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## A Muong Nong-type Georgia tektite

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**Abstract**—A large (130 g), layered tektite was found just south of Riddleville, Georgia, USA, in July 1993. The specimen has a bulk composition similar to that of splash-form Georgia tektites, but with a much wider range in composition (e.g., the silica content ranges from 69–99 wt%) and it contains numerous white opaque inclusions. Portions of the specimen were studied to determine the petrography, major and minor element, and strontium and neodymium isotopic composition, water content, magnetic properties, ferric/ferrous ratio, and <sup>40</sup>Ar/<sup>39</sup>Ar age. The white opaque inclusions were found to be zircon crystals, many of which had partly or completely decomposed to baddeleyite plus SiO<sub>2</sub> glass. The trace element, strontium and neodymium isotopic ratios, water content, age (~34.5 Ma), and magnetic properties are all similar to normal Georgia tektites. Mössbauer data indicate Fe<sup>3+</sup>/Fe<sup>2+</sup> ratios between 0.07 and 0.16. This specimen has all the characteristics of a Muong Nong-type tektite, except that it is not as strongly enriched in volatile elements, including water, as are the Australasian Muong Nong-type tektites. The lack of a strong enrichment in volatile elements, plus the fact that many of the included relict zircons have partly or completely broken down to baddeleyite plus SiO<sub>2</sub> glass, indicates that this specimen was heated more intensely than most zircon-bearing Australasian Muong Nong-type tektites. The occurrence in the northeastern corner of the Georgia strewn field is consistent with a proposed source crater near Deep Sea Drilling Project Site 612 off the coast of New Jersey.

### 1. INTRODUCTION

Muong Nong-type tektites are blocky, layered tektites without splash-form shapes. They are named after a region in Laos where they were first found (Lacroix, 1935). They are often larger than splash-form tektites; Koeberl (1992) reported two Australasian specimens that weighed ~24 kg each. Australasian Muong Nong-type tektites generally contain more vesicles, are more heterogeneous on a millimeter scale, and have higher volatile element contents than Australasian splash-form tektites (Koeberl, 1992; Schnetzler, 1992). Coesite and relict mineral grains (quartz, zircon, rutile, chromite, monazite) have been recovered from some rare specimens of Australasian Muong Nong-type tektites (Walter, 1965; Glass and Barlow, 1979; Glass et al., 1986). The relict mineral grains exhibit evidence of shock metamorphism (Glass and Barlow, 1979). Petrographic and chemical studies of Australasian Muong Nong-type tektites indicate that they formed at lower temperature and/or were heated for a shorter time than the splash-form tektites (Barnes, 1990; Koeberl, 1992).

Muong Nong-type tektites occur in the northern parts of the Australasian strewn field (mostly in Indochina); however, none have been found in the Ivory Coast strewn field and only a few rare specimens have been reported from the Central European strewn field (Meisel et al., 1989; Glass et al., 1990). Muong Nong-type tektites have also been reported from the North American strewn field. Wittke and Barnes (1988) have described a possible Muong Nong-type bediasite (from

Texas) and Koeberl and Glass (1988) reported Muong Nong-type tektite fragments from Deep Sea Drilling Project Site 612 on the continental slope off New Jersey, USA.

The specimen discussed in this report is the first Muong Nong-type tektite to be found in the Georgia part of the North American strewn field. It was found by one of the authors (RLS) just south of Riddleville in Washington County in proximity to a gravel quarry (32°53.3'N, 82°40.4'W) (Fig. 1) on July 31, 1993. Formations exposed in this area include the Tobacco Road Sand and the younger Altamaha Formation. However, the area has been highly disturbed by earth moving equipment and, therefore, the relationship of the specimen to the local stratigraphy is unknown. It weighs 130 g, measures ~4 × 5.5 × 6 cm, and the surface exhibits obvious layering (Fig. 2) due to differential solution. The specimen is sub-rounded with some relatively flat surfaces. It does not exhibit any evidence of recent breakage. As this was the first Muong Nong-type tektite found in Georgia, a consortium was established to study this specimen. We discuss the results of that study in this report. After samples were taken for this study, the specimen was returned to the owner (R. L. Strange).

### 2. METHODS

After the Muong Nong-type tektite (MNGaTek) specimen was cleaned, weighed, and photographed, one end of the specimen was cut off and four, approximately 2 mm thick, slices were removed. One slice was broken into four parts each weighing between 0.52

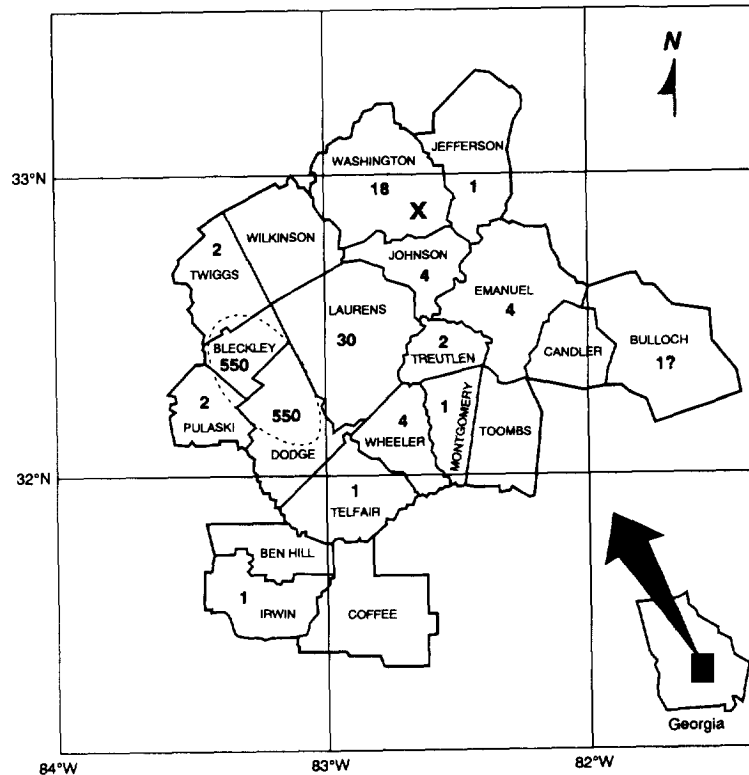


FIG. 1. Map of Georgia tectite strewn field showing where the specimen (MNGaTek) discussed in this report was found (x). The numbers indicate the known number of Georgia tectites recovered from a given county. The area inclosed with a dashed line is where most Georgia tectites have been found. Modified after Povenmire (1995).

and 1.03 g and distributed to members of the consortium for study. Another slice, originally weighing 3.39 g, was polished on both sides and used for Mössbauer studies. The other two slices, weighing 3.97 and 5.38 g, respectively, were used for petrographic studies.

The 5.2 g end piece was crushed and sieved into three size fractions ( $<74 \mu\text{m}$ ,  $74\text{--}149 \mu\text{m}$ , and  $>149 \mu\text{m}$ ). The  $74\text{--}149 \mu\text{m}$  size fraction was then put through heavy liquid separation (using S-tetrabromoethane) in order to determine the range in composition of the MNGaTek

specimen and to search for mineral inclusions. The specific gravity of the liquid was successively lowered from 2.96–2.17 using methanol. After each successive lowering of the specific gravity, the grains with higher densities than the heavy liquid were recovered. This process was continued until all grains were retrieved. Thirty-three specific gravity fractions were recovered in this fashion. The grains that were heavier and lighter than the bulk of the glass were studied using a binocular microscope with up to  $50\times$  magnification and grains that appeared to contain inclusions were removed for later study. The inclusions were identified by X-ray diffraction using a Gandolfi camera and studied with a petrographic microscope. In addition, glass fragments from each specific gravity fraction were mounted in epoxy on 2.54 cm (1") diameter glass discs. The glass fragments were ground down to expose a flat interior surface and polished for major element analysis using an energy dispersive X-ray analyzer (Princeton Gamma Tech System 4) in combination with a Cambridge S90B scanning electron microscope (Glass, 1989).

The water contents of the MNGaTek specimen and two splash-form Georgia tectites were determined using a Perkin Elmer 1760X Fourier-transform-IR spectrometer (see Koeberl and Beran, 1988, for details of the method). Trace element analyses were done using instrumental neutron activation analysis (Koeberl, 1992).

Rubidium-strontium and Sm-Nd isotopic compositions and concentrations were determined by isotope dilution thermal ionization mass spectrometry. An approximately 100 mg sample of the tectite was digested in a mixture of HF and  $\text{HClO}_4$ , spiked with isotopically enriched tracers, and then separated into Rb, Sr, Sm, and Nd fractions using standard cation exchange techniques (Blum et al., 1995).

The magnetic measurements were made on part ( $\sim 0.5$  g) of one of the 2 mm thick slices referred to above. This sample was broken into seven smaller fragments weighing 8.5–87.2 mg each. Each of the small fragments was measured independently on an automated Faraday-type magnetic balance. The sample was suspended in a helium atmosphere with a thermocouple adjacent to, but not touching, the sample. To determine the Curie constant, magnetic susceptibility,

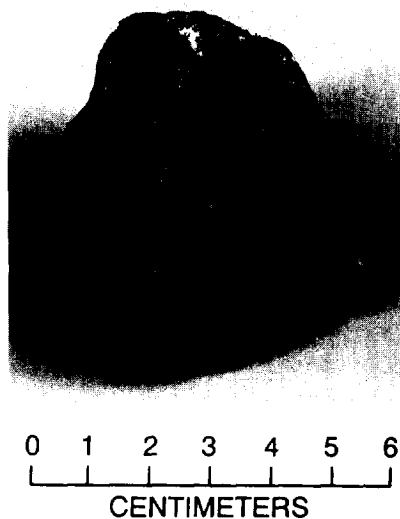


FIG. 2. Photograph of the specimen (MNGaTek) discussed in this report.

and the magnetization, measurements were made as a function of temperature (77–300°K) at a constant magnetic field (3200 Oe), and also as a function of the applied magnetic field (500–3200 Oe) at a constant temperature (300°K). The measurements were similar to those previously made on splash form tektites (Senftle and Thorpe, 1959; Thorpe and Senftle, 1964).

Several  $^{57}\text{Fe}$  Mössbauer spectra were obtained at 295°K for two circular areas (9.5 mm and 19 mm, respectively) on a 0.6 mm thick slice of MNGaTek (measuring approximately  $2.4 \times 4.5$  cm). For details of the analytical method see Evans and Leung (1979).

Laser-fusion  $^{40}\text{Ar}/^{39}\text{Ar}$  data were obtained for MNGaTek using equipment in the geochronology laboratories of the USGS in Menlo Park, California. Submillimeter-size glass fragments of the tektite were melted with a 5-W argon-ion laser at the highest temperature attainable (1500°C) and the argon isotopic composition was measured with an ultrasensitive rare gas mass spectrometer. The general procedures used for  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of geologic materials in the Menlo Park laboratory, including the reactor fluence characteristics, irradiation scheme, and methods of determining corrections for interfering argon isotopes were described by Dalrymple et al. (1981), Dalrymple (1989), and Dalrymple and Duffield (1988). Specific analytical procedures are described by Izett and Obradovich (1994).

### 3. RESULTS

#### 3.1. Petrography

Polished sections of the MNGaTek specimen exhibit obvious layering due to variations in the color of the glass (Figs. 3, 4a), which ranges from yellow-green to pale brown to dark brown. Overall the layers are gently curved, but they are sharply folded in parts of the specimen. Schlieren are generally parallel to the layers, but are often wavy or contorted (Fig. 4).

Vesicles are common to abundant, but most are  $<100 \mu\text{m}$  in diameter. Their diameters range from  $<2 \mu\text{m}$  up to  $740 \mu\text{m}$ . All the vesicles are spherical in shape (Fig. 4). There is some variation in abundance of the vesicles in different parts of the specimen, but, in general, there does not appear to be any correlation between vesicle abundance and layering; however, one pale yellow-green region does not contain any vesicles.

Lechatelierite particles are common. Some are equant in shape, but most are flattened to elongate (Fig. 4c). Most are bubbly and some are frothy. The largest observed lechatelierite particle is  $0.9 \times 1.3$  mm, although a thin elongate particle about 3 mm in length was also observed. The long axes of the lechatelierite particles are generally parallel to the layering. Based on 1000 point counts, the specimen contains 0.8 vol% vesicles and 0.3 vol% lechatelierite particles.

Several small (generally between 20 and  $60 \mu\text{m}$ ), white, opaque inclusions were observed in the slices (Fig. 4d). Nine similar appearing inclusions, still partly enclosed in tektite glass, were recovered from the heavy liquid separations ( $\sim 4$  inclusions/cm<sup>3</sup> of glass). X-ray diffraction patterns indicate that five are zircon, three are baddeleyite, and one is a mixture of zircon and baddeleyite. The largest zircon measures  $40 \times 80 \mu\text{m}$ .

Each of the slices exhibits considerable strain birefringence (Fig. 4b) that correlates with the layering and is concentrated around the larger lechatelierite particles.

#### 3.2. Major and Trace Element Composition

The major element compositions of forty-six glass fragments from the heavy liquid separations were determined us-

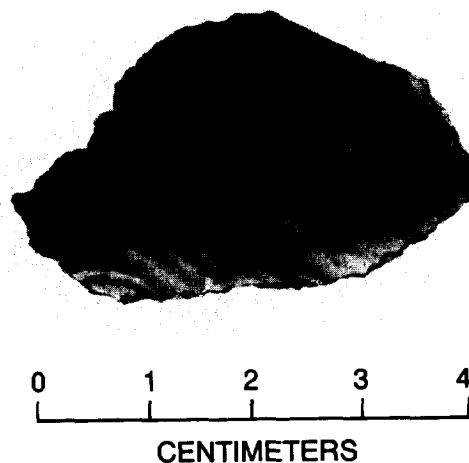


FIG. 3. Photograph of 2 mm-thick slice of MNGaTek showing vesicles and dark- and light-colored layers.

ing energy dispersive X-ray analysis (Table 1; Fig. 5). The silica content of the MNGaTek specimen was found to range from 69–99 wt%. Thus, this one specimen has a greater range in composition than all previously analyzed splash-form North American tektites combined (Fig. 5). However, the higher silica contents are probably due to analyses of lechatelierite particles or to overlap of the beam onto lechatelierite particles. A break in slope on the  $\text{K}_2\text{O}$  vs.  $\text{SiO}_2$  diagram (Fig. 5) indicates that the change from glass to glass plus lechatelierite takes place at about 86 wt% silica. Between about 77 and 84 wt%  $\text{SiO}_2$ , the MNGaTek specimen has a composition similar to that of previously analyzed splash-form North American tektites, except for slightly higher MgO and  $\text{K}_2\text{O}$  and slightly lower FeO and  $\text{Na}_2\text{O}$  contents (Fig. 5). Below 77 wt%  $\text{SiO}_2$  the MNGaTek values are more similar to the tektite fragments found at DSDP Site 612 than to bediasites and Georgia splash-form tektites.

The average silica content of MNGaTek, based on 210 random spot analyses, is  $84.2 \pm 2.0$  wt% (Table 2). Thus, the MNGaTek specimen has a slightly higher average silica content than do the splash-form Georgia tektites. Similarly, the Australasian tektites with the highest  $\text{SiO}_2$  contents are the Muong Nong-type.

Very little trace element data have been published for Georgia tektites. Haskin et al. (1982) published abundance data for eighteen trace elements for two Georgia tektites and Dod et al. (1988) reported abundances for twelve trace elements for three additional Georgia tektites. We determined the abundances of thirty-five trace elements for MNGaTek. In order to be able to compare our results for the MNGaTek specimen with normal splash-form Georgia tektites, we also determined trace element abundances for three splash-form Georgia tektites. We obtained lower abundances for Ba and higher abundances for Zr and Rb than those reported by Haskin et al. (1982), otherwise our trace element abundances agree well with those reported by Haskin et al. (1982) and Dod et al. (1988).

The minor and trace element abundances of the MNGaTek specimen are similar to those of splash-form Georgia tektites; however, the MNGaTek specimen appears to have somewhat

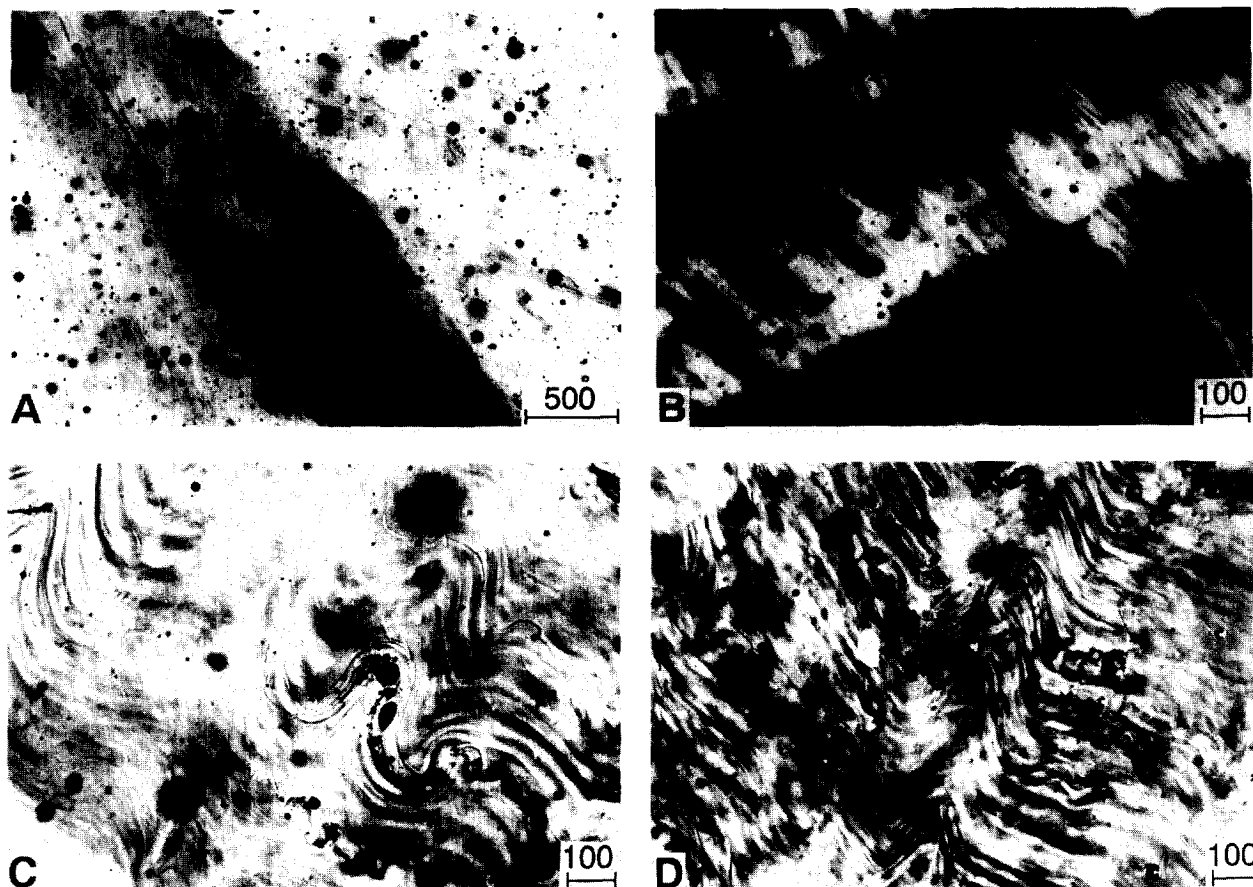


FIG. 4. Photomicrographs of petrographic features of MNGaTek. (a) Note layering and vesicles (transmitted light), (b) strain birefringence (transmitted light with crossed polarizers), (c) lechatelierite particles (transmitted light), and (d) white opaque inclusion, probably a shocked zircon (transmitted and reflected light). Scale bars in micrometers.

higher Ba and somewhat lower Sc, Cr, Co, Sr, Zr, and REE contents (Table 3; Fig. 6).

### 3.3. Water Content

Three measurements were made of the water content using IR spectrometry. It was found that at least within a 2–3 mm area the water content is homogeneous with a value of 0.007 wt%. The water content was also measured in two splash-form Georgia tektites (GT-2 and GT-4, see Tables 1 and 3 for composition). They both contained 0.02 wt% H<sub>2</sub>O. Gilchrist et al. (1969) found water contents ranging from 0.005 to 0.021 for seven bediasites, and water contents of 0.012 and 0.016 for a Georgia tektite and the Martha's Vineyard tektite, respectively. Thus, it appears that the MNGaTek specimen has a slightly lower water content than the splash-form North American tektites.

### 3.4. Strontium and Neodymium Isotopic Composition

The  $\epsilon_{\text{Sr}}$  and  $\epsilon_{\text{Nd}}$  values measured for the MNGaTek are 148.4 and –6.5, respectively (Table 4). These values plot at the center of the field of analyses of North American tektites taken from the literature (Shaw and Wasserburg, 1982; Ngo et al., 1985; Stecher et al., 1989), and are distinct from values

for Haitian K-T boundary tektites (Fig. 7) (Premo and Izett, 1992), moldavites (Central European tektites) (Shaw and Wasserburg, 1982), tektite fragments from DSDP Site 612 (Stecher et al., 1989), Australasian tektites (Shaw and Wasserburg, 1982; Blum et al., 1992), and Ivory Coast tektites (Shaw and Wasserburg, 1982). Consideration of the  $\epsilon_{\text{Sr}}$  and  $\epsilon_{\text{Nd}}$  values of various samples of North American tektites (see Inset, Fig. 7) reveals that the  $\epsilon_{\text{Nd}}$  values of the eleven North American tektite samples that have been analyzed are indistinguishable within the analytical uncertainties. In contrast, the  $\epsilon_{\text{Sr}}$  values display considerable variability, which is far greater than the analytical uncertainties.

### 3.5. Magnetic Properties and Fe<sup>3+</sup>/Fe<sup>2+</sup> Ratios

Like splash-form tektites, the seven fragments of MNGaTek studied for magnetic properties are all paramagnetic (zero magnetization); however, unlike splash-form tektites the other magnetic properties shown in Table 5 exhibit significant variations from fragment to fragment (see Senftle and Thorpe, 1959). The variation in the Curie constant reflects either the changes in the Fe<sup>3+</sup>/Fe<sup>2+</sup> ratio from point to point within the sample, or the presence of superparamagnetic crystallites. The variation in the temperature-independent component of the total magnetic sus-

Table 1. Oxide compositions of MNCaTek fragments<sup>1</sup>, splash-form Georgia tektites, and DSDP Site 612 tektites fragments.

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO <sup>2</sup>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	Total
MNCaTek									
584-4-33	93.42	3.46	0.69	0.26	0.06	0.12	1.22	0.19	99.42
584-5-9	92.96	2.44	0.13	0.37	1.29	0.08	0.06	0.25	97.58
584-4-30	91.95	4.62	0.28	0.34	0.20	0.45	1.53	0.06	99.43
584-6-8	90.56	5.27	0.66	0.29	0.17	0.33	1.90	0.13	99.31
584-1-2	89.87	5.57	0.80	0.42	0.27	0.42	1.87	0.19	99.41
584-3-4	88.92	6.15	0.76	0.42	0.28	0.46	2.07	0.21	99.27
583-2-B	87.45	7.15	0.75	0.43	0.29	0.39	2.40	0.26	99.12
583-1-B	86.78	7.42	0.73	0.47	0.35	0.54	2.60	0.21	99.10
605-28A	86.22	7.85	1.22	0.52	0.35	0.55	2.26	0.26	99.23
583-1-F	85.78	8.25	1.11	0.58	0.41	0.53	2.34	0.30	99.30
579-1-2H	85.45	8.47	1.45	0.62	0.32	0.45	2.32	0.24	99.32
583-2-I	84.61	8.88	1.36	0.60	0.45	0.38	2.52	0.33	99.13
605-19A	84.38	9.11	1.32	0.66	0.44	0.71	2.46	0.36	99.44
583-1-D	83.77	9.54	1.45	0.60	0.48	0.47	2.64	0.35	99.30
579-1-2G	83.48	9.83	1.81	0.61	0.39	0.52	2.39	0.30	99.33
579-1-2K	82.91	10.01	1.75	0.73	0.44	0.68	2.52	0.31	99.35
579-1-1B	82.86	9.97	1.78	0.57	0.51	0.67	2.60	0.39	99.35
605-24A	82.42	10.30	1.97	0.68	0.48	0.58	2.56	0.42	99.41
583-2-G	81.62	10.76	2.14	0.74	0.51	0.42	2.58	0.37	99.14
605-20A	80.89	11.56	1.97	0.80	0.59	0.79	2.36	0.47	99.43
579-1-2D	80.48	11.66	2.17	0.82	0.56	0.65	2.45	0.54	99.33
605-25B	79.92	11.85	2.35	0.87	0.63	0.73	2.57	0.49	99.41
583-4-F	79.61	11.85	2.48	0.91	0.64	0.66	2.75	0.47	99.37
579-1-2J	79.07	12.01	2.77	0.85	0.64	0.84	2.58	0.58	99.34
605-4A	78.58	10.70	3.75	1.44	1.09	0.81	2.48	0.58	99.43
579-1-1I	77.76	13.37	2.68	0.89	0.65	0.87	2.58	0.53	99.33
579-1-1G	77.64	13.23	2.80	0.93	0.62	0.80	2.65	0.68	99.35
585-4-6	77.51	12.63	3.09	0.93	0.59	1.07	2.85	0.63	99.30
579-1-2A	77.03	13.45	2.94	1.07	0.76	0.87	2.52	0.69	99.33
605-6A	76.42	13.13	3.82	1.08	1.01	0.82	2.61	0.61	99.50
605-1B	76.21	11.42	4.24	1.74	1.70	0.94	2.54	0.64	99.43
585-6-8A	75.84	13.70	3.76	1.03	0.62	0.94	2.76	0.68	99.33
585-5-5	75.15	11.68	4.13	1.94	1.97	1.16	2.52	0.78	99.33
605-17B	74.58	12.30	4.22	1.79	2.15	1.05	2.71	0.67	99.47
605-17A	73.94	12.62	4.35	1.91	2.18	1.09	2.69	0.70	99.48
583-4-A	73.53	12.26	4.41	2.04	2.45	1.25	2.55	0.65	99.14
605-18B	73.35	12.63	4.61	2.01	2.20	1.31	2.59	0.71	99.41
605-17C	72.26	13.10	4.93	2.22	2.33	1.29	2.58	0.75	99.46
585-5-4B	71.59	13.28	5.03	2.20	2.93	1.18	2.49	0.66	99.36
605-18A	71.35	13.62	5.01	2.23	2.60	1.37	2.49	0.72	99.39
585-1-5	69.50	15.23	5.43	2.27	1.67	1.41	3.01	0.84	99.36
585-3-3	69.19	15.63	5.72	2.28	1.42	1.33	2.84	0.92	99.33
Splash-form Georgia Tektites <sup>3</sup>									
GT-2	81.94	10.62	2.06	0.71	0.48	0.55	2.55	0.46	99.37
GT-4	82.12	10.49	1.99	0.71	0.49	0.58	2.54	0.45	99.37
GT-3	80.51	11.75	2.40	0.90	0.56	0.46	2.24	0.55	99.37
579-2	80.35	11.36	2.74	0.81	0.54	0.66	2.40	0.47	99.33
DSDP Site 612 Tektite Fragments									
391-1-1	77.50	12.00	4.12	1.11	0.64	0.51	2.71	0.66	99.25
350-6	77.50	13.10	2.82	0.95	0.68	0.92	3.10	0.46	99.53
350-7	76.30	13.80	2.92	1.00	0.75	0.96	3.08	0.48	99.29
391-1-2	75.20	13.60	3.80	1.29	0.97	0.76	3.13	0.72	99.47
350-4	74.10	14.00	4.20	1.33	0.63	0.84	3.58	0.74	99.42
376-6	74.20	14.10	4.59	1.28	0.68	0.64	3.56	0.71	99.76
350-5	73.00	14.30	4.50	1.44	0.68	0.88	3.61	0.82	99.23
350-2	72.80	14.50	4.50	1.40	0.66	0.92	3.68	0.86	99.32
350-3	72.70	14.60	4.48	1.42	0.69	0.86	3.70	0.82	99.27
350-1	72.50	14.90	4.52	1.42	0.68	0.93	3.58	0.80	99.33
391-4-1	71.90	15.00	4.55	1.42	1.28	1.49	2.96	0.84	99.44
391-1-4	71.00	15.80	4.46	1.26	0.71	0.91	4.56	0.67	99.37
376-2	70.70	14.40	7.51	1.36	0.86	0.78	3.47	0.69	99.77
391-4-4	69.90	15.00	4.91	2.21	2.26	1.32	3.02	0.94	99.56

<sup>1</sup>Compositions of fragments recovered from the various heavy liquid separations. The compositions of four fragments composed of >99 vol% SiO<sub>2</sub> are not included.

<sup>2</sup>Total iron reported as FeO.

<sup>3</sup>Samples G-2, G-3, and G-4 are from Roddy, Georgia, and sample 579-2 is from Dodge County, Georgia.

ceptibility can be ascribed to crystalline temperature-independent paramagnetic phases in the glass. The maximum variation in the total magnetic susceptibility is about 21%, whereas in a given splash-form tektite it is generally less

than 5%. The variation of these magnetic parameters indicate the inhomogeneous distribution of solid phases present in the glass, which is a distinctly different phenomenon than that found in splash-form tektites. In general, the val-

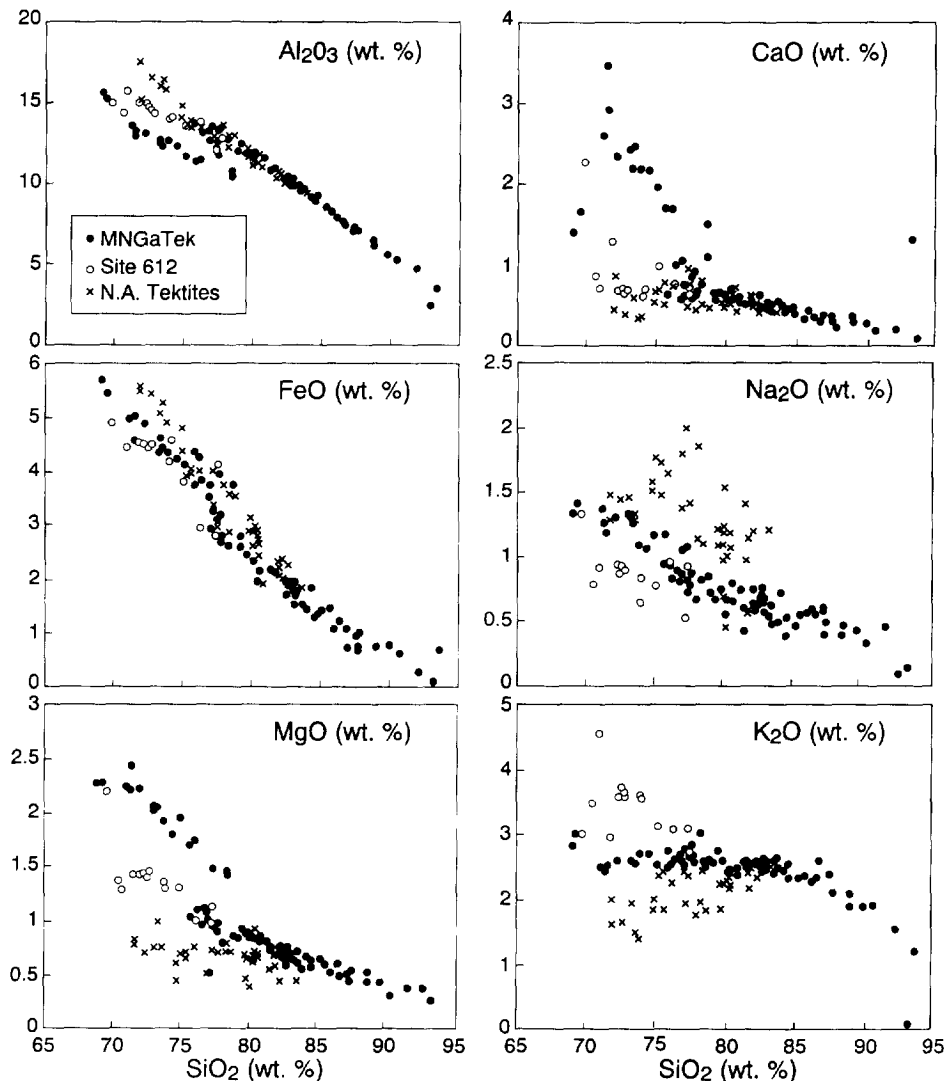


FIG. 5. Major oxide contents versus silica content for MNGaTek, splash-form North American tektites, and DSDP Site 612 tektite fragments. Compositional data for North American tektites from Chao (1963), Schnetzler and Pinson (1963), Cuttitta et al. (1967), Garlick et al. (1971), O'Reilly et al. (1983), and Dod et al. (1988).

ues of the Curie constant and the temperature-independent component of the susceptibility are slightly lower than those found for normal Georgia tektites (Thorpe and Senftle, 1964); but, as the Fe concentration of the MNGaTek is lower than that reported for the splash-form Georgia tektites, the magnetic data for the two types of tektite are consistent.

$^{57}\text{Fe}$  Mössbauer spectra were obtained for two distinct regions of MNGaTek. One region was  $\sim 250\text{ mm}^2$  and the other was  $\sim 75\text{ mm}^2$ . There were no obvious differences in the visual appearance of the two regions. The spectra from the two regions were similar in overall appearances and could be fitted to the same qualitative distribution of spectral components. Quantitatively, however, the spectra were quite different. The difference in quadrupole splittings exceeded the standard error for each spectral component (cf. Table 6). The  $\text{Fe}^{3+}/\text{Fe}^{2+}$  ratio of the two regions are significantly different (Table 6). The lower

$\text{Fe}^{3+}/\text{Fe}^{2+}$  ratio is similar to that found in splash-form georgiites (Table 6). These data indicate that, in addition to obvious inhomogeneities (*infra vide*), there are submicroscopic chemical inhomogeneities due to the presence of Fe-bearing crystalline phases. Such inhomogeneities have not been observed in splash form tektites even when associated with distinct morphological features such as the flange, anterior, and posterior regions of flanged tektites or the head and tail regions of teardrop-shaped Australasian tektites.

### 3.6. $^{40}\text{Ar}/^{39}\text{Ar}$ Ages

The mean age for five fragments is  $34.52 \pm 0.10\text{ Ma}$ . The ages were calculated using decay constants recommended by the Subcommittee on Geochronology of the IUGS (Steiger and Jäger, 1977). The error assigned to the ages is at the  $1\sigma$  level and includes an evaluation of the precision error (0.3–

Table 2. Average composition (based on 30 spot analyses) plus/minus one standard deviation for samples of MNGaTek used for magnetic studies (see Table 5).

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO <sup>†</sup>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	Total
H-1	83.50	9.62	1.56	0.67	0.46	0.73	2.47	0.37	99.38
$\sigma$	2.87	1.80	0.43	0.17	0.14	0.28	0.18	0.12	
H-M	85.08	8.70	1.26	0.56	0.42	0.58	2.47	0.31	99.38
$\sigma$	1.70	1.05	0.31	0.10	0.07	0.14	0.13	0.09	
H-2	84.31	9.04	1.43	0.57	0.40	0.78	2.52	0.34	99.39
$\sigma$	2.05	1.28	0.36	0.12	0.10	0.15	0.18	0.09	
H-3	83.71	9.57	1.56	0.61	0.44	0.69	2.52	0.35	99.45
$\sigma$	1.42	0.90	0.27	0.09	0.06	0.17	0.11	0.06	
H-4	83.49	9.52	1.63	0.64	0.56	0.76	2.55	0.37	99.57
$\sigma$	1.58	1.02	0.37	0.09	0.13	0.16	0.10	0.07	
H-5	84.59	8.99	1.23	0.56	0.40	0.75	2.59	0.30	99.41
$\sigma$	2.45	1.62	0.57	0.15	0.09	0.17	0.16	0.10	
H-6	84.41	8.89	1.31	0.54	0.39	0.76	2.59	0.31	99.20
$\sigma$	2.17	1.42	0.40	0.11	0.08	0.17	0.11	0.08	
Average	84.2	9.19	1.43	0.59	0.44	0.72	2.53	0.34	
$\sigma$	2.0	1.30	0.39	0.12	0.10	0.18	0.14	0.09	

<sup>†</sup>Total iron reported as FeO.

0.5%) of the fluence-calibration parameter,  $J$ . It is important to note that the  $^{40}\text{Ar}/^{39}\text{Ar}$  method is a relative one and that ages of unknown samples are relative to assigned ages of fluence-monitor minerals. The age of MNGaTek reported above is relative to the age of sanidine (27.92 Ma) from the Taylor Creek Rhyolite of New Mexico (Dalrymple and Duffield, 1988), which was used as a fluence-monitor mineral. The age of 27.92 Ma for Taylor Creek Rhyolite is relative to an age of 513.9 Ma for MMhb-1 hornblende (Lanphere et al., 1990). The age of MNGaTek relative to an age of 520.4 Ma (mean of eighteen geochronology laboratories worldwide, Samson and Alexander, 1987) for the MMhb-1 hornblende standard is  $35.01 \pm 0.10$  Ma.

The  $^{40}\text{Ar}/^{39}\text{Ar}$  age of MNGaTek reported herein (34.52 Ma, relative to 513.9 Ma for MMhb-1 hornblende or 35.01 Ma, relative to 520.4 Ma for MMhb-1 hornblende) is coeval with K-Ar, fission-track, and  $^{40}\text{Ar}/^{39}\text{Ar}$  ages for North American tektites as reported by Zähringer (1963), Bottomley et al. (1979), Storz and Wagner (1971), and Obradovich et al. (1989).

#### 4. DISCUSSION

The geographic location,  $^{40}\text{Ar}/^{39}\text{Ar}$  age, and major element, trace element, and strontium and neodymium isotopic composition of MNGaTek support its identification as a North American tektite. However, its characterization as a Muong Nong-type tektite is somewhat more problematical.

A compilation of neodymium and strontium isotope analyses of North American tektites from the literature (Fig. 7, inset) illustrates that there is little variability in  $\epsilon_{\text{Nd}}$  ( $-6$  to  $-7$ ) but considerable variability in the  $\epsilon_{\text{Sr}}$  values ( $\epsilon_{\text{Sr}} = 108$ – $129$ ). Shaw and Wasserburg (1982) and Blum et al. (1992) explained similar observations made on other tektites (especially Australasian) as being due to fractionation of Rb from Sr by surficial processes. The MNGaTek specimen has an  $\epsilon_{\text{Sr}}$  value of 119, which is intermediate between the two georgiaites. Although we are dealing with small samples of subgroups within the North American tektites, it appears that the MNGaTek specimen has a very close affinity to the georgia-

ites with respect to its strontium isotopic composition. None of the North American tektites (including MNGaTek) have  $\epsilon_{\text{Sr}}$  or  $\epsilon_{\text{Nd}}$  values within the range for the DSDP Site 612 tektites (Stecher et al., 1989) (Fig. 7), which led Stecher et al. (1989) to suggest that the two groups of tektites either formed by more than one impact or that a single impact sampled two very distinct lithologic layers in the tektite formation process. The close similarity in the  $\epsilon_{\text{Sr}}$  and  $\epsilon_{\text{Nd}}$  values of the MNGaTek specimen and the splash form North American tektites is consistent with a comparison of splash-form and Muong Nong-type indochinites which have restricted and nearly identical ranges in  $\epsilon_{\text{Sr}}$  and  $\epsilon_{\text{Nd}}$  values (Blum et al., 1992).

Muong Nong-type tektites were originally defined as blocky, layered tektites (or tektites without shape) (Lacroix, 1935). The MNGaTek specimen is the largest Georgia tektite known. The large size, blocky appearance, and layering indicate that is not merely a deeply etched fragment of a splash-form Georgia tektite. Thus, based on the original definition, the MNGaTek specimen could be called a Muong Nong-type tektite. However, Koeberl (1992) has pointed out several additional characteristics that distinguish Australasian Muong Nong-type tektites from splash-form tektites. These include: (1) higher concentration of volatile elements; (2) chemical heterogeneity on a millimeter scale; (3) larger and more abundant vesicles, that may be elongate; and (4) the presence of relict mineral grains in some specimens.

MNGaTek is definitely heterogeneous on a millimeter scale and it does contain numerous relict zircon crystals. It also contains common to abundant spherical vesicles and the maximum size is within the range observed for a group of nineteen Muong Nong-type Australasian tektites. The abundance of vesicles (0.8 vol. %) is at the lower end of the range observed for eighteen Muong Nong-type Australasian tektites ( $<0.2$ – $12.8$  vol%; avg.  $\sim 3.7$  vol%); but higher than for most splash form tektites. Although elongate vesicles are common in Muong Nong-type Australasian tektites, most, if not all, Muong Nong-type Australasian tektites contain spherical vesicles and some contain only spherical vesicles.

Koeberl (1992) found that Australasian Muong Nong-type tektites are enriched in elements such as B, F, Cl, Cu,

Table 3. Minor and trace element abundances in three Georgia tektites and the Muong Nong-type Georgia tektite (MNGaTek).

	GT-2	GT-3	GT-4	MNGaTek	Georgiaste Average	Georgiaste Standard Deviation
Na (wt%)	0.80	0.52	0.76	0.79	0.69	0.12
K (wt%)	1.91	1.71	1.89	1.77	1.84	0.09
Sc	6.42	8.44	5.91	4.85	6.92	1.09
Cr	25.9	20.5	24.8	19.3	23.7	2.3
Fe (wt%)	1.48	1.79	1.41	1.42	1.56	0.17
Co	8.37	6.14	7.77	4.93	7.43	0.94
Ni	16	14	23	14	18	4
Zn	13	13	13	14	13	0
Ga	15.3	2.5	6.2	8.9	8.0	5.4
As	0.27	0.26	0.06	0.27	0.20	0.10
Se	0.07	0.09	0.06	0.08	0.07	0.01
Br	0.18	0.11	0.21	0.11	0.17	0.04
Rb	78.2	68.2	72.5	72.9	73.0	4.1
Sr	200	170	150	128	173	21
Zr	188	225	190	160	201	17
Ag	0.05	0.03	0.03	0.03	0.04	0.01
Sb	0.07	0.032	0.10	0.088	0.067	0.028
Cs	1.58	1.23	1.41	1.41	1.41	0.14
Ba	400	361	370	456	377	17
La	23.1	24.3	17.8	15.9	21.7	2.8
Ce	38.9	47.7	36.9	37.1	41.2	4.7
Nd	19.7	24.7	20.4	17.9	21.6	2.2
Sm	4.13	4.77	3.95	3.31	4.28	0.35
Eu	0.89	1.06	0.85	0.79	0.93	0.09
Gd	4.1	4.5	3.56	3.28	4.05	0.39
Tb	0.58	0.73	0.57	0.47	0.63	0.07
Dy	3.3	4.4	3.1	2.9	3.60	0.57
Tm	0.26	0.34	0.25	0.23	0.28	0.04
Yb	1.81	2.15	1.71	1.54	1.89	0.19
Lu	0.24	0.29	0.24	0.21	0.26	0.02
Hf	3.45	4.59	3.59	3.54	3.88	0.51
Ta	0.62	0.74	0.56	0.51	0.64	0.07
W	0.11	0.18	0.19	0.13	0.16	0.04
Ir (ppb)	<0.3	<0.2	0.09	<1	0.03	0.04
Au (ppb)	1.5	49	1.1	0.8	1.3	0.2
Hg	0.01	0.02	0.01	<0.08	0.01	0.00
Th	5.02	5.87	4.74	4.89	5.21	0.48
U	2.17	0.79	2.14	1.29	1.70	0.64
K/U	3687	6582	3551	6214	4078	
Zr/Hf	54.49	49.02	52.92	45.20	51.85	
Hf/Ta	5.56	6.20	6.41	6.94	6.06	
La/Th	4.60	4.14	3.76	3.25	4.17	
Th/U	2.31	7.43	2.21	3.79	3.06	
La <sub>N</sub> /Yb <sub>N</sub>	8.62	7.64	7.03	6.98	7.77	
Eu/Eu*	0.661	0.699	0.693	0.733	0.685	

All data in ppm except as noted. Standard deviations are in the same units as the data.

Zn, Ga, As, Br, Pb, Se, and Sb by factors of 1.5–25. We did not obtain data for B, F, Cl, Cu, or Pb in MNGaTek, but it is clear that Zn, Ga, As, Se, and Br, are not highly enriched in the MNGaTek specimen compared with splash-form Georgia tektites (Table 3).

Thus, the MNGaTek specimen appears to meet all but possibly one of the criteria for identification as a Muong Nong-type tektite. It does, however, have some characteristics that distinguish it from most, if not all, Australasian Muong Nong-type tektites. Not only is it not as enriched in volatile elements as Australasian Muong Nong-type tektites, but it also has a lower water content than would be expected for Muong Nong-type tektites. In addition, many of the zircons recovered from MNGaTek have partly or completely broken down

to baddeleyite plus SiO<sub>2</sub> glass. Zircons are one of the most abundant relict mineral grains recovered from Australasian Muong Nong-type tektites, but very few of them show any evidence of breakdown to baddeleyite plus SiO<sub>2</sub> glass.

The lack of any significant volatile element enrichment, plus the fact that many of the relict zircons have partly or completely decomposed to baddeleyite, indicates that the MNGaTek specimen was heated more intensely than most previously studied Australasian Muong Nong-type tektites. Thus, this specimen is in some respects a transitional form between a typical Muong Nong-type tektite and a splash-form tektite. Izokh and An (1983) describe some Vietnam tektites which they refer to as intermediate types; however, these tektites are splash-form tektites with “lam-

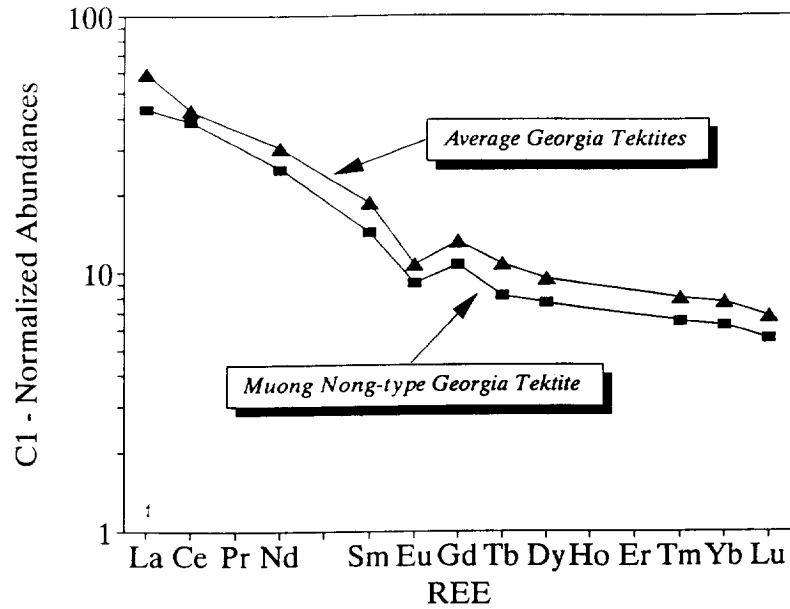


FIG. 6. REE abundances for MNGaTek and average Georgia tektite normalized to CI chondritic abundances. Normalization factors from Taylor and McLennan (1985).

ination and vesiculation similar to that of the Muong Nong specimens.”

In principle, one can calculate the  $Fe^{3+}/Fe^{2+}$  ratio from the Curie constant and the total Fe analysis, if there are no particulates in the glass. However, the magnetically determined ferric/ferrous ratios of MNGaTek (0–0.63) are highly variable and often higher than the values found by Mössbauer spectroscopy. We speculate that the variable and generally higher  $Fe^{3+}/Fe^{2+}$  ratios may be due to a small amount of superparamagnetism resulting from submicroscopic particles in portions of the specimen, which would not affect the  $Fe^{3+}/Fe^{2+}$  ratios determined by Mössbauer spectroscopy. Thus, the combination of the magnetic and Mössbauer spectroscopic

measurements suggests the presence of Fe-containing particulate matter in the MNGaTek glass which could be the result of either lower formation temperatures, as is generally accepted, or slower cooling than experienced by splash-form tektites.

It has been suggested that Muong Nong-type tektites were heated less intensely than the splash-form tektites and that they, therefore, have not been transported far from the source crater (Barnes, 1990; Koeberl, 1992). It may, therefore, be significant that the MNGaTek specimen was found in the extreme northeastern part of the georgiaite sub-strewn field. Previous workers suggested that the source crater for the North American strewn field is near Deep Sea Drilling Project

Table 4. Sm-Nd and Rb-Sr isotopic data for MNGaTek, North American tektites, and Barbados tektites.

	Nd (ppm)	Sm/Nd	$\epsilon_{Nd}$	$^{143}Nd/^{144}Nd$ ( $\pm 2\sigma$ )	Sr (ppm)	Rb/Sr	$\epsilon_{Sr}$	$^{87}Sr/^{86}Sr$ ( $\pm 2\sigma$ )
MNGaTek	13.93	0.1945	-6.5	0.512304 ( $\pm 26$ )	148.4	0.492	119.3	0.712904 ( $\pm 29$ )
North American mean	29.3 (n = 5)	0.1965 (n = 5)	-6.5 (n = 5)		143.4 (n = 6)	0.431 (n = 4)	121.8 (n = 6)	
Georgiaite mean	22.6	0.1952	-6.6		142.7 (n = 2)		118.0	
Bediasite mean	31.5 (n = 3)	0.1975 (n = 3)	-6.5 (n = 3)		143.6 (n = 3)	0.455 (n = 3)	118.0 (n = 3)	
Barbados tektite mean	29.3 (n = 3)	0.1965 (n = 3)	-6.4 (n = 3)		145.3 (n = 3)	0.406 (n = 3)	111.6 (n = 3)	

MNGaTek data from this study: Sr and Nd isotope ratios normalized to  $^{86}Sr/^{86}Sr = 0.1194$  and  $^{146}Nd/^{144}Nd = 0.7290$ , respectively; NBS-987 and Caltech nNd $\beta$  yielded  $^{87}Sr/^{86}Sr = 0.710274 \pm 16$  ( $2\sigma$ , n = 10) and  $^{143}Nd/^{144}Nd = 0.511926 \pm 32$  ( $2\sigma$ , n = 6) respectively; total procedural blanks were < 70 pg Sr and < 20 pg Nd; concentrations are  $\pm 0.2\%$  for Sr, Nd, and Sm, and  $\pm 0.5\%$  for Rb; and  $\epsilon$  notation indicates deviation in parts in  $10^4$  of the  $^{143}Nd/^{144}Nd$  and  $^{87}Sr/^{86}Sr$  ratio from the chondritic uniform reservoir and unfractionated mantle reservoir, respectively (see Blum et al., 1995, for more details). North American tektite mean and georgiaite data from Shaw and Wasserburg (1982), bediasite data from Stecher et al. (1989), and Barbados tektite data from Ngo et al. (1985).

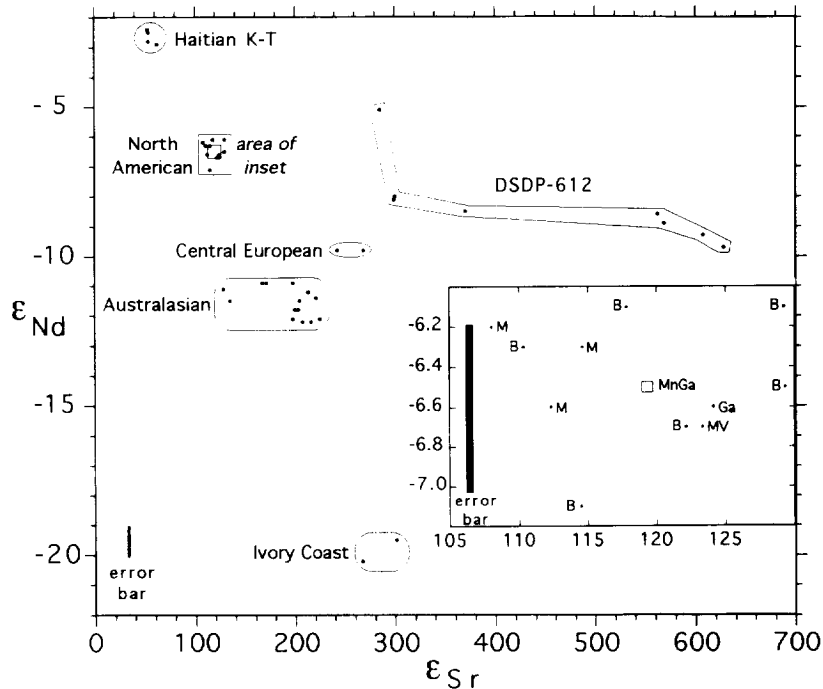


FIG. 7.  $\epsilon_{Nd}$  vs.  $\epsilon_{Sr}$  for MNGaTek (this study) and tectites from the other known strewn fields. Bediasite data from Shaw and Wasserburg (1982) and Stecher et al. (1989); georgiaite data from Shaw and Wasserburg (1982); Martha's Vineyard tectite data from Shaw and Wasserburg (1982); Barbados microtektite (or tectite fragment) data from Ngo et al. (1985); Haitian K/T boundary glass data from Premo and Izett (1992); Central European tectite (moldavite) data from Shaw and Wasserburg (1982); DSDP Site 612 tectite fragment data from Stecher et al. (1989); Australasian tectite data from Shaw and Wasserburg (1982) and Blum et al. (1992); and Ivory Coast tectite data from Shaw and Wasserburg (1982). Abbreviations used in insert: B = bediasites; Ga = georgiaite; M = microtektites or tectite fragments from Barbados; MNGa = Muong Nong-type tectite or MNGaTek (this study); MV = Martha's Vineyard tectite.

(DSDP) Site 612 on the continental slope off New Jersey where an 8 cm thick layer of tectite glass and impact ejecta was found (e.g., Thein, 1987; Koeberl and Glass, 1988; Glass, 1989). Poag et al. (1994) suggested that a large (~85 km diameter) impact crater of late Eocene age lies buried underneath the mouth of Chesapeake Bay, and they speculate that this "crater" (which has yet to be confirmed as being of impact origin) may be the source of the North American tectite strewn field. The suggestion that this structure is an impact crater is supported by evidence of shock metamorphism in the overlying sediments (Koeberl et al., 1995). The occurrence of MNGaTek in the northeastern part of the Georgia strewn

field is consistent with a source crater in the general area of the Chesapeake Bay "crater."

## 5. CONCLUSIONS

We have shown that a large (130 g), layered glass object found south of Riddleville, Georgia, in July 1993, is a North American tectite and that it is probably a Muong Nong-type tectite. It is the largest Georgia tectite known and the only North American tectite found to contain numerous relict zircons, as well as baddeleyite (formed by breakdown of zircon). It may be significant that the MNGaTek specimen was

Table 5. Magnetic properties of seven fragments of MNGaTek.

Sample	Mass (mg)	Curie Constant ( $\times 10^3$ emu/g)	Temperature Independent Magnetic Susceptibility $\chi_i$ ( $\times 10^6$ emu/g)	Total Magnetic Susceptibility $\chi_0$ ( $10^6$ emu/g)	
				at 300°K	at 77°K
H-1	8.5	0.710	-0.496	2.1	8.66
H-2	54.67	0.629	0.0723	2.35	8.06
H-3	55.92	0.652	-0.060	2.16	8.21
H-4	87.22	0.638	-0.055	2.18	8.16
H-M	15.27	0.624	-0.114	2.01	7.85
H-5	81.95	0.593	-0.106	1.90	7.31
H-6	78.43	0.625	-0.096	2.03	7.82

Table 6. <sup>57</sup>Mössbauer parameters and Fe<sup>3+</sup>/Fe<sup>2+</sup> ratio of MNGaTek and georgiaite-2339.

Mössbauer Absorber	Spectral Components	$\Delta E_Q$ mm s <sup>-1</sup>	$\delta^1$ mm s <sup>-1</sup>	Integrated Intensity (%)	Fe <sup>3+</sup> /Fe <sup>2+</sup> Ratio <sup>2</sup>
MNGaTek - 0.75	a	2.86(3)	1.15(2)	5(1)	0.07 ± 0.01
	b	2.32(2)	1.05(1)	38(5)	
	c	1.82(1)	1.00(1)	31(4)	
	d	1.31(1)	0.97(1)	19(2)	
	e	1.76(2)	0.36(2)	7(1)	
MNGaTek - 0.38	a	2.59(2)	1.09(4)	29(1)	0.16 ± 0.01
	b	2.00(1)	1.04(1)	32(1)	
	c	1.56(1)	1.00(1)	22(1)	
	d	1.14(2)	1.02(1)	3(1)	
	e	1.67(2)	0.45(1)	14(1)	
Georgiaite - 2339 <sup>3</sup>	a	2.70(1)	1.12(1)	12(1)	0.05 ± 0.01
	b	2.22(1)	1.05(1)	40(1)	
	c	1.72(1)	1.00(1)	34(1)	
	d	1.21(1)	0.96(1)	9(1)	
	e	1.75(2)	0.39(1)	5(1)	

<sup>1</sup>Relative to Fe metal.

<sup>2</sup>Ratios of integrated intensity of component e to the sum of integrated intensities of components a-d.

<sup>3</sup>From Empire, Georgia.

Numbers in parentheses are standard errors in last digit of the preceding parameter value.

found in the northeastern edge of the Georgia strewn field in the direction of an 85 km diameter structure, buried beneath the mouth of Chesapeake Bay, which has been proposed as a possible source crater for the North American tektites.

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*Editorial handling*: S. R. Taylor

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