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SMITHSONIAN MISCELLANEOUS COLLECTIONS  
VOLUME 143, NUMBER 4

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Charles D. and Mary Vaux Walcott  
Research Fund

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COMPARISON OF TEKTITE SPECIMENS  
FROM EMPIRE, GEORGIA, AND  
MARTHA'S VINEYARD,  
MASSACHUSETTS

(WITH SIX PLATES)

By  
ROY S. CLARKE, JR.  
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(PUBLICATION 4465)

CITY OF WASHINGTON  
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COMPARISON OF TEKTITE SPECIMENS FROM  
EMPIRE, GEORGIA, AND MARTHA'S  
VINEYARD, MASSACHUSETTS <sup>1</sup>

By ROY S. CLARKE, JR.,<sup>2</sup> AND MAXWELL K. CARRON <sup>3</sup>

(WITH SIX PLATES)

INTRODUCTION

The recent find of a tektite at Gay Head, Martha's Vineyard, Mass., has been reported by Kaye, Schnetzler, and Chase (1961). This specimen, representing a possible new occurrence of tektites, was generously submitted by the finders to us for laboratory study. The Martha's Vineyard tektite (USNM 2082) arrived when we were completing study of a tektite from Empire, Ga. (USNM 1396), which has been at the U. S. National Museum since 1938. A similarity between these two specimens was immediately suggested by their close agreement in color, density, and magnetic properties. Further study of the Martha's Vineyard tektite established that a truly remarkable similarity does exist. This report presents new physical and chemical data and photographs for both of these specimens. The possible significance of the unexpected nature of these data and the ambiguous conclusion to which they lead are discussed. Either this new group of tektites has much more uniform properties than would be expected, or else there is room to doubt their authenticity.

ACKNOWLEDGMENTS

The authors are indebted to a number of their colleagues who have supported and contributed to the studies presented here. Most of these workers are cited at appropriate places in the text. Frank E. Senftle, Irving Friedman, and E. C. T. Chao, of the U. S. Geological Survey, should receive special mention, as they have had an active interest in this work since its inception. Their suggestions, criticisms, and experimental observations are included below. Paul D. Low-

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<sup>1</sup> Publication authorized by the Director, U. S. Geological Survey.

<sup>2</sup> U. S. National Museum, Smithsonian Institution.

<sup>3</sup> U. S. Geological Survey, Washington 25, D. C.

man, Jr., of the National Aeronautics and Space Administration, and E. P. Henderson, of the Smithsonian Institution, have generously shared their knowledge of tektite specimens and literature with the senior author in many helpful discussions.

#### PREVIOUS WORK

The initial identification of tektites from Georgia was made by E. P. Henderson of the Smithsonian Institution's Division of Mineralogy and Petrology. Two specimens (USNM 1396) were submitted for examination and an identification was made during 1938. Confirmation of Georgia as an area of tektite occurrence has been reported by Barnes and Bruce (1959). Bruce (1959) has published a general discussion of tektite finds in Georgia, and included in his paper are photographs of several specimens. Cohen (1959) has discussed Georgia tektites with particular reference to their similarity to moldavites and bediasites. His paper includes a compilation of physical properties and spectrochemical data. Senftle and Thorpe (1959) have measured the magnetic susceptibility and intensity of magnetization for the Georgia tektite and for a number of other tektites, and have discussed the significance of these measurements. Reynolds (1960) and Gentner and Zähringer (1960) have measured potassium-argon ages for the major tektite groups. These data show that Georgia tektites and bediasites are of similar age, but that moldavites are much younger. Stair (1955a, 1955b, 1956) has published the absorption spectra and a photomicrograph of this same Georgia specimen. He also gives a photograph of a second Empire, Ga., tektite. The measurements reported in the literature on Georgia tektites by all the workers cited above have been made on portions of one specimen, USNM 1396.

The only previous experimental work using material from the Martha's Vineyard tektite other than a chemical analysis reported by Kaye et al. (1961) is that of Pinson and Schnetzler (1960). These authors have determined rubidium and strontium contents and strontium isotope ratios.

#### MORPHOLOGY AND INTERNAL STRUCTURE

The two tektite specimens with which we are particularly concerned have both similarities and striking differences in gross morphology. Plate 1 is a direct-light photograph of (A) the Empire, Ga., and (B) the Martha's Vineyard, Mass., tektites. Plates 2 and 3 are photographs of these specimens after ammonium chloride smoking to bring

out surface features. All photographs of the Martha's Vineyard tektite show the complete object before removal of material for analysis. Over half of the Empire, Ga., specimen has been consumed in experimental studies, and plate 1, A, shows the remaining portion of this specimen. Plate 2 shows the front and back surfaces of this specimen after it had been cut to remove a slice for study. The distance between halves approximates the material that has been removed.

Plates 5 and 6 are previously unpublished photographs of other Georgia tektites. They were furnished to the authors by E. P. Henderson and are included here as background material. Plate 5, A and B, are photographs of a second Empire, Ga., specimen (also having catalog number USNM 1396), a complete individual that is preserved in the collection of the U. S. National Museum. A tektite from Plainfield, Ga., belonging to G. A. Bruce is shown in plate 5, C and D. Plate 6, B, shows a tektite found near Osierfield, Ga., lent by A. S. Furcron, of the Georgia Geological Survey. Dimensions of these tektites are given in table I.

TABLE I.—*Approximate size and weight of specimens*

Locality	Length of longest axis cm.	Length perpendicular to longest axis cm.	Maximum thickness cm.	Weight g.	Illustrated in—
Empire, Ga. <sup>a</sup> . . . . .	~6.5	~3.5	~1.0	>25	Pl. 2
Empire, Ga. . . . .	3.3	2.7	1.4	13.4	Pl. 5, A, B
Plainfield, Ga. . . . .	3.5	2.9	0.9	11.2	Pl. 5, C, D
Osierfield, Ga. . . . .	4.7	4.4	0.6	17.8	Pl. 6, B
Martha's Vineyard, Mass. . . . .	5.3	3.9	1.0	17.8	Pl. 3

<sup>a</sup> Lengths given were estimated from photographs of cut specimen, and thickness was measured on remaining portion of specimen.

The most striking feature of the four Georgia tektites is their disklike shape; three are nearly circular. These specimens are rather uniformly covered with many shallow pits and grooves which produce generally smooth surfaces and edges. The disk shapes and general surface features are suggestive of the moldavites. Disk shapes are known among moldavite specimens but are rare among the other tektite groups (Suess, 1900; Barnes, 1940; Baker, 1959).

The Martha's Vineyard specimen appears to be a sector of a roughly circular disk about 3 inches in diameter. The smooth fracture surfaces on the sides of the specimen imply that it has been broken from a parent mass after formation of its surface features. The deeply serrated edge of the Martha's Vineyard specimen is different from

anything that has been observed on Georgia tektites,<sup>4</sup> and it is an uncommon feature of tektites in general. The surface relief is also much more pronounced for this specimen. It has sharp ridges on the top and bottom surfaces and particularly on the serrated edge. These sharp, relatively unabraded features imply that the Martha's Vineyard tektite has not been transported far by normal geologic processes subsequent to sculpturing. An unusual feature of this specimen is that the edge pattern appears to be radial, while the surface pattern on the interior of the disk appears to be concentric (pl. 3, A).

There is a remarkable similarity between the Martha's Vineyard specimen and a photograph of a moldavite published by F. E. Suess (1900, pl. V, fig. 5b). Our specimen appears, at first glance, to be a part of this specimen studied long ago by Suess. However, this apparent duplication is due to the fact that Suess's photograph is enlarged. His figures 5a and 5c show this tektite at natural size. It is obvious that the Martha's Vineyard tektite must have come from a parent of greater diameter than Suess's specimen.

It has been stated above that the Martha's Vineyard tektite is apparently a part of a larger disk-shaped object, probably 3 inches (7.6 cm.) in diameter. If this assumption is valid, the parent body of this specimen was larger than any disk-shaped tektite of which we are aware. The hypothetical parent tektite would have a diameter-to-thickness ratio of 7.6, which is greater than that of any tektite known to us. Even if a 2-inch diameter is assumed, this tektite would still have a very high ratio, approximately 5. The Osierfield, Ga., tektite (pl. 6, B, and table 1), with a ratio value of 7, is the only other tektite we know of in this range.

The internal structure and inclusions in the Empire, Ga., and Martha's Vineyard specimens are shown in the accompanying photomicrographs. Plate 4, A, is a photomicrograph taken with white transmitted light of a slice 0.25 cm. thick cut radially from the Martha's Vineyard tektite. Plate 4, B, is of the same area using plane polarized light, crossed nicols. Plate 4, C and D, are photographs of a slice 0.07 cm. thick of the Empire, Ga., tektite. If allowance is made for the differences in thickness between the two sections, the similarity in pattern and character of inclusions is apparent. Some of these inclusions are well outlined and are of lower index of refraction than the surrounding glass. They show wavy extinction and have not been positively identified. Barnes (1940) has proposed that similar inclusions in bediasites are lechatelierite. Sparsely distributed small round

<sup>4</sup> Bruce, G. A., personal communication, 1960.



and elongated bubble cavities are also present, appearing in the photomicrographs as dark spots.

Pronounced flow structure, or flow lines, indicative of inhomogeneity within the glass, appears in both specimens. This structure is revealed by variation in index of refraction resulting presumably from

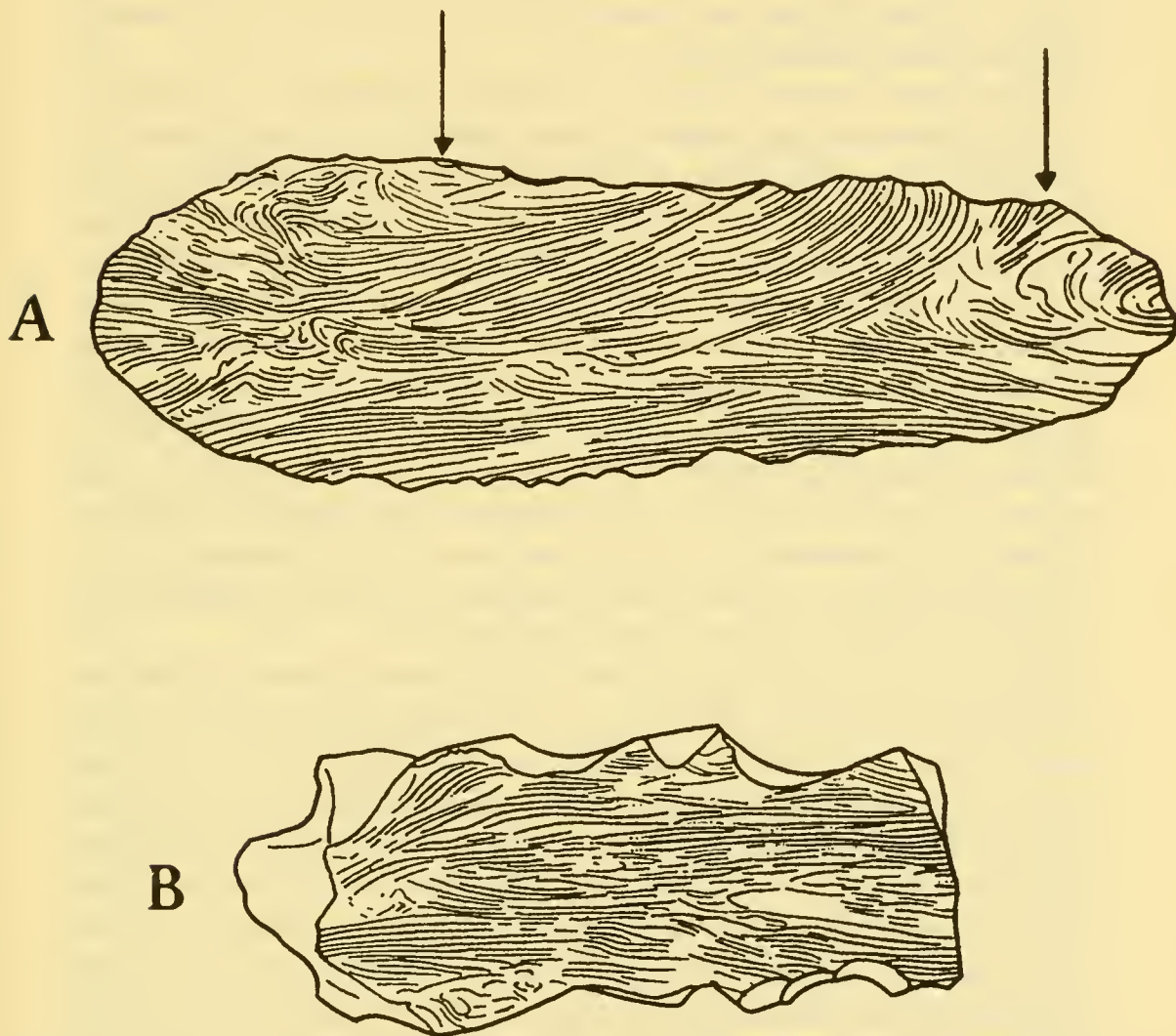


FIG. 1.—Flow structure diagram prepared from slice of (A) Empire, Ga., tektite, and (B) Martha's Vineyard, Mass., tektite.  $\times 3$ .

minor compositional differences (pl. 4, A and C). Strain is also present in these glasses and is associated both with the flow structure and inclusions. This strain is evident from the anisotropism that is observed in the sections with plane polarized light, crossed nicols (pl. 4, B and D).

The flow structure of both specimens here studied in detail conforms quite well to the surface of the specimens. In figure 1 are given flow structure drawings prepared from a projected image of the sections

used in making the photomicrographs (pl. 4). Figure 1, A, is of a section from the flat end of the Georgia tektite specimen (pl. 1, A). The slice from which figure 1, B, was prepared was taken several millimeters in from the left broken edge of the Martha's Vineyard specimen positioned as in plate 1, B, extending approximately two-thirds of the way into the specimen and parallel to that edge. This relationship of surface to flow structure is unusual for tektites in general (Barnes, 1940; Baker, 1959).

The present external surfaces of these specimens are essentially secondary features due largely to chemical etching. Indeterminant factors such as the original shape of the specimen, the susceptibility of its various parts to chemical attack, the nature of the chemical environment and the time through which it has acted, and mechanical effects, combined to produce the present surface features of these tektites. The main surface features, pitting and grooving, have no obvious relation to the internal structure of the material. Tektite surface pits are sometimes referred to as bubble cavities, but it is unlikely that bubbles within the glass were responsible for the pitting on the tektites we studied. It has been mentioned above that the bubbles present in the sections were small and sparsely distributed (pl. 4). Their concentration in the medium and their individual diameters are both minute when compared to the surface pits.

The internal flow structure, however, is related directly to delicate striae that are readily observable as a secondary surface feature on these specimens. The striae frequently occur where the flow structure is truncated by the specimen surface and undoubtedly result from slight differences in susceptibility to chemical attack. The left-hand piece of the Empire, Ga., tektite shown in plate 2, A, exhibits striation which is of particular interest because it indicates the extent to which flow structure conforms to the surface of the specimen. The striae follow the edge of the specimen and suggest that the flow structure pattern based on the section (fig. 1, A) holds in a general way for the complete specimen. The arrows in figure 1, A, indicate areas where the U-shaped striae on the surface of the specimen (fig. 1, A) terminate.

Striae are obvious on the surfaces of the Martha's Vineyard tektite (pl. 3, A and B) and especially on the serrated edge (pl. 3, C). The concentric external pattern is consistent with the flow structure illustrated from the section (fig. 1, B). The second Empire, Ga., tektite (pl. 5) is a striking example of surface expression of internal structure. The more irregular pattern on this tektite probably indicates a more contorted flow structure. Surface striation of this type

is also present on the Plainfield (pl. 5, C and D) and Osierfield (pl. 6, B), Ga., specimens and can be seen in the photographs.

Plate 6, A, is an enlargement of a small area of the surface of the Plainfield, Ga., specimen. It shows several features that are common to all the specimens with which we are concerned and one feature that is peculiar to this specimen. The latter is an apparently glassy mass, or protuberance, that projects from the bottom of a surface cavity (pl. 6, A; and slightly to left of center in pl. 5, C). This protuberance is firmly attached to the body of the specimen and apparently resulted from chemical attack on a volume of glass containing an inclusion or inhomogeneity of more resistant composition. No measurements of properties or composition of this protuberance were possible as the owner desired to maintain the specimen intact.

All these tektites show what appear to be several generations of surface pits, a feature particularly apparent on close examination of plate 6, A. Around the top edge of the cavity containing the protuberance there are four outlined depressions, apparently the remnants of previous pits that have grown together and been largely obliterated by the younger central pit. The photograph also shows numerous examples of pits within pits, and pits overlapping pits. A particularly interesting pattern can be seen in the lower right-hand corner of plate 6, A. A raised, rather white area is surrounded by five distinctly outlined grayish areas that seem to have been formed as a result of enlargement of pits. This feature and the glassy protuberance described above provide direct evidence that the internal composition of the material has at least a limited control on the surface features that develop. A number of very small pits possibly could have resulted from bubbles within the glass, but it is impossible to identify any of these from the photograph.

To summarize: Study of the detailed morphology of these specimens supports the idea that chemical weathering, controlled to a slight extent by variations in composition of the material, is the main agent responsible for the formation of these surface features. We find no evidence either in the gross shapes or on the surfaces of these specimens that suggests a history of aerodynamic shaping.

#### PHYSICAL PROPERTIES

A comparison of some of the physical properties of the two specimens is given in table 2. All the properties listed are remarkably similar.

Density measurements were made by weighing the suspended specimens in air and in carbon tetrachloride of accurately known density

at the temperature of measurement. The resulting bulk density figures of 2.330 for the Georgia tektite and 2.332 for the Martha's Vineyard tektite agree within the limit of error of the measurement (estimated to be 0.002 g./cm.<sup>3</sup>). These density figures are slightly lower than the lowest specific gravity figure (2.334) given by Barnes (1940) for bediasites and are in the middle of the range of density figures (2.303 to 2.367 g./cm.<sup>3</sup>) he gives for moldavites. Conversion of Barnes's specific-gravity values to densities is not possible because of insufficient data. The difference between our values and his lowest

TABLE 2.—*Comparison of physical properties of the Martha's Vineyard and Georgia tektites*

Property	Georgia tektite (USNM 1396)	Martha's Vineyard tektite (USNM 2082)
Color .....	Light olive green	Light olive green
Weight (g.) .....	11.4 <sup>a</sup>	17.76 <sup>b</sup>
Index of refraction.....	1.485±0.003 <sup>c</sup>	1.4852±0.0004 <sup>d</sup>
Density (g./cm. <sup>3</sup> ) .....	2.330	2.332
Magnetic susceptibility (e.m.u./g.)..	3.6×10 <sup>-6</sup> •	3.90×10 <sup>-6</sup> †
Magnetization .....	0°	0 <sup>†</sup>

<sup>a</sup> Remaining portion of specimen.

<sup>b</sup> Complete specimen.

<sup>c</sup> Determined by I. Friedman, U. S. Geological Survey.

<sup>d</sup> Bulk index determined by E. C. T. Chao, U. S. Geological Survey.

<sup>e</sup> From Senftle and Thorpe (1959).

<sup>†</sup> Determined by A. Thorpe, U. S. Geological Survey.

bediasite value could be more apparent than real. The close agreement of density values for the two specimens under study combined with their chemical compositions (table 4) confirms the impression obtained from transparent sections that bubble size and distribution in the two materials are the same.

The index of refraction of both the Martha's Vineyard and Georgia tektites is 1.485. This value is slightly less than the smallest value ( $N_{Na}=1.488$ ) given by Barnes (1940) for bediasites and in the middle of the range ( $N_{Na}=1.4798$  to 1.4961) he gives for moldavites. Barnes (1940, pp. 522-523) has used the Gladstone and Dale relationship to plot index of refraction and density data to show relationships of these data for the various tektite groups and other natural glasses. The data for the Martha's Vineyard and Georgia tektites give a specific refractivity of 0.208, which falls in the moldavite area of Barnes's plot, outside of the area where moldavites and bediasites overlap.

Magnetic data for a number of tektites and other glasses have been obtained and discussed by Senftle and Thorpe (1959). The magnetic

susceptibility values depend both on the total amount of iron present and the proportion of oxidized to reduced iron. The Martha's Vineyard and Georgia tektites contain approximately the same total iron (table 4). The slightly higher proportion of oxidized iron in the Martha's Vineyard tektite is consistent with the slightly higher magnetic susceptibility value observed for this specimen. The magnetic susceptibility values for the Georgia and Martha's Vineyard tektites fall in the range between the highest moldavite value ( $3.0 \times 10^{-6}$  e.m.u./g.) and the lowest bediasite value ( $4.2 \times 10^{-6}$  e.m.u./g.) reported by Senftle and Thorpe (1959). The zero magnetization value, a value which is typical for tektites in general, is interpreted to mean essentially complete solution of iron in the tektite glass. These observations are indicative of a history of high-temperature treatment during formation of the glass.

#### ABSORPTION SPECTRA

The spectral transmission of a number of tektites, including the Empire, Ga., specimen, in the ultraviolet, visible, and near infrared regions of the spectrum (300 to 5,000 millimicrons) has been reported by Stair (1955a, 1955b, 1956). Cohen (1958) has given absorption spectra for a number of tektites in the region 300 to 2,600 millimicrons. He points out that his curves and Stair's are in agreement for the region they treat in common, and that the Empire, Ga., tektite curve agrees particularly well with that of moldavites. Cohen (1958) interprets these curves as being consistent with the high ferrous to ferric iron ratio observed in chemical data on tektites (table 4), while Stair (1955a) tentatively interprets them as indicative of high ferric iron.

A new determination of the absorption spectrum of the Empire, Ga., tektite, along with that of the Martha's Vineyard spectrum, is given in figure 2. These curves are directly comparable to those of Cohen and were obtained by using a Cary Model 14 recording spectrophotometer.<sup>5</sup> Highly polished specimen slice surfaces were prepared, using 0- to 2-micron diamond powder followed by magnesium oxide.<sup>6</sup> The Georgia tektite slice used for the photomicrograph in plate 4, C and D, was further polished and used for the absorption measurement. Masks with identical light transmission areas slightly

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<sup>5</sup> Dr. Walter Shropshire, Jr., Division of Radiation and Organisms, Smithsonian Institution, did the instrumental work in obtaining these curves.

<sup>6</sup> Grover C. Moreland, Division of Mineralogy and Petrology, U. S. National Museum, Smithsonian Institution, prepared the polished slices.

smaller than the smallest specimen were prepared for use in the sample and reference beam of the spectrophotometer. A blank correction was determined by measuring the absorbance with the masks in position previous to mounting the specimens.

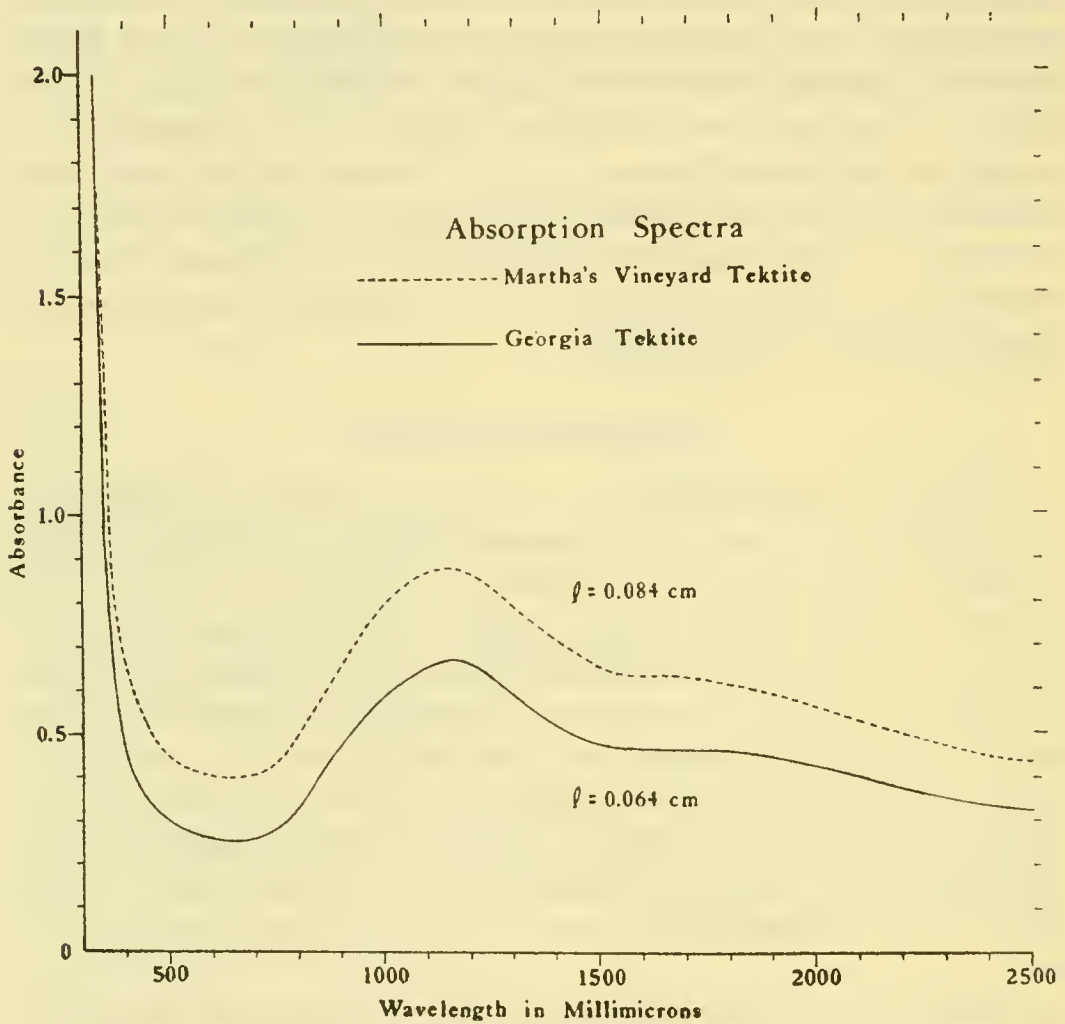


FIG. 2.—Absorption spectra of the Empire, Ga., and Martha's Vineyard, Mass., tektite specimen.

The curves in figure 2 are essentially identical. The greater absorption of the Martha's Vineyard slice can be attributed to sample thickness, suggesting that these two materials adhere to Lambert's law and have the same extinction coefficient.

#### SPECTROGRAPHIC AND CHEMICAL ANALYSES

Semiquantitative spectrographic analyses of both tektites are shown in table 3. Assuming that this type of analysis is within a factor of only 2 of the correct value, one can say that the analyses of both speci-

mens are essentially the same with the exception of boron, lead, beryllium, and yttrium. The high boron and beryllium contents are undoubtedly due to contamination. The mortar in which the Martha's Vineyard tektite was ground had previously been used for grinding

TABLE 3.—*Semiquantitative spectrographic analysis<sup>a</sup> of the Georgia and Martha's Vineyard tektites*

Element	Georgia tektite <sup>b</sup> percent	Martha's Vineyard tektite <sup>b</sup> percent
Si .....	M	M
Al .....	7	7
Fe .....	1.5	1.5
Mg .....	0.3	0.3
Ca .....	0.3	0.3
Na .....	0.7	0.7
K .....	1.5	1.5
Ti .....	0.15	0.3
Mn .....	0.07	0.07
Ag .....	0.00007	0.00007
B .....	0.003	0.015
Ba .....	0.03	0.03
Be .....	0.0003	0.003
Co .....	0.0015	0.0015
Cr .....	0.0007	0.0007
Cu .....	0.0007	0.0007
Ga .....	0.0003	0.0003
Nb .....	0.0015	0.0007
Ni .....	0.0015	0.0015
Pb .....	0.00015	0.007
Sc .....	0.0007	0.0007
Sn .....	0.0007	0.0007
Sr .....	0.007	0.007
V .....	0.007	0.007
Y .....	0.0015	0.007
Yb .....	0.00015	0.00015
Zr .....	0.015	0.015

<sup>a</sup> Figures are reported to the nearest number in the series 7, 3, 1.5, 0.7, 0.3, 0.15, etc., in percent. These numbers represent midpoints of group data on a geometric scale. Comparison of this type of data with that obtained by quantitative methods shows that the assigned group includes the quantitative value about 60 percent of the time.

<sup>b</sup> Analyst: Helen W. Worthing, U. S. Geological Survey.

hambergite,  $\text{Be}_2(\text{OH})\text{BO}_3$ , and this probably accounts for the high values for these elements. The high lead and yttrium values could not be accounted for. The following elements were looked for and not found: As, Au, Bi, Cd, Ce, Dy, Er, Eu, Gd, Ge, Hf, Ho, In, Ir, La, Li, Lu, Mo, Nd, Os, Pd, Pr, Pt, Re, Rh, Ru, Sb, Sm, Ta, Tb, Th, Tl, Tm, W, Zn. Only elements to which the method is sensitive in

amounts of 0.01 percent or less are included in this list. The analytical procedure used has been described in detail by Waring and Annell (1953).

The chemical analyses of both specimens are essentially the same (table 4). The analysis reported here for the Martha's Vineyard tektite also agrees equally well with the independent analysis of a different part of the same specimen given by Kaye et al. (1961).

TABLE 4.—*Chemical analyses of the Georgia and Martha's Vineyard tektites*

Elemental oxide	Georgia tektite <sup>a</sup> percent	Martha's Vineyard tektite <sup>b</sup> percent
SiO <sub>2</sub> .....	80.54	80.6
Al <sub>2</sub> O <sub>3</sub> .....	11.21	11.3
Fe <sub>2</sub> O <sub>3</sub> .....	0.33	0.4
FeO .....	2.40	2.2
CaO .....	0.61	0.7
MgO .....	0.65	0.7
MnO .....	0.05	0.05
Na <sub>2</sub> O .....	1.16 <sup>c</sup>	1.1
K <sub>2</sub> O .....	2.38 <sup>c</sup>	2.4
H <sub>2</sub> O <sup>-</sup> .....	None	<0.1
H <sub>2</sub> O <sup>+</sup> .....	0.02	<0.1
TiO <sub>2</sub> .....	0.43	0.5
Total .....	99.78	99.9

<sup>a</sup> Analyst: M. K. Carron, U. S. Geological Survey.

<sup>b</sup> Analyst: R. S. Clarke, Jr., Smithsonian Institution.

<sup>c</sup> Analyst: W. W. Brannock, U. S. Geological Survey.

A gravimetric chloride determination was also done on a small sample of the Georgia tektite. The figure of 0.03 percent chloride obtained represents a limiting value. Chloride could not be present in a concentration greater than this, but the true value could be considerably less. The analysis of the Martha's Vineyard specimen is reported to only one decimal place because of the small size of sample used for analysis.

The chemical data on the Georgia and Martha's Vineyard glasses (table 4) fit quite well into the general pattern of tektite analyses as presented by Barnes (1940) in his review of this subject. The high silica, high alumina, high ferrous to ferric iron ratio, and the excess of potassium oxide over sodium oxide are all typical of tektite analyses. The moldavites are the only tektite group that have silica contents as high as those obtained in our analyses, and moldavites are the group most similar in physical and morphological character to our material. It is of interest to compare Barnes's moldavite



analyses in some detail to the new data. Barnes's analysis No. 5 was excluded from the comparison because of its atypical ferrous to ferric iron ratio and the possibility that this reflects either a peculiar oxidizing history for this specimen or analytical error.

Only two of the nine moldavite analyses have a higher silica content (82.3, 82.7 percent  $\text{SiO}_2$ ) than the new analyses, and two have essentially the same value (80.5, 80.7 percent  $\text{SiO}_2$ ). The remaining analyses range from 77.8 to 80.0 percent  $\text{SiO}_2$ . The total iron for the new analyses is within the range given for moldavites, but our analyses suggest an appreciably higher proportion of  $\text{Fe}_2\text{O}_3$  (seven of the moldavite analyses report only  $\text{FeO}$ ). A recent moldavite analysis given by Vorobbev (1960) has a total iron in the expected range with a ferrous-ferric ratio similar to that obtained for the Martha's Vineyard and Empire, Ga., material. Our analyses show a lower proportion of  $\text{CaO}$  in the alkaline earth fraction, and the total  $\text{CaO} + \text{MgO}$  is only about half of that observed for the moldavites. The total alkalis are within the range given by Barnes, but the proportion of  $\text{Na}_2\text{O}$  is considerably higher. The ratio of percent  $\text{K}_2\text{O}$  to percent  $\text{Na}_2\text{O}$  is smaller on the average by a factor of slightly greater than 3. These observations relating to chemical composition establish that the Georgia and Martha's Vineyard glasses are significantly different from moldavite glass as we understand it today.

The similarity of composition shown by our analyses seems to be extended in the recent publication by Barnes (1960) of a chemical analysis of a light green tektite from Fayette County, Tex. Its composition is very close to that of the Georgia and Martha's Vineyard material. Minor differences are a slightly higher  $\text{SiO}_2$  and a higher proportion of  $\text{Na}_2\text{O}$  in the combined alkalis. These differences are so small that they suggest a relationship between this specimen and the two we have studied. Barnes (1960) also states that this material contains no bubbles and is significantly different from bediasites.

Ehmann (1960) has reported on a study of nickel-iron ratios in tektites and other glasses. Neutron activation analysis was used to determine accurate Ni values, and tektites were observed to have  $\text{Ni}/\text{Fe}(\times 10^4)$  values ranging from 4.7 to 57, with a moldavite having a value of 10. It is interesting that the value of this ratio is 9 for the Martha's Vineyard, Mass., and Empire, Ga., specimens calculated on the basis of our semiquantitative spectrographic Ni value of 0.0015 percent.

## DISCUSSION

The physical and chemical properties given here for the glasses from Martha's Vineyard, Mass., and Empire, Ga., show a remarkable and unexpected similarity. The measured physical properties show no significant differences. The pattern of compositional similarity shows variations for only four of the elements detected. This observed similarity is a significant observation that requires further examination.

The chemical data in the tektite literature would not lead one to expect such close similarity of properties for two specimens selected at random from widely separated geographic points. In his comprehensive paper Barnes (1940) gives bulk chemical analyses taken from the literature for 43 specimens from the three major tektite groups (24 indochinites, 10 moldavites, 9 australites). No two of them suggest agreement comparable to that which has been observed for the Martha's Vineyard and Empire, Ga., specimens. These analyses demonstrate that considerable natural variation of chemical composition exists within the same group of tektites. Larger variations are observed from one tektite group to another. Barnes also points out that compositional variations, as indicated by index of refraction measurements, are observed for different portions of the same specimen.

The explanation of this observed similarity would seem to lie in one of two areas. The first possibility is that our understanding of tektite specimens and their occurrence is based on inadequate and fragmentary data, so that the observed coincidence is actually an event of reasonable probability. The second possibility, and one that should not be too casually dismissed, is that we are dealing with artificial materials of related origin. Regardless of which explanation pertains, it is obvious that this problem requires further detailed study.

There is little room for doubt that the major tektite groups, such as australites, indochinites, and moldavites, are geologic occurrences, the results of natural processes. Georgia tektites have been placed in the tektite category largely on the basis of analogy, as these glass objects have similar chemical and physical properties to known tektites. However, the total number of specimens that have been found in Georgia is very small in comparison to the large number that have been found for the major groups. Weights of specimens are not available, but certainly the total for all the 12 reported Georgia finds (Bruce, 1959) must be only some fraction of a pound. Detailed observations relating these few specimens to their geologic environment have not been recorded and seem not to have been made. The situa-

tion with regard to the Martha's Vineyard specimen, a unique find so far for this region, is equally unsatisfactory.

A general similarity in appearance between moldavites and Georgia tektites has been frequently noted. This similarity, as was suggested earlier, also holds true in the same very broad sense for the Martha's Vineyard tektite. However, similarity to one class of objects does not preclude similarity to another class. In fact, the Martha's Vineyard tektite shows an interesting similarity to the bottom of a bottle now in the collections of the Smithsonian Institution (USNM 58.115A). This olive-green bottle was probably made in Keene, N. H.,

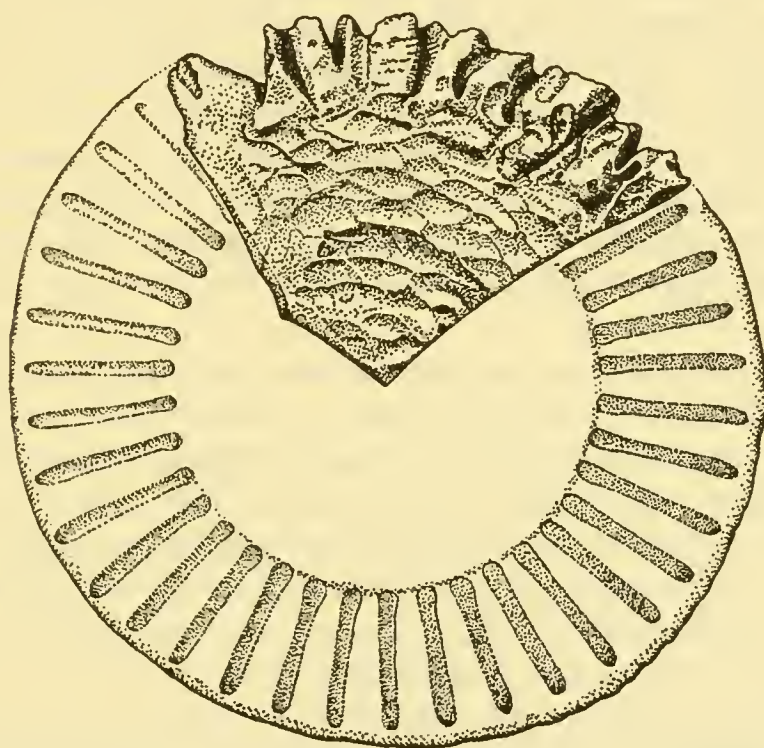


FIG. 3.—Scale drawing of bottom of a bottle from Smithsonian Institution collection (cat. No. 58.115A) with Martha's Vineyard tektite superimposed. The bottle was probably made in Keene, N. H., during the period from 1825 to 1850.

in the second quarter of the 19th century.<sup>7</sup> The chemical composition of this bottle is undoubtedly quite different from that of the Martha's Vineyard tektite. Its index of refraction is greater than 1.50, and under the microscope this grain appears to be ordinary unstrained bottle glass. However, the radius of curvature, the periodicity of the radial pattern along the curved edge, and the circular pattern in from the edge (see fig. 3) of the Martha's Vineyard speci-

<sup>7</sup> Paul V. Gardner, Division of Ceramics and Glass, U. S. National Museum, Smithsonian Institution, oral communication.

men are suggestive of the mold from which the Keene, N. H., bottle must have been made.

An argument commonly used to support a natural rather than artificial origin for tektites is based on the relatively high temperatures required to melt glass of tektitic composition. We have difficulty attaining these temperatures today; therefore, we are apt to conclude unjustifiably that these temperatures must have been unattainable in the fairly recent past. However, there is evidence that leads one to doubt this reasoning. An example is given in the studies of Hubbard, Jenkins, and Krumrine (1952), in which they compare the properties of modern commercial glasses to Amelung glasses. These antique glasses were made in the large factory of Johann Friedrich Amelung near Frederick, Md., in the years around 1800. Hubbard et al. report that these old glasses ". . . had working temperatures considerably higher than any of the modern commercial glasses studied, with the exception of fused silica and Vycor." They further noted considerable difficulty in working these glasses after heating to 1500°C., the highest temperature to which they cared to take Globar furnaces.

Glass has been a common item in commerce along the east coast of the United States since the early Colonial period, and it is a byproduct of many industrial and manufacturing operations. There is a possibility that starting with the proper raw materials—perhaps by accident—glass of the composition of the Georgia and Martha's Vineyard tektites could have been formed in this still difficultly attainable high-temperature range. Had Precambrian feldspar or other geologically old materials been included among the raw materials from which this peculiar glass was made, another difficulty could possibly be reconciled. Conceivably the mysterious process that formed the glass could have produced a product that retained sufficient radiogenic argon-40 to give the approximately 30-million-year ages that have been reported in the literature for the Empire, Ga., specimen (Reynolds, 1960; Gentner and Zähringer, 1960). Admittedly, this suggestion is contrary to normal laboratory experience; however, this type of measurement as applied to tektites is too new to be accepted without reservations.

Two criteria are commonly accepted in defining and identifying tektites. The first is that the specimens are of natural occurrence within a given although perhaps not completely delineated geographic area; the second is that they are glasses of an unusual range of chemical compositions, exhibiting characteristic physical properties.

It should be clearly demonstrated that both of the above hold before specimens are accepted as proven tektites. The natural occurrence requirement seems not to have been proven beyond reasonable doubt in the case of Georgia and Martha's Vineyard specimens. Certainly, the history of specimens found to date in these localities is not overwhelming evidence of their natural origin (Bruce, 1959; Kaye et al., 1961).

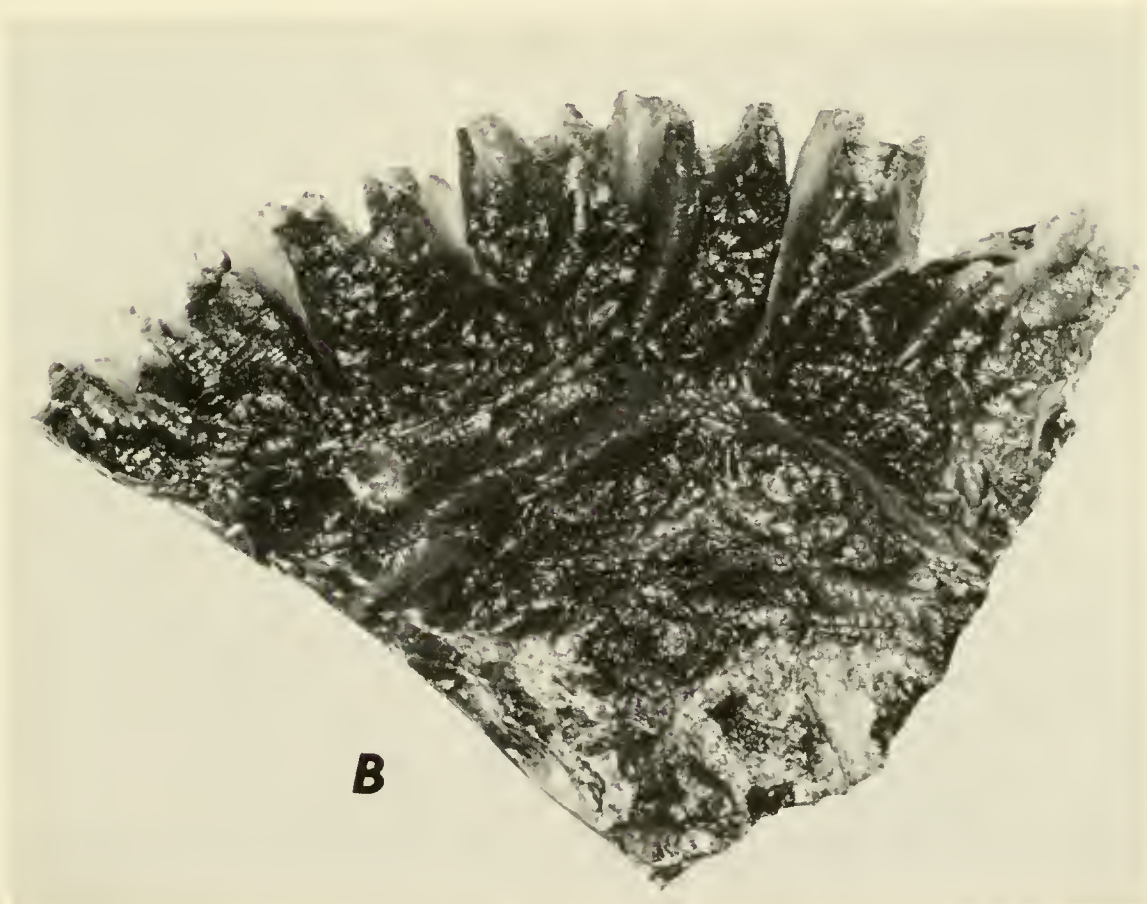
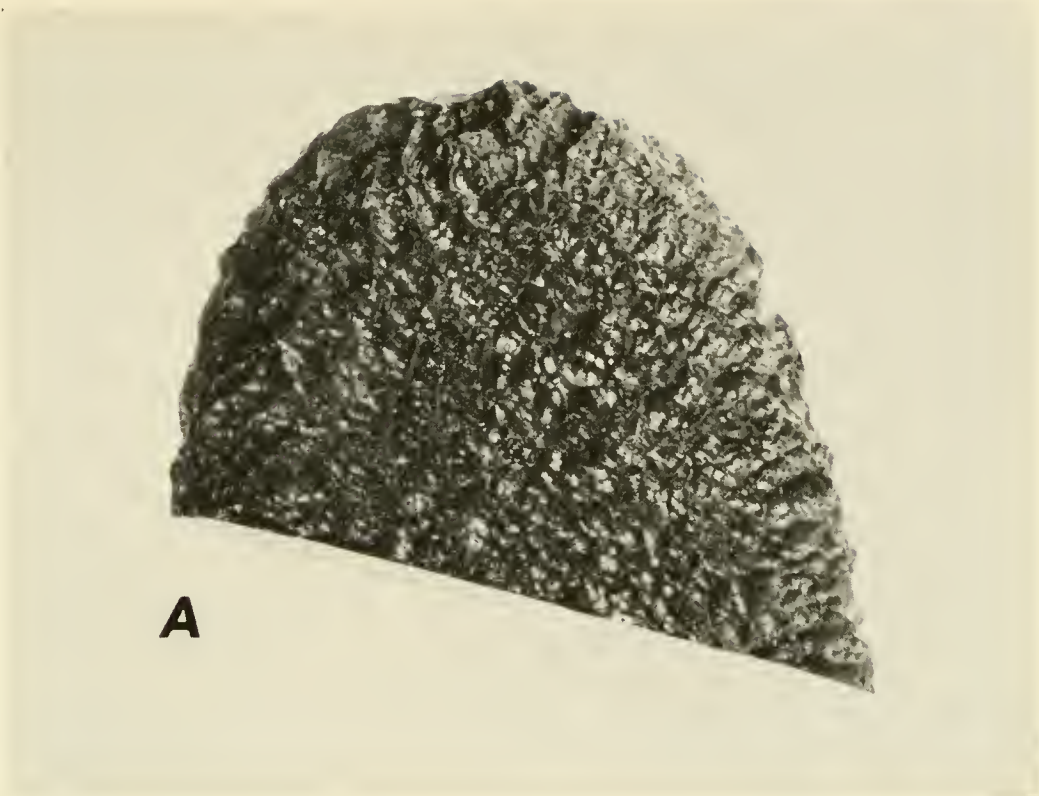
The data that have been given point to a current weakness in our understanding of tektites. It has not been possible to take two glass objects, found 20 years and 1,000 miles apart, into the laboratory and, after studying their chemical and physical properties, report unequivocally that they are tektites. Had the specimens under study belonged to one of the major recognized tektite groups, and had their properties been fairly typical of that group, a reasonably certain identification could undoubtedly have been made. However, chemical composition apparently separates the specimens from Martha's Vineyard, Mass., and Empire, Ga., from known tektite groups. The specimens have properties that are typical of tektites but not exclusive for tektites. All the properties that we were able to measure have a counterpart in natural or artificial glasses. Further information on these tektites, particularly their field occurrence, is required before a final judgment should be made. A disproportionate amount of laboratory work cannot compensate for the lack of sufficient field data. A typically geological approach is needed for a problem that remains basically a geological problem.

### CONCLUSIONS

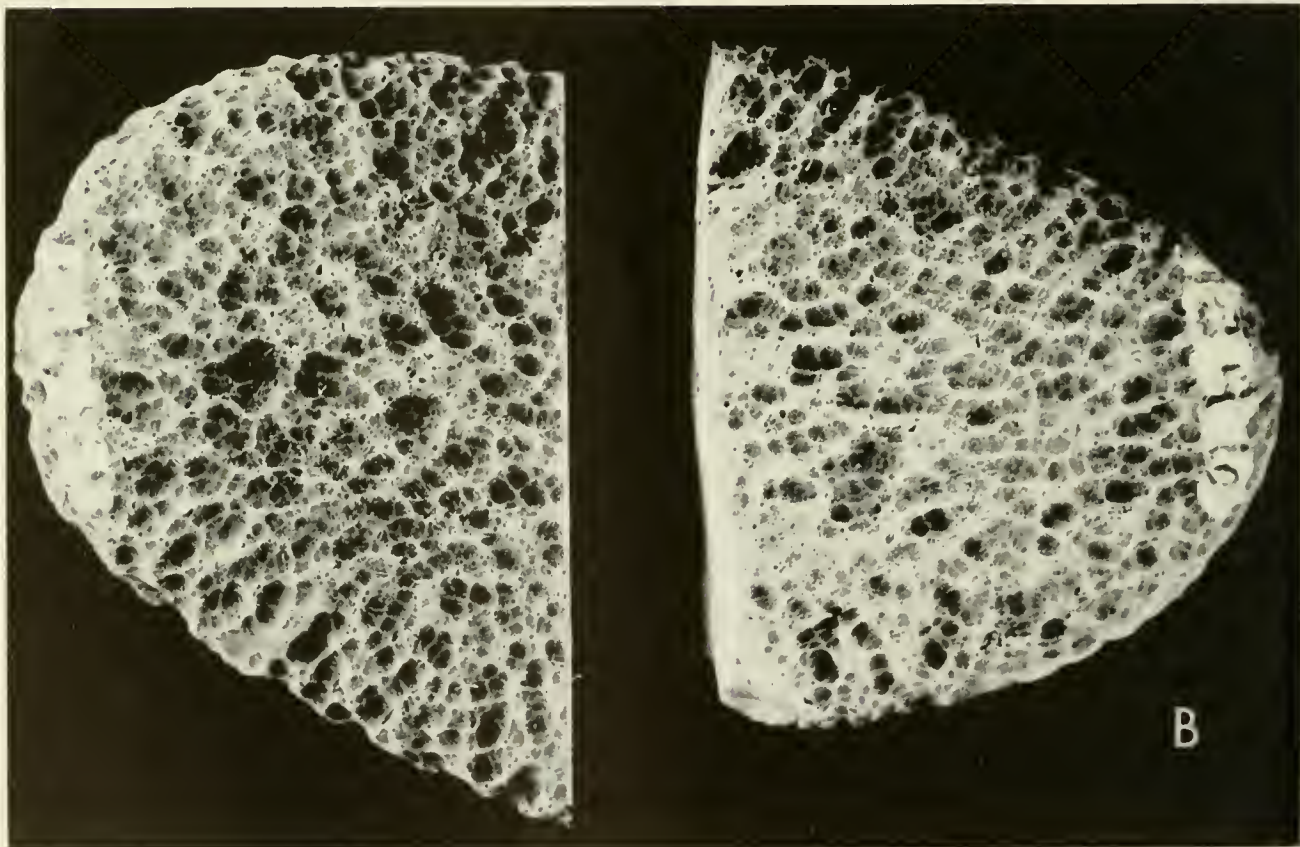
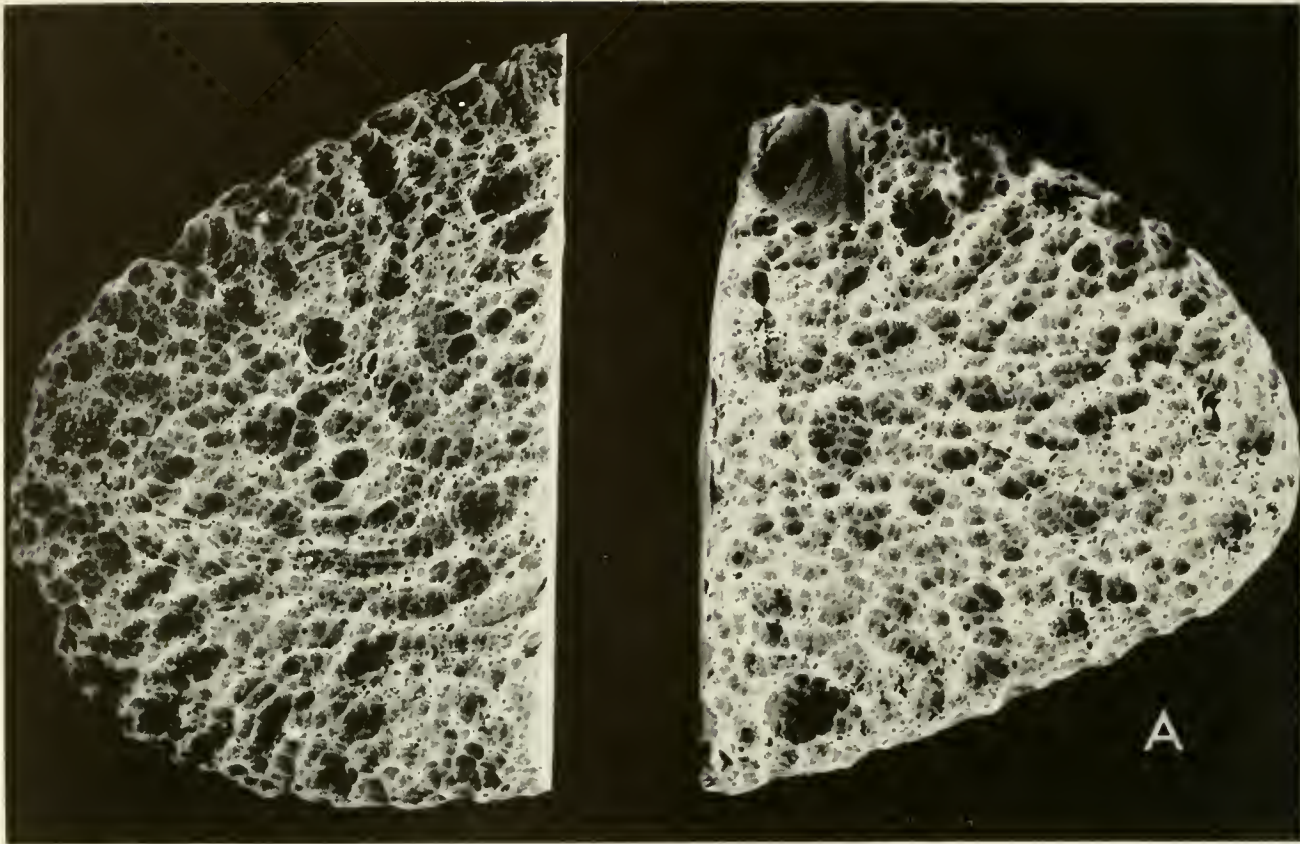
In the chemical and physical data that have been presented, there is nothing inconsistent with the claim that the Georgia and Martha's Vineyard glasses are tektites—tektites in the sense of the major tektite groups. However, there is likewise nothing in these data to prove categorically that only a natural origin can account for the specimens. Conceivably some type of artificial origin, perhaps an accidental one, is possible. Certainly it would be premature to assume that Martha's Vineyard is a valid tektite locality. The cause of our inability to solve this problem at present—and this seems to apply also to problems concerning the major tektite groups—is the lack of geological evidence relating specimens to their occurrence. Until the occurrence is understood, speculation as to origin lacks foundation.

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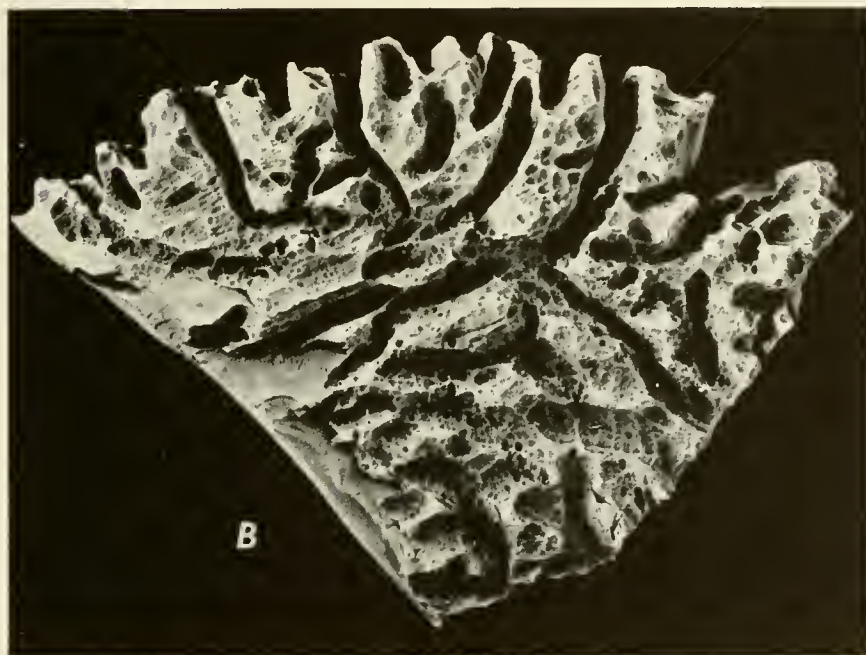
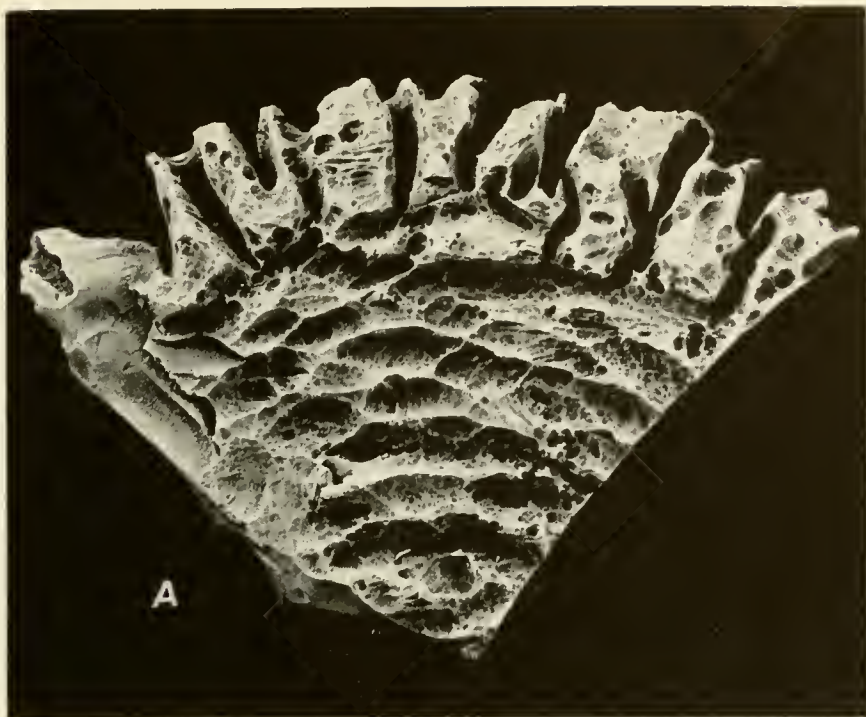


Tektite photographs taken with direct lighting. A, Tektite from Empire, Ga., USNM 1396,  $\times 2$ . B, Tektite from Martha's Vineyard, Mass., USNM 2082,  $\times 2$ .

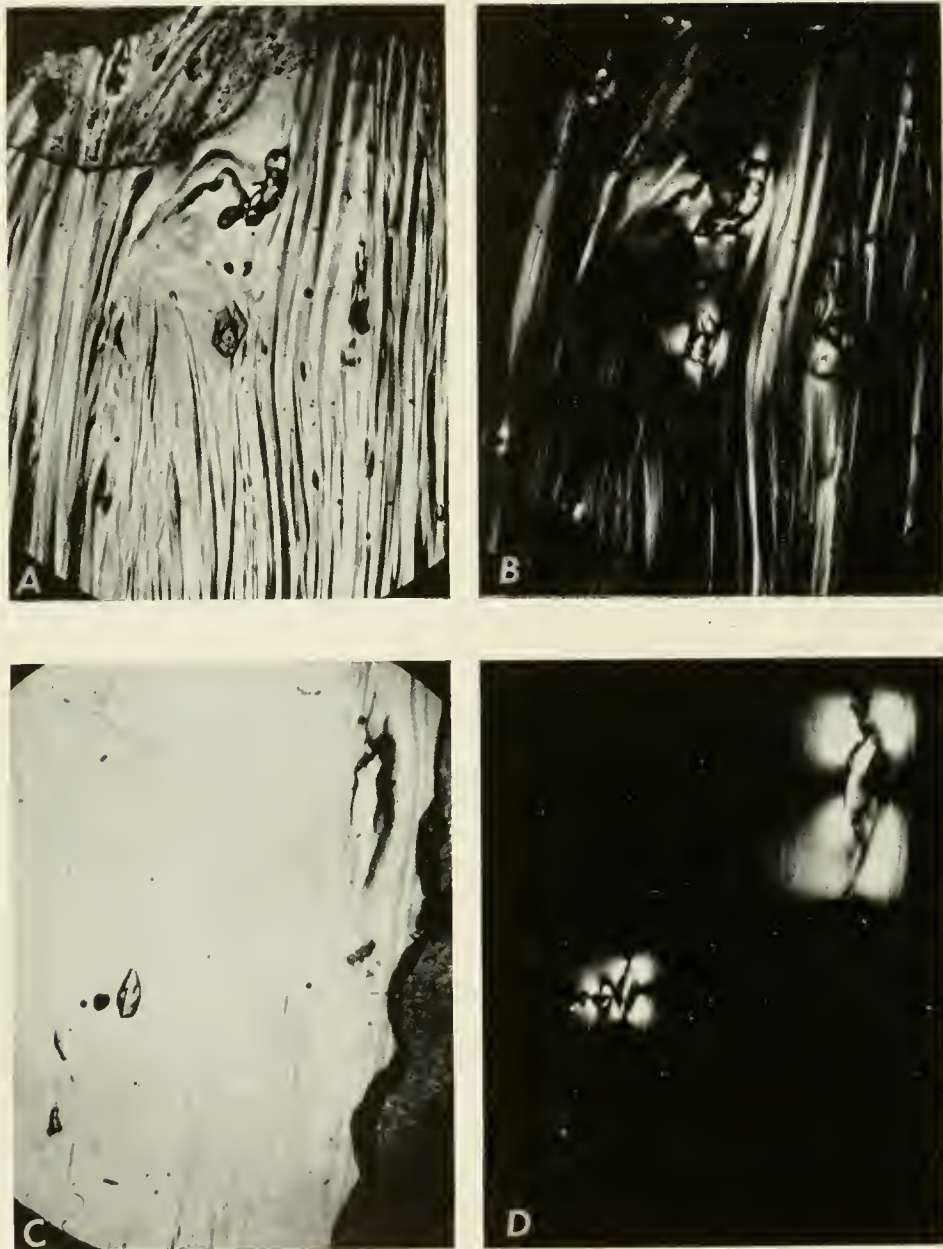


Empire, Ga., tektite after slicing to remove material for analysis. The specimen has been smoked with ammonium chloride to bring out surface features. USNM 1396,  $\times 2$ .



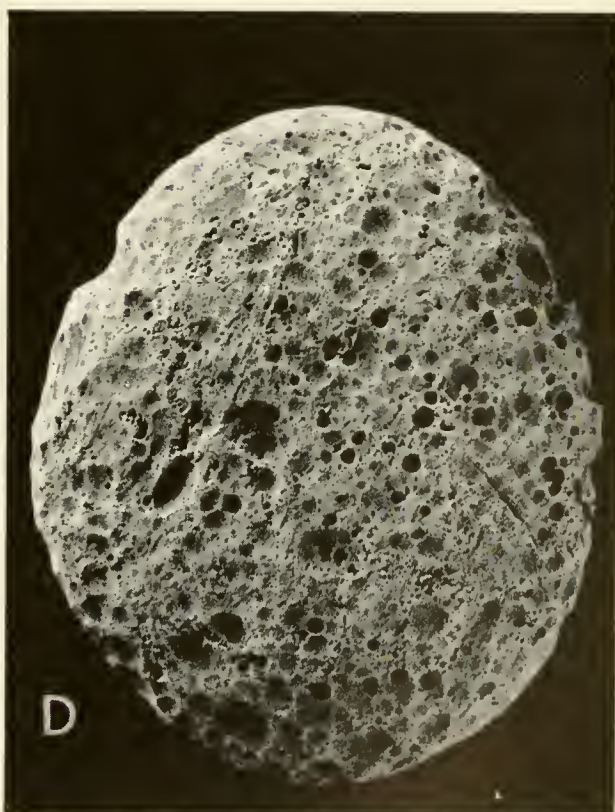
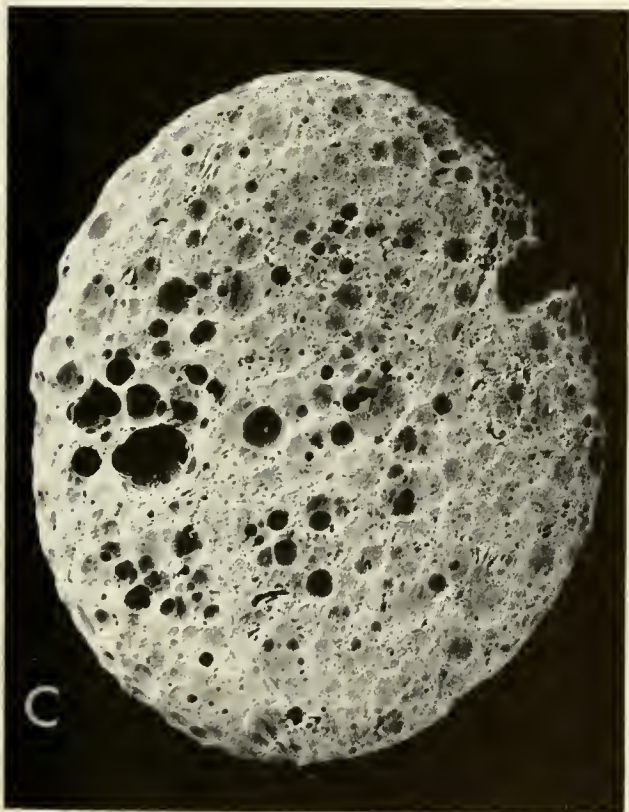
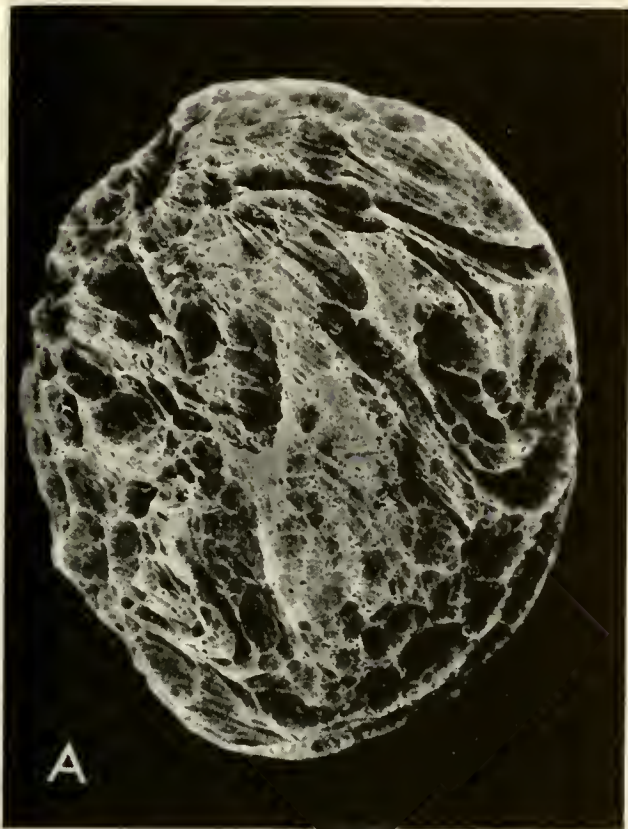


Martha's Vineyard, Mass., tektite photographed after ammonium chloride smoking. 17.8 g. USNM 2082,  $\times 1\frac{1}{2}$ . B, Surface opposite that shown in A. C, Photographed down deeply serrated edge.



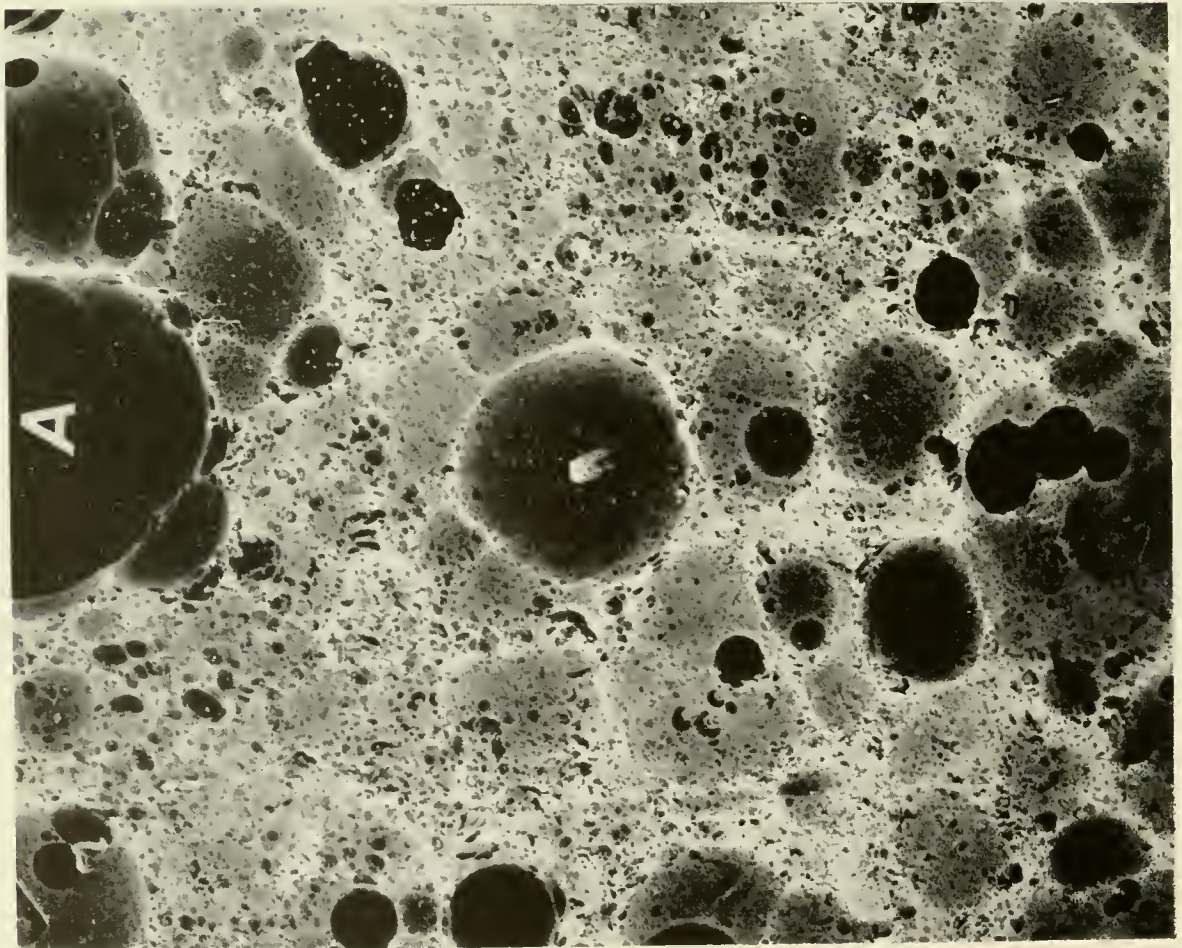
A, B, Photomicrograph of a 0.25-cm. slice of Martha's Vineyard tektite,  $\times 10$ . A, White transmitted light; B, crossed nicols.

C, D, Photomicrograph of a 0.07-cm. slice of the Empire, Ga., tektite,  $\times 10$ . C, White transmitted light; D, crossed nicols.

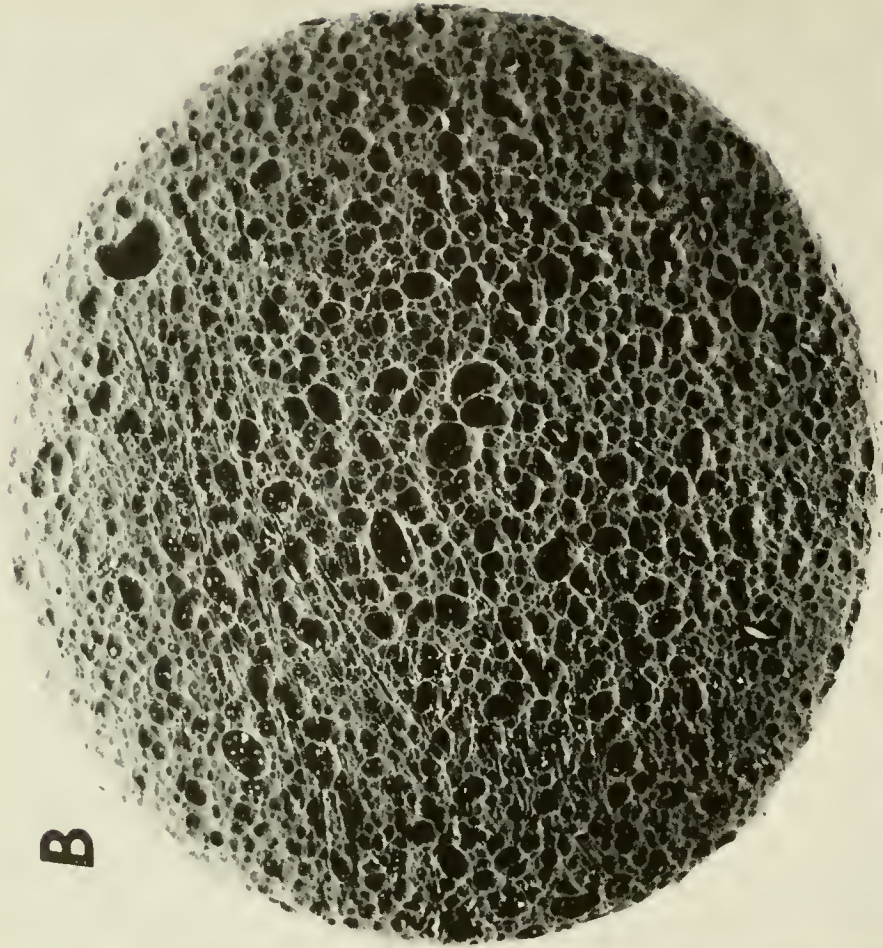


A, B, A second Empire, Ga., tektite specimen, ammonium chloride smoked. 13.4 g. USNM 1396,  $\times 2$ .

C, D, Plainfield, Ga., tektite, ammonium chloride smoked. Property of G. A. Bruce. 11.2 g.  $\times 2$ .



A, Details of small area of Plainfield, Ga., specimen, ammonium chloride smoked.  $\times 10$ .



B, Osierfield, Ga., tektite, ammonium chloride smoked. Property of Georgia Geological Survey, lent by A. S. Furcron. 17.8 g.  $\times 2$ .