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Some obscure problems in structures occurring within artificial and natural glasses (rhyolites, tachylites, etc.) receive light from the study of fulgurites, as representatives of instantaneous fusion, and frequently, as it will be shown, of equally rapid devitrification.

Hitherto, however, a constitution of homogeneous glass has been universally observed, under the microscope, in all sand fulgurites, without the least trace of devitrification in the largest masses.[1] Occasional cloudy stains of brown iron-oxide and black manganese-oxide have been noted, and frequent enclo-

[1]"A Perfect Glass," ARAGO (*Ann. d. Ch. et. d. Phys.*, Vol. XIX (1821), p. 290) and all later investigators.

sure of remnants of quartz-grains[2] and of bubbles, both more abundant near the outer walls of fulgurite.[3] In rock-fulgurites, a single instance of devitrification has been recorded. The results of examination of four fulgurites will now be described.

I. Fulgurite (lightning-tube) from sand, Poland; a small fragment, together with thin cross-sections, prepared by Mr. James Walker, of the New York Microscopical Society. This fulgurite is of small size, from 5 to 8mm in diameter, with central aperture or lumen usually 2.5 to 4mm in diameter, and glass wall varying mostly from 0.6 to 2.0mm in thickness, roughened outwardly by adhering sand-grains in a continuous coating. The photomicrographs (Figs. 1 and 2) may serve to explain certain features as yet unrecognized in other fulgurites.

The wall presents, under low magnifying power, an apparently homogeneous glass, streaked by occasional cloudy wisps of brownish and reddish iron-stains, and be sprinkled with swarms of bubbles of varying size.

The inner surface of the lumen is for the most part smooth and shining, with boundary sharply defined in cross-section (Fig. 1), as in other fulgurites; but, here and there, a few points, pustules and needles of glass are found to project, of a length up to 0.17mm. For the origin of the central lumen an explanation long accepted has been that suggested by Watt for the hollows in a fulgurite-mass, "the expansion of moisture while the fusion existed.[4] In this cross-section the outline is nearly circular, with maximum and minimum axes as 4:3; in another it is still more elliptical. This difference, common in sand-fulgurites, has been attributed to distortion of the tube by pressure of the surrounding sand upon the fulgurite while still plastic. In one cross-section, one side of the tube appears partly crushed together, with coalescence of opposite parts of the wall into a blebby mass of coarse bubbles and partial obliteration of the

[2] VON GÜMBEEL, *Zeits. d. D. geol. Ges.*, Vol. XXXIV (1882), pp. 647—648.
J. S. DILLER, *Am. Jour. Sci.*, Vol. XXVIII (1884), pp. 252—258.
G. P. MERRILL, *Proc. U.S. Nat. Mus.* (1886), p. 84.

[3] Best shown in the longitudinal and cross-sections of a sand-fulgurite by A. WICHMANN (*Zeits. d. D. geol. Ges.*, Vol. XXXV (1883), Pl. XXVIII).

[4] *Phil. Trans. Roy. .Soc. Lond.*, Vol. LXXX (I790), p. 302.

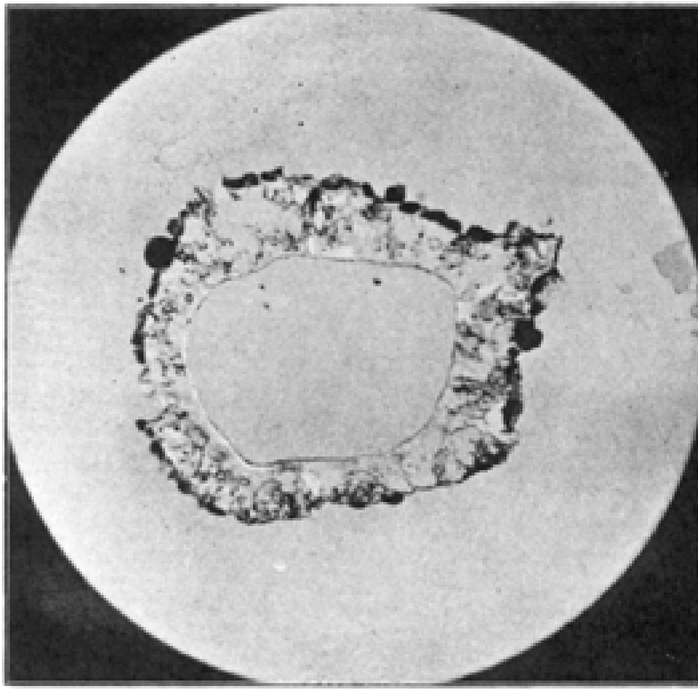

Figure 1: Sand-Fulgurite, Poland. X l0. Photomicrograph of cross-section.

lumen. The characteristics of such a fulgurite seem therefore to be naturally divided into those developed during the sudden dilatation of the tube, and those which may have ensued during its quick compression and in places partial collapse.

In regard to the distribution of the bubbles or vesicles, three vaguely marked bands may be distinguished:[5] a marginal tract, next the lumen, comparatively free from vesicles and clear: a middle portion of the wall comprising most of the larger vesicles; and the gathering of dark swarms of the more minute vesicles toward the outer margin.

The last (partly shown in Fig. 2) vastly predominate in number over the larger vesicles, are almost universally spherical, vary greatly in diameter down to Iμ or less, and compose the dark

[5]In a fulgurite from Milton, Florida, no definite order of arrangement occurred. (MERRILL, *loc. cit.*, p. 90).

clouds, seen under low magnifying power, on inner side of sand-grains adhering to outer side of the wall. Others are also dispersed more irregularly in lines and bands through patches of the glass (best shown under magnifying power of at least 300 times). A careful search was made among these dark bubbles, particularly the most minute, by means of a tenth-inch objective of good definition, for traces of enclosed water, but no liquid could be distinguished. From this I conclude that any watery vapor, derived from moisture present in the sand, has been mostly expelled in the explosions, and also that this has probably had far less to do, in expansion of the lumen and formation and compression of bubbles, than the elastic force evolved by sudden heating of the large volume of air occupying the interstices of the sand-grains. The bubbles should therefore be more properly denominated air-vesicles (*luft-blasen*) than vapor- or steam-cavities (*dampf-poren.*)

The larger vesicles, which mostly occupy the middle part of the tube-wall, seem to have been produced by crowding together and coalescence of smaller ones. The largest, which have been perforated and emptied, in making the thin section, present light outlines, up to 0.2 to 0.3mm in diameter, mostly elliptical, but also oval, pearshaped, lenticular, triangular, or squeezed together in groups, with contiguous walls flattened by pressure in direction tangential to the tube-wall. Even a particular vesicle may vary much in size and in form of cross-section at different depths, as if distorted after formation. The longer axes of the elongated vesicles are in general disposed radially[6] toward the lumen of the tube, though occasionally one may lie obliquely or even at right angles to that direction, as if twisted around by a sudden thrust. All the facts seem to point to strong lateral or tangential compression of the vesicles within the surrounding glass wall, and to their consequent extension and distortion in the direction of relief.[7]

The sudden expansion of air and vapor by the electric discharge has thus effected the dilatation of the lumen, the gen-

[6]A position already recognized in other fulgurites by Wichmann and Rutley.
[7]One writer considers "this radial arrangement .... possibly indicative of a rudimentary crystallization in the fulgurite glass" (RICHARDSON, *Min. Collector*, Vol. III (1896), p. 132).

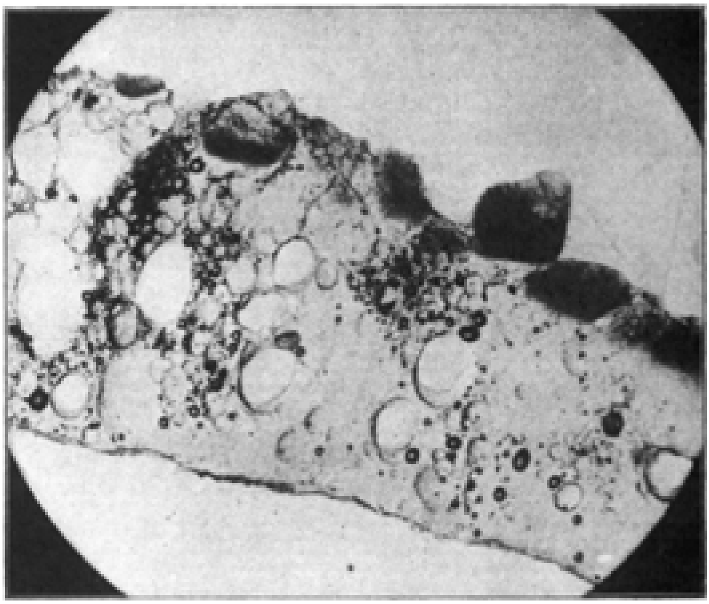

Figure 2: The same. x 50. Part of wall.

eration of bubbles throughout the fused glass, and the coalescence of those first formed into the larger vesicles. The relief of this tension outwardly, toward the margin of the tube, first caused the radial elongation of the larger vesicles and extension of conical projections and wings from outer side of the plastic tube, aided, doubtless, by lateral offshoots of the electric current.[8] Then, in the moments succeeding the passage of the main current, the effects of sudden condensation, lateral contraction and recoil are shown in the instances of partial collapse of the tube, in the reverted distortion of vesicles, *i. e.*, inwardly toward the lumen, and in explosion of some bubbles nearest the lumen into pustules and points of glass over its surface. Where the glass retained its plasticity longer, the vesicles have recovered their normal spherical form; this condition seems to have been regained in nearly all fulgurites whose vesicles have been

[8]MERRILL, *loc. cit.*, 87. One consequence of these offshoots, and of the ozonized atmosphere thereby developed, is shown in the reddish stains, due to oxidation of iron, in the sand surrounding a fulgurite, to the distance of 3 or 4 inches; *e.g.*, in that found near Starczynow, Poland (ROEMER, *N. Jahrb. f Min.*, 1876, pp 33-40).

carefully examined by others. It is to be noted that elongated vesicles in radial position have been recorded in only two cases of rock-fulgurites, in both within partially devitrified glass, as found in one by Rutley and in the other by Wichmann; in the latter case (viz., fulgurite III, beyond) I have made the same observation, in addition to fulgurites I, II, and IV. Their exclusive association, therefore, with devitrification may be a consequence of more sluggish movement and imperfect recovery from distortion within the more viscous crystallite-laden glass.

Another feature, quite distinct in the vesicles of larger size, is the separation of each from the surrounding glass by a limpid pellicle, never exceeding 0.2μ in thickness. This appears both in cross-section, with sharply differentiated outlines, and also in jagged remnants around the margin of an emptied vesicle, on surfaces of the thin section, like the edges of a broken egg-shell. It may be considered a glass coating, suddenly chilled and condensed in contact with the bubble, at first consolidation of the tube-wall.

Around the outer margin of the wall occurs, as usual in sand-fulgurites, a continuous row of adhering sand-grains (Fig.1), semi-fused and to that extent rendered white and opaque. These grains are partly rounded and from 0.2 to 0.6mm across. All were successively examined around the thin cross-section by the usual optical methods, those of feldspar being generally recognizable by traces of cleavage, cloudy alteration, oblique extinction, lower interference-colors than those of quartz, and more or less complete biaxial interference-figures, whose negative character could often be distinguished. Out of 35 grains 23 were identified as orthoclase, the remainder as quartz. In the more angular grains wavy extinction testified to remaining mechanical stress. The indications are that the original sand was very fine and highly feldspathic, free from mica and with few ferruginous particles.

While the outer extremity of a sand-grain, so attached to the glass wall, often retains its translucency and color entirely uninjured by the electric discharge, this is sharply divided from an altered milk-white inner portion, in which the change consists mainly, with quartz, in very minute fracturing and consequent opacity. This passes, with feldspar, into a translucent border, next the glass, in which minute needles or crystallites abound, suggesting immediate devitrification after fusion. From this border very irregular milky threads descend into the glass in a confused network, swarming with the most minute air bubbles, approaching 1 or 2µ in diameter. In this vicinity, also, fibrous threads or streaks of glass occur, which display, between crossed nicols, feeble colors of aggregate polarization.

On reception of this fulgurite from Mr. Walker, he stated: "I have noticed in several places on the outside of the tube .... some very fine threads of fused quartz, like delicate spider-webs, connecting the sand-grains, as if the partly fused grains had been forced apart while still soft." This new feature in fulgurites I can confirm. The glass threads are colorless, brownish, or sometimes black; generally smooth and glistening, but occasionally roughened; more or less curved; passing from grain to grain of the adhering sand, but sometimes projecting as if broken; mostly 0.4 to 1.1mm in length, and 0.015 to 0.04mm in width.[9] In the glass between neighboring sand-grains many minute round holes are also perceptible[10] under a low magnifying power, apparently produced by exploded bubbles. In several cases, in the glass behind a sand-grain, there is a limpid band with faintly marked outline (best shown in photomicrograph, Fig. 2), the latter corresponding to the back contour of the sand-grain. This must mark its original position before it was jerked outward to a distance of half its diameter and the space behind filled in at once with clear glass, distinct because free from bubbles. To the force and extent of this outward jerk, in some instances, the glass threads doubtless owe their formation.

Between crossed nicols the thin section at first appears dark, like a homogeneous glass, with the exception of the ring of highly refracting sand-grains outside and occasional gleams of

[9]A coating of sublimed silica is often found upon the carborundum crystals manufactured in the electric furnace at Niagara Falls. The interlaced threads of quartz of which it is composed much exceed the dimensions of the natural threads above described. They differ also in the variation of diameter in a thread and in the common occurrence of a peculiar beading along many threads.
[10]MERRILL, *loc. cit.*, p. 84.

reflection from scattered air-vesicles. In ordinary light, under low magnifying power, a faint granulation is discernible throughout the glass. This is resolved under higher power (X 300) into an irregular, sparse to abundant distribution of crystallites through a predominant glassy base, from the margin of the lumen to the fusion-border of the sand-grains. No special concentration occurs, except in occasional richer wisps and streaks, like diffusion-streams, across minute patches of clearer glass. In general they are scattered in the same way among and near to the air-vesicles. In some cases, however, an elongated vesicle is surrounded by a band of perfectly clear glass, free from microlites, 5 to 10μ in width, which broadens to 20 or 30μ opposite the ends of the major axis of the vesicle. This has been plainly due to compression and extension of an original envelope of viscid glass, chilled and consolidated by proximity of the vesicle, before devitrification could take place within this envelope. But in general throughout the glass we may recognize one condition that has favored crystallization, in the influence of absorbed vapors, through the abundantly intermixed bubbles.[11]

These microlites are straight or curved, sometimes lathshaped, less than 1μ in length in some cloudy aggregates, but largely 3 to 13μ, or even extend into threads, often bent or crooked, 30 or 40μ in length. They lie in all positions and never display any fluidal arrangement,[12] though the larger number seem to be radially disposed toward the center of the fulgurite-tube. Between crossed nicols the microlites exhibit very feeble double refraction, mostly pale gray, here and there brightening into pale greenish-white of the first order. All these forms appear to represent the regeneration of feldspar. A very few margarites were also distinguished, and one spherulite of about 3μ diameter, made up of concentric shells, which exhibited a faint cross, remaining fixed on rotation.

[11]As in the pumiceous glass of the fulgurite of Little Ararat III, as well as in the devitrified glass of Monte Viso, of which Rutley states that the vesicles are sometimes so closely packed that the glass is quite spongy. However, the pumiceous glass of other fulgurites has been found entirely homogeneous.

[12]In fulgurite-lumps from Florida, Merrill recognized a fluidal structure in the homogeneous glass near bubbles, "as if by sudden expansion of a steam-bubble in the plastic material" (*loc. cit.*, p. 87).

This unique occurrence of devitrification in the glass of a sand fulgurite is perhaps mainly connected with the high proportion of feldspar in the original sand. Such a chemical constitution must have approached that of the rhyolite[13] used in the experiments of Barus and Iddings, whose viscosity and whose electric conduction, when fused, were both found to exceed those of the less acid rocks, and led to the conclusion that "electric conduction increases with the degree of the acidity of the magma..... Since fusibility decreases in a marked way as the composition of the magma approaches pure silica, it follows that, in a series of different magmas, electric conduction at any given temperature increases in proportion as the viscosity increases." From this it must be inferred that the more quartzose sands, when once melted by a lightning stroke, have offered the viscous medium of readiest passage to the current.

Exception has been rightly taken, however, to the assumption that the material of a fulgurite-tube was necessarily or entirely "quartz-glass."[14] The general distribution of feldspar in notable quantity through ordinary sands is a fact in favor of the suggestion of Wichmann and Harting, that the minerals of comparatively ready fusibility have served as flux and thus ended in reducing the more refractory. Particularly then in this fulgurite do we need to consider not only the relative fusibilities of feldspar and quartz, but also the relative degrees of their solvency in contact with the first formed portion of molten glass, doubtless so instantaneous in formation as to be independent of all differences in fusibility, solution, conduction or any other property of the various sand-grains.

To throw light on this question and on the variations, recorded beyond, in devitrification of such natural glasses, a preliminary examination was made of a specimen of artificially vitrified gneiss, with brown glassy fracture, obtained from the hearth of a limekiln at Tuckahoe, N.Y. This had been evidently thoroughly roasted and deprived of moisture but not fused (as

[13]Silica, 75.5 per cent.; alumna, 13.25; soda, 4.76; potassa, 2.85, etc. Heated in a platinum crucible, it melted at 1500° C., was very viscous ("a stiff paste") even at 1600°, and quite viscid at I700°. *Am. Jour. Sci.*, Vol. XLIV (1892), pp. 242-249.
[14]See v. GÜMBEL, *loc. cit.*, and *idem.* Vol. XXXVI (1884), pp. 179-180, and criticism by A. WICHMANN.

the gneiss structure still perfectly survived, in the undisturbed parallel biotite-scales), saturated with slag from the kiln, and finally thrown out and slowly cooled upon the refuse dump. In a thin section under the microscope, the results of the action of fused glass upon the original minerals of the gneiss were found to be as follows: a slight solvent attack upon the biotite, rendering it in part opaque, with brown haloes and cloudy wisps of iron oxide feathering out into the adjacent glass, apparently by quiet molecular diffusion; a decided but partial solution of the quartz, of which a small portion survived in angular remnants, still in place; and complete solution and disappearance of the feldspar. The main mass of the saturated rock had thus been converted into pure colorless glass, with a few coffee-colored stains, without any trace of crystallites or new stony matter, notwithstanding its slow cooling. However, globules of clear glass, about 0.5mm in diameter, were abundantly interspersed, colorless like their matrix and with little adherence, since many had become loosened and removed from the surface of the thin section during the process of grinding. It was consequently inferred:

1. That minerals of acidic constitution, feldspar and quartz, may be largely carried into solution, in contact with fused glass, at a temperature below their thermal melting points.

2. That their fused products tend to cohere *in situ* in spheroidal globules, through possession of a different degree of density, viscosity and contraction on cooling, from that of the surrounding glass.

3. That the process of devitrification has been prevented in this vitrified gneiss by the peculiar constitution, probably the acidity, of the unsaturated glass, and by an insufficient period of cooling.

In the development of a sand-fulgurite by almost instantaneous fusion, it is unlikely that any selective power could have been exerted among the sand-grains, through their slight variations in fusibility, conductivity or other property. All within a radius of a few millimeters were suddenly and completely fused, with a limitation so sharply defined, in this fulgurite, that, in any sand-grain, the quartz or feldspar may remain entirely unaltered within an interval of about 0.02mm of the same material fused and again devitrified. The molten mass of its wall became a supersaturated solution of feldspar, with specially strong solvency, however, toward any external quartz-grains within its reach, through the tendency to form more acid silicate. Such action probably accounts for the increased amount of silica which has been determined in fulgurite-glass over that in the original sand in several instances.[15] In this fulgurite also the preponderance of feldspar over quartz in the attached sand grains may possibly have become exaggerated by the slower solution of the former mineral.

The view has been advanced[16] that a selective power of fusion has been exerted by the electric current among the grains, but without regard to their fusibility: the poorer conductors (quartz grains), offering so strong resistance as to become heated to the point of fusion, those substances which are the best conductors (iron-oxides and feldspars) escaping with least injury. It is notable, however, that it is not a good conductor but quartz only which has ever been recognized in remnants of grains enclosed in the glass of other sand-fulgurites, and that no remnants what ever are enclosed within the glass of this fulgurite, apparently because so rich in flux.

Three rock-fulgurites will now be described in the order of increasing devitrification.

II. *Fulgurite* on gneiss, near *Split Rock, Lake Champlain, New York*; specimen collected by Professor William Hallock, of Columbia University, immediately after the lightning-stroke, as described in his accompanying article. Thin sections of this granite-gneiss were prepared, one in plane parallel to and within about 0.03mm of the fulguritic crust, the other in cross-section. The rock is found to present a surface somewhat dulled by weathering, and to consist, to about 70 per cent of its vol-

[15]In a fulgurite from Union Grove, Ill., silica 91.66 per cent. in the Rlass to 84.83 in the sand; in another, 95.9I in the glass, to about 90 in the sand. (MERRILL, *loc. cit.*, p. 85.)

[16]MERRILL, *loc. cit.*, p. 87. Diller notes, however, in a fulgurite on hypersthene-basalt, that the sequence of alteration is according to degree of fusibility of the components of the rock, greatest in the groundmass, then hypersthene, then feldspar, and least in olivine.

ume, of feldspars, microcline, microperthitic orthoclase and a little plagioclase, besides much quartz and a small amount of magnetite, biotite, garnet, and rutile, but no trace of fulguritic glass. No undulatory extinction occurs between the nicols, as evidence of strain.

The fulgurite-pellicle is entirely superficial,[17] brittle, and with slight adherence to the rock, from 0.l to 0.3mm in thickness, nearly white, consisting chiefly of a minutely blebby hyaline crust with blistered, glistening surface, whose bubbles, rarely exceeding 0.2mm in diameter, are nearly spherical but somewhat elongated normally to the surface of the rock. On careful examination of these, in a flake mounted in balsam, under a good tenth-inch immersion objective, no water of condensation could be detected in any vesicle.

Many short glass fibers occur, sometimes with globular ends, resembling some of those in "Pele's Hair" from the crater of Kilauea, Hawaii. This white pumiceous slag is quite uniformly attached to the predominant surfaces of feldspar, though pierced by the uncovered gray grains of quartz. It is dispersed over the rather even surface of the hard gneiss in radial, somewhat dendritic forms, often many inches in length, thinning out into feathery fleeces at the margins. Wherever these pass over minute plates and seams of the dark minerals of the rock, the blebby fulgurite assume a yellow, red, brown, or black color, as a dark enamel, or in the form of tiny spherules.[18]

The white material, when flaked off and mounted in Canada balsam, reveals a limpid glass, dispersed with very few and minute straight microlites and very rarely rhombic plates; the latter display rather bright interference-colors between crossed nicols and parallel extinction.[19] Where thinnest, the glass remains isotrope and dark, while the thicker portion, generally toward the center of the flake, glows with the greenish-white of

17. Similar superficial films of fulgurite have been often observed, by Humboldt in Mexico, by Brun in the Alps, by Ramond on mica-schist, on limestone, and on phonolite in the Pyrenees and Auvergne.

18. Over the fulgurite-crust on hornblende-gneiss at Mount Blanc distinct white and dark globules were dispersed: "the fused surface of each crystal solidified almost exactly *in situ*, except where sputtering of the molten matter was caused" (RUTLEY, *Quar. Jour. Geol. Soc.* (1885), pp. 152-156). The inclosed globules in the slag saturated gneiss of Tuckahoe may represent a similar tendency to isolation.

the first order of Newton's colors; in places the color reaches the sky-blue of the second order, exactly like a thin scale of the underlying feldspar. The indications are that devitrification had begun, throughout the glass, in globulites too extremely minute for distinction, even under high magnifying power, but whose concentrated effect in depolarization becomes visible, between the crossed nicols, in the thicker parts of the flakes. The flakes of brown or colored glass, however, are found to be uniformly isotrope. It should be noted that, as the greater thickness of these flakes approaches or exceeds 0.5mm, it is probable that the presence of crystallites might hardly have been recognized in a ground section of the ordinary thinness, 0.02 to 0.05mm. In such an investigation plane surfaces are not indispensable, and the examination of splinters of a glass may serve an important office. Evidences of incipient devitrification, in fulgurites and other glasses, have possibly escaped detection by observers relying entirely on examination of thin sections.

The facts above described load to the following conclusions:

1. We have here to do with different conditions from those which attended the sand-fulgurite I, viz., the lessening force of a divided electric current, passing over the surface of a compact rock-mass. The effect of the electric action on this solid surface of gneiss has been more diffuse, feeble, and superficial than in the sand-fulgurite, and, in this case, confined to the feldspar.

2. The fulgurite crust has been produced almost entirely by fusion of surfaces of feldspar-grains rather than of quartz, and in small degree by that of the iron-containing minerals. The property of fusibility, rather than that of imperfect conduction, has determined the amount of attack on each grain. Each kind of glass, colorless and colored, is sharply confined to the mineral surfaces from whose fusion it originated, with little tendency to intermixture.

[19]The homogeneity of glass which apparently prevailed in all fulgurites examined by the early observers led naturally to the statement in 1884 that the absence of crystallites" may be used as a means of distingnishing fulgurite from other natural glasses" (J. S. DILLER, *Am. Jour. Sci.*, Vol. XXVlII (1884), pp. 252—258). In 1889, Rutley made the first and hitherto the only record of the occurrence of devitnficatoin in a vesicular fulgurite-glass on glaucophane-schist, at Monte Viso, Cottian Alps. The crystalline forms consisted of globulites, margarites, and longulites, and even symmetrical microliths (*Quar. Jour. Geol. Soc.*, Vol. XLV (1889), pp. 60-66).

3. The bubbles throughout the fulgurite-crust owe their formation chiefly to expansion of air, and in part doubtless of steam, derived from moisture in the weathered surface of the rock. Their sputtering explosion has probably produced the tiny fibers over the blebby surface.

4. The surprising partial devitrification, which has instantaneously followed fusion throughout the delicate white pellicle, has been evidently facilitated by the supersaturated feldspar solution of which the molten glass almost entirely consisted, and by its consequent unstable molecular condition.

III. Fulgurite in augite-andesite, summit of *Lesser Ararat, Armenia*. The specimen was one of those collected by Dr. E. O. Hovey, of the American Museum of Natural History, New York.

The fulgurite material from this peak has received repeated study in the field or laboratory by successive observers. Abich[20] detected only pure glass in the fulgurite, but in such abundance that he suggested the name "fulgurite-andesite" for the material on the apex of the peak. Gustav Rose[21] also came to the same conclusion, and determined the difficult fusibility of the glass on thin edges. A. Wichmann[22] made the most careful petrographic study of this and other fulgurites and distinguished this as "entirely homogeneous glass," without any alteration of the andesite at the sharply defined contact. He considered the bubbles as vapor-cavities (*dampf-poren*), and gave a clear representation of the structure of a lightning-tube in a well-drawn cross-section. The results of my own examination, which follow, differ in some important particulars.

The augite-andesite of this peak, though consisting of fresh plagioclase-feldspar, with some partly decayed augite, hornblende, orthoclase, and magnetite, is deeply disintegrated by weathering, so that, in some blocks, its grains crumble readily under pressure from one's fingers. It is also traversed, even in the most solid material, by numerous cavities and channels, a few millimeters in width, of most irregular form, crossing and

[20] *Sitz. Akad. Wiss. Wien*, Vol. LX (1870), I. Abth., pp. 153-161.
[21] *Zeit. d. D. geol. Ges.*, Vol. XXV (1873), pp. 112, 113.
[22] *Idem.*, Vol. XXXV (1883), pp. 849-859.

connecting with each other at intervals of a few centimeters. Most of these passages, in the more decayed specimens I have examined, in the collection of Dr. Hovey, are one or two centimeters in width, and often coated by the olive-green fulgurite glass to a depth of 1 to 1.5mm; some are even solidly filled up by the glass, with a cross-section of 5 to 8mm in diameter or over. Other cavities of exactly the same form and size were noticed, adjoining but not connecting, which are now and appear always to have been entirely free from fulgurite. Most, if not all of these, therefore, seem to be preexisting cavities, later occupied in many cases by fulgurite. A confirmation of this is found, by optical examination of the thin sections, in the absence of undulatory extinction in the grains of minerals adjacent to the fulgurite, *i.e.*, the lack of any indication of strain likely to have resulted from actual perforation of the rock by lightning. On the other hand, certain other specimens in the collection from the same peak are penetrated by cylindrical winding tubes,[23] lined or filled with the dark glass, which seem clearly to owe their perforation to the action of electric discharges upon more disintegrated blocks of the crumbling rock.

The glass is found to be rich in bubbles, especially toward and near the surface of the inner rock-wall, and in places even blown up into blebs and blisters. All of the smaller vesicles and most of the larger are approximately spherical. In none of these could any water of condensation be discovered under a tenth-inch objective; their contents appear to be entirely gaseous, *i. e.*, chiefly derived, in all probability, from expansion of air rather than steam. Many of the larger vesicles present a more or less elongated form, with major axis always arranged in position at right angles to the adjacent rock-wall. This distortion of vesicles in the glass of a rock-fulgurite may be always attributed, in my opinion, entirely to the reaction of pressure inward, *i.e.*, toward the lumen, which has instantaneously followed the passage of the electric discharge, mainly

[23]The approximately cylindrical form of the latter, and their curved windings, have been well represented by Rutley, from the fulgurite furrows on glaucophaneschist at Monte Viso, Cottian Alps (*loc. cit.*, plate).

from expansion of the collected bubbles, partly from increased volume of the glass during fusion of the rock.

When crushed splinters of the glass are examined, though found sometimes entirely amorphous, as reported by Wichmann and others, it is also in places rich in bunches of stony matter, isolated needles (with bright interference-colors between crossed nicols and parallel extinction) and clusters of microlitic fibers, sometimes radiating around a bubble.

Again, at the line of contact between this glass and the andesite-wall, an intermediate stony layer occurs, 0.15 to 0.70mm in thickness, containing a few obscure outlines of bubbles. This plainly consists of wholly devitrified glass, made up of a felt of irregularly crossing needles, fibrous curved wisps, or straight bundles, some rectangular in form, 0.08 to 0.20mm in length, whose axes lie mostly parallel to the line of contact with the adjacent rock-wall. In the straight bundles an extinction-angle of about I9° is uniformly obtained, often with undulatory phase, and all offer the characteristics of orthoclase. There is a remarkable resemblance, if not identity, of these fibrous aggregates, in form, structure, and optical character, to the artificial microlitic bundles obtained in the experiments of J. S. Diller (loc. cit.) by long fusion of amorphous fulgurite-glass in crucibles.

The difference of the above results from those hitherto reported from study of the fulgurite of this peak may be attributable to variation in the structure of the fulgurite, particularly in regard to devitrification, in different parts of the surface.

IV. *Fulgurite* from summit of *Central Butte, Little Missouri Buttes, Wyoming*; specimen collected by Mr. John D. Irving. This is a small fragment of phonolite, apparently from the edge of intersection between two joints, down which corner the fulgurite runs in a shining, cream-colored, slightly brownish crust, about 15mm wide and 3mm thick. On a fractured cross-section it shows distinct lamination parallel to the surface of contact, as if the latent structure had been developed by weathering.

The rock consists mainly of orthoclase-phenocrysts, whose idiomorphic character is obscured by fractures, imbedded in a smaller volume of granular, somewhat ochreous holocrystalline groundmass, through which needles of hornblende, plagioclase, apatite, and granules of magnetite are dispersed. Between the crossed nicols, the transparent minerals, in a thin section, generally display a decided undulatory extinction, in evidence of condition of strain.

This fulgurite exhibits under the microscope the unique character of a wholly devitrified mass, light brownish-gray, delicately laminated in cross-section (*a*, Fig. 3) by a very irregular flow structure,[24] with interruptions and intersections of laminæ suggesting those observed in the cross-stratification of certain sand deposits. Some laminæ, especially near the contact-line (*e.g.*, just below *c'*) are bent and faulted, with ends slipped past each other. The thicker laminæ consist of very minute, colorless needles, fibers, and granules, in an irregular felted mass, through which obscure circular and elliptical outlines (*b*, etc.) indicate the position of numerous original bubbles, now flattened, freed from gas, and even partly obliterated. With this darker material, evidently entirely devitrified glass, there occur frequent alternations (*d, d*, etc.) of thin films of a microscopic breccia or "mylonite," shining brightly between the crossed nicols. This is composed apparently of rock-dust,[25] made up chiefly of angular splinters of feldspar; a few coarser fragments of the same are also irregularly interspersed (*f*). Along the line of contact (*d'*), the same angular dust is drawn out in streaks or gathered in embayments. Its origin is well shown next the Carlsbad twin of orthoclase (*c-c'*), whose outer end (*c'*), projecting into the fulgurite current, has been shattered into this dust to a depth of 0.1 mm, seemingly after the adjoining fulgurite laminæ had somewhat consolidated. This and other feldspar-grains lying along the edge of the stream, have been completely encircled by fulgurite, with an inner film of angular dust, marking the outline of the minutely-shattered surface of feldspar.

[24]Compare the thin underlying coat, in which fusion is less complete, with dark fluidal banding, and which envelops numerous crystal remnants, described by Diller in the "mixed zone" of fulgurite-glass in immediate contact with basalt at Mt. Thielson (*loc. cit.*). Of this he states, it is difficult to conceive how it has been produced, " unless it is due to the repulsion of the particles among themselves."

[25]Apparently related to the opaque whitish layer, between the glass and rock, in the fulgurite of Monte Viso, and referred by Rutley to altered titanite.

Figure 3: Rock-Fulgurite, Wyoming. X 50. Cross-section of contact.

This micro-breccia is brought out between the crossed nicols in distinct bright stripes. The phonolite groundmass generally shows rather deeper embayments by fulgurite-attack than the feldspar-grains; but the hornblende-needles seem to lie entirely unaffected, even in immediate contact (*h*) with the fulgurite stream.

It is possible that the devitrified crust which constitutes this fulgurite may be a remnant of an inner stony layer (as in Fulgurite III), from which a glass-coating may have been scaled off during weathering; but of the latter there is no evidence, and the stony crust now occurs coated by small lichens. Yet the peculiar structure of this crust, with its alternations of micro-crystalline and of micro-brecciated laminæ, signifies that devitrification has not been a secondary process due to weathering of a glass.

RÉSUMÉ

Considerable variation appears, in the characteristics of these rock-fulgurites, from two probable causes: the variations in the electric current, in regard to volume, intensity, duration, and a probable series of successive discharges, in some cases, within the same fulgurite (IV); and the difference of the rock-material in the three specimens, gneiss, andesite, and phonolite.

In regard to the duration of a lightning-flash, it is understood not to have usually exceeded one hundred thousandth of a second (Sylvanus Thompson). The discharge is known to be oscillatory, surging back and forth, and even in many cases, like that observed by Professor Hallock, apparently persistent and continuous for some moments. Nevertheless, allowing for the long retention of the image of the flash upon the retina, its duration is rarely likely to have much exceeded the above quoted minute interval.

The results of the electric action are of two classes, superficial and internal.

The superficial consist, in succession, of fracture of outer pellicle of exposed minerals: fusion in situ of the surface of more fusible grains: and development of bubbles in the enamel of molten glass from expansion of moisture and air, with frequent explosions and spattering of glass globules.

The internal results comprise the penetration of preëxisting cavities of the rock, and often the actual piercing of surface of outcrop or blocks, if softened and disintegrated by weathering, by lightning-tubes of symmetrical cross-section, as well as passage downward through fissures and joints.

This has been accompanied by fracture and fusion of pellicles over the surfaces thus traversed, especially of the more fusible minerals and groundmass; development of air- and vapor bubbles in the molten coating; and sometimes, at least, a succession of waves, sweeping downward fused glass and rock-dust, in a series of alternating films, the oldest nearest the rock-wall and subjected to frequent dislocation.

At the moment of cessation of the electric current, there have followed reaction from the intense pressure, expansion of vesicles, and regurgitation of glass upon the surface of the rock from some filled lightning tubes;[26] explosion and disappearance of bubbles nearest the surface, distortion of many by inward relief of pressure, or general recovery of spherical form; and partial devitrification of the glass, occasionally complete, where certain favorable conditions have prevailed—probably the presence of moist air in intermixed bubbles, a supersaturated neutral glass, and an overheated or slowly-cooling contiguous sheet of rock.

The instantaneous regeneration of feldspar only, in the form of microlites, in every instance, in the series I have examined, seems at first somewhat at variance with the conclusions of Lagorio as to the particularly difficult saturation of a molten silicate by the oxides represented in that mineral. But we have here, apparently, a far different magma from that employed in the experiments of Pelouze, artificial glass, *i. e.*, from every evidence, a supersaturated solution of feldspar in its own fused material. In such a magma-solution, a combination of silica, alumina, and alkali molecules, must find conditions highly favoring ease and rapidity in recrystallization.

ALEXIS A. JULIAN.

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[26]First recorded by HUMBOLDT, in rock-fulgurite on volcano of Nevada de Toluca, Mexico (*Ann. d. Ch. et d. Phys*, Vol. XIX (1821), p. 299.)

Explanation of Figures

Fig. 1. Sand-Fulgurite, Poland.—Photomicrograph of cross-section, showing sharply defined outline of central lumen, the glass wall with its vesicles, and ring of dark semi-fused sand-grains, adhering to the irregular outer boundary of the fulgurite. X l0.

Fig. 2. The same.—Photomicrograph of section of part of the wall, showing forms, radial distension, and distribution of the vesicles, the smaller and darker ones still occupied by air. Several of the sand-grains appear along the outer boundary, each with its inner crescent of limpid glass. The inner dark part of a grain indicates the side which has been partly fused; the outer clear part, that which remains unaltered. X50.

Fig. 3. Rock-Fulgurite, Central Butte, Wyoming.—Drawing of cross section, showing line of contact (*d'*, *h*, *c'*, *e*) between phonolite, p, and fulgurite, a.

b. Obscure flattened vesicles.

c-c'. Carlsbad twin of orthoclase, with shattered ends, surrounded by feldspar-dust and devitrified glass, enclosing a few bubbles.

d, d, d. Films of rock-dust, alternating with laminæ of devitrified glass.

d'. Film of rock-dust along the contact.

e. Projecting corner of feldspar-grain, shattered by the electric current.

f, etc. Feldspar fragments scattered through the fulgurite.

h. Green hornblende needle, unaffected by the fulgurite-stream. X 50.

THE EVENT

PETRIFIED LIGHTNING FROM CENTRAL FLORIDA

A PROJECT BY ALLAN MCCOLLUM

CONTEMPORARY ART MUSEUM
UNIVERSITY OF SOUTH FLORIDA

MUSEUM OF SCIENCE AND INDUSTRY
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