Reports

Coesite Discovered in Tektites

Abstract. *Coesite has been identified by x-ray diffraction and electron microprobe chemical analysis as a constituent of inclusions in Muong Nong type tektites from Phaeng Dang, Thailand. The fine coesite grains are mixed with coarse quartz in the core of the inclusions, and the core is surrounded by frothy lechatelierite. The mixture of* SiO_2 *phases indicates that these tektites have been quenched from high temperatures and that modifications in texture and chemical composition from the original parent material have been minimal.*

The number of investigations on tektites has increased enormously because there are indications that tektites may come from the moon. Many of these investigations are prompted by the belief that some knowledge of the nature and origin of the moon's surface can be obtained before man's landing there.

Barnes (*1*) has pointed out the peculiarities of the Muong Nong type tektites, and in describing their chemistry and petrology has indicated that this tektite type is rich in silica (generally about 80 weight percent SiO_2), has a layered appearance, and relatively abundant inclusions of silica glass (lechatelierite) which is often bubbly or frothy. He has further described (*2, 3*) the occurrence of crystalline inclusions as well as peculiar nonspheroidal bubbles. Muong Nong type tektites are found in the area of Thailand.

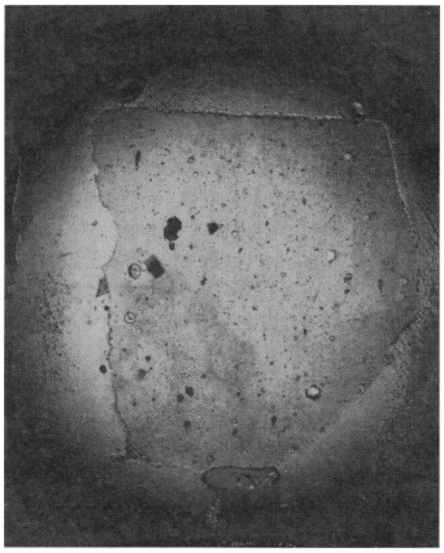

Fig. 1. Thin section with crystalline inclusion. Inclusion is above and to the right of the square dark area which is a raster burned into the sample by the microprobe. The area of the section is about 1 cm². Transmitted unpolarized light.

I have examined an unusual inclusion in a thin section of a Muong Nong type tektite from Phaeng Dang, Thailand (*3*). The very small (less than a millimeter) inclusions have cores of brownish material with a birefringence which was barely discernible. In each case the core was surrounded by a rim of frothy lechatelierite (Figs. 1 and 2). The abundance of these inclusions in this material is such that one inclusion occurs in about every other thin section. Since the core generally has a diameter of 0.1 mm or less, the abundance of this material in these specimens is probably less than 100 parts per million.

Electron microprobe analysis showed that the inclusions are approximately 100 percent SiO_2, quartz being the reference standard. In addition, the microprobe was used to check the bulk composition of a tektite specimen in which an inclusion was found even though the composition of the Muong Nong tektites from Phaeng Dang has already been presented by Barnes (*1*). The method for this analysis was similar to a random point-count method used in petrographic analysis. One hundred points around the entire 1-cm² area of the tektite section were analyzed for Si, Fe, and Al. The percentage (by weight) values were obtained from x-ray intensities by comparison with a series of standard synthetic glasses of tektite compositions, the necessity of corrections thus being obviated.

The results of the microprobe analysis are shown in the histograms in Fig. 3. Since the points analyzed did not happen to include any lechatelierite (which is of minor abundance in the section) the silica value indicated by the histogram is probably low by about 1 percent (by weight). Nevertheless, the values obtained from Fig. 3, namely, 79.5 percent SiO_2, 3.5 percent Fe oxide (*4*), and 9.8 percent Al_2O_3, agree very well with the values for Muong Nong type tektites of Barnes (*1*).

The first x-ray diffraction pattern was obtained with a Chesley-type pinhole camera. In this instrument the x-rays are collimated by the fine bore (0.076 cm) of a length (1 cm) of lead barometer glass. The sample, in the form of a fragment of a thin section, is attached to sticky mylar tape and placed on the brass sample holder. The sample holder is then clamped into a bracket which is adjustable so that the spot to be analyzed can be positioned over the bore of the collimater tube. The x-rays penetrate the sample, and the diffraction pattern appears on the film which is clamped to the pedestal in the other half of the camera.

The accuracy of the *d*-values (interplanar spaces) obtained with this type of camera is greatly limited because of its small size. The distance from sample to film must be accurately known, and this was measured by calibration from the strong (104) reflection of a calcite standard which was run independently since the small size of the sample did not permit the use of internal standards. Measurement of the diffraction lines themselves was the major source of error. For example, with CuKα radiation, the major line, if measured as 0.555 cm resulted in the value *d* being 3.111, but if determined as 0.560 cm resulted in *d* being 3.088.

In Table 1 the results of several diffraction analyses of one inclusion are compared with the values obtained for

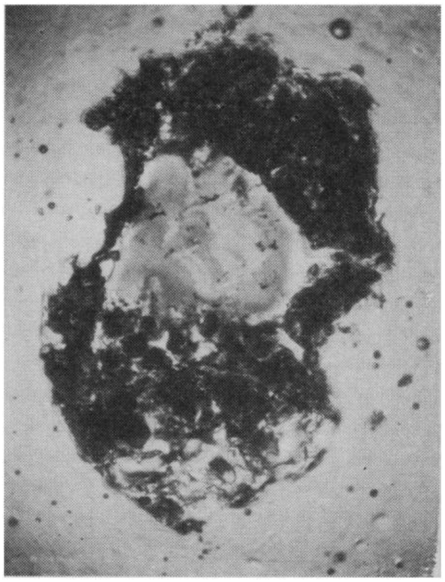

Fig. 2. Inclusion shown in Fig. 1 with core and rim of lechatelierite. Diameter of inclusion is about 0.5 mm. Plane polarized light.

Table 1. X-ray diffraction pattern data for standard coesite and tektite.

Coesite stand.*		ASTM† stand.			Sec. 1, Exp. 4*		Sec. 1, Exp. 12*		Sec. 1, Exp. 13‡	
I	*d* (Å)	*I*	*d* (Å)	hk*l*	*I*	*d* (Å)	*I*	*d* (Å)	*I*	*d* (Å)
		5	6.22	020						
		5	4.40	021						
8	3.424	50	3.432	130,						
				111	5	3.447	5	3.380	5	3.426
10	3.088	100	3.098	002,						
				040	10	3.102	10	3.077	10	3.099
5	2.750	15	2.77	220,						
				(041)	1	2.75	5	2.742	3	2.755
5	2.694	15	2.68	131					3	2.705
2	2.484	5	2.350	201,						
				$\bar{2}41$			5	2.491		
1	2.288	10	2,303	112,						
				150			5	2.297	1	2.311
1	2.183	10	2.195	240,						
				$22\bar{3}$			3	2.254	1	2.267
2	2.031	10	2.034	151,						
				310‡			1	2.041	3	2.032
1	1.839	10	1.846	330			2	1.861		
2	1.784	10	1.789	$\bar{2}61$			2	1.794	1	1.795
3	1.706	15	1.716	260,						
				222‡			4	1.716	2	1.716
		10	1.711	113,						
				$\bar{3}52$‡			4	1.708	2	1.703

* Average of two measurements. † American Society of Testing Materials. ‡Average of three measurements.

a coesite standard, the material for which was donated by J. Fahey of the U.S. Geological Survey. The measurement error can be appreciated when the values obtained for coesite are compared with the accepted values of Dachille and Roy (*5*).

In view of the fact that microprobe analysis showed the composition of the inclusions to be SiO_2, the measurement error and the fact that the values obtained for many measurements centered about the accepted values for coesite, the identification of coesite as a constituent of the inclusions is considered quite reliable. In Fig. 4 the diffraction patterns obtained for one sample and a coesite standard may be compared directly. Two exposures of the sample are used so that the darkened inner lines as well as the weak outer lines can be compared with the standard. Although the holes in the centers of the films are offset owing to movement of the films, the centers of the two sets of diffraction rings are coincident.

Since coesite seldom produced discrete spots in the diffraction pattern, the number of individual grains in the sample volume must be quite large—somewhat over a hundred with random orientation. The average diameter of these grains must be on the order of 1 micron in order to permit continuous diffraction lines from a sample volume of about 10^{-9} cm^3. In addition, there seems to be little or no preferred orientation of either the quartz or the coesite.

Quartz was identified in another inclusion (Table 2). Diffraction patterns at several locations of this inclusion showed a slight increase in the ratio of coesite to quartz in the center as opposed to that at the periphery of the brownish core.

The total diameter of the inclusions was about 0.5 mm. In every case, however, the brownish, fine-grained material, which contained the coesite, was rimmed by frothy lechatelierite and made determinations of index of refraction on the aggregate impossible. Probably the lechatelierite was formed by melting of the crystalline silica aggregate. The petrographic relationship of the aggregate to the lechatelierite is shown at high magnification in Fig. 5.

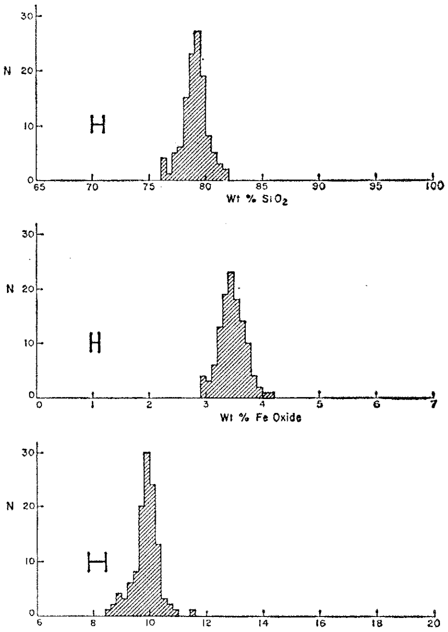

Fig. 3. Results of microprobe analysis of 100 random points in the section shown in Fig. 1. Brackets in each histogram show the limits of the 4-σ statistical variation to be expected at a 95-percent confidence level from the number of quanta counted in the analyses.

The index of refraction of the bulk glass of the tektite was 1.492.

A small (1 g) sample of a Phaeng Dang tektite was cleaned and coarsely crushed. Portions were placed in a shallow dish containing an oil of refractive index close to that of the bulk tektite glass. From this material about seven fragments which contained inclusions were selected, mounted on a glass rod, and exposed to x-rays in a Debye-Scherrer camera.

The diffraction pattern obtained by a 12-hour exposure of this material is compared with the pattern of a coesite standard (Fig. 6); only two coesite lines are apparent in the pattern of the sample. Weaker lines are obscured because of the abundance of spots produced by the quartz grains, scattering by glass in the sample, and the long exposure time. The smooth, continuous appearance of the coesite lines, especially when compared with the broad spots produced by the quartz, is an indication that the quartz in this sample occurs in several large grains whereas the coesite occurs as many, very fine grains.

The patterns also indicate that the abundance of quartz is much greater than that of coesite. Thus the abundance of coesite in the tektites is probably much less than the 100 ppm abundance of the inclusions themselves. This emphasizes the value of the pinhole camera in these determinations since without the selectivity of the collimator, the coesite lines are considerably obscured by those of quartz.

Discovery of coesite in nature was first made by Chao *et al.* (*6*) in samples of (shocked) Coconino sandstone from Meteor Crater, Arizona. Other occurrences have since been reported, and in each case the origin of the coesite was attributed to impact metamorphism. Thus the coesite in the tektite inclusions probably has a similar origin.

The relative sizes of the quartz and coesite grains in the inclusions, as determined from the x-ray patterns, tend to indicate that the reaction of quartz to form coesite has been incomplete.

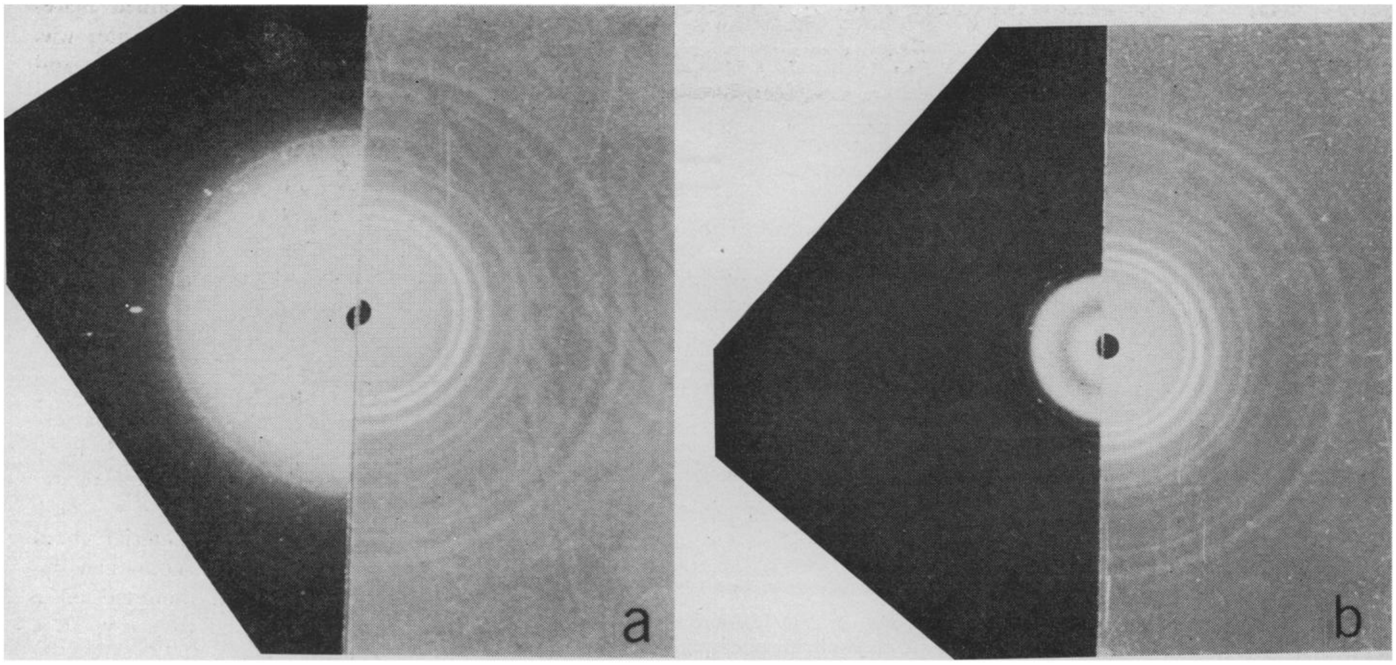

Fig. 4. Transmission diffraction patterns taken with Chesley camera cut and matched to enable comparison of the coesite pattern (on the right) with coesite in the inclusion (on the left). *a*, Developed to show light outer rings; *b*, developed to show dark inner rings in the pattern of the inclusion.

However, the observation (*7*) that coesite, when exposed to temperatures from 1100° to 1350°C for short periods, decomposed to metastable quartz prompted investigation of this decomposition at higher temperatures. Because of the presence of lechatelierite which is obviously derived from the crystalline silica, the temperatures to which the inclusions were exposed probably exceeded 1700°C for periods of the order of seconds (enough time to permit bubbles to form and to allow for excess heating and subsequent cooling but not enough to allow homogenization of the silicate glasses). In runs on coesite which lasted 6 minutes and 1 hour at both 1500° and 1600°C, the run products consisted of cristobalite in the 1-hour runs and cristobalite plus a small amount of coesite in the 6-minute runs. Therefore, at higher temperatures, cristobalite is to be expected as the decomposition product of coesite, an indication that the quartz of the inclusions is probably primary. Furthermore, all the diffraction lines produced by the inclusion in one section could be attributed to coesite; this indicates that quartz, if present at all, was a very minor constituent.

Table 2. Diffraction analysis of second section.

Mineral*	ASTM			Sec. 2 Exp. 10		Sec. 2 Exp. 18	
	hk*l*	*d*	*I*	*d*	*I*	*d*	*I*
Q	100	4.26	35	4.25	8	4.22	5
C	130	3.43	50	3.50	3	3.50	7
Q	101	3.34	100	3.34	10	3.29	10
C	002	3.098	100	3.076	5	3.12	3
C	220	2.77	15	2.73	1	2.74	2
C	131	2.68	15			2.65	3
Q	110	2.46	12	2.45	4	2.45	2
Q	102	2.28	12	2.28	2	2.23	3
C	240	2.195	10			2.198	3
Q	200	2.128	9	2.115	2	2.129	3
Q	201	1.980	6	1.964	4	1.962	2
Q	$\underline{1}12$	1.817	17	1.808	5	1.820	5
C	$\bar{2}61$	1.789	10			1.779	1

* C, coesite; Q, quartz.

An extremely important question is the condition of formation of the frothy lechatelierite. DeCarli and Jamieson (*8*) have shown that crystalline quartz can be made amorphous by shock at temperatures no greater than 1100°C during the shock and 700°C immediately after the shock. These temperatures would be insufficient to mobilize the glass to the extent that bubbles could form, and the pressure effects of the shock would certainly prevent the formation of bubbles. Cooling from this temperature must have been quite rapid in order to prevent the formation of cristobalite from the coesite.

This consideration imposes fairly stringent conditions on theories of the origin of tektites. Calculations by Greenland and Lovering (*9*) indicate that tektite spheres of 1-cm radius (approximately the size of the Phaeng Dang fragments) would cool from 2000°K to 1000°K in about 35 seconds. According to this, then, tektites might cool from 1700°C to the temperature at which the coesite decomposition is slowed considerably in an interval of about 10 seconds. In view of the amount of cristobalite experimentally formed in 6 minutes, 10 seconds is probably about the maximum quench time permitted. As reported (*9*), the time required for a tektite of 5-cm radius to cool through the same temperature limits is about 175 seconds. In this period, a detectable amount of cristobalite would probably have formed. This limitation on the size is

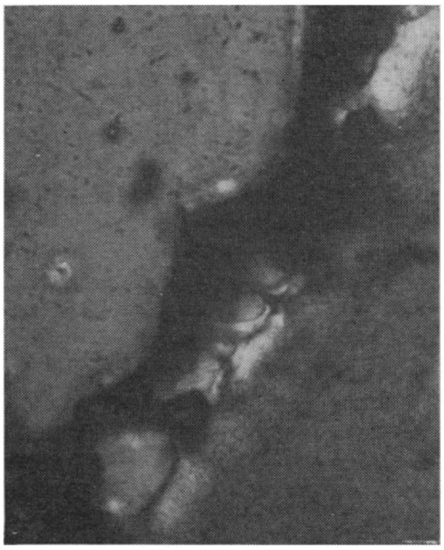

Fig. 5. Photomicrograph of tektite glass (upper left), frothy lechatelierite (center) and crystalline inclusion (lower right) in transmitted, plane polarized light. Width of field of view approximately 0.1 mm. Note filaments of lechatelierite which support inclusion in place and lack of apparent contact between inclusion and tektite glass.

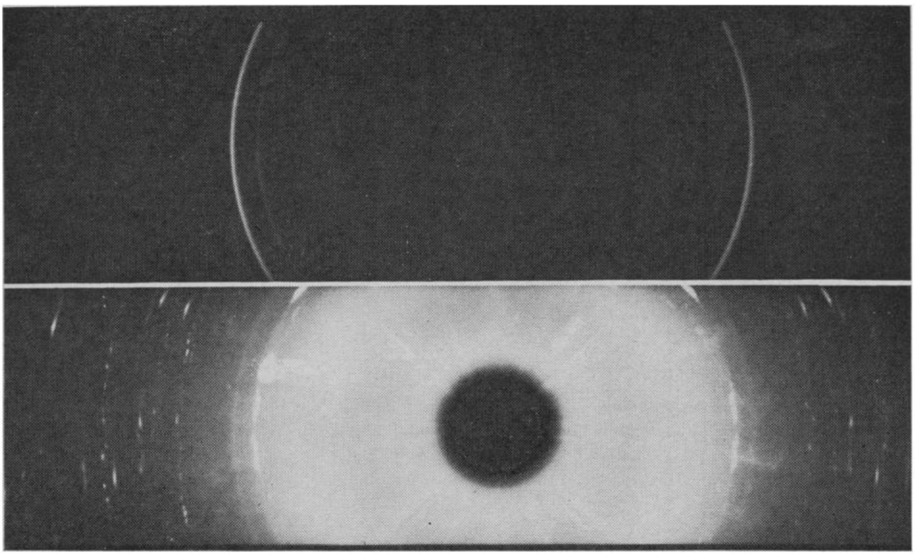

Fig. 6. Debye-Scherrer patterns of coesite (above) and inclusion-glass mixture (below). Weak broad line can be attributed to coesite as well as one weaker line toward the center of the pattern. Other intense spots are due to coarse grains of quartz.

in disagreement with the origin for the Muong Nong tektites proposed by Barnes (*10*) who suggested that they have formed by melting of terrestrial rock and the subsequent collection of this melt into pools.

There is a strong possibility that heating effects due to and immediately after the shock resulted in extreme heating of the crystalline material of the inclusions while the less dense tektite glass remained at relatively low temperatures. This would permit formation of coesite to be quenched quickly through the use of the body of the material as a heat sink.

Thus the rapid heating and cooling cycle to which the tektites were subjected would not permit a great deal of movement and homogenization of any separate phases in the original tektite material. Thorough mixing of the constituents to the degree shown by the histograms of Fig. 3 would certainly take many minutes at even moderately high temperatures. The material from which the tektites were formed was either glass or extremely fine-grained before the quartz was transformed to coesite by impact metamorphism. This limitation on the source material places a severe restriction on the terrestrial origin of tektites. Certainly the Phaeng Dang tektites could not have formed through mixing of the melts of various sedimentary rocks as proposed by Taylor (*11*), and this casts a doubt of such a source material for other tektites. It also seems unlikely that the comets or meteorites which formed the several tektite-strewn fields would be able, in each case, to select already homogenized material from which to make tektites.

The occurrence of the coesite-lechatelierite mixture could conform with either the Chapman (*12*) lunar-direct entry hypothesis in which debris from a lunar impact is ejected to the earth or to the O'Keefe (*13*) lunar-parent body hypothesis in which the coesite would be formed in a large body with sharp thermal gradients around the inclusions with subsequent removal of the fragments by erosion from the parent body rather than by ablation as liquid drops. Alternately the frothy lechatelierite could be formed as liquid drops by ablationary heating of the parent body.

The bulk composition of the Muong Nong type tektites and the analysis of the Phaeng Dang specimen reported here serve to relate these tektites to other tektites in the Far Eastern strewn field since, as Barnes has already pointed out (*1*), these tektites are end-members being richer in SiO_2 and correspondingly depleted in other constituents. It may, of course, be coincidence that those tektites which show the results of a low degree of heating and a rapid quench happen to be those with the greatest silica content. On the other hand, it may be reasonable to infer that the other tektites were derived from material similar in composition as well as texture to the Muong Nong type tektites perhaps by fractional volatilization.

The discovery of coesite in tektites is consistent with a lunar origin of this material. Furthermore, the primary nature of the texture which is indicated by the lack of decomposition products supports O'Keefe and Cameron's (*14*) suggestion that the original material was an acidic ash flow or welded tuff. The relatively high silica content of the source material may be due to several factors affecting the differentiation of lunar rocks which are discussed by Walter (*15*).

Note added in proof: Several analyses of less siliceous Muong Nong type tektites reported by Barnes (*1*) were overlooked. Nevertheless, the most siliceous indochinites are of the Muong Nong type and thus far coesite has been found only in those rich in silica. Further effort to determine the occurrence of coesite in tektites is certainly indicated. Since the preparation of this report, inclusions similar to those described here have been identified visually in specimens from Kan Long Dong.

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References and Notes

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2. ———, *Science* **142**, 1651 (1963); *Geochim. Cosmochim. Acta* **28**, 1267 (1964).
3. This inclusion was first noticed by Dr. M. Ross of the U.S. Geological Survey. He pointed it out to Dr. J. A. O'Keefe of NASA who in turn brought it to my attention. Several more inclusions were then found in other sections of the same and other Phaeng Dang specimens which had been obtained from V. E. Barnes of the University of Texas.
4. For the purpose of analysis, Fe oxide is defined as iron oxide in the approximate ratio generally found in tektites, $Fe_2O_3 : FeO :: 1 : 10$.
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16. I thank M. Ross of the USGS and J. A. O'Keefe of NASA for drawing attention to these inclusions; F. Wood and J. Bishop for aid in the analytical and experimental work; K. Fredriksson and G. Arrhenius for use of the Chesley camera; J. A. O'Keefe and P. DeCarli for helpful discussion; and V. E. Barnes, who collected and donated the tektite material.

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