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Chemical composition of North American microtektites and tektite fragments from Barbados and DSDP Site 612 on the continental slope off New Jersey

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We have determined the major element and trace element content of tektite fragments and microtektites found in deep-sea sediments from Barbados and DSDP Site 612 on the continental slope off New Jersey. The major element and trace element contents were determined using energy dispersive X-ray analysis and instrumental neutron activation analysis, respectively. The compositions are consistent with the conclusion that the samples from both occurrences belong to the North American tektite strewn field. The chemistry of the samples from both occurrences is, however, not identical with the bediasite or georgianite chemistry. There are differences especially in the lower sodium and higher K and Cr and possibly higher volatile element contents of the tektite fragments from DSDP Site 612. The differences in chemistry between bediasites, georgianites, and the tektites from the sites analyzed here show that there are geographical variations in composition in the North American strewn field like in the Czechoslovakian or Australasian strewn field. The relatively high volatile element contents (e.g., Sb and Au) of the Site 612 tektite fragments, together with the occurrence of mineral inclusions and a layered structure of some specimens, indicates that these specimens are (or close to) Muong-Nong-type tektites. If the DSDP Site 612 tektites are Muong-Nong type, then the source crater has to be close to that site and is therefore probably on the continental shelf as had previously been suggested. Tektites on land usually occur in deposits which are much younger than the tektites — the so-called age paradox. The association of tektites and microtektites together in one layer with a stratigraphic age that is consistent with the radiometric age would seem to resolve this paradox.

1. Introduction

Tektites belonging to the North American strewn field are found in Texas and Georgia [1] (Fig. 1). The tektites found in Texas are called bediasites [2], and those found in Georgia have been referred to as georgianites. One tektite found at Martha's Vineyard, Massachusetts, has also been identified as a North American tektite [3]; but because only one specimen was found, it was not known if the strewn field actually extends that far to the northeast. Another puzzling find was a tektite specimen found in a cabinet once used by the late Dr. A. Poldevaart at Columbia University. A scrap of paper found with the specimen read: "Tektite, Cuba Behre Probably from North of San Domingo (these last six words are crossed out) sent from Havana, Cuba Exact loc? Given by Senor Pablo Llaguna" [4]. The specimen is definitely a tektite and its composition and age indicate that it is a North American tektite; however, the finder of the tektite could not be located and therefore the place it was found could not be determined. If the Poldevaart tektite is actually from Cuba and if the Martha's Vineyard specimen actually fell close to where it was found, then the North American tektite strewn field is much larger than previously thought. Several relatively recent discoveries support such a conclusion.

Microtektites which on the basis of chemical, isotopic, and age data were interpreted as belonging to the North American tektite strewn field have been found in the Caribbean Sea and Gulf of Mexico [5–7] (Fig. 1). Tektite fragments, as well as microtektites, also have been found in deep-sea deposits on Barbados [8,9]. The major oxide composition and age of the Barbados tektite fragments and microtektites suggest that they too belong to

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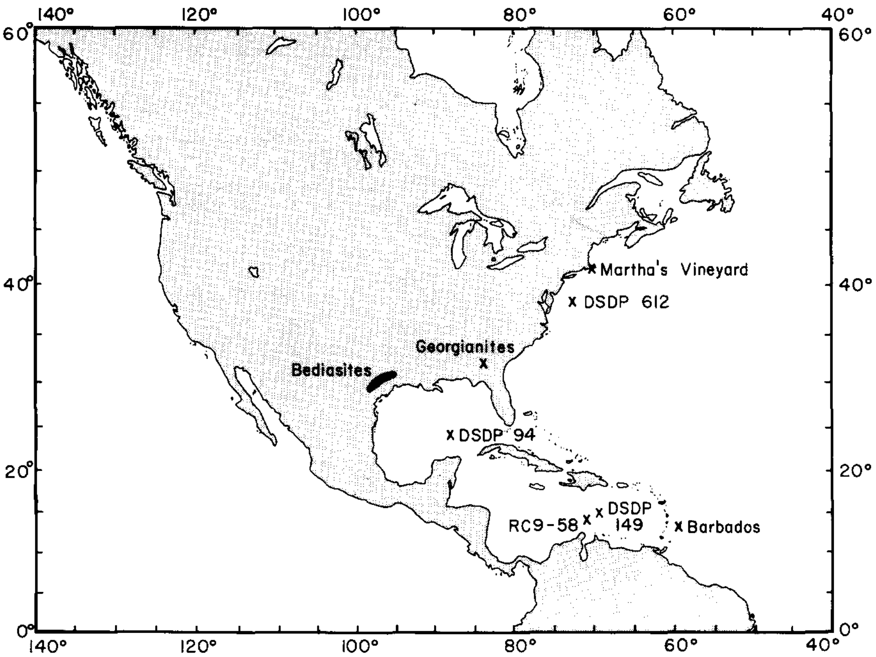

Fig. 1. Map showing the North American tektite strewn field and the sample locations at Barbados, DSDP Site 612, and *Martha's Vineyard*. Also shown are two sites in the Caribbean Sea (DSDP 149 and RC9-58) and one in the Gulf of Mexico (DSDP 94) where North American microtektites have been found.

the North American tektite strewn field [9,10]. Nd and Sr isotopic composition of the tektite fragments and microtektites from Barbados is consistent with this conclusion [11]. The occurrence of North American tektites and microtektites on Barbados and in the Carribean Sea and Gulf of Mexico indicates that the strewn field is larger than previously thought, and it also suggests that the North American tektite discovered in Poldevaart's collection could have actually been found in Cuba.

More recently a layer of tektite fragments and microtektites has been found in late Eocene sediments from Deep Sea Drilling Project (DSDP) Site 612 on the continental slope off New Jersey [12,13] (Fig. 1). The age and composition of this tektite debris suggest that it also belongs to the North American strewn field.

In this paper we provide additional compositional data in support of the conclusion that the microtektites and tektite fragments, found in late Eocene deposits on Barbados and at DSDP Site 612 on the continental slope off New Jersey, are part of the North American tektite strewn field.

2. Analytical methods

Major element abundances were determined by energy dispersive X-ray analysis (EDS) of polished sections. Glasses prepared by Corning and analyzed by the United States Geological Survey were used as standards. The spectra were corrected for background, atomic number, absorption, and fluorescence effects using a computer program by Princeton Gamma Tech.

Trace element analyses were performed using instrumental neutron activation analysis (INAA). The samples were subjected to two irradiations each (5 minutes and 2 days) followed by multiple counting cycles. The INAA methods used here are discussed in more detail by Koeberl et al. [14,15].

3. Major element composition

As a group, the North American tektites can be distinguished from tektites in other strewn fields by their low CaO and MgO contents: both CaO and MgO are generally less than 1% by weight

TABLE 1

Major element data for tektite fragments and microtektites from Barbados and DSDP Site 612 and North American tektites for comparison

	Barbados						
	microtektites selected analyses			tektite fragments selected analyses			range (18)
SiO_2	79.5	79.1	77.4	77.4	79.5	82.0	76.9 –85.6
Al_2O_3	12.5	12.1	12.9	13.5	12.1	10.3	7.97–14.8
FeO *	2.35	2.42	3.02	3.98	3.45	2.48	1.37– 3.98
MgO	0.74	0.92	0.80	0.64	0.58	0.48	0.13– 1.13
CaO	0.19	0.74	0.75	0.59	0.57	0.65	0.52– 0.87
Na_2O	1.17	1.24	1.23	1.26	1.29	1.23	1.15– 1.52
K_2O	2.49	2.71	2.73	1.94	1.93	2.42	1.73– 2.54
TiO_2	0.62	0.43	0.69	0.71	0.59	0.41	0.40– 0.71
	DSDP Site 612						
	microtektites selected analyses			tektite fragments selected analyses			range (8)
SiO_2	71.36	73.37	75.28	72.3	74.2	77.6	71.9 –77.8
Al_2O_3	15.44	14.47	13.19	15.1	14.0	13.1	13.0 –15.1
FeO *	5.18	5.00	4.19	4.8	4.5	2.8	2.7 – 5.0
MgO	1.15	1.14	1.02	1.2	1.1	0.7	0.7 – 1.4
CaO	1.13	0.74	0.99	0.85	0.9	1.0	0.8 – 1.0
Na_2O	1.47	0.57	0.78	0.3	0.2	0.5	0.2 – 0.6
K_2O	2.95	3.61	3.02	3.8	3.6	3.1	3.0 – 3.8
TiO_2	0.87	1.01	0.71	0.85	0.77	0.56	0.55– 0.85

	Bediasites		Georgianites		Martha's Vineyard tektite	Cuban tektite
	average (21)	range (21)	average (8)	range (9)		
SiO_2	76.37	71.9 –80.2	81.5	79.8 –83.6	80.5	74.8
Al_2O_3	13.78	11.2 –17.6	10.71	9.50–11.7	11.2	15.
FeO *	3.98	2.29– 5.75	2.50	1.83– 3.14	2.69	4.4
MgO	0.63	0.37– 0.95	0.55	0.37– 0.69	0.69	0.7
CaO	0.65	0.49– 0.96	0.51	0.40– 0.69	0.69	1.2
Na_2O	1.54	1.20– 1.84	1.19	1.00– 1.53	1.00	1.1
K_2O	2.08	1.60– 2.43	2.39	2.22– 2.51	2.37	2.0
TiO_2	0.76	0.59– 1.05	0.49	0.42– 0.60	0.53	0.8

* All iron given as FeO; ( ) = number of analyses.

Data sources: Barbados samples [10,18]; DSDP Site 612 [19] and this paper; bediasite average and range [16]; georgianite average and range [17]; Martha's Vineyard [17]; Cuban tektite [4].

[16,17]. The Georgia tektites generally have higher SiO_2 and lower Al_2O_3 than the bediasites (Table 1) [17]. The "Cuban" tektite is generally similar to bediasites in composition, but apparently has lower Na_2O content [4]. On the other hand, the Martha's Vineyard tektite is generally similar in composition to the Georgia tektites, but again apparently has lower Na_2O than most Georgia tektites [17].

The microtektites and tektite fragments from Barbados and DSDP Site 612 generally have major oxide compositions similar to major oxide compositions of North American tektites and like the North American tektites they have low CaO and MgO contents (Table 1) [9,10, 12, 19]. The tektite fragments from Barbados are relatively silica rich and thus are more similar to the Georgia tektites than to the bediasites. The microtektites from Barbados have a wider range in composition which overlaps the bediasites as well as the Georgia tektites. The tektite fragments and microtektites from DSDP Site 612 generally have lower SiO_2 contents than those from Barbados (Table 1) [13,19] and are thus more similar to bediasites than to the Georgia tektites except for their K_2O

TABLE 2

Trace element abundances (ppm) in tektite fragments and microtektites from Barbados, DSDP 612, and selected North American tektites for comparison

	Barbados					DSDP Site 612		Bediasite		Georganite	Martha's
	BTF1	BTF2	BTF3	BTF4	BMT	612A	612B	BED8401	LET-6	DGA-1	Vineyard M.V.
Na (%)	1.41	1.32	1.07	1.27	0.73	0.406	0.407	1.13	1.14	0.83	0.78
Sc	9.9	9.0	9.0	8.5	4.6	9.5	10.5	9.16	15.7	6.9	10
Cr	110	67	75	40	50	110	115	26	68	22	31
Mn	258	365	200	263	495	610	590	252	–	–	397
Fe (%)	2.22	2.07	1.53	2.16	1.50	3.0	3.6	1.90	4.45	1.63	2.06
Co	20	19	10	13	20	8.5	8.0	9.1	17.8	6.7	7.6
As	< 2	< 2	1	1	2.5	0.6	0.9	1	–	–	–
Rb	84	< 150	170	90	< 130	85	90	73	70	66	72
Zr	< 400	< 400	< 350	< 400	< 600	< 350	240	152	290	160	190
Sb	< 2	< 3	< 1	< 1	< 2.5	2.0	1.7	0.05	–	–	–
Cs	11	11	10	7	6	5	5	1.33	2.3	1.0	1.7
Ba	< 800	< 800	< 700	< 700	< 1000	700	700	450	390	620	390
La	29	23.7	11	19.6	15	29.3	29.5	22.9	45.9	19.6	< 50
Ce	75	52	20	30	38	55	66	60.7	97	43	–
Nd	32	28	–	13.5	20	34	40	26	–	–	–
Sm	9.0	8.30	3.18	5.8	4.45	8.3	8.6	5.2	9.6	4.03	–
Eu	1.56	1.30	0.43	1.14	0.59	0.73	0.75	1.20	2.02	0.97	–
Gd	10	–	5	–	–	7	–	–	–	–	–
Tb	1.5	–	–	1.0	0.8	1.1	1.3	0.62	1.31	0.59	–
Dy	7.2	4.55	4.8	4.6	4.0	6.6	6.7	3.8	–	–	–
Tm	–	–	–	0.5	–	0.9	–	–	–	–	–
Yb	5.0	4.5	4.0	3.0	3.5	5.0	4.2	1.69	3.93	1.73	–
Lu	0.4	0.4	0.62	0.31	0.5	0.35	0.40	0.35	0.62	0.29	–
Hf	7.1	4.1	< 5	6.7	3	6	5.8	5.1	7.8	4.7	–
Ta	3	3	2	2	< 6	1	1	0.70	–	–	–
Au	–	0.003	–	–	–	–	0.06	–	–	–	–
Th	6.6	6.8	–	4	4	8.5	10	6.8	9.0	4.9	–
U	< 3	< 4	< 4	< 4	< 6	–	3.6	1.82	3.1	1.25	–
Sample weights (mg)	1.490	0.920	0.902	1.299	0.077	12.94	6.790				

Data sources: BTF1–BTF4, BMT, 612A this work; BED8401 [20]; LET-6 and DGA-1 [21]; M.V. [17].

and Na_2O contents. The Site 612 tektites generally have higher K_2O and lower Na_2O contents than the bediasites (Table 1) and therefore have K_2O/Na_2O ratios more similar to the Georgia tektites.

4. Trace element composition

Up to 26 trace elements were determined for four tektite fragments (BTF 1–4) and a composite of two microtektites (BMT) from Barbados, and for two pieces of a tektite fragment from DSDP Site 612 (Table 2). In general, the chondrite-normalized REE data for the DSDP Site 612 fragments is intermediate between a bediasite and a Georgia tektite which were chosen to represent an upper and a lower limit of REE abundances among North American tektites (Fig. 2) (see also [22]). An exception is that the DSDP Site 612 fragments have a more pronounced Eu anomaly. The Barbados samples also plot within the range of North American tektites (see also [23]), except that the microtektite sample has lower overall REE abundances and a slightly more pronounced Eu anomaly than the tektite fragments (Fig. 3).

5. Discussion

Major and trace element compositions of the Barbados and Site 612 tektite fragments clearly

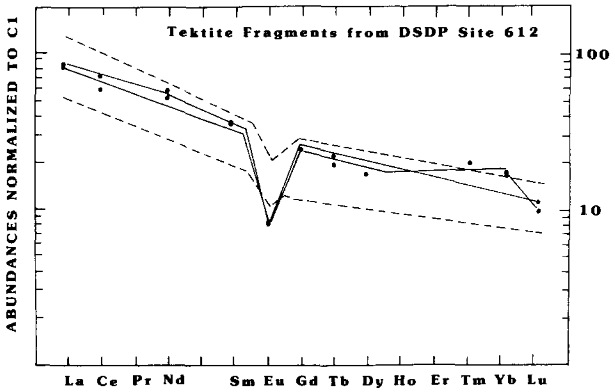

Fig. 2. Chondrite-normalized rare earth element abundance pattern for two fragments from DSDP Site 612, compared with bediasite LET-6 (upper dashed line) and georgianite DGA-1 (lower dashed curve) (data from [21] and unpublished data (C.K.)).

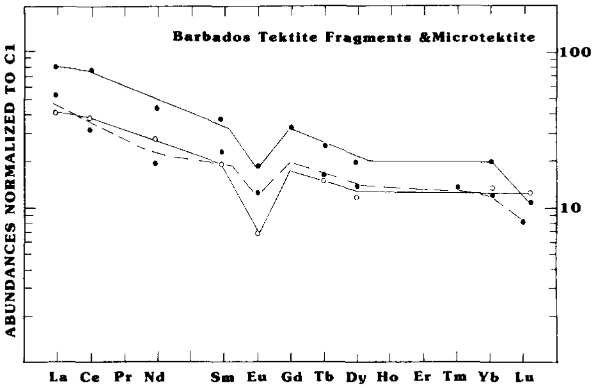

Fig. 3. Chondrite-normalized rare earth element abundance patterns for two tektite fragments and one microtektite sample from Barbados. The open circles denote the microtektite sample.

indicate a connection with tektites from the North American strewn field. There are, however, a few differences which may be of some interest. The bediasites and georgianites generally have K_2O contents < 2.6 wt.%. The tektite fragments from Site 612, however, generally have K_2O contents $> 2.6\%$. On the other hand, the Na_2O contents of the Site 612 tektites are generally low compared to other North American tektites (Tables 1 and 2). This results in K_2O/Na_2O ratios that are generally much higher than for other North American tektites (generally > 5).

As far as K_2O/Na_2O ratios are concerned, there is no overlap between georgianites and bediasites [24]. The Cuban tektite has a K_2O/Na_2O ratio between these two groups, while the Martha's Vineyard tektite has a K_2O/Na_2O ratio close to the Georgia tektites. The Barbados tektites have K_2O/Na_2O ratios similar to those of the Georgia tektites.

The refractory trace element contents of the Barbados and Site 612 samples are almost indistinguishable from other North American tektites (Table 2). However, the Cs contents of the Barbados and Site 612 tektites are higher than the Cs content of other North American tektites and the Rb contents are slightly higher. The higher Cs and Rb contents may reflect a more highly differentiated feldspar component present in the Site 612 tektites. In addition, the tektite material from Barbados and Site 612 generally have lower Eu contents (Table 2; Figs. 2 and 3), resulting in a more pronounced Eu anomaly. Furthermore, some of the Barbados and Site 612 tektite fragments have high Cr contents (up to 115 ppm) in comparison with other North American tektites (Table 2). The high Cr content of some specimens may reflect incorporation of a varying proportion of some ultramafic component, similar to what has been observed in different glasses from the Zhamanshin Crater [25]. The cobalt contents in three of the Barbados samples are just above the upper limit previously reported from North American tektites. This may not be significant, although it again indicates some difference between the Barbados tektite material and other North American tektites.

Tektites generally have radiometric ages that are older than the deposits they lie on. Thus the stratigraphic ages of the tektites are younger than their radiometric ages. This age paradox has led some workers to dispute the radiometric ages or to propose that the tektites were somehow kept in limbo between the time they were formed and the time they fell to the Earth's surface (see e.g. [26,27]). The stratigraphic ages of the microtektites from the various strewn fields are consistent with the radiometric ages of the tektites. This discovery would seem to have solved the problem, but instead some authors have questioned the relationship between microtektites and tektites (e.g. [26]). The discovery of tektite fragments physically associated with microtektites in sediments with stratigraphic ages consistent with their radiometric ages at Barbados and DSDP Site 612 provides additional evidence for the genetic relationship between tektites and microtektites, at least for the North American strewn field. Furthermore, since the major and the trace element compositions of the tektites and microtektites from both Barbados and DSDP Site 612 (as shown in Tables 1 and 2) are consistent with each other and with the other North American tektites, we feel that the age paradox finally has been resolved.

The layer of tektite debris at Site 612 is about 8 cm thick. This layer consists primarily of tektite glass and impact ejecta including shocked mineral grains [12], coesite [28] and stishovite. The great abundance of impact ejecta and tektite glass, including some possible Muong-Nong-type material, suggests that Site 612 is near the impact site. Furthermore, Shaw and Wasserburg [29] have suggested, based on Sm-Nd and Rb-Sr isotope data, that the source crater is on a continental shelf. Recently a 30 km diameter impact structure, called Montagnais, was discovered on the Scotian Shelf south of Halifax [30]. Preliminary age determinations indicate that the crater may be ~ 50 m.y. old and therefore it would be too old to be the source of the North American tektites. However, additional studies are required to better define the age. In addition, there is the possibility of one or more craters on the shelf which have so far escaped detection or have not yet been recognized as impact structures.

6. Conclusions

The chemical data presented in this report supports previous conclusions that the tektite fragments and microtektites found at Barbados and DSDP Site 612 on the continental slope off New Jersey are part of the North American strewn field. There are, however, some compositional differences between Barbados and Site 612 tektites and the bediasites and georgianites suggesting that there are more chemical subgroups in the North American strewn field than just bediasites and georgianites, similar to what we observe from the Australasian and Czechoslovakian strewn fields. Among the most notable differences are the high Cr content and high K_2O/Na_2O ratio of the DSDP Site 612 tektites. This may indicate that the parent material was slightly heterogeneous and mixing between different source rocks took place. The Site 612 tektites also appear to have higher volatile element content (e.g., Sb and Au) which along with the presence of mineral inclusions (i.e., quartz) and the layered appearance of some of the specimens suggests that some of the tektite specimens at this site may be closer to the Muong-Nong-type tektites than to splash form tektites. This conclusion has to be supported, however, by more detailed investigations of volatile element contents and inhomogeneities — analyses for which larger samples would be needed.

We note that the co-occurrence of tektite fragments and microtektites with similar compositions at both Barbados and DSDP Site 612 supports previous conclusions that the microtektites are genetically related to the tektites. The occurrence of North American tektite fragments and microtektites in sediments with stratigraphic ages consistent with their radiometric ages resolves the age paradox and indicates that the tektites fell immediately after their formation in a hypervelocity impact on earth.

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