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Their Structure and Formative Factors

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INTRODUCTION

So much has been written during the past century on the origin, structure and occurrence of fulgurites, or lightning tubes, found in many parts of the world that it would seem as though little remains to be added to the literature on the subject; but the discovery of a considerable number of unusually large and complete specimens in Holt and Stanton Counties, Nebraska, which exhibit remarkable definition of the particular features that have occasioned so much controversy regarding their formative processes, has added an important type to the representatives of this phenomenon and afforded clearer interpretation of the origin of certain disputed structures.

These fulgurites, like others of their class, are only rough, corrugated tubes of dirty-grey, spongy glass, formed of melted sand grains, which, created in a fraction of a second by a temperature of at least 1200° C., cooled too rapidly for recrystallization, and simply consolidated in their present shape as a spongy mass of glass. But they mark the trail of an electric spark, or lightning stroke, that shot its way for 15 feet or more, (40 feet in one case), through compact sand as readily as it did through the air whence it came.

With no inherent beauty of either form or color, they appear rather unattractive objects of mere curiosity to the casual observer, but a study of the stupendous and complex forces involved in their composition stimulates an increasing interest in the causes of their construction.

An excellent historical sketch of the literature and a bibliography of the subject is contained in a paper by Walter L. Barrows (School of Mines Quarterly, Vol. XXXI, No. 4) and a review of the references given therein reveals a very fragmentary condition of the literature and a general superficiality in treatment, most of the papers being mere reports of occurrence. While most writers have advanced some theory as to the mode of formation of the tubes and their structure, the greatest diversity of opinion has centered on the causes of the corrugations on the outer surfaces.

It is the purpose of this paper to describe first the detailed structure of the specimens furnished and further to discuss the evidence supplied by other examples in support of the two prevailing theories on the origin of their form.

Particular emphasis is laid on the flowage and vesicular characters so exceptionally defined in the types presented and too often neglected as of secondary importance, but which seem to the writer to be of fundamental significance in their history.

STRUCTURE AND FORMATIVE FACTORS

The observations contained in this report were made on two segments: one, hereinafter designated as specimen A, from a branch of the complete fulgurite shown in Pl. 1 from Stanton County, and a second, B, from Holt County.

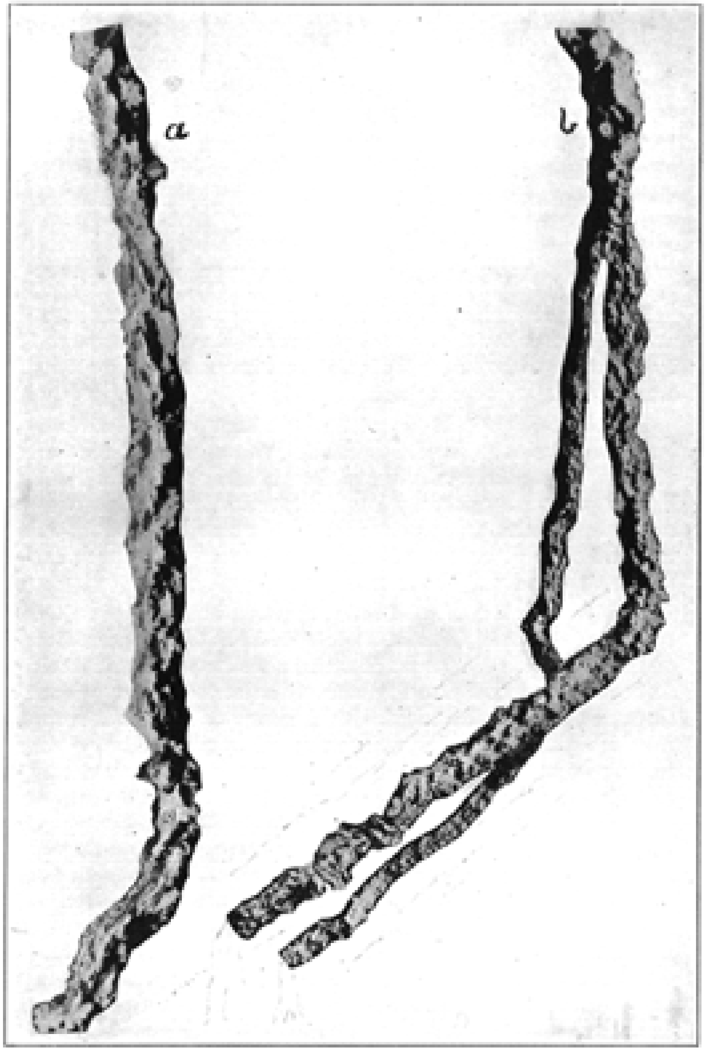


Plate 1: The Stanton County Fulgurite. The lower nine feet. The part *a* belongs on the part *b*.

The first piece, A, received in 1912 from Prof. Erwirn H. Barbour of the University of Nebraska, was $1^1/_2$ inches long, tapering from 18 mm. to 11 mm. in extreme diameter; the

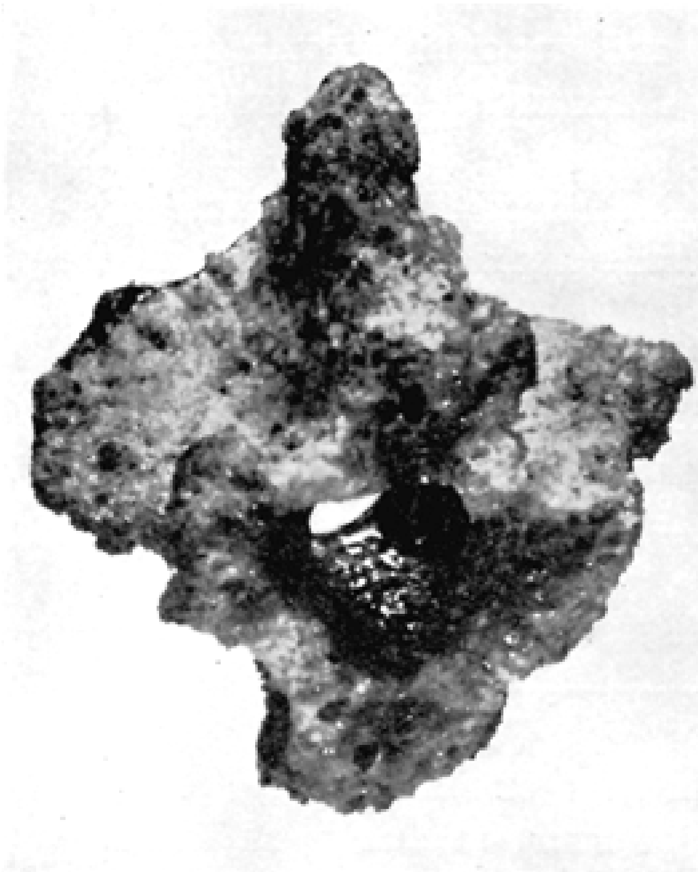


Figure 25: Oblique view of short piece of symmetrical end of specimen: a, looking through bore, and showing three complete ridges in perspective, and the four on the front face. Glassy surface of the bore indicated. X 4.

second piece, B, from Holt County, being about 2 inches long and of about the same diameter.

Although the characters exhibited in these short lengths represent but a small percentage of the wide range of variation apparently present in the total length of 15 feet, the general principles involved in the parts described, apply equally to all parts.

FIG. 26. Thick section of specimen A, showing the general form of a rectangular cross, and the dark colored bands in the middle plane of each ridge, Iying in two right-angle planes. Some of the larger vesicles are prominent and smaller ones can be seen with magnification. Thin section of same shown in Fig. 30. X 4.

The complete specimen itself, to be described in another part of this report, has not been seen by the author of this section, but a photograph of the nearly complete mount of 9 feet, received some time after the studies were made on the above fragments, has in no manner modified the conclusions already derived.

MACROSCOPIC CHARACTERS

Perhaps no simile to describe the general appearance of sand fulgurites could be more appropriate than that employed by Darwin who described the specimens as resembling shriveled stalks, or elm bark.[1]

The Nebraska specimens present the same general characteristics that distinguish all sand fulgurites, being irregular, roughly corrugated, tubular masses of greyish colored and highly vesicular glass, with their exterior surface very much roughened by loosely adherent grains that lie in an external zone of exhausted thermal influence and were thus subjected to but slight fusion.

But the prominence of the corrugations and even the symmetry in some parts of these specimens is an expression of an unusual development of certain features, both in their form and structure (see Fig. 25). The corrugations project from the body of the tube as thickenings or keel-like lumpy ridges of varying heights, interrupted in places, branched, sometimes arranged in a diagonal direction, but commonly extended about parallel to the long axis of the tube.

The inner surface of the tube is smooth, glassy, and somewhat pitted by exploded gas vesicles which were formed in the viscous condition of the glass; while generally circular in cross section at most points, the lumen is often broadly dilated at some sections, or otherwise distorted.

The subsequent flexure of the viscous glass that composed the walls of the original tube advanced, in some types, beyond the stage represented in the above specimens, this resulting in the complete closure of the tube, producing a solid bar of the same material at some points. This condition also probably occurs in some parts of the Nebraska material, not yet revealed, but the above mentioned specimens are of the usual tubular type, with a continuous bore through the whole length of both.

The projection of the solid wing-like masses or ridges from an approximately circular wall has been the subject of much

[1] Voyage of H. M. S. Beagle, pp. 59-62 (Apleton, 1895).

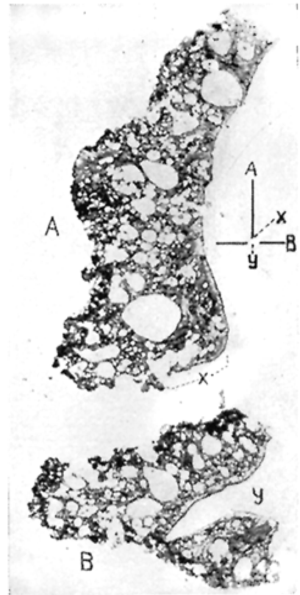


Figure 27: (Left) End view of specimen from Mackinaw City, Michigan, in the collection of the American Museum of Natural History, New York City. Natural size.

Figure 28: (Right) Transverse and longitudinal section of one ridge through planes of the same diverticulum at y. Transverse section B shows complete outline of diverticulum, much rounded by subsequent after rupture of vesicle. Longitudinal section A, is at right angle to B and above it, showing at x, the upper border of same tubular diverticulum y. C, diagram of relative position of sections on a plane parallel to surface of lumen. X 4.

speculation regarding the origin of their relation to the main body of the tube; and although the unconformity of inner and outer surfaces is extreme in types like the Holt County specimen, the same method of formation has applied in some degree to those types with less prominent ridges. The contour of the lumen always represents the final stage of the same general flowage of melted glass that produced the corrugations, but the contour may also be modified by various conditions to be hereinafter considered. Specimen B, Holt County, was very much smaller at one end than the other, the small end appearing more massive than the larger end; but these differences in appearance are due entirely to the reduction of the diameter of the lumen, since the wall and ridges of both ends contain the same relative amount of material. Measurements of specimen A are given below.

Diameter of lumen....................	(at largest end) greatest 7 mm.
	(at smallest end) greatest 2 mm.
Exterior diameter across crest of ridges..........	longest 18 $^1/_2$ mm.
	shortest 11 mm.
Exterior diameter between ridges (bottom of furrows).................................	longest 9 mm.
	shortest 6 mm.
Greatest height of ridge from edge of lumen..................	9 mm.
Thickness of wall at bottom of furrows..........................	2 mm.

An unusual feature of this specimen is the arrangement of the four vigorous ridges in two right-angle planes along the tube, in section forming a broad Ionic cross on the outer surface of a circle (Fig. 26).

This quadrilateral symmetry is more uniform in the height of the ridges at the smaller end, where the ridges form a fairly rectangular cross, with broad limbs, and a small hole in the center. But this regularity is not continuous at all sections, the abrupt reduction or a nick in one or two ridges, or slight deflection, causing a somewhat irregular distribution of these elements about the lumen.

While this quadrilateral symmetry is a much more pronounced feature in the Holt County specimen than in any other yet observed, a similar tendency toward quadrilateral arrangement of mass is sometimes indicated in parts of other types. Through most sections this symmetry is evident, though the ridges may vary in height, and if absent in section, may again appear in the following section; but the photograph of the complete specimen shows that this character is not continuous and appears only in short lengths. A spiral rotation of these ridges which has been noted in fulgurites by Gumbel, Bayley, and Barrows is also indicated in this.

The frequency of this tortion in many reported fulgur is always strongly suggestive of a primary origin of the ridges resulting from a corresponding rotation of the lightning. But

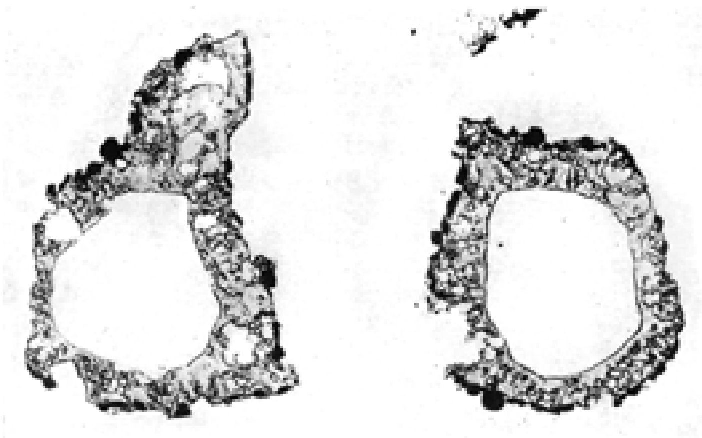


Figure 29: Sections of the Poland specimen made by Julian figured in his "A Study of the Streamers in Fulgurites," Journal of Geology, Vol. IX, No. 8, 1901.

in any attempt to follow this spiral beyond very short limits, one becomes hopelessly lost in a complex of subdivisions and reverse directions.

To trace such an hypothesis of origin to a primary cause it becomes necessary to establish some fixed form of the lightning spark having lateral processes corresponding to the two planes of the ridges and advancing spirally.

If such a fixed form of lightning be assumed it must then be explained why the effects are not uniform in a fairly uniform sand; why some are either parallel to the long axis or branched, why they vary in number, why they rotate in opposite directions.

About the strongest proof that the spirally inclined wings are not expressions of spiral movement of the lightning, is derived from the evidence reported by W. S. Bayley, showing a reverse direction of the spiral on opposite sides of the same tube, which could not result from a continuous spiral motion.

Close study of this feature will show that this torsion is more apparent than real, and is only confined to occasional ridges for limited distances; but it is a common characteristic of any kind of collapsing tube.

Sections of all fulgurites formed in sand that contains colored minerals will exhibit some kind of darker colored bands

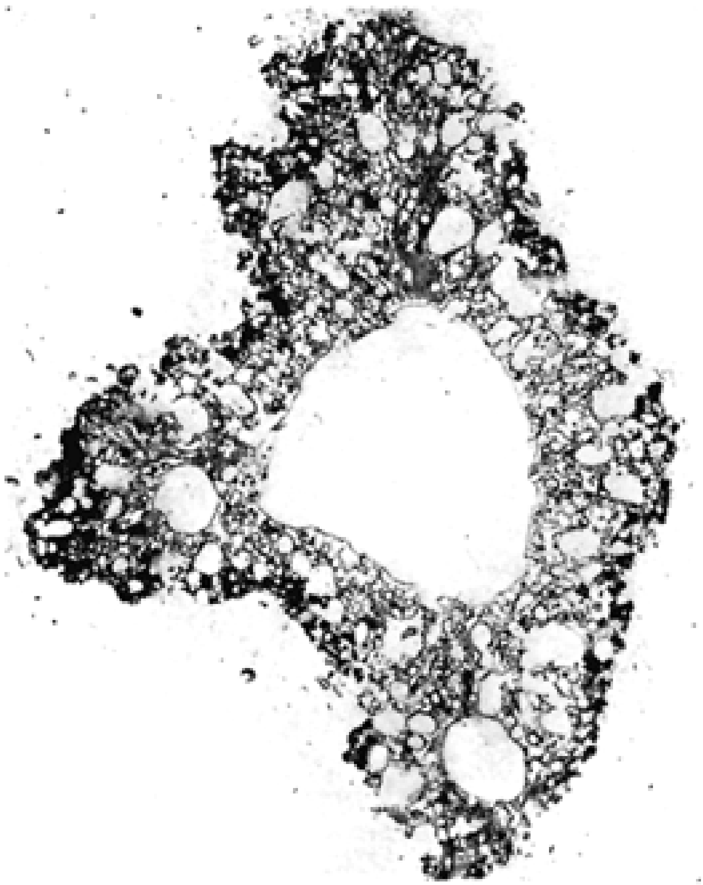


FIG. 30. Finished section of Fig. 26, reversed. showing quadrilateral symmetry of ridges, each with mid-mass of colored flow streamers. Presence of largest vesicles in main ridges evident in all this series Plumose radiation of flow distinct, on right side of upper ridge. Crest of bottom ridge broken up and separated. X 4.

or streaks within the corrugations, in proportion to the richness of these materials; although they may not be conspicuous on a broken surface they usually become quite distinct upon grinding the surface smooth. This is another feature more pronounced in the Nebraska specimen than in others observed; it appears as a diffused band of very dark colored glass in the median plane of each ridge, extending from the crest of the

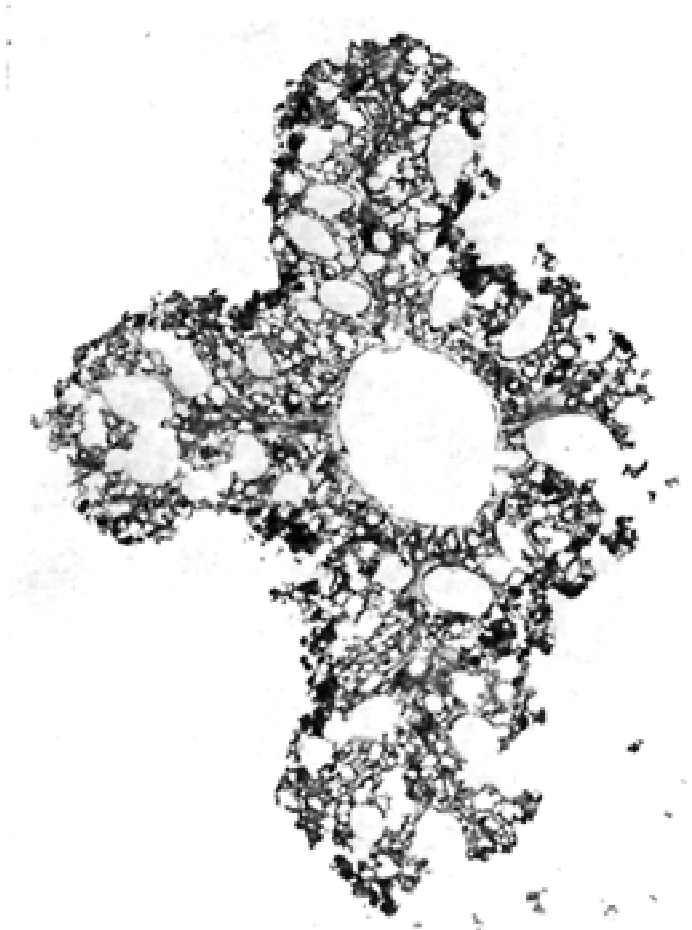


FIG. 31. Section about 1/4 inch from Fig. 30. General features the same, showing the top, right, and left wings of Fig. 30 complete, but the bottom one much reduced. Specially heavy mass of color streams in right wing. X 4.

ridge to the surface of the lumen, and represents the diffused suture plane of two coalesced walls of a fold or crease in an ordinary cylindrical tube. Fig. 26, and other sections.

The significance of this dark band is evidenced by its structure, and constitutes one of the most important clues to the process of ridge formation, and development of the whole fulgurite.

The general relationship of these dark bands to the ridge is best understood by the study of short sections, one-fourth to one-half inch long, and also by longitudinal sections. As the walls are semi-translucent these dark bands are seen to form a kind of dividing wall in the mid-plane of each ridge; and along the surface of the bore where they issue, the edge of this mid-plane wall forms a diffused stripe along the surface. The continuity and vigor of these dark streamers bear a direct relation to the continuity and vigor of the surrounding ridge, the most prominent ridge having the richest and best-defined colored mid-lines, and the low, short, and indefinite ridge having corresponding streaks of weaker irregularly distributed colored streams.

In a specimen from Mackinaw City, Michigan, (Fig. 27), in the collection of the American Museum of Natural History, there was apparently a very high percentage of iron the sand, producing intensely colored streamers often terminated as globular masses in the lumen, resulting in a brill iridescent botryoidal surface.

MICROSCOPIC CHARACTERS

EXTERIOR SURFACE

In the Holt County specimen the iron oxides, so plentifully distributed through the loosely attached exterior sand grains or occurring as deep stains on the surface of, or penetrating, cracked grains, appear in favourable spots to have been reduced to metallic iron, forming a spattered or globulated mesh, entangling and cementing together those lightning fused quartz or feldspar grains just exterior to the zone of glass, or attached to the surface of some glassy matter that has been extruded between unfused grains. The amount of these aggregate masses in the superficial zone, affords some basis for estimating the percentage of iron content in sand. From the abundance of this material and its comparatively low melting point, it would seem most probable that the coloring of the dark streaks was derived principally from this element, reduced from the oxide.

As ferro-magnesian minerals (pyroxenes, amphiboles or biotite) seem to be absent as determined by the preserved external grains, if they ever were present in the sand, it is possible that the numerous yellow-brown granules, both isotropic and anisotropic, but indeterminable, may represent some decomposed product of this group. It is also possible that these iron globules are refused iron grains, or that some of the yellow-brown granules in the outer zone are completely or partially fused limonite or hematite grains.

Internal Structure

The two most conspicuous structural features revealed in thin microscopic sections, are first, the spongy character of the mass composing the walls and ridges of the tube, made by the network of glass around the numerous vacuoles of various dimensions; second, the undulations of the glass, especially pronounced in the colored streams in the median plane of the ridges. Both features are evidence of the flowing movement that has occurred in the once viscous and frothy mass.

One important fact which will be noticed throughout the following series of illustrations, is, that the inner surface of the lumen never conforms to the exterior surface, this indicating some kind of distortion of what once was a fairly uniform tube. At the proximal end of the same fulgurite, however, formed nearer the surface of the ground, the walls are relatively thinner and the conformity of both walls is very marked.

Occasionally an unusually deep pit may appear in cross section as a diverticulum of the inner wall extending into the mid-line of a ridge, and thus presenting an apparent parallelism of both walls, but a section of the same diverticulum at right angle to the cross section (longitudinal sect would show no such conformation with the outer surface but would show that it was merely a small tubular lateral branch of the central lumen into the wall, not longitudinally extended.

Gas Vesicles

These conditions are due to an exploded large median gas vesicle that has its fractured edges extended and rounded out

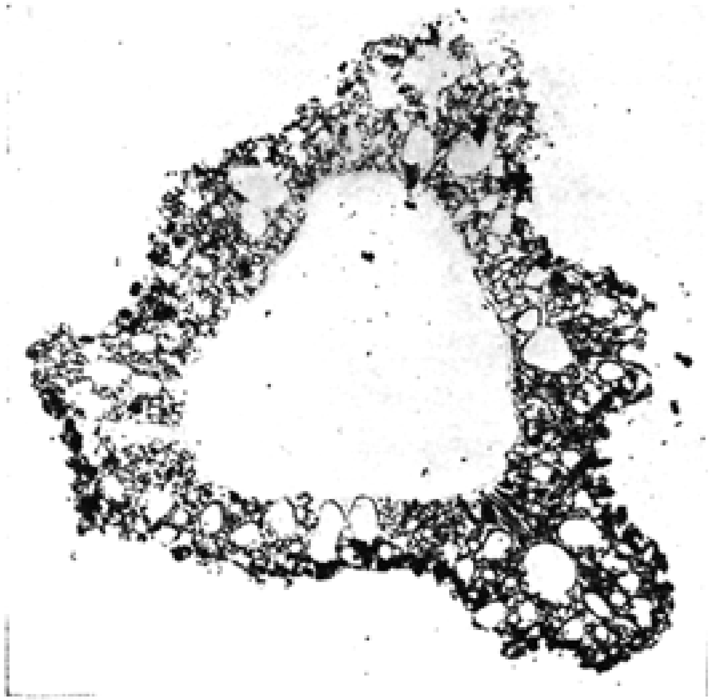


Figure 32: Quadrilateral symmetry lost by deflection of axes and intercalation of new ridges. Heavy mass of colored stream in lower right wing. X 4.

by subsequent flow, forming a small tube. An example of this is shown in Fig. 28, which includes cross and longitudinal sections of the same lateral tube, or diverticulum, which happened to be large enough to allow two sections. The upper border of the tube is shown on one edge of the longitudinal section.

It is the rupture of these vesicles into the cavity of the bore that causes the pitted appearance on the surface. The variation in shape of the openings is dependent on the period of the rupture; those that were broken through in the last stage of viscosity and movement retained their thin un-healed edges, while those that have exploded during high viscosity and greatest movement were most modified by a rounding out or stretching of their edges. All intermediate conditions of this process may be found, and it is a potent factor in the distortion

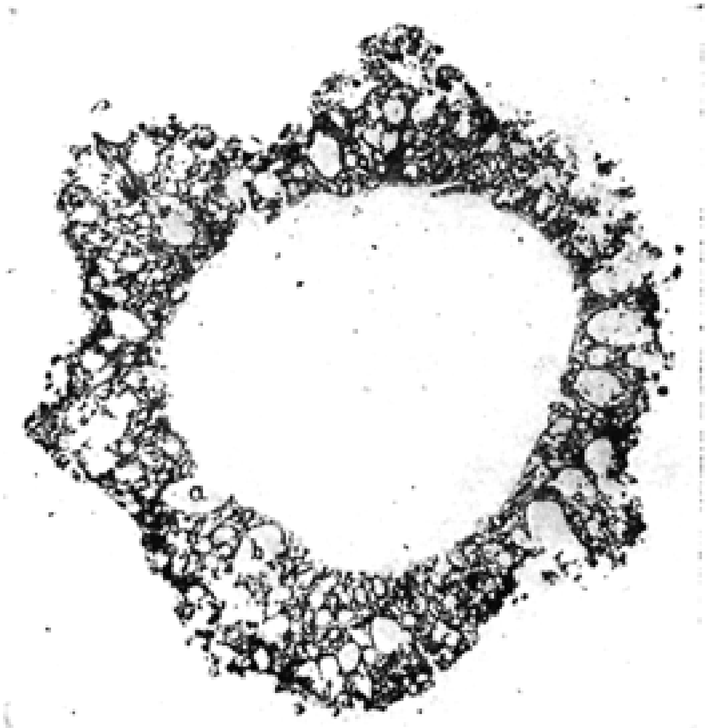


Figure 33: Normal contour, about 1 inch from Fig. 30. Ridges less prominent but the largest having the most pronounced color streams. One vesicle (a) ruptured and partly modified by subsequent flowage another vesicle (b) bulged into lumen, preceding rupture. X 4.

of the inner surface, often causing considerable embayments of the lumen into the body of the wall mass as illustrated in the Poland specimens shown in Fig. 29.

Two pouch-like protrusions with walls of uniform thickness that occurred on one large specimen, one at the fork of a branch, and the other on the branch a few inches below the fork, might in themselves appear to be exceptions to the rule of unconformity, but as they represent only a small percentage of the total diameter of the tube at this section, their relation to the complete contour would be about the same as a large bubble in an ordinary wall. It is interesting to note, however, that this local modification of the otherwise dislocated wall was simply flexed here in a pocket of uniform thickness without flowage or coalescence, thus preserving this area in one of the primary conditions.

Fig. 30 is the finished section of the slice shown in Fig. 26 but reversed in presentation. Because of the greater compression of the mass of the walls in this region, the colored flow streamers in the mid-line of each ridge are more vigorously developed. The high percentage of colored minerals in the original cylindrical walls is here condensed, although many thin streaks of the same material may be seen in other parts of the mass. In two of the ridges the distinctly re-curved or plumose flowage direction is very pronounced as shown by the colored lines, refraction lines of densities, and arrangement of vesicles. It will be noticed that the lumen of this section is relatively smaller than in the succeeding sections made at planes further removed.

Fig. 31 is near the preceding section (Fig. 30) as will be noted by the general similarity of contour. The lumen is larger, and one ridge carries an especially heavy midrib of the colored streamers.

Fig. 32 is still further removed and approaches the average contour, with one well defined appressed ridge showing the strong colored midrib.

Fig. 33 shows the average contour. The ridges are relatively low, but nevertheless each contains a median mass of colored streamers. The lumen also shows at one point, a short diverticulum caused by the explosion of a large gas vesicle, slightly modified on its ruptured edges. This is an example of intermediate form which exploded just before the flowage ceased, so there was but little modification of its broken edges. In Fig. 28, however, considerable flowage has continued after the surface of the lumen was punctured, permitting an extension of, and rounding out, of its broken edges.

One almost constant feature, to be noticed in all cross sections here shown, is the presence of extra large gas vesicles in all the ridges, this denoting their influence in the ridge formation by the pressure they exerted inward. While some large vesicles appear in the normal parts of the wall, they have in some cases been shown to be only a part of a very large vesicle that was incorporated in a ridge mass that would have shown as such in an adjoining section on either side. Large vesicles do occur which have only expanded inwardly or laterally to thicken a wall more or less uniformly, this clearly demonstrating that their influence is secondary and not primary.

It must be appreciated that all these pictures give but a meager idea of the section itself. The colored streaks, but slightly differentiated in the photographs, are very strongly pronounced under the microscope, and the light refractions between the glasses of different densities which furnish one of the most characteristic guides to the detailed study of the flowage, cannot be rendered with their full values in a picture. Fig. 34 is a longitudinal section exactly parallel to the mid-plane of one ridge, (largest) and a little oblique to the opposite ridge, across the lumen. This shows the same distinct flowage of the glass along this plane, but not the definite linear arrangement or elongation of the vesicles so characteristic of the cross sections. A little more of this character is suggested in Fig. 28 but there is a marked difference in the general character of the two planes. This difference is very strong evidence that there was more compression laterally than longitudinally, resulting in more discoid forms with their flattened sides longitudinal.

A great percentage of these larger vesicles represent the coalescence of two or more smaller cells, but the majority are the original cells formed by the expanded gases that were enclosed by a film of glass formed by the fusion of the surface of those grains surrounding an interstitial space in the sand. The expansion of such a vesicle in one direction may involve some superficial matter, while in the other direction it may vary in its distension and either replace a whole grain or coalesce with an adjoining vesicle.

Many of these vesicles have their walls coated with granules, some of which are the unfused residues of a disintegrated crystal area that has survived a temperature just below the critical fusion point. These being caught within a gas cavity, their preservation in this stage appears to have been insured by a partial insulation from the heated mass and also by the higher pressure within the cell, which immediately raises the fusible point of the mineral. This feature is very clearly shown in the slide used

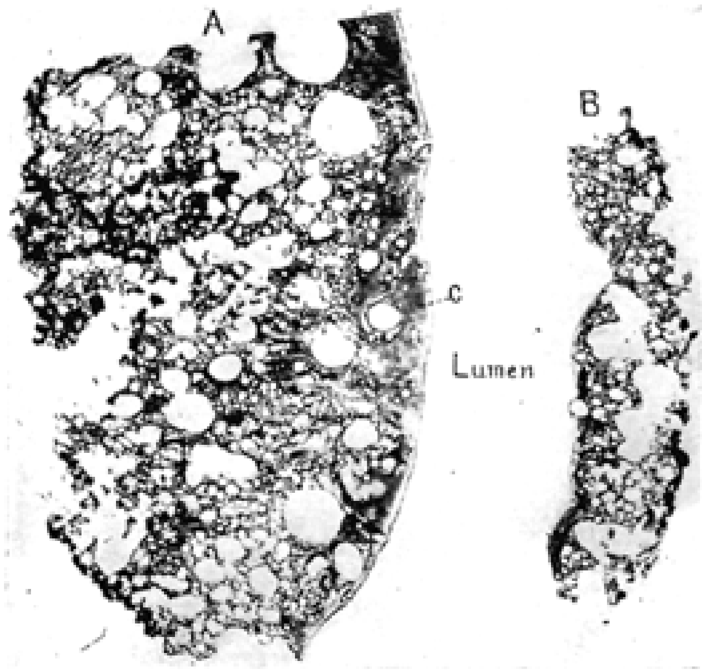


Figure 34: Longitudinal section of two ridges in situ, across lumen. A, exact mid-plane of high ridge. B, slightly oblique to mid-plane of low ridge. L, lumen of tube. Colored flow streamers well defined becoming diffused near surface of lumen. X 4.

by Julien[2] in his description of a fulgurite from Poland, and may be the structure he referred to as the first observed crystallites in a fulgurite, as nothing else resembling crystallites can be found in this section.

Certain very small vesicles, near the still visible original outline of completely fused grains, suggest the possibility that simple fusion might have resulted in vaporization, developing a vesicle of mineral gas. The original contour of many partially fused grains, especially near the exterior surface, are at least often clearly indicated by chains of such bead-like vesicles; and although the vesicles of interstitial origin are readily distinguished by the dirty character of their contents, it is also probable that many of these chains of clear globules may arise between the contact surfaces of closely fitting grains.

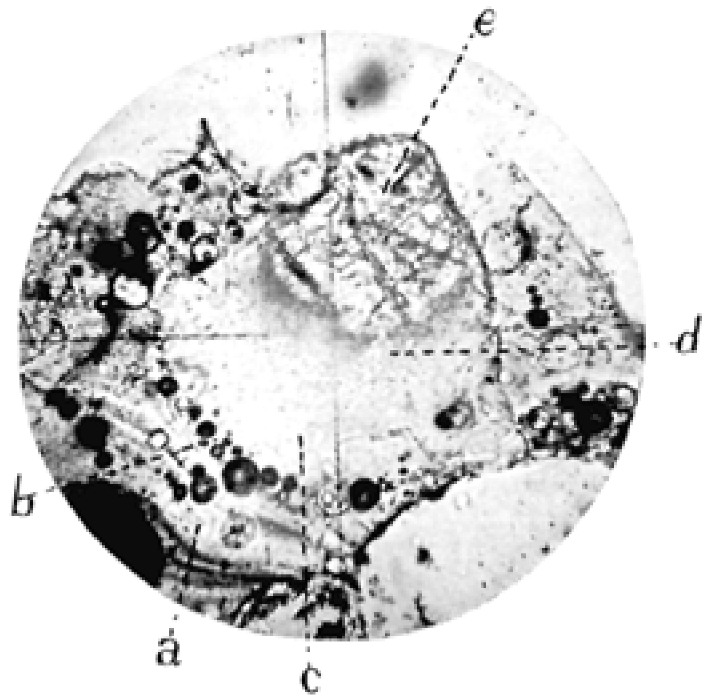


Figure 35: Quratz grain on exterior surface of a ridge. Section nearly exactly transverse to optic axis.
a, Zone of vitreous flow.
b, Row of beadlike interspatial air cells, and superheated gas vesicles along contact surface of adjoining fused grain.
c, Vitrified zone of complete fusion, and destruction of crystalline properties.
d, Granulated zone of partial fusion grading into e.
e, The crystal remnant very much cracked.
X 110.

In a zone near the exterior surface are numerous dense aggregates of minute bubbles, which are generally drawn out into wavy strings conforming to the general flowage curve of the glass, but increasing in general size toward the lumen. These were first mentioned by Wichmann in 1883, and again referred to by Julien as "dark swarms of minute vesicles near the outer margin." The origin of these bubbles is not so clear in the section described by Julien (Fig. 29), but the transition stages, so

[2] Journal of Geology, Vol. IX. No. 8, 1901.

clearly displayed in the Holt County specimen show that these dense aggregates of minute bubbles are derived from the expansion of gas or fluid cavities, or air spaces and cracks, preexisting in quartz and decomposed feldspars.

This is a highly important factor in the vesicular structure of all fulgurites, but rarely definable in its incipient stages. These crystal cavities, forming clusters, and the cracks resulting in chains of bubbles, begin to expand at a comparatively low temperature in the first stages of melting, when the plasticity of the mass is just sufficient to yield to the expansion of the included gas, and before fusion is complete. The gradation of this process is best seen in the center of a grain that has been completely melted on its internal border, with its central area only semi-fused and still granulated, each granule separated by a film of glass but still retaining its optical properties sufficient for determination of character by aggregate effect. The expansion of crystal or crack cavities in a zone between these two conditions, actually causes the enclosure of some of these crystalline granules, which still show faint optical effects (Figs. 35 and 36).

This condition can be very readily mistaken for recrystallization. In the certain identification of recrystallization and in identifying the contents of all vesicles, great caution is necessary not to confound the original contents of a cavity with the abrasive powder with which the section is ground, as this is sometimes very difficult to eliminate. Another kind of vesicle, not easily distinguished in the photograph of the Holt County specimen, consists of cavities formed between the coalescing surfaces of projecting irregularities during the flow of the mass.

The greatest percentage of the vesicles are more or less elongate in cross section; those in the cylindrical segments between the ridges of the tube wall lie with their longer axis about radial to a common center, but those within the ridges, especially conspicuous in the higher ones, form two distinct series with their major axes convergent to the median plane of the ridge, and not radial to the common center as usually described.

The elongation of the larger vesicles in the Holt County specimen is not so pronounced as in some other types studied. The serial arrangement of the smaller vesicles of the ridges in recurved convergent flow-lines, begins at right angles to the exterior surface, and becoming curved inward, finally merges with the median plane flowing toward the lumen, conforming with the general flowage curve of the vitreous mass, producing a somewhat plumose system with the dark-colored streamers as a midrib. This elongation and bilateral curvature of convergent flowage merging into the median flow of colored streamers, is the most significant evidence of secondary inward movement of the viscous mass, in the process of ridge formation.

Colored Streamers

The quantity and vigorous development of the yellowish brown and bluish-gray undulating streamers of glass which form a sort of midrib of all ridges of any prominence, are uncommonly developed in the Holt County specimen. It is the aggregate of these colored streamers that form the dark median centers so conspicuous on even broken surfaces of this material, but usually visible to some extent in all fulgurites.

Viewed in thin sections, these colored streamers may constitute a considerable mass between widely separated gas cells, or may subdivide into several thinner threads flowing through the walls of a complex tangle of smaller vesicles (Figs. 37, 38, 39).

Although the most strongly developed streamers are always associated with the best developed ridges, they are not wholly confined to the main ridges even in those sections of quadrilateral symmetry above described; minor patches and shreds of less pronounced character, may occur anywhere in the walls between the main ridges: but such rarely extend much beyond the surface of the lumen and only form an indefinite core to an incipient ridge.

Besides the different manner of distribution and relationship to the ridges the two types of colored masses have a marked distinction in their flowage character and other details of structure, as an evidence of two kinds of movement in their differentiation.

Those streamers that form the median plane of well-developed ridges, hereinafter to be designated as contact flows, are

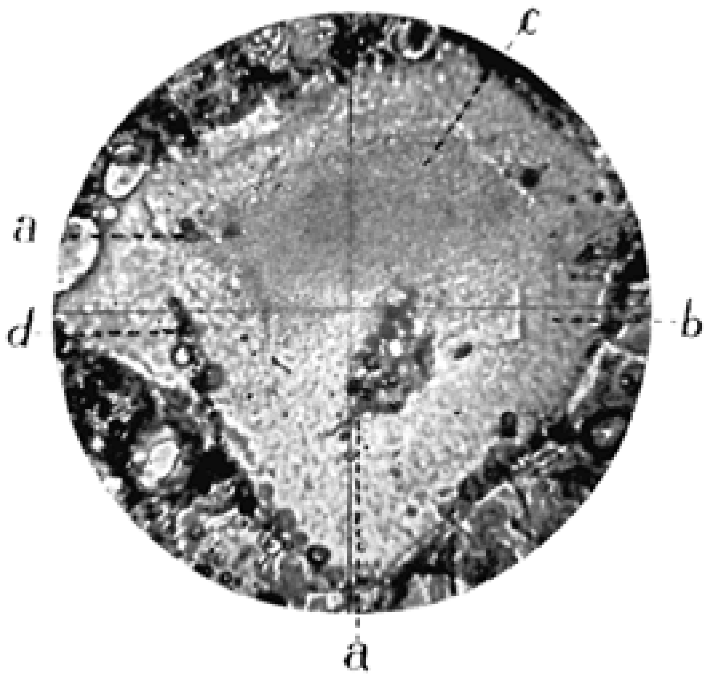


Figure 36: Feldspar grain with gas cell inclusions.
a, Group of preexisting gas cavities in zone between complete fusion and partial granulation. Expanded before complete fusion, and some enclosing crystalline granules showing faint optical effects.
b, Zone of complete fusion.
c, Granulated remnant of grain. Shows faint biaxial figure.
d, Original contour outlined by series of interstitial air cavities caught between adjacent grains.
X 170.

more prolonged, better defined, or more positive in their direction of flowage than the patches associated with minor ridges, which are more diffused or negative in their flowage character.

While the same movements have operated with the same effect upon both the colored and colorless glass, the undulations of the heterogeneous mixture are much emphasized by the contrast of the colored material; the prolonged movement of certain regions, as compared with the limited action of other parts, is thus clearly defined; especially where the continuous streamers are distended by the expansion of the enmeshed gas, showing

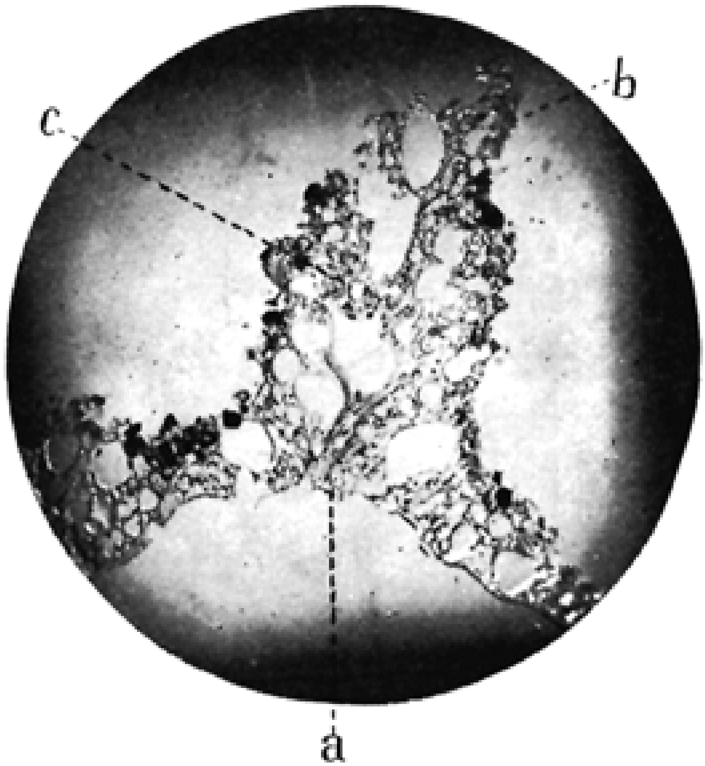


Figure 37: Transverse section of tube, showing one ridge and part of thin wall proper, on each side of base forming the furrows between the ridges.

a, Fluxion band of colored streamers forming the dark median mass seen in Fig. 26, extending from crest of ridge to border of lumen interrupted in continuity by large vesicles, around which they sometimes flow and converge to the median plane.

b, Mass of iron oxide, sometimes showing as the source of the colored streamers. Also opaque, weathered grains of feldspars and other minerals around exterior surface, sometimes filling vesicles. See Fig. 38.

c, One of the numerous small convergent colored streams detailed in Fig. 38.

X 3 1/2

the continuity of flow on both sides or often a deflection of current into divergent flow streams.

It must be remembered that these sections show an extremely limited plane of thickness, averaging only 0.05 mm., and structures that show in the plane of a given section, may be continuous in sections above or below it, but the loss of the

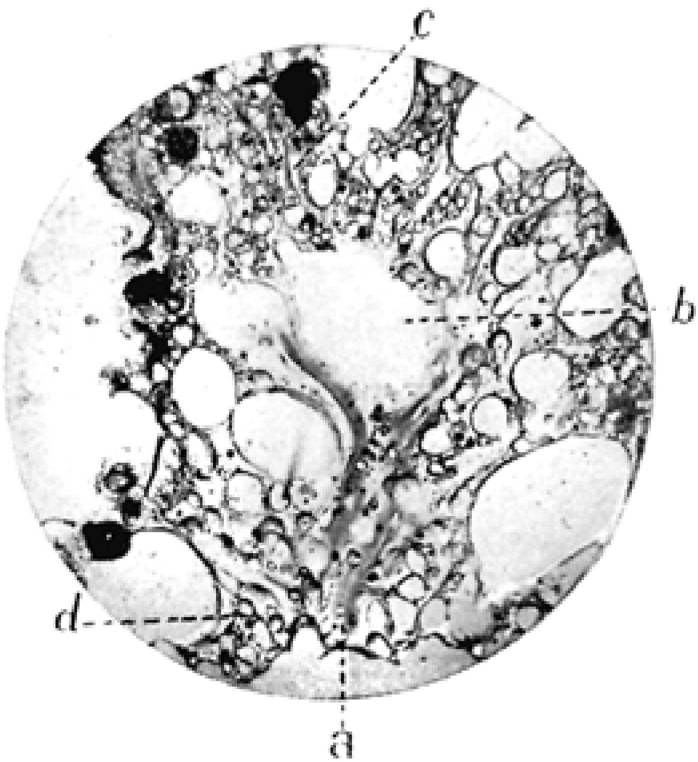


Figure 38: Transverse section of basal half of same ridge seen in Fig. 37.
a, Yellow brown and bluish fluxon band in the mid-plane.
b, Large vesicles interrupting the continuity of inward flow of the numerous small streams of group c.
c, One of a group of narrow colored streams interrupted by vesicle b, but sometimes seen as a continuous flow to median plane.
d, Short isolated flow.
X 12 l/2

planes containing these structures destroys much interpretative value. Much more instructive interpretation is obtained from sections one-sixteenth inch in thickness, with top light, or sometimes with transmitted light.

The colored streamers in the region of the ridge crest, and some that extend to the exterior surface, consist of numerous small branches converging toward the central stem, with the appearance of exfoliation from the median mass, but actually

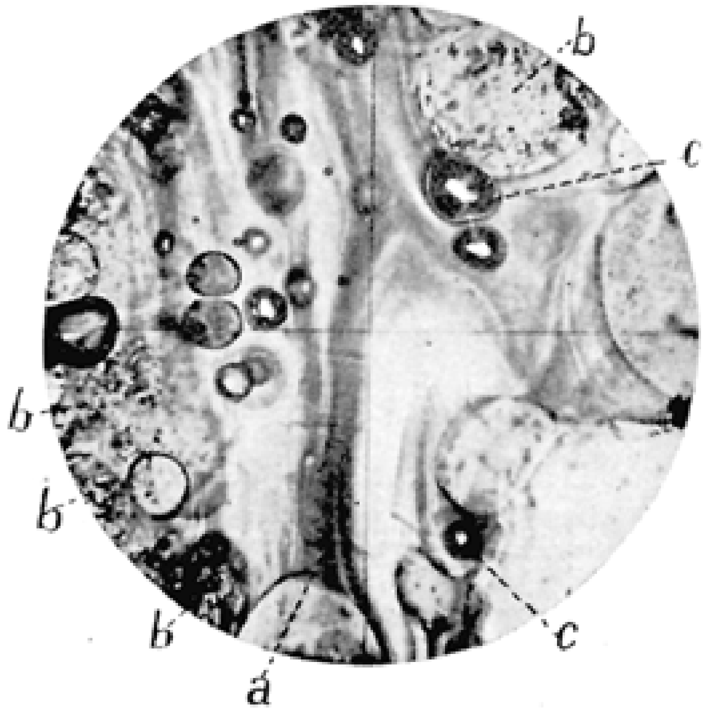
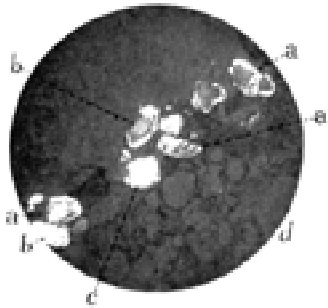


Figure 39: Enlarged view of c, Fig. 38 same portion.
a, Part of same central flow mass partly diffused.
b, Vesicles with enclosed minute crystal fragments and granules probably of interspatial origin.
c, Clear vesicles of gas origin in superheated magma.
X 110.

representing the confluence of melted, colored grains, some even from the exterior surface, of the originally tubular walls, to unite in a general midplane flowage mixture of both colored and colorless glass.

Colorless Masses

In this same outer zone the colored branches are accompanied by colorless masses, both of which, frequently at the extreme surface, flow between and surround completely-preserved crystalline grains and semi-fused fragments of quartz



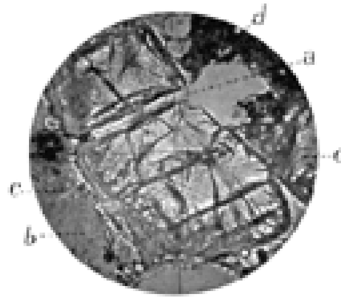


Figure 40: (Left) Crossed nicols. Band of loosely adherent grains on exterior surface of tube. All show some effect of heating, usually in lighter colored border, (lower birefringence).

a, Quartz grains cracked, showing lower birefringence and granulation following cracks.
b, Quartz grain with pure color in central portion and only border of lower order.
c, Feldspar with granulated border.
d, Vitreous region just visible.
X 50.

Figure 41: (Right) Quartz grain lying in wall proper (furrow) considerably below exterior surface, in deepest layer of crystal grains. Is slightly granulated on inner border. Section nearly transverse to optic axis and shows complete uniaxial figure. Quartz cleavage developed by sudden cooling. (See Dana). Shows considerable resemblance to feldspar cleavage.

a, Crystal parted along one cleavage plane, and fused on its contact surface.
b, Fused portion of an adjacent grain.
c, Crystalline remnant of same grain.
d, Aggregation of crystal granules and foreign matter exterior touartz grain.
e, Feldspar grain.
X 110.

and feldspar, lying in a superficial layer on the outer surface of the fulgurite.

Sometimes a colored thread can be directly traced to a surface grain of partly fused reddish-brown isotropic or anisotropic altered mineral of indeterminate character, presumedly an iron oxide, and the colorless elements frequently arise in the same manner: while the colorless portions of the flow are usually vitreous to their extreme outer limits, it is occasionally seen to emerge from a vestigial crystalline mass that retains only sufficient diagnostic properties to determine its biaxial character. The presence of this semi-fused, colorless, biaxial mass, presumably feldspar (orthoclase), and the vitreous flow, both colored and colorless Iying between surrounding, perfectly intact crystalline grains of the same minerals, suggests two hypotheses regarding the significance of this relationship:

(1) That the vitreous and semi-vitreous matrix surrounding unfused grains, may be partly composed of some extremely low-fusing mineral not sufficiently preserved anywhere for identification, on account of its complete vitrification even beyond the superficial zone of crystalline quartz and feldspar grains.

(2) That the crystalline grains were imbedded by pressure into the partly cooled glass.

Regarding the first hypothesis, the improbability of such a low-fusing mineral being present in the sand may be judged from a consideration of the following table (taken from Iddings "Igneous Rocks," Vol. 1, pp. 82-86):

Mineral	*Melting Point*
Plagioclase group	1340-1532
Centigrade Albite	1120-1175
Orthoclase	1190
Sanidine	1140-1150
Microcline	1150-1175
Leucite	1275-1298
Nephelite	1059-1110
Sodalite	1050-1130
Analcite	880- 890
Biotite	1155-1160
Muscovite	1160-1255
Rhombic pyroxene	1185-1380
Augite	1150-1180
Aegirite	930- 945
Acmite	925- 930
Hornblende	1175-1180
Arfvedsonite	920
Magnetite	1175

From this it will be seen that among the colorless minerals the melting points of all plagioclase feldspars are much higher than those of the orthoclase group, which average about 1150°. Leucite must be excluded as a possibility on account of its much higher melting point. Some evidence of nephelite and sodalite would certainly be preserved with their melting points so little below that of quartz and feldspars. But the presence of either of these, or analcite with the lowest melting point of all, is precluded by the relative softness of all three; with only H 5.5, neither could have survived the same amount of attrition evidently experienced by the associated quartz and feldspars.

Micas are also sufficiently high to remain even better pre served than feldspars but show no signs of their presence.

Among the colored minerals, as neither rhombic pyroxenes (augite, hornblende) are ever preserved in crystalline form, even with the same melting point as orthoclase feldspars, if they ever were present in the sand, it seems most probable that the iron oxides derived from their atmospheric decomposition, and fusing at a much lower point, are represented by the yellow-brown flow masses and globules on the exterior surface.

The low melting aegirite, acmite, and arfvedsonite therefore remain as the only crystalline ferro-magnesian mineral possibly present in the sand, which could have been melted by a lower temperature in the outer zone, sufficient to flow around unaltered feldspars, and leave no crystal remnants; but as these are as readily decomposed by atmospheric agencies as other amphiboles and pyroxenes, and also less common than hornblende or augite, it is most improbable that these were ever present in the sand.

Therefore the entire absence of ferro-magnesian minerals, in any phase, and which if present in the sand when struck by lightning, would be as well-preserved in the external zones as the quartz and feldspars, all being subjected to the same range of temperatures, must eliminate this group as a possible source of the iron content.

But the occurrence of globular masses of what appears to be fused iron oxide clinging to the exterior surface of the superficial grains is a strong indication that this colored material was melted under a lower temperature than the silicates, and where this same element was subjected to the higher temperature of the internal zones forming the body of the fulgurite wall, the iron oxides retained their viscosity for a longer period than the higher fusing quartz and feldspars with which they partly combined, and they became a considerable factor in the modeling of the ridges.

Unfused Grains Imbedded in the Walls

A far more probable explanation of the relationship of this vitreous flow around crystalline grains, however, is, that the unfused grains were shifted and imbedded in the rapidly cooling melted mass by the external pressure of the inwardly moving sand, and by the crumpling of the tube walls, after the temperature of the glass was too low to melt the imbedded grains.

This conclusion is not only consistent with the local relations, but is also the natural sequence of many other evidences of profound changes in form from a simple glass tube. The actual composition of the sand can only be determined by ex-

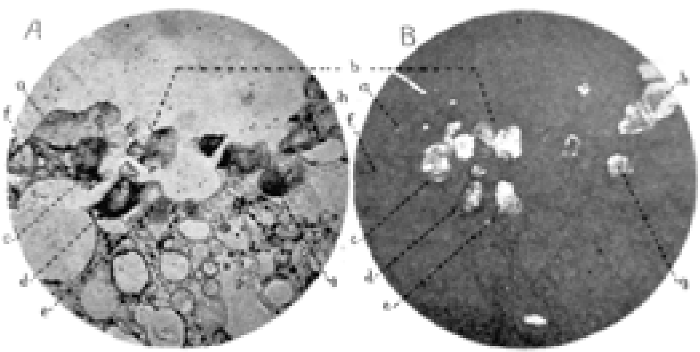


FIG. 42. Series of exterior grains displaced by contraction and folding. A. Plane polarized light. B. Crossed nicols.

a, A biaxial mineral on surface, semi-crystalline on exterior, and vitreous on its interior portion, but all external to wholly crystalline feldspar, c.
b, Cluster of five unaltered grains pressed into glass by external movement of sand, and against c, d, e.
c, Feldspar, fused on internal border, granulated in middle, but wholly crystalline in external portion.
d and e, Quartz grains in same condition as c, all three being pressed into the glassy zone by the group b.
f, Quartz, unaltered; looking through optic axis.
g. Semi-fused grain deeply embedded in glassy zone.
h, Feldspar, cracked, with lower birefringent border and with impression of a detached grain externally.
X 50.

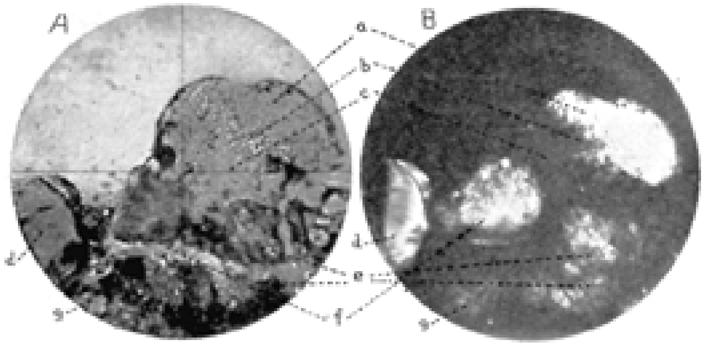


Figure 43: A. Plane polarized. B. Crossed nicols. A Biaxial mineral on exterior surface of the crest of a ridge.
a, Exterior crystalline portion still giving good optical reactions.
b, Zone of semi-fused crystal with fringing structure very much resembling the character of albite when heated to 1125° Cent. See Iddings, Carnegie Institute of Washington, No. 31, Pl. XIX.
c, Zone of vitrified crystal; grain apparently squeezed outward by f and e during folding of crest.
d, Feldspar, very slightly granulated on interior margin.
e, Quartz grain.
f, Feldspar, granulated.
g, Feldspar fragment.
X 110.

amination of that Iying beyond the possible influence of any heat, but such material was unfortunately not collected.

The interior terminations of the median colored streamers near the surface of the lumen, involving also the colorless matter, become much contorted and diffused and exhibit a complex of flowage distinctly different from that of the stringy part. This difference in the nature of the two extremes of the same flow is essential evidence of different factors in the process of its formation, affecting the metamorphosis of the entire fulgurite.

Many modifications of these color masses exist, intermediate between the above-described stringy type of positive flow characterizing the median plane of all prominent ridges and the negative type without definite direction, which occur in small patches in the zone near the lumen. These latter, being in the same zone as the interior terminations of the positive flows, exhibit the same diffused and reflex movements of the whole mass in that zone. Some patches may even show a circumferential direction of flow.

Peripheral Contraction and Sand Pressure

Although the prevailing current of movement in the mid-plane of the ridges was inward toward the lumen, much local complexity of flowage was caused by the compression and elongation of the vesicles under the general stress of peripheral contraction and sand pressure. This complex of flowage is more graphically displayed in the peculiar optical effect between crossed nicols, which sometimes resembles incipient recrystallization; but a closer study and consideration of what first appears like strings of aggregate birefringence, resolves into a complex of refraction effects of an intricate mineral mixture of various densities which have consolidated as glass before homogeneity of the mixture could be established.

Flow Structure

Oblique light will also afford a distinct aid in the interpretation of these intricate flows, but perhaps the best understanding is obtained with a binocular microscope and top light, which enables one to follow several planes at once.

Vitrification of Crystalline Structures

Probably the most attractive feature in all fulgurites when seen between crossed nicols, is that series of birefringent mineral grains referred to above, which lie in a narrow zone around the exterior surface. These grains are a concomitant product of all sand fulgurites, but vary in number, character, and distribution according to the constituents of the sand, and mode of fusion. Although the greater bulk of the mass is composed of completely fused sand, and their crystalline properties totally destroyed in their conversion to glass, many grains are preserved even within the limits of this very narrow exterior zone, which show every grade of decomposition by heat from glass to unaltered crystal.

In cross section, they occur in interrupted irregular layers, the most superficial ones being best preserved, but rarely failing to show some effect of heat (Fig. 40). Some grains on the inner

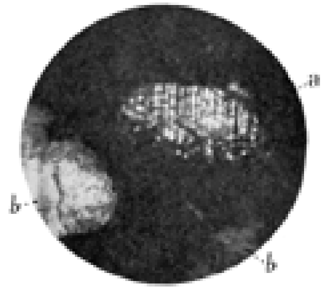
 

Figure 44: (Left) Crossed nicols. Grain of orthoclase on exterior surface of fulgurite tube. Orthopinacoid section, showing good basal and clinopinacoid cleavage. Shows lower order of birefringence around border and through the body of grain (lighter color). Slight granulation on edge. Slightly cracked.

Figure 45: (Right) Crossed nicols. Exterior grains.
a, Microcline.
b, Quartz.
X170.

border of this zone, in an advanced condition of change, may be entirely vitrified on their internal half with their original contour indicated either by a line of minute vesicles as referred to above, or by curved refraction lines or by other traces; while the external end of the same grain may still retain granular vestiges of crystalline structure (Figs. 35 and 36). Others may show large vesicles only within vaguely outlined grains. Another grain in about the middle of this zone, may show only granular disintegration on its internal end, and clear unaltered crystal on its external end (Figs. 41, 42, and 43). Occasionally favourably located grains which may exhibit this latter phase, may also show the initial expansion of crystal or fluid cavities, or species in cracks, Iying just internal to a partially melted granular area (Fig. 36).

The use of the term "zone" as applied in this connection, must be understood as merely relative or general, since the originally defined zone has become so overlapped, folded, distorted, and intermingled in the general collapse of the tube wall, that no such definite distinction can now be made. It is only in places that the gradational effects can now be observed, and from these the total results estimated. When the amount and kind of displacement is once recognized, many apparent anomalies are clarified.

The clusters ("dark swarms" of Julian), near the exterior surface and the flowing chains of minute bubbles, commonly present in all fulgurites, also have their origin in this zone from the same cause, e.g., the expansion at this critical temperature of air spaces in decomposed minerals, especially feldspars.

The relation of many of these semi-fused grains having their internal ends fused, although now lying outside of crystalline areas of adjacent grains, is the result of the imbedding and shifting process caused by the subsequent contraction of the tube and movement of the sand. In Fig. 42, c, d, and e are more vitreous on their internal surface than on their external, and just outside them is a group of five wholly crystalline grains not effected by heat but subsequently pressed into the glassy matrix and imbedding c, d, and e still deeper. (Due allowance must be made for the shift in position of the broken section); h, is a grain but slightly effected by heat, but not melted on its internal side; this is surrounded by a thin layer of glass, but the impression of another grain is seen on the outer side, which probably pressed it deeply enough into the heated glass to cause the cracks and alter the surface to lower birefringence.

In Fig. 43 the same kind of shifting has occurred, bringing the vitrified areas of some grains outside of the crystalline areas of other grains.

In the process of dissolution of the grains, the outward radiation of heat advances along cleavage planes and expansion cracks which become vitrified on both sides and continue to multiply and subdivide in all directions with increasing temperature until reduced to an aggregate of very minute crystal fragments, each surrounded by a vitreous shell.

Even in some of the last stages of this disintegration, the aggregate of the crystal fragments may still afford very satisfactory optical factors for the determination of mineral characters; the most remarkable of these being the complete preservation of the optic orientation of the original crystal. In most cases the transition between unaltered, granular, and vitreous structure is imperceptible.

In the outermost series of loosely adherent grains some individuals may indicate but slight granulation around its margin and the remainder be entirely crystalline, although usually finely cracked. (Figs. 40 and 41).

While the most superficial members of this series have entirely escaped the fusing temperatures and indicate no trace of disintegration, they nevertheless always show the effect of sufficient heat to cause a few cracks or at least the border of lower birefringence color around the entire surface and also along both sides of any cracks that may be present, indicating the earliest stages that occur in the complex process of final dissolution (Fig. 40). The color effect of this initial change, between crossed nicols, is an intricate pattern of a lower order color on a field of higher order, and these thermal effects are readily distinguished from a similar appearance produced by the thinner edges of an eroded grain.

It is therefore evident, from this outermost series of crystalline grains, showing the incipient stages of alteration, that the first effect of heat is to lower the order of double refraction around the surface of the grain, and also to effect both sides of the concurrently developed cracks (Figs. 40, 41). Increasing temperature finally vitrifies these surfaces and multiplies the ramifications of finer cracks, along each of which the same process of disintegration progresses, surrounding each crystalline fragment with a matrix of melted mineral, until every fragment is eventually absorbed in a uniform flux of amorphous glass.

The peculiar interest in these areas of lowered birefringence, is, that although the influence of the heat has evidently modified its crystalline or molecular structure in a manner sufficient to alter some of its optical properties, there is absolutely no deviation of the optic axis in the affected areas from the axis of the unaffected portion of the same crystal.

It is also in sections of this outer zone that some of the globulated iron masses occurring on the outer surface, above described, can be seen to graduate from solid opaque globules, to light brown diffused patches, partly drawn to glass.

Determination of the Unfused Minerals

This belt of unfused minerals affords the only data at present available for estimating the character and percentage of component sand elements. Quartz is apparently the dominant mineral in the sand, as it constitutes the majority of determinable grains. Feldspars are secondary in amount and probably mostly orthoclase; but only one exceptionally favourable grain of this mineral could be identified without doubt, as all the factors of determination were clear and distinct (Fig. 44). One grain of microcline was fairly represented (Fig. 45).

Many of the feldspars are kaolinized or otherwise altered by atmospheric agencies before fusion, but this condition is easily distinguished from the granulation of partially disintegrated grains. In some cases these altered opaque grains seem to be clarified by the initial effects of heat. The precise identification of most of these feldspars is impossible owing to heat effects, atmospheric alterations, or the entire absence of some essential feature of orientation like cleavage, or crystal face, etc., and the grains can only be assumed to be orthoclase from general appearance and partial determination.

Considering the necessity of obtaining many complex factors for the absolute determination of feldspars, and that the possibilities of such definite data are only rarely sufficient in one possible section to identify positively any single grain in fulgurites, the assurance of Julian[3] in his observations on a similar fulgurite from Poland, that "out of 35 grains 23 were identified as orthoclase, the remainder as quartz," is not warranted by the section on which his identification is based, and which I have recently examined. As only 25 out of 53 grains, examined in this particular section he thus described proved to be biaxial, 28, or more than 50 per cent, were uniaxial and therefore could not be feldspars of any kind.

As the primary factors in the determination of feldspars are derived from its positive or its negative character and extinction angle, determined by the acute bisectrix and as a positive feldspar is negative in one plane and a negative feldspar is positive in one plane, it is difficult to understand upon what evidence such positive identification of orthoclase was obtained from this section which has all optical reactions so obscured or obliterated by decomposition or thermal effects, having no crystal faces, cleavage or other factors of orientation sufficient to determine positively even one grain of feldspar.

[3] Journal of Geology, Vol. IX. No. 8, 1901. pp. 678-681.

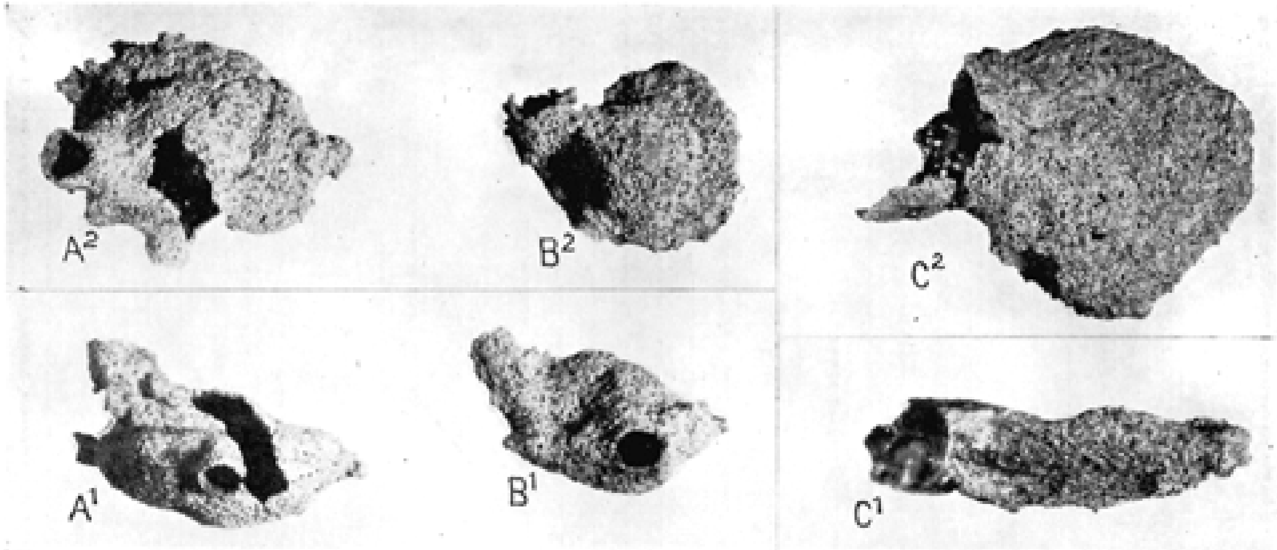


Figure 46: Two views of terminal sacks.
A^1, B^1, C^1, side view showing approximate position as found.
A^2, B^2, turned downward 90°.
C^2, turned upward 90°.
Natural size.

Queries

It would be a matter of considerable value in this study to ascertain the relative specific gravity of the fulgurite mass, and of the sand that had occupied the same space previous to fusion, in order to determine if the fulgurite still represents all of the original sand, fused but merely displaced. Would all the cavities, including the lumen and gas cells, equal the interstitial space in the sand, and was there any loss by escaped gases? It would also be very instructive to learn from chemical analyses of both the sand and fulgurite, if there has been any addition or subtraction of some element in the building of the fulgurite.

Primary Flexure of Glass Tube

There probably remains in no portion of this mass any vestige of the primary flexure of the glass caused exclusively by the action of expanded gas vesicles; because secondary convergent movement of all parts immediately succeeded the release of internal air pressure in the tube, in response to the external pressure of the surrounding sand, this resulting in complete distortion of all original forms.

Terminal Sacks

One of the most remarkable modifications of fulgurite structure found associated with the Holt County material are the three vitreous sacks shown in Fig. 46, which seem to be the first forms of this phase ever reported.

Some branches of the fulgurites of this locality are frequently terminated by these bulbous sacks, which, as suggested by Prof. Barbour, were evidently formed in local pockets of finer sand or clay, or slightly calcified sand, which retained a higher percentage of moisture.

As they do not occur on a common level, they cannot be attributed to a common water level as first suspected, this level being indicated by a different structure, to be discussed in other relations.

Their precise relation to the tubular portion, the character of the sand surrounding them and any evidence of the continuation of the lightning beyond them, are all features of vital importance in their history, worthy of the most critical field study; with the limited information at present available it is much regretted that fuller description cannot now be given. Two views of these specimens are shown in Fig. 46. They are all generally flattened, and are found with this flatter side lying horizontally in the sand. A, is an irregular discoid form, with only one large broken opening on one end. The other two, however, (B and C) have two openings on the appressed edge, those on the longest axis having a tubular neck with broken walls, apparently connecting with the tubular stem, the other very short with thin tapering edges like a blow-out hole, or perhaps indicating the final range of fusion temperature.

Except around the edges they are uniformly extremely thin walled, and probably represent the primary phase of fusion in all the walls of the tubular portions, but chilled in this condition before much expansion of the vesicles occurred. Therefore, they are relatively denser than the tubular sections, less or only minutely vesicular, highly vitreous throughout, but with the usual character of glassy, irregular, lumpy inner surface and only rarely pitted.

Considering all these unusual characters, it is very evident that these sacks were formed under conditions entirely different from those effecting the tubular parts; all these characters are readily explained by the presence of moisture or even wet sand, in which such a product would be a very natural result.

The vesicles, besides being less numerous than in the tubular parts, are in most cases very minute and more isolated, and thus do not present the spongy appearance of the normal structure. The large vesicles appear to be confined to the exterior surface where they open out.

The exterior surface, though having a general resemblance to the tubular portion, possesses some features distinctly different. There are no loosely adherent grains, but all are firmly cemented together by at least semi-fused surfaces, or by a matrix of glass. Many unfused grains are deeply imbedded in this glassy matrix, and occasionally a quartz grain forms a minute window to the interior cavity.

The greater area of the shell of these sacks average only the thickness of a sand grain, and many perforations occur, sometimes through original sand spaces, and sometimes caused by the burning out of organic matter.

The most significant difference in the structure of this external surface and that of the tubular types, is, that all the exploded vesicles open on the exterior surface instead of the interior as in the tube form.

Sufficient heat evidently remained in the discharge to melt the sand and create a large volume of steam under high pressure; the relatively low temperature of the sand always maintained at these depths, or near underground waters of the plains, more rapidly chilled the viscous lining to the cavity than in the upper levels in dry hot sand: the air spaces between the dry sand of the upper levels being replaced in the lower levels by more or less free water, the consequent steam bubbles between the grains expanded outward against the lesser resistance, because the lining of semi-rigid glass and combined steam pressure within the sack, offered the greater resistance.

The only evidence of flowage, collapse, or coalescence resembling that in the tubes, is around the folds of the edges. One considerable flowage mass occurs within the right edge of specimen A, Fig. 46, and the inner edge of all are decidedly rounded, not conforming with the exterior surface, showing a flow modification of the internal walls of the fold.

Another vital factor operating against extensive flowage movement, was the greater compactness of the sand, due to the presence of moisture and possibly some degree of calcification, so there remained only one force to exert a subsequent modification of its original form; while sufficiently flexible to yield to the weight of the sand mass above it, a general depression flattened the cavity with enough displacement to admit some readjustment of the soft edges.

As the holes on the lateral edge, assumed to be blow-out holes, are circular in form showing no distortion due to compression, it would seem for this reason that they occurred after the flattening process, but there are too many objections to this conclusion.

The steam pressure in the cavity at one moment was sufficient to expand the walls against the resistance of the sur rounding sand, and even to displace it, and the retraction or compression of that cavity could not begin until the force that expanded it was relaxed or became less than the surrounding pressure tending to restore it.

The expansion of the vitreous lined walls from its primary dimension resulted in a general stretching and thinning and final rupture of the attenuated wall in many places, causing the perforations above described. The numerous holes thus caused by the separated film of glass, provided many additional vents for the dissipating internal pressure, besides the entering and blow-out tubes. During one stage of the subsequent compression of this cavity, the increasing rigidity of the glassy wall was added to the resistance against complete collapse, arresting any further movement.

As the original pressure must have been dissipated before this period, and no renewed pressure could accumulate in the sieve-like sack, it follows that a blow-out could not occur in this stage, especially of a more rigid film.

It seems necessary to conclude from these considerations that the blow-out hole must have been coincident with the stretching and thinning of the whole wall before collapse, at the moment of highest pressure in some weaker spot, its circular form being preserved by rapid cooling of its very thin walls. The slight movement of the more flexible main mass did not effect the form of the more rigid edge.

It is also possible that these holes may be the continuing tube of the nearly exhausted lightning bolt itself.

In the locality where these specimens were found they were abundant enough to furnish many forms, and it was noted by the collector that some branches were terminated by a gradation of the vitreous tube, passing through phases in which the walls were composed of whitish sand too incoherent for removal, and further on to form mere streaks of a meally-like composition, and finally became lost in a broad diffused mass.

These changes in the tube are simply due to the reduced velocity of the spark and consequently reduced temperature which was only sufficient to partially fuse the individual sand grains, but not rendering them fluid enough to unite by coalescence. The "meally" streaks represent the area of still further reduced heat that was only sufficient to burn or partly fuse isolated grains of the lowest fusibility.

Some of these phases have been noted in various collections. Some fragments of a small tube found at South Amboy, N. J., have a wall thickness of only a single grain, and are so loosely coherent that they crumble upon the slightest touch; the grains are white, only semi-fused and pressed together instead of fused, apparently corresponding to one of those stages of the Nebraska specimen.

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THE EVENT

Petrified Lightning from Central Florida

A Project by Allan McCollum

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