neolithic settlement reveals their value as palaeoenvironmental indicators. They indicate: (1) local palaeoenvironmental conditions depending on the topographical situation in a complex dune relief; (2) climatic change during the mid-Holocene from northerly rains to southerly rains; and (3) the northernmost limit of important thunderstorms and rainfall activity since this time in the southern Central Sahara.

Key words: fulgurites, lightning, thunderstorms, Sahara, Holocene, climatic change, palaeosols, Neolithic.

Introduction

Fulgurites are formed by the melting and rapid solidification of mineral substrata (mostly quartz sands) during lightning strikes to the ground (latin '*fulgur*' = lightning). The term 'fulgurite' was apparently first used by Withering (1790; cited by Harland and Hacker, 1966). Fulgurites are nonvolcanic, natural glasses like impactites and tectites (Feldmann, 1988). They figure as irregular tubular-shaped vitreous formations and their configuration attests to the lightning path through the ground. As they are real glasses, fulgurites are very resistant to weathering. Usually they are well preserved under natural conditions and may attest to fossil lightning strikes to the ground even after a long lapse in time.

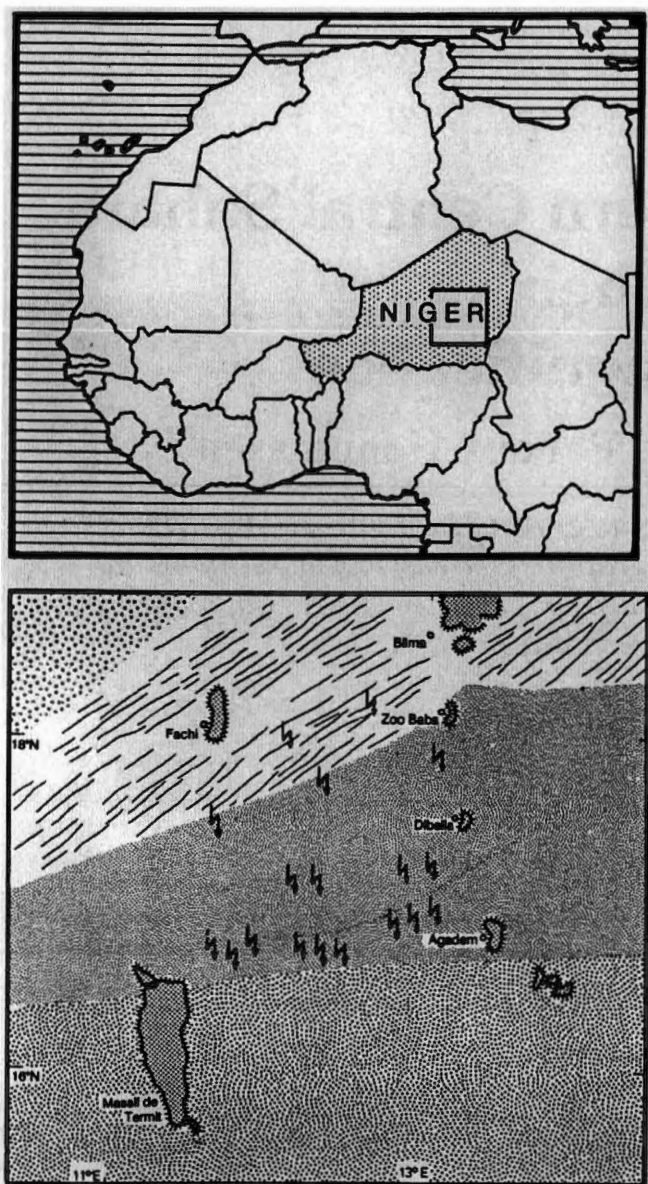
The distribution pattern of fulgurites also represents the distribution pattern of former thunderstorms/lightning strikes to the ground. Therefore, in this study they are taken as indicators of thunderstorm/lightning strike activity in the southern Central Sahara from the mid-Holocene on (relative dating).

Topographic situation

The fulgurites described in this article were found in the Grand Erg de Bilma and in the Erg de Ténéré between 11.5°

and 13.5°E and 16.5° and 18.5°N (Figure 1). These two Ergs show the typical geomorphological features of the southern Central Sahara plains: extensive sand sheets which grade into trade wind-oriented dune fields farther to the south and are interrupted by N-S-oriented cuestas that sometimes take the shape of isolated massifs or plateau remains. These cuestas link the plateaux surrounding the Murzuk Basin in the north and the fossil dune complexes of the Lake Chad region in the south.

The fulgurite sites are concentrated in the area of fossil dune complexes of the southern Sahara and northern Sahel. The dune complexes accumulated during an arid period before 15 000 BP ('*Karémien*' after Servant, 1983). On these ancient dunes, relicts of palaeosols are well preserved near rock outcrops and cuestas, as well as in middle and lower slope areas of the interdune depressions within the ergs. In such leeward positions, palaeosols were affected by only relatively weak deflation during later periods of aridity. The yellow-brown (10 YR 5/6 dry) to red-brown (5 YR 5/8 dry) relicts of cambic B horizons, overlain by mobile aeolian sand sheets and longitudinal dune ridges, display an increasing intensity of rubefication and increasing thickness (about 1 m near Bilma to more than 2 m at the Massif de Termit) from north to south. According to the pedostratigraphical results of Grunert (1988) and Völkel (1989), these palaeosols developed during the Late Pleistocene to early Holocene wet



-  fulgurites
-  escarpments
-  serir
-  active linear dunes
-  without vegetal cover
(older dune complexes)
-  with disperse vegetal cover

Figure 1 The study area in eastern Niger. Fulgurites are most common in the fossil dune complexes of the southern Sahara. The distribution pattern of lightning symbols shows the decrease in fulgurite concentration to the north. Definite results on fulgurite concentration in the vegetation-covered fossil dunes farther to the south are not yet available.

period between 14 000 and 7000 BP ('*Tchadien*' of Servant, 1983). Palaeosols of the mid-Holocene (Neolithic) wet period, 6500–3500 BP (Michel, 1973) are more weakly developed (Völkel, 1989). They can only be identified on lee dunes of middle Holocene age at the cuestas.

In the lower parts of extended interdune depressions, ancient dune sands are white, due to bleaching under former reducing conditions. Together with diatomitic silt and clay deposits this indicates an early to mid-Holocene limnic trans-

formation of many of the depressions (Servant-Vildary, 1978; Baumhauer, 1986; 1990; 1991). The fulgurites occur topographically above the palaeolimnic deposits, in mid-slope positions. They are concentrated in a rim 2 to 5 m in vertical extent, around the interdune depressions. All fulgurite sites are characterized by the presence of a very poorly consolidated, bleached substratum in exactly the same position (cf. Lacroix, 1931/32) (Figure 2). It should be mentioned that large concentrations of Neolithic artifacts are also found at the fulgurite sites. The presence of the two phenomena in the fossil dune relief may reflect contemporaneous fulgurite formation and Neolithic settlement.

Methods

Analytical studies were made on fulgurite samples taken during an expedition to Niger in 1990.

Optical studies

Untreated fulgurite fragments were studied under the binocular microscope (Wild) at magnifications up to $\times 50$. The construction and characteristics of the central void surface and of the external surface were observed. From several fulgurites, thin sections (30 μm thickness) were made (longitudinal and cross sections). The thin sections were analysed under normal transmission light and under polarized light (Leitz Aristoplan Microscope).

Chemical analyses

Powder preparations of fulgurites were studied by X-ray analyses (Philips-Zählrohr-Goniometer, CoK_{α} -radiation), in the sector of 2° to $45^{\circ} 2\theta$. The total amounts of main and trace elements of bulk samples of fulgurites and the particular surrounding sandy material were determined by fluorescent X-ray analysis. The content of organic carbon was determined by a C/N analyser (Carlo-Erba).

The morphology and composition of fulgurites

The fulgurites were found as fragments up to 20 cm long at the surface, extending to a maximum depth of 10 cm (Figures 3–5). Evidently, their present-day distribution is either on the surface or parallel to the surface at a shallow depth. The localization of the fulgurites shows that they were formed in continuous, branching networks several meters in extent, similar to root networks of plants. This characteristic concurs with the results of Calas *et al.* (1965) and confirms the hypothesis of Schonland (1950) that the path of the lightning strike through the ground often follows plant roots.

The diameter of the fulgurites, which generally have an irregular four-point shape and sometimes a cylindrical cross-section, is 1–4 cm (Figure 4). A less than 3-mm thick crust of glassy SiO_2 may surround cristobalite and quartz grains in the cortex with a hollow tubular center, 1–2 cm maximum diameter. Enclosed air bubbles may give the glassy material a foamy structure (cf. Julien, 1901) (Figures 5–10).

The colour of the fulgurites varies between yellowish grey (2.5 Y 6/2), dark grey (5 Y 2/2) and black. Dark grey and black colours possibly result from coaly organic matter due to the burning of plant roots. The content of organic carbon amounts to about 0.1%. Manganese oxides, which also could cause a black colour, have not been detected.

The fulgurite fragments prepared as thin sections represent a variety of fulgurite types: white/grey/brownish, transparent/foamy/translucent (cf. O'Keefe, 1963). As it was already evident from the untreated samples, thin sections clearly

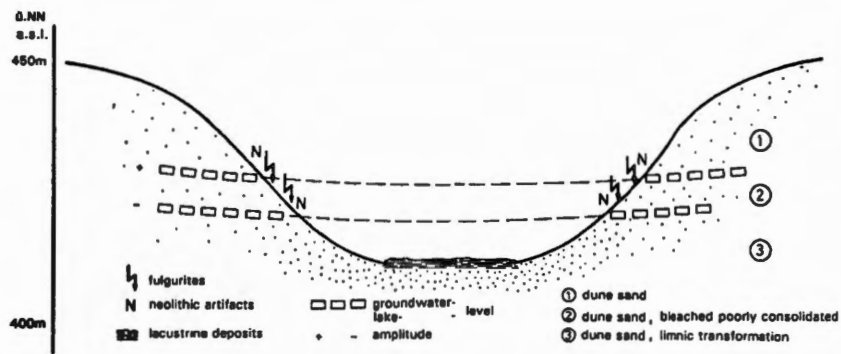


Figure 2 The topographic position of fulgurite sites in interdune depressions of the Grand Erg de Bilma and the Erg de Ténéré; their relation to Neolithic artifacts and to the bleaching/limnic transformation of the dune sands is shown.

show the glassy-foamy structure. The centre of the fulgurites is an open tubular-shaped space, 1–2 cm diameter, oriented along the longitudinal axis of the fulgurites (Figure 5). It may be subdivided by glass bridges. This central tube is surrounded by a layer of completely vitrified quartz, named 'lechatelierite' (Lacroix, 1915), consisting of 90–99% SiO₂ (Lacroix, 1931/32; Calas *et al.*, 1965) in which relatively large air bubbles (diameters up to several 100 μm), flattened parallel to the surface, are enclosed. This material has the tendency to break in screens. The glass 'structure' of the lechatelierite matrix is 'perfect' in that its differentiation from the object slide is difficult in normal transmission light and also in polarized light and must be made respectively to the space orientation in the sample preparation.

In the external parts of the fulgurites, the contours of the melted quartz grains are usually visible (Figures 7 and 10). According to the intensity of heat and pressure during the lightning strike, the former quartz grains are preserved in various states of transformation (types 2 and 3 were only identified in a few of the samples):

- (1) The most affected type is found close to the central void. Here, the former quartz grains were completely melted, but the glass melt did not flow. The grain contours remain

visible in the glassy matrix, but no quartz crystal structure is preserved (Figure 7).

- (2) In the outermost cortex of the fulgurites there are grains, the proximal parts of which were completely melted as described in (1); distal parts of these grains were transformed into cristobalite with its typical 'Ballenstruktur' (agglomerated structure) (Pichler and Schmitt-Riegraf, 1987) (Figure 10).
- (3) Grains on the outside of the fulgurites and others that are enclosed in 'pockets' were completely transformed into cristobalite. These grains evidently did not suffer complete melting.

Another characteristic of fulgurites is the air bubbles enclosed in the glassy matrix, which may be so numerous that they give the material a foamy structure (cf. Julien, 1901). Due to weathering of the surface of the central void the air bubbles may be exposed. This results in many small depressions which give a matt appearance to the otherwise glossy surface. The air bubbles also present in a variety of forms from the inner to the external parts of the fulgurites:

- (1) Near the central void there are fewer but relatively larger

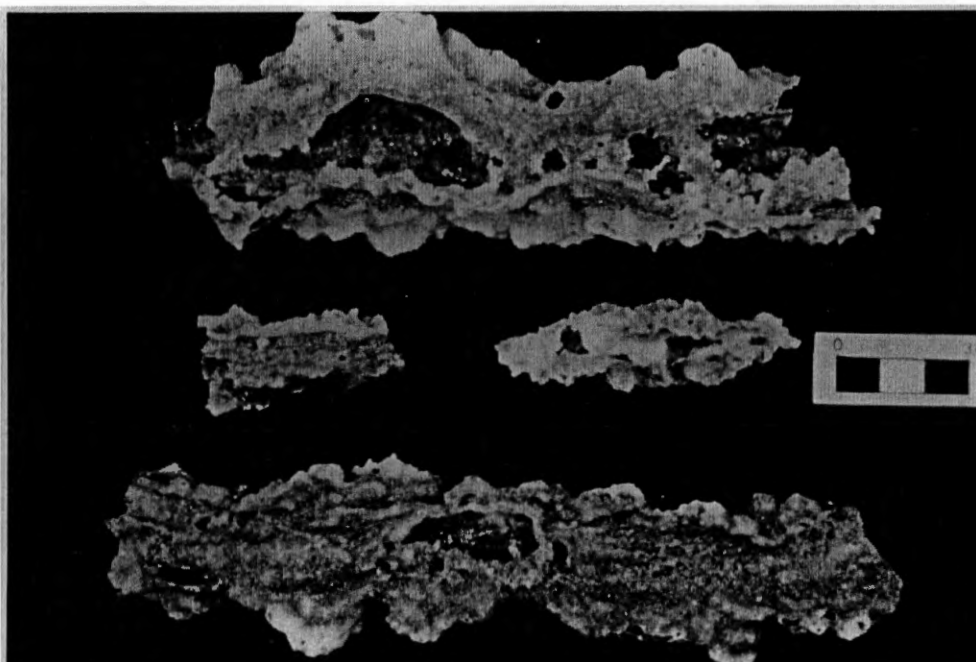


Figure 3 Fulgurites from the Grand Erg de Bilma (Niger). Scale bar = 3 cm.

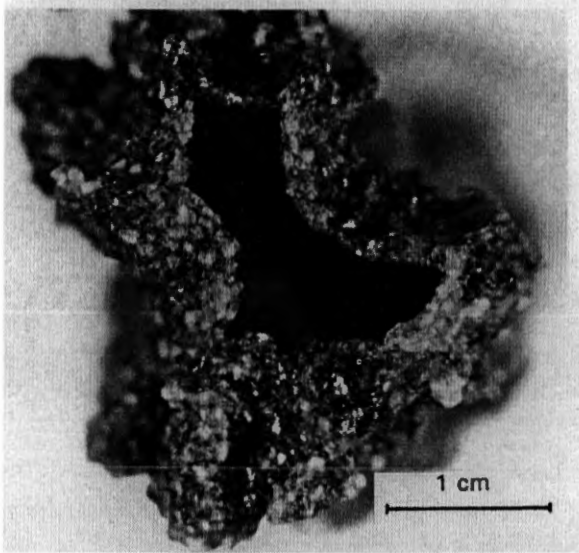


Figure 4 Cross section of a fulgurite. The lechatelierite matrix and the cortex of melted and partially transformed quartz grains surround the central tubular void. The four-point shape was formed during the collapse of the central void, caused by the surrounding pressure immediately after the lightning passage and substrate melting.

air bubbles. Their diameters are up to several 100 μm and they are flattened parallel to the surface (Figure 8).

- (2) In the external parts there are higher concentrations of many small air bubbles (diameters up to 50 μm ; Figure 9). They may be spheroidal or elongated perpendicular to the surface. First, this shows the pressing of the bubbles towards the cortex during the formation of the central void; secondly, it indicates a shorter period of melting in the external parts, inhibiting gas evacuation or combination of the air bubbles.

In the glassy lechatelierite matrix, at some distance from the central void (distance >100 μm) there are flow structures

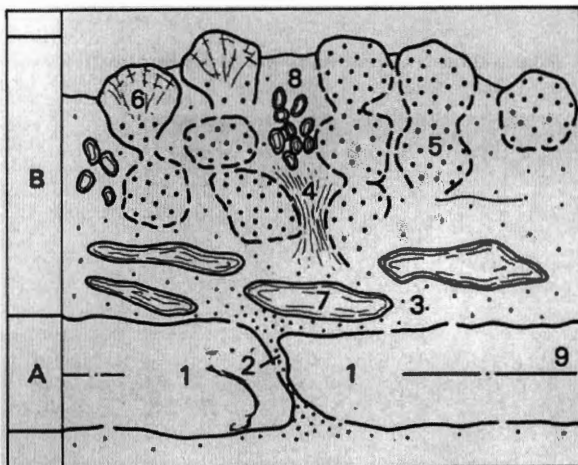


Figure 5 Longitudinal section of a fulgurite (schematic):

- (1) central tubular void, parallel to the longitudinal axis of the fulgurite (9), diameter 1–2 cm (A);
 (2) glass bridge (lechatelierite);
 (3) lechatelierite matrix (Figure 6);
 (4) flow structures (Figure 6);
 (5) former quartz grains, melted with preserved contours (Figure 7);
 (6) quartz grains, partially transformed into cristobalite (Figure 10);
 (7) large flattened air bubbles near the central void (Figure 8);
 (8) small air bubbles (Figure 9);
 (9) longitudinal axis of the fulgurite;
 (A) diameter of the central tubular void: 1–2 cm;
 (B) thickness of the fulgurite crust: 3–4 mm maximum.

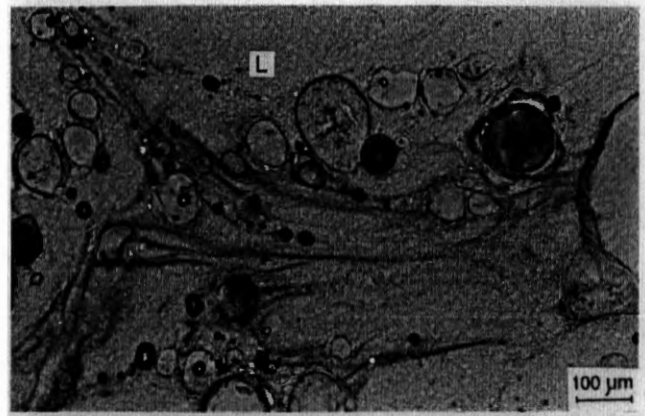


Figure 6 Lechatelierite matrix (L) with flow structures and enclosed air bubbles. (All photographs are taken from thin sections; normal transmission light).

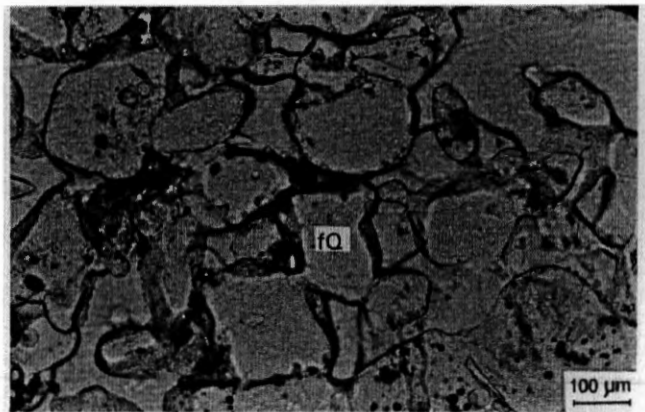


Figure 7 Former quartz grains (fQ), melted and solidified with preservation of their contours.

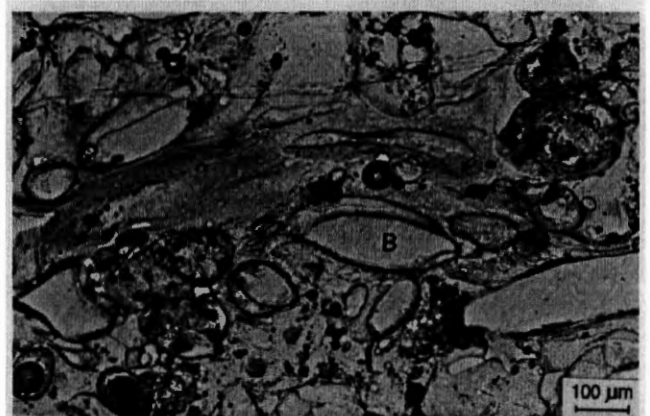


Figure 8 Large flattened air bubbles (B) near the central void. The air bubbles are surrounded by lechatelierite matrix with air bubbles and microlites.

containing nonspecified iron compounds which give a brownish colour and make them more visible (Figure 6). These structures reflect the melt flow, which resulted from the melting of the substratum, and the outward pressure during the explosion-like extension of pore air and pore water in the tubular central void (= lightning path) after the lightning strike. Where the glassy matrix reaches the surface of the fulgurites, there are often overturned grains indicating the movement of the melt. Completely carbonized remains of

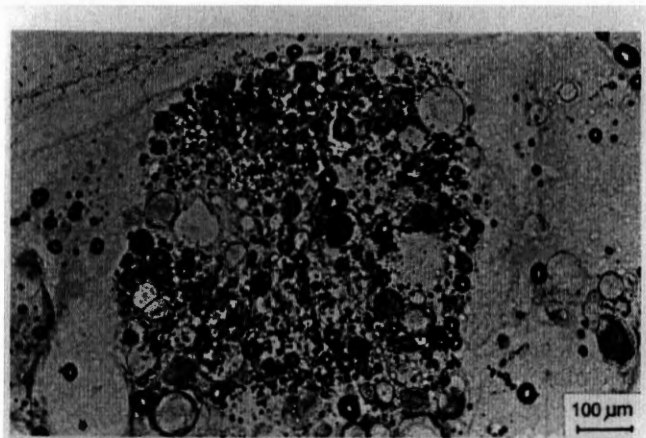


Figure 9 Small air bubbles in the cortex of a fulgurite, giving the lechatelierite matrix a foamy structure.

organic matter may also be enclosed in the external parts of the glassy matrix.

X-ray analyses of powder preparations of fulgurites only showed minor peaks between 3.2 and 5.7 Å indicating amorphous material without further specification. In the X-ray analysed samples, there were no signs of crystallized material. The cristobalite mentioned above was only detected by thin section studies.

The total amounts of main and trace elements from bulk samples of fulgurites and from the surrounding sandy material were determined by fluorescent X-ray analysis (Table 1). Fulgurites at Zoo Baba (Z 24) were found some metres above a bank of a palaeolake within a corrugated relict of a yellowish brown (10 YR 6/6) cambic B horizon overlying a light yellow (10 YR 8/4) C horizon. In both horizons, hydromorphic characteristics are still absent. Samples of the Grand Erg de Bilma between Zoo Baba and the Massif de Termit (T) were collected at sites with hydromorphic bleaching of dune sands. The dune sands as well as the fulgurites show a predominance of SiO₂. Compared with the surrounding sand, all fulgurites display lower concentrations of Al, Fe, Ti and Zr. Total element analyses of about 100 samples of palaeosols on fossil dunes indicate Zr concentrations between 150 and 800 mg kg⁻¹; the majority of them have concentrations between 250 and 500 mg kg⁻¹.

Formation of fulgurites

Based on the fact that *in situ* fulgurites indicate the point of lightning strikes to the ground and the lightning path through the ground, we must suppose that the concentration of fulgurites in the mid-slopes of interdune depressions indicates

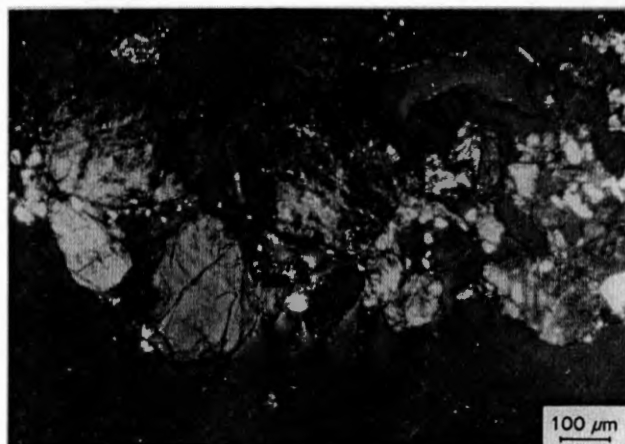


Figure 10 Thin section of the external part of a fulgurite. The glassy lechatelierite matrix is seen in the upper part of the photograph. In the middle, there are quartz grains that are partially transformed into lechatelierite or into cristobalite. The lower part of the photograph shows the sample porter (polarized light).

a high frequency of lightning strikes in this topographical position.

The localization of lightning strikes depends on two processes (Gary, 1989):

- (1) The formation of a strong electric field inside the thundercloud where, normally, positive charges are localized in the upper parts of the cloud and negative charges in the lower parts. The electrical discharge is effected by lightning. According to Moore and Vonnegut (1977), the cloud must be 3–4 km thick for the build-up of sufficient electrical charge. Strong convection, precipitation and a rapid vertical development are also important. Moore and Vonnegut estimate precipitation in the order of 3 mm hr⁻¹ is sufficient for lightning discharge. Proctor (1991), however, remarks that lightning strokes to the ground in particular are related to heavy rains, with the highest lightning activity at the borders of rain centres.
- (2) The lightning discharges from the cloud to the ground and therefore the localization of the lightning strike is based on the condition that a negative electrical charge exists not only at the cloud base but also at the ground surface. Just before the lightning discharge there is an inversion of the positive earth-surface charges (normally about 100–150 V m⁻¹) into negative charges, combined with an enormous multiplication of the charge up to -10 to -15 kV m⁻¹ at the same time. This change in electrical charge conditions enables the lightning strike to the

Table 1 Element contents and TiO₂/Zr ratios (Ti/Zr) of bulk samples from fulgurites (Fu) and the surrounding dune sand (Bw horizon, C horizon) of sites near Zoo Baba (Z) and the Massif de Termit (T).

Profile Sample	Z 24 Bw	Z 24 C	Z 24 Fu	T 2 C	T 2 Fu	T 3 C	T 3 Fu	T 4 C	T 4 Fu
SiO ₂ (%)	98.20	97.23	98.23	97.90	98.40	96.73	98.56	96.87	98.9
Al ₂ O ₃ (%)	0.92	0.82	0.42	0.81	0.66	1.46	0.45	1.32	0.66
Fe ₂ O ₃ (%)	0.25	0.11	0.06	0.12	0.12	0.45	0.10	0.37	0.13
TiO ₂ (%)	0.10	0.07	0.03	0.10	0.06	0.23	0.04	0.21	0.07
Zr (ppm)	294	261	52	337	134	405	43	622	92
Ti/Zr	0.34	0.27	0.58	0.30	0.45	0.57	0.93	0.34	0.76

ground. Its final destination is fixed only at the last moment, because the negative ground charge is 'drawn towards' the lightning. The electrical charge equilibrium between the cloud and the earth's surface therefore depends on the electrical field on the ground that is next to the descending lightning discharge being stronger than the surrounding electrical fields (Gary, 1989). 'St-Elmo's Fire' and the high risk of lightning strike at exposed topographical points (Müller-Hillebrand, 1960) are related to this phenomenon.

In the lightning channel from the cloud to the ground, temperatures between 20 000 and 30 000°K were measured (Gary, 1989), in the lightning path through the ground, temperatures up to 3000°C are mentioned by Feldmann (1988). The single steps of the whole process take only several milliseconds each. During the explosion-like extension of soil air and soil water in the area of the lightning path during the lightning strike, the central tubular void is formed and the molten material is pressed to the exterior. The glass melt solidifies immediately with the rapid subsequent cooling (100°C s⁻¹; Feldmann, 1988). At the same moment, the surrounding pressure becomes effective and may cause the collapse of the tubular void. This effect explains the common four-corner shaped cross-section of the fulgurites (Schonland, 1950).

According to Norin (1986), the electrical resistance and the presence of soil water are important in determining the path lightning takes through the ground. Norin, who investigated lightning effects on rock surfaces in Sweden, explains that these factors orient the lightning paths along existing zones of weakness such as water- or clay-filled fissures. Prentice (1977), too, insists on the importance of topographical features and ground discontinuities such as faults, groundwater currents or river borders in the distribution pattern of thunderstorms and lightning strikes.

The discrepancy in the element concentrations between sand and fulgurites (Table 1) indicates that the fulgurites were not formed merely by the melting of sand. Due to different melting and volatilization temperatures of quartz, Al-silicates and Ti- as well as Zr-bearing heavy minerals, a differentiated redistribution and an enrichment of mobilized elements within the glassy matrix of the fulgurites must have occurred. The heavy mineral Zircon, which is most stable with respect to temperatures of melting (about 2700°C) and volatilization (about 5000°C) (Wearst, 1976), remained relatively unaffected. Redistribution and enrichment of the element Zr within the fulgurites was therefore relatively weak. An overproportional enrichment of silica and other elements caused a dilution of Zr in the glassy substance. Mass balances with Zr as an index element (Table 2) are hypothetical in character, because they assume that Zr remained completely immobile during the lightning strike. However, balances of all

Table 2 Mass balances of fulgurites against the surrounding sand of sites near Zoo Baba (Z) and the Massif de Termit (T) with Zr as index element; enrichment of element oxides in %.

Sample	Z 24	T 2	T 3	T 4
SiO ₂	407	152	859	590
Al ₂ O ₃	156	105	190	238
Fe ₂ O ₃	173	151	109	137
TiO ₂	115	51	64	125
Zr	0	0	0	0

sample pairs display the highest enrichment for Si and the lowest for Ti, which corresponds with the differences in temperatures for melting and volatilization, which are lower for quartz and Al-silicates (1100–1600°C/2230–2590°C respectively) and higher for Ti-minerals (e.g., rutile: 1850°C/2500–3000°C) according to Wearst (1976) and Deer *et al.* (1977).

Discussion

According to the distribution pattern of the investigated fulgurite sites we can say that in the mid-slope position of interdune depressions in the southern Sahara, strong electrical fields were built up which were stronger than those in the surrounding dunes that reach 10–20 m above the fulgurite zone. Discontinuities of the geological bedrock are unlikely to account for this phenomenon. On the contrary, the fossil dune complexes (the substratum) are quite homogeneous, covering the bedrock over almost the whole study area. Also, the large scale distribution pattern of the fulgurite sites does not indicate any relationship to geological variation, and an ancient relief completely different from that of today is unlikely to have been the reason for the electrical field configuration.

We suppose that the formation of the electrical field, and so the passage of the lightning through the ground, were determined by the hydrological setting. The fulgurite rim corresponds almost exactly with the limit between groundwater/lakewater level in the dune bodies and the dry dune sands lying above. The groundwater level may not have been much higher than the lake level because the capillary rise of groundwater in the dune sands remained limited. Therefore, we can only partially agree with the remark of Moore and Vonnegut (1977) that fulgurites are the result of lightning strikes in dry sands. Rather, we concur with the remark of Schonland (1950) that many fulgurite sites indicate palaeoclimatological conditions which were different from the present-day climate and that some humidity in the substratum is necessary for fulgurite formation (Lacroix, 1931/32; Harland and Hacker, 1966).

On the other hand, the existence of soudanian vegetation in the southern Sahara during the early Holocene wet period with a maximum of humidity between 10 000 and 7500 BP must also be taken into consideration (Schulz, 1987; Neumann, 1988). For instance, the root systems of high trees, whose crowns may have dominated the surrounding dunes, would have allowed the passage of the lightning strikes to the mid-slope areas. The study site of the oasis of Fachi contains several tree species (Neumann, 1988) which are common at the borders of ephemeral rivers in the Sahel today (e.g., *Acacia albida*) or even in the Guinean zone. This second possible explanation also indicates the position of the lake/groundwater level in the mid-slope position of the interdune depressions.

As already mentioned above, the fulgurites were found exclusively as fragments at or close to the present-day surface. Nevertheless, the coincidence of fulgurites and the extremely poorly consolidated bleached substratum with the Neolithic artifacts and also the arrangement of the fragments in easily reconstructable networks show that they have not been transported far since the time of their formation. The present-day position at the surface may be explained by deflation of former overlying dune sands and soils. Deflation may be regarded as one reason for the fragmentation of the mechanically low-resistant fulgurites, because it took away the mechanically supporting sands. Also, trampling by man and

animals since Neolithic times around the water points in the dune depressions might be taken into considerations.

There exists many publications which treat of Late-Pleistocene and Holocene climatic conditions in the Sahara. These range from palaeoclimatic modelling (e.g., Kutzbach, 1980; Adams and Tetzlaff, 1984) to the palaeoclimatological interpretation of geomorphological and hydrological data (e.g., Busche, forthcoming; Durand and Lang, 1986), and hydrobiological data (Servant-Vildary, 1978; Baumhauer, 1986; 1990; 1991; Gasse, 1987). Fulgurite distribution patterns allow some conclusions concerning regional palaeoclimatological conditions in the study area during their formation (according to their topographical position related to Holocene lacustrine sediments and Neolithic artifacts, respectively during the mid- and the late-Holocene).

On a large scale, the fulgurite sites characterize a region of important thunderstorm activity and contemporaneous soil humidity in present-day (hyper-)arid regions of the southern Sahara. The present-day annual rainfall recorded at nearby weather stations are: Bilma 19.8 mm yr⁻¹, Agadez 146.6 mm yr⁻¹, N'Guigmi 225.6 mm yr⁻¹ (Annuaire Météorologique du Niger, 1981–85). Because of the increasing continentality to the east, estimated annual rains of 20 to 50 mm in the study area seem realistic. Supposing that the northward displacement of thunderstorm activity depends on increased advection of humid air masses reaching the same latitude, we can conclude that during the time of fulgurite formation an advective rain regime reached the latitude of Zoo Baba/Dibella. This was similar to the present-day rainy season during summer in the Sahel under monsoonal climatic conditions. Transferred to the mid- and late-Holocene wet periods, the modern decrease in advection to the north and the same decrease in annual rains (Rowell and Blondin, 1990) would explain the minor fulgurite concentration to the north. This corresponds with the zonality of palaeosol characteristics (e.g., Figures 11 and 12), indicating a decrease in weathering intensity and in the duration of humid conditions during the late-Holocene wet period from south to north.

The extreme disaggregation and the bleaching of the dune sands in the fulgurite rim indicates a relatively long-term stable groundwater level. Durand and Lang (1986) assume a high groundwater level north of Lake Chad during the period from 9500–6500 BP (*Nigéro-Tchadien inférieur*), but also – under different climatic conditions – until 4000 BP. The zone influenced by soilwater/groundwater of which the upper limit sustained lightning strikes (indicated by the lightning paths

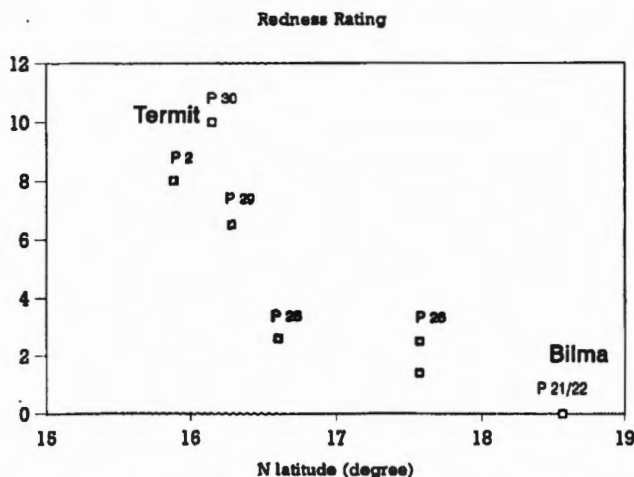


Figure 11 Redness rating (Schwertmann *et al.*, 1983) versus latitude of autochthonous cambic B horizons of late-Holocene palaeosols in the Grand Erg de Bilma.

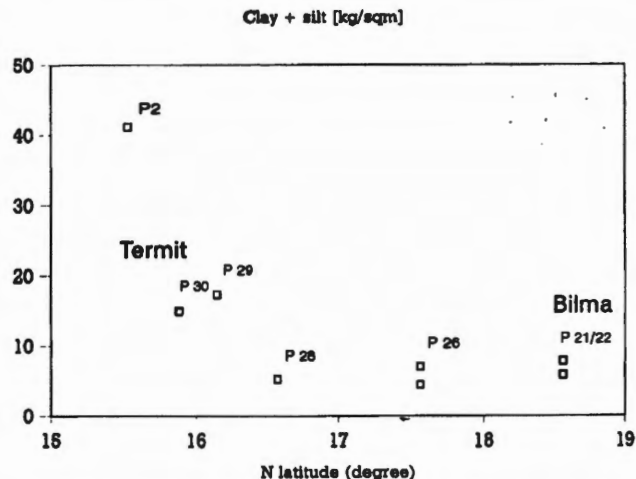


Figure 12 Quantities of fines (clay + silt) in autochthonous cambic B horizons of late-Holocene palaeosols in the Grand Erg de Bilma.

through the ground), must have been dominated by up to 20 m high, dry dunes.

Therefore, even when relatively heavy rain fell farther north than today during the time of fulgurite formation, in the same area there must have existed dry dunes without vegetation cover. Indeed, our palaeolimnological studies in the Grand Erg de Bilma indicate a wet period with open water or swampy areas near mobile dunes for both the early and mid-Holocene (Baumhauer, 1991). Today we find similar conditions in the 'Desert du Tal', northwest of N'Guigmi where during the recent climatic variations there was a permanent zone of active (immobile) dunes with north Sahelian vegetation cover nearby (indicated by aerial photographs from the 1960s and field studies during 1987 and 1990).

The results discussed above concern the study region of the 1990 expedition. Fulgurites without further specification of the regional or local context are reported by Calas *et al.* (1965) from the Sahara and by Gardi (1978) from the Manga region north of Lake Chad. Up to now there are no reports of fulgurites from the modern Sahel zone south of 14°30'N. To ascertain whether fulgurites are truly absent in this zone, or whether they are not found because of the vegetation cover or have been destroyed by land cultivation, requires further investigations.

Conclusions

On the basis of the studies presented above we are able to reach conclusions about the activity of seasonal advection and convection with thunderstorm activity and heavy rains in the region of the southern Sahara during the mid- and late-Holocene. The northern limit of important thunderstorm activity was situated at about 18°N, at the latitude of the oases Zoo Baba and Dibella. The large-scale distribution pattern of the fulgurite sites and their northward decreasing concentration in the study area reflect the south-to-north decrease of thunderstorm frequency and intensity. A corresponding decrease of the annual rains was probably related to this.

The thunderstorm and rain distribution in the study area is easy to explain supposing a monsoonal climatic regime which prevails today in the Sahel farther south. So the fulgurites of eastern Niger attest to pluvial conditions dominated by the southern regime in the mid-Holocene. This was followed by increasing aridity during the late-Holocene (cf. Baumhauer, 1990). Considering the uncertainties indicated by the relative

dating of the fulgurites, this conclusion concurs with the results of other studies in the domains of morphopedology (Grunert, 1988; Völkel, 1989), palaeobotany (Schulz, 1987; Neumann, 1988) and palaeoclimatology (e.g., Servant, 1983; Durand and Lang, 1986), which indicate a transition during the mid-Holocene from rains coming from the north to rains coming from the south.

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The expedition during which field studies and sampling were

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