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Letter

Lightning-induced shock lamellae in quartz

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Abstract

Using transmission electron microscopy we show that planar deformation lamellae occur within quartz in the substrate of a rock fulgurite, i.e., a lightning-derived glass. These lamellae exist only in a narrow zone adjacent to the quartz/fulgurite boundary and are comparable to planar deformation features ("shock lamellae") caused by hypervelocity impacts of extra-terrestrial objects. Our observations strongly suggest that the lamellae described here have been formed as a result of the fulgurite-producing lightning strike. This event must have generated a transient pressure pulse, whose magnitude, however, is uncertain at this stage.

Keywords: Shock lamellae, fulgurite, lightning, planar deformation features, transmission electron microscopy

Introduction

On average, a total of nearly 1.4 billion lightning discharges occur annually around the globe, equivalent to an average of 44 ± 5 lightning flashes per second, of which approximately 10% are typically ground strikes (Christian et al. 2003). Cloud-to-ground lightning strikes are highly energetic and very short events (millisecond range; see Rakov and Uman 2006; Uman et al. 1978) with peak lightning currents that are typically on the order of tens of kA (MacGorman and Rust 1998), but may exceed 200 kA (Rakov and Uman 2006). As the electrical resistance of air at ambient temperature is large, the air is rapidly heated when such large currents flow through it (MacGorman and Rust 1998), leading to instantaneous peak air temperatures of 25 000–30 000 K (Rakov and Uman 2006). Highly energetic lightning can dissipate a total of 1–10 GJ over the extensive channel in a cloud, of which 1–10 MJ are estimated to be delivered to the strike point (Borucki and Chameides 1984; Rakov and Uman 2006). This energy transfer may cause rapid heating of the target material to temperatures above 2000 K (Essene and Fisher 1986; Frenzel et al. 1989; Pasek and Block 2009) as well as rapid physical and chemical changes (Appel et al. 2006; Essene and Fisher 1986; Frenzel et al. 1989; Pasek and Block 2009), and results in the formation of fulgurites, i.e., natural glasses produced by fusion of rock, unconsolidated sediments, or soils through cloud-to-ground lightning (Pasek et al. 2012). As the energy transfer is so fast, high-energy lightning flashes may also cause high pressures (>10 GPa?) when they strike the ground, possibly leading to shock metamorphic effects in the target material (Collins et al. 2012; Frenzel et al. 1989; Wimmenauer 2003).

The aim of this study is to report evidence, collected using transmission electron microscopy (TEM), for the presence of shock lamellae in a quartz crystal, which forms the substrate of a rock fulgurite found at Les Pradals, France. In this brief paper, we will not present the mineralogical and microstructural details of the actual fulgurite.

Materials and methods

Polished thin sections (~ 30 μm thick) of a hand specimen from Les Pradals, France, were first investigated with a petrographic microscope, using plane-polarized, cross-polarized, and reflected light. Subsequently, one of the thin sections was coated with 20 nm of carbon and studied in backscattered electron (BSE) mode with a CAMECA SX-100 electron microprobe (EMP) equipped with five wavelength-dispersive crystal spectrometers, which were used for quantitative chemical analysis of individual minerals in the granite substrate and of the fulgurite matrix. The analytical conditions were as follows: an acceleration voltage of 15 kV; a beam current of 10 nA, measured on a Faraday cup; and a beam diameter of 3–8 μm. Synthetic and natural international reference materials were used as standards. Due to the porous structure of the fulgurite matrix, chlorine was analyzed to monitor the influence of the embedding epoxy, but its contents usually lay below the detection limit. Counting time on peak positions was 8–10 s (to keep heating of the delicate glass structure as low as possible), and typically half of that on the background positions on either side of the peaks. The raw data were corrected using the PAP procedure (Pouchou and Pichoir 1984).

Foils used for the TEM investigation were cut from one of the studied thin sections using an FEI FIB200 focused ion beam (FIB) milling instrument (Wirth 2004). The areas to be cut were coated with a 1 μm thick platinum layer to reduce charging and cut using 30 kV gallium ions. The cuts were made perpendicular to the surface of the carbon-coated thin section, yielding TEM-ready foils (~15 × 10 × 0.15 μm), which were placed onto a lacy-carbon copper grid.

The TEM investigations were carried out at 200 kV with a FEI Tecnai F20 X-Twin instrument, equipped with a high-angle annular dark-field detector and an energy-dispersive X-ray spectrometer, which allowed for qualitative compositional analysis.

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Results and discussion

Field observations

At Les Pradals, Commune de Mons, Département Hérault (France), lightning struck a coarse-grained granitic rock (grain size: 5–10 mm across) consisting of quartz, potassium feldspar, albite, muscovite, and bluish tourmaline (schorl), as well as accessory Mn-rich almandine garnet, apatite, and zircon. The studied fulgurite occurrence is one of several similar finds, formed by lightning impact on granite and metamorphic rocks of the region, and testifies to the extraordinary violence of such events.

The outcrop shown in Figure 1a has been blown apart along earlier fissures, scattering meter-sized angular blocks in the dense brushwood vegetation surrounding it. The rock body left in place shows blackish decorations on all prominent edges and fractures and exhibits similar dark crusts on the adjoining surfaces (Figs. 1b and 1c). These crusts terminate typically along the edges of quartz or feldspar fracture planes and may be reduced to small droplets on exposed crystal faces (Fig. 1d). Documented lightning strikes have produced similar blast characteristics and vitreous surface coatings on silicate rocks and masonry in the Schwarzwald ("Black Forest", Germany), Vosges (France), and other regions (Appel et al. 2006; Müller-Sigmund and Wimmenauer 2002; Wimmenauer 2003, 2006; Wimmenauer and Wilmanns 2004; Gieré, unpublished work). The continuous surface coatings of the Les Pradals fulgurite cover areas of several square centimeters to square decimeters and exhibit a thickness of only a few tens of micrometers. This appearance is distinct from typical rock fulgurites, which are melt coats limited to small impact spots (Frenzel et al. 1989; Grapes and Müller-Sigmund 2009; Pasek et al. 2012).

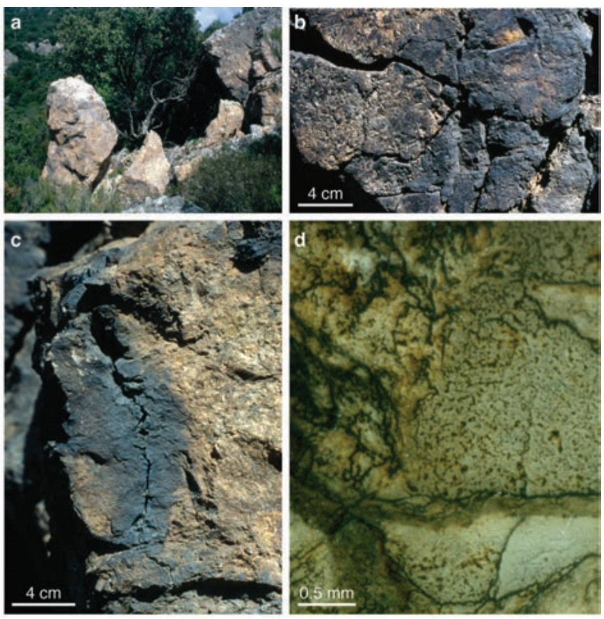

Figure 1. Photographs taken at the studied fulgurite locality near Les Pradals, France. (**a**) Photograph of the lightning-fractured outcrop. The surfaces facing the observer in upper right are covered with black fulgurite. The block in the left foreground is approximately 2 m high. (**b**) Detail of rock surface covered with the dark fulgurite coating. (**c**) Fracture blackened by the lightning, which caused the black fulgurite coating. (**d**) Detail of a feldspar surface, which is partially covered with dark, glassy fulgurite coatings in the form of narrow decorations (left side of image) and small droplets (right side). The pattern of black decorations seen in the upper left corner (photograph taken by P. Rustemeyer) is reminiscent of a Lichtenberg figure. (Color online.)

Characterization by optical and scanning electron microscopy

Observation with an optical microscope shows the blackish coating noted in the field to be a thin, nearly opaque layer (Fig. 2a) of fairly constant thickness, only locally exceeding 50 µm (Figs. 2b and 2c). The fulgurite layer consists of an optically isotropic matrix, in which many small (<1 µm to several micrometers across) non-isotropic mineral inclusions are embedded. The matrix also contains black, carbonaceous particles, which cause the observed opacity.

Examination of polished sections by reflected light microscopy revealed that the fulgurite layer is highly vesicular, a typical feature of fulgurites caused by vaporization of rocks struck by lightning (Essene and Fisher 1986; Frenzel et al. 1989; Frenzel and Ottemann 1978; Grapes and Müller-Sigmund 2009; Martin Crespo et al. 2009). This vesicular appearance is also observed in BSE images, which further reveal that the fulgurite layer is heterogeneous, showing strong grayscale contrast due to variations in the mean atomic number of the phases present (Figs. 2b and 2c). Fractures cut parts of the layer or, in some cases, the entire fulgurite layer (Fig. 2c). In some places the fulgurite layer is separated from the granitic substrate by cracks, which are roughly parallel to

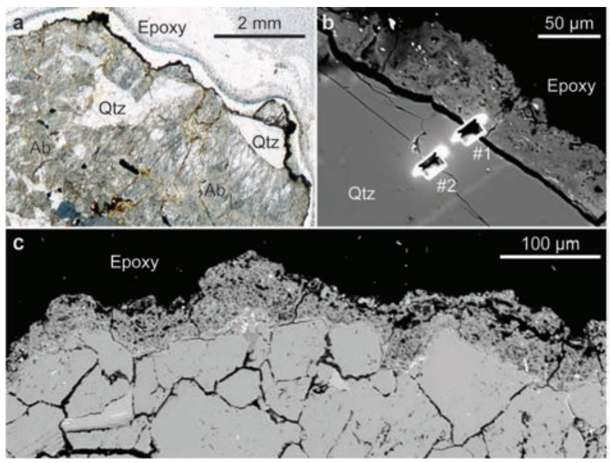

Figure 2. Photomicrographs of the boundary between the fulgurite layer and its substrate. (**a**) Thin section photograph, taken in plane-polarized light, showing the granitic rock (lower left part of image) and the opaque to dark brown, thin fulgurite coating, which traces the original rock surface. The granite is composed of clear quartz, turbid albite, and bluish tourmaline (bottom left). Opaque areas within the rock are carbon-coating relics. (**b**) BSE image of fulgurite rim (spongy texture) on quartz. It shows fractures crossing the fulgurite layer, a crack separating it from the quartz substrate, and the two locations from which focused ion beam foils were cut (no. 1, no. 2). Deformation bands were only seen in the foil from position 1; (**c**) BSE image of foamy fulgurite layer mainly on quartz substrate. Fulgurite contains inclusions of mineral fragments and micrometer-sized bright spheres of variable composition, interpreted as captured fly ash particles. Abbreviations: Qtz = quartz; Ab = albite. (Color online.)

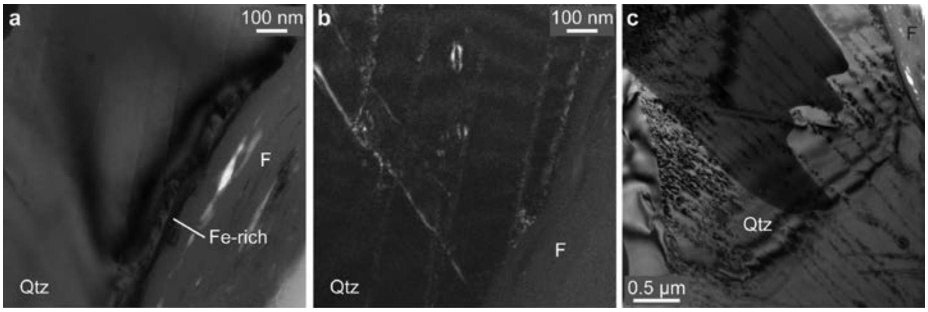

FIGURE 3. TEM images of the granite/fulgurite interface. (**a**) Bright-field image showing planar deformation lamellae in quartz (left), an iron-rich zone at the interface with the fulgurite layer (dark, labeled as "Fe-rich"), and the amorphous fulgurite with pores (bright lenticular features); (**b**) dark-field image, obtained using (01$\bar{1}$0) of quartz, of the same area as that displayed in **a** showing the planar deformation lamellae in quartz as set of bright, parallel bands crossing the image from upper right to lower left; (**c**) overview bright-field image showing undamaged quartz on the extreme left, separated from lightning-damaged quartz by a sharp boundary, and the fulgurite layer in the upper right. Dark shadow is an artifact due to the FIB sample preparation. Image **a** shows detail from the upper right part of image **c**, but it was taken first and thus, does not show the electron beam damage to the lamellae seen in image **c**. Abbreviations: Qtz = quartz; F = fulgurite.

the substrate surface (Fig. 2b). These cracks were most probably caused by sample preparation.

Fulgurite composition

The chemical composition of the fulgurite matrix was determined by spot analyses using an EMP. As a result of the high porosity of the fulgurite layer (Fig. 2c), the analytical totals of the EMP data are low, typically between 80 and 90 wt%. The glassy fulgurite matrix contains on average 69 ± 6 wt% SiO_2 and is poor in total alkalis (Table 1), and thus may be classified as dacite according to the Na_2O+K_2O vs. SiO_2 nomenclature of Middlemost (1994). The composition of the fulgurite matrix is relatively homogeneous, and the concentrations of CaO, Na_2O, and K_2O are always low, irrespective of the substrate mineral (quartz, albite, potassium feldspar, or muscovite). The elevated contents of P_2O_5 and SO_2 (Table 1) cannot be attributed to these substrate minerals and thus, given the presence of lichen on many surfaces not covered by fulgurite, may result from biogenic material present on the rock surface at the time of the lightning strike. A relatively high phosphorus content, however, is not unusual for fulgurites (Grapes and Müller-Sigmund 2009; Martin Crespo et al. 2009; Pasek and Block 2009; Pasek et al. 2012). We were unable to determine the bulk carbon content of the fulgurite layer at Les Pradals due to its extreme thinness. However, another fulgurite we studied from the nearby locality of Bardou contains approximately 18 wt% elemental carbon (determined with a LECO RC-412 multiphase carbon analyzer).

TABLE 1. Bulk chemical composition of the glassy fulgurite matrix (in wt%), as determined by EMP analysis

Component	Average	σ_{n-1} (n = 4)
SiO_2	69	6
TiO_2	0.1	0.1
Al_2O_3	9	2
FeO	2	2
MgO	0.8	0.4
CaO	1.3	0.5
Na_2O	0.2	0.1
K_2O	1.2	0.4
P_2O_5	0.2	0.1
SO_2	0.5	0.4
Total	84	

Characterization by transmission electron microscopy

The TEM investigation showed that the fulgurite matrix is entirely amorphous. Embedded in this non-crystalline matrix, however, are various mineral grains and pores. The pores are typically elongated and aligned in a direction that is parallel to the boundary between substrate and fulgurite (Fig. 3a). In many areas of the fulgurite matrix, the pores are aligned around the embedded crystals, resembling flow textures in volcanic glass (Vernon 2000). Minerals identified so far in the fulgurite glass include quartz, hematite, magnetite, Sr-bearing barite, chlorite, and a 10-Å sheet silicate.

In a quartz grain located at the interface between the fulgurite layer and the substrate (position 1 in Fig. 2b), we observed a set of distinct, sharp, remarkably straight, and parallel lamellae (Fig. 3). These lamellae are comparable in appearance to the planar deformation features (PDFs) observed by TEM in quartz from rocks that were subjected to shock metamorphism as a result of a meteorite or experimental projectile impact at pressures >10 GPa (Ashworth and Schneider 1985; French and Koeberl 2010; Goltrant et al. 1991; Langenhorst and Deutsch 2012; Stöffler and Langenhorst 1994). The lamellae studied here are partially crystalline, as seen in dark-field TEM images (Fig. 3b). Lamellae were observed only in a narrow zone (2.8–3.2 μm wide), which extends from the fulgurite/substrate interface into the interior of quartz and terminates in a sharp boundary with a lamella-free zone (left-hand side of Fig. 3c). We interpret this abrupt termination as the boundary between compressed and uncompressed areas (i.e., the shock front) and indicative of where the compressive force dropped below the threshold value for quartz to record it in the form of lamellae.

The spacing between adjacent lamellae varies between 51 and 333 nm, with an average of 152 ± 58 nm (28 measurements). Close inspection of Figure 3c reveals that some of the lamellae show bifurcations, implying that not all the lamellae are strictly parallel to each other. However, the planar nature of these lamellae and the absence of dislocation arrays exclude the possibility that they might represent sub-grain boundaries. The lamellae are oriented at an acute angle to the substrate/fulgurite interface. Further away from the fulgurite/substrate boundary, in the interior of the substrate (position 2 in Fig. 2b), the quartz does not display any PDFs.

Despite the high susceptibility of quartz to damage by the electron beam, we were able to obtain a high-resolution TEM image of one lamella from the area shown in Figure 3a using very short exposure time (0.2 s). This image (Fig. 4a) was used to create a fast-Fourier-transformation image, which allowed us to index the resulting diffraction spots. Our analysis revealed that the lamellae are oriented parallel to (01$\bar{1}$0) of quartz (Fig. 4b), which corresponds to one of the prism faces.

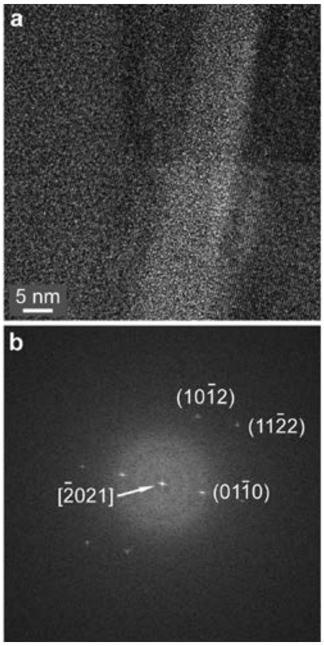

FIGURE 4. TEM image of a planar deformation lamella in quartz. (**a**) High-resolution image showing a planar deformation lamella in quartz from the area seen in Figure 3a. The slightly brighter contrast of the deformation lamella shows no lattice fringes thus indicating a non-crystalline state. The brighter contrast is due to lower density of the non-crystalline material resulting in reduced mass absorption contrast; (**b**) fast-Fourier-transformation image of the planar deformation lamella shown in **a** displaying the diffraction spots with the respective Miller indices. Note the strong diffuse scattering intensity from the non-crystalline part of the image.

IMPLICATIONS

The orientation of the lamellae described here corresponds to the composition plane of Dauphiné twins, which can be induced by applied pressure, by β-α quartz transition on cooling, and by intense dynamic stresses (e.g., meteorite impacts, seismic rupture; see Wenk et al. 2011). The lamella orientation observed in our sample is different from that reported for quartz affected by meteorite impacts or experimental shock load, where the PDFs are most commonly parallel to the {0001} basal planes or, at high pressures, parallel to the $(10\bar{1}n)$ rhombohedral planes, where $n = 0$ (rare), 1, 2, 3, and 4 (Ferrière et al. 2009; Grieve et al. 1996; Stöffler and Langenhorst 1994). Another difference to observations of quartz impacted by a high-velocity solid projectile is that in quartz from Les Pradals the lamellae are not visible optically in the narrow (~3 μm) deformation zone. However, previous optical studies on wider (~30 μm) shock zones within fulgurite substrates at other localities reported the occurrence of planar deformation lamellae, albeit without TEM evidence (see photomicrographs in Frenzel et al. 1989). In combination with the indirect evidence provided by neutron diffraction data (Ende et al. 2012) and with theoretical considerations (Collins et al. 2012), our study shows that lightning is indeed capable of producing shock lamellae in minerals.

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