Meteoritics & Planetary Science 34, 197–208 (1999)
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Ocean Drilling Project Hole 689B spherules and upper Eocene microtektite and clinopyroxene-bearing spherule strewn fields

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(Received 1998 July 15; accepted in revised form 1998 December 1)

Abstract–Montanari *et al.* (1993) reported a positive Ir anomaly in the upper Eocene sediments from Ocean Drilling Program Hole 689B on the Maud Rise, Southern Ocean. Vonhof (1998) described microtektites and clinopyroxene-bearing (cpx) spherules associated with the Ir anomaly in Hole 689B and suggested that they belong to the North American and equatorial Pacific cpx strewn fields, respectively. We searched a suite of 27 samples taken through the spherule layer from Hole 689B, and we recovered 386 microtektites and 667 cpx spherules. We studied the petrography of the microtektites and cpx spherules and determined the major element compositions of 31 microtektites and 14 cpx spherules using energy dispersive x-ray analysis. We also determined the minor element compositions of eight microtektites using instrumental neutron activation analysis. We found that the peak abundance of cpx spherules is ~2 cm below the peak abundance of the microtektites (~128.7 m below sea floor), which suggests that the cpx spherule layer may be slightly older (~3–5 ka). The microtektites are mostly spherical and are generally transparent and colorless. They are similar to the North American microtektites in composition, the biggest differences being their generally lower Na_2O and generally higher Zr, Ba, and Ir (up to 0.3 ppb) contents. We agree with Vonhof (1998) that the Hole 689B microtektites probably belong to the North American tektite strewn field. We calculate that the number of microtektites (>125 μm)/cm^2 at Hole 689B is 52. This number is close to the concentration predicted by extrapolation of the trend of concentration *vs.* distance from the Chesapeake Bay structure, based on data from other North American microtektite-bearing sites. Thus, the North American strewn field may be at least four times larger than previously mapped. The Hole 689B cpx spherules range from translucent yellow to opaque black, but most are opaque tan to dark brown. They are generally spherical in shape and all are <125 μm in diameter. Some contain Ni-rich spinels in addition to clinopyroxene microlites. The cpx spherules are petrographically and compositionally similar to cpx spherules previously found in the northwestern Atlantic Ocean, Caribbean Sea, Gulf of Mexico, equatorial Pacific, and eastern Indian Ocean. The abundance and widespread geographic occurrence of these spherules suggest that the strewn field may be global in geographic extent. Assuming a global extent, we estimate that there may be at least 25 billion metric tons of cpx spherules in the strewn field. Based on age, size, and geographic location, we speculate that the 100 km diameter Popigai crater in northern Siberia may be the source of the cpx spherule layer.

INTRODUCTION

Two types of impact-generated spherules occur in upper Eocene marine deposits: (1) microtektites and (2) clinopyroxene-bearing spherules (microkrystites). Upper Eocene microtektites—found in the Gulf of Mexico, Caribbean Sea, northwest Atlantic off New Jersey, and Barbados—appear to be part of the North American tektite strewn field (*e.g.*, Donnelly and Chao, 1972; Sanfilippo *et al.*, 1985; Glass *et al.*, 1985, 1998; Keller *et al.*, 1987; Thein, 1987; Koeberl and Glass, 1988; Glass, 1989; McHugh *et al.*, 1996). Clinopyroxene-bearing (cpx) spherules have been found in the northwest Atlantic off New Jersey, the Caribbean Sea, Gulf of Mexico, equatorial Pacific, and eastern equatorial Indian Ocean (*e.g.*, Glass *et al.*, 1982, 1985, 1998; Keller *et al.*, 1987). North American microtektites and cpx spherules are found at the same sites in the Gulf of Mexico, Caribbean Sea, and northwestern Atlantic Ocean. At these sites, the microtektites and cpx spherules are stratigraphically closely associated. At some of these sites, the microtektites and cpx spherules appear to be in the same layer. At other sites, however, the cpx spherules are clearly in an older layer, although the two layers may overlap (Glass *et al.*, 1982, 1998). The number of upper Eocene spherule layers is not agreed upon.

Glass *et al.* (1985) proposed that there were just two layers: the North American microtektite layer and the slightly older cpx spherule layer. Keller *et al.* (1987) agreed that there was only one microtektite layer but concluded that the cpx (or crystal-bearing) spherules occurred in two separate layers. They proposed that the cpx spherules in the Indian Ocean and western equatorial Pacific were older than the cpx spherules at the other sites. Hazel (1989) reexamined the data of Glass *et al.* (1985) and Keller *et al.* (1987), using graphic correlation techniques, and concluded that there were at least six upper Eocene spherule layers. Glass (1990) argued against the multiple-layer hypothesis and again concluded that there were probably only two upper Eocene spherule layers: the North American microtektite layer and the cpx spherule layer. In this paper, we assume that the two-layer hypothesis is correct.

The cpx spherules contain Ni-rich spinels and the cpx spherule layer is associated with a positive Ir anomaly in Core RC9-58 and at DSDP Sites 69A, 94, 149, 166, 167, 216, 292, 315A, and 462 (Glass *et al.*, 1985; Keller *et al.*, 1987; Glass and Burns, 1987). An Ir anomaly was also found associated with the microtektite/cpx spherule layer at Site 612, but the peak in Ir concentration is ~15 cm above the cpx spherule layer (Keller *et al.*, 1987; Glass, 1989). To our knowledge, Ir has not been measured at the remaining cpx

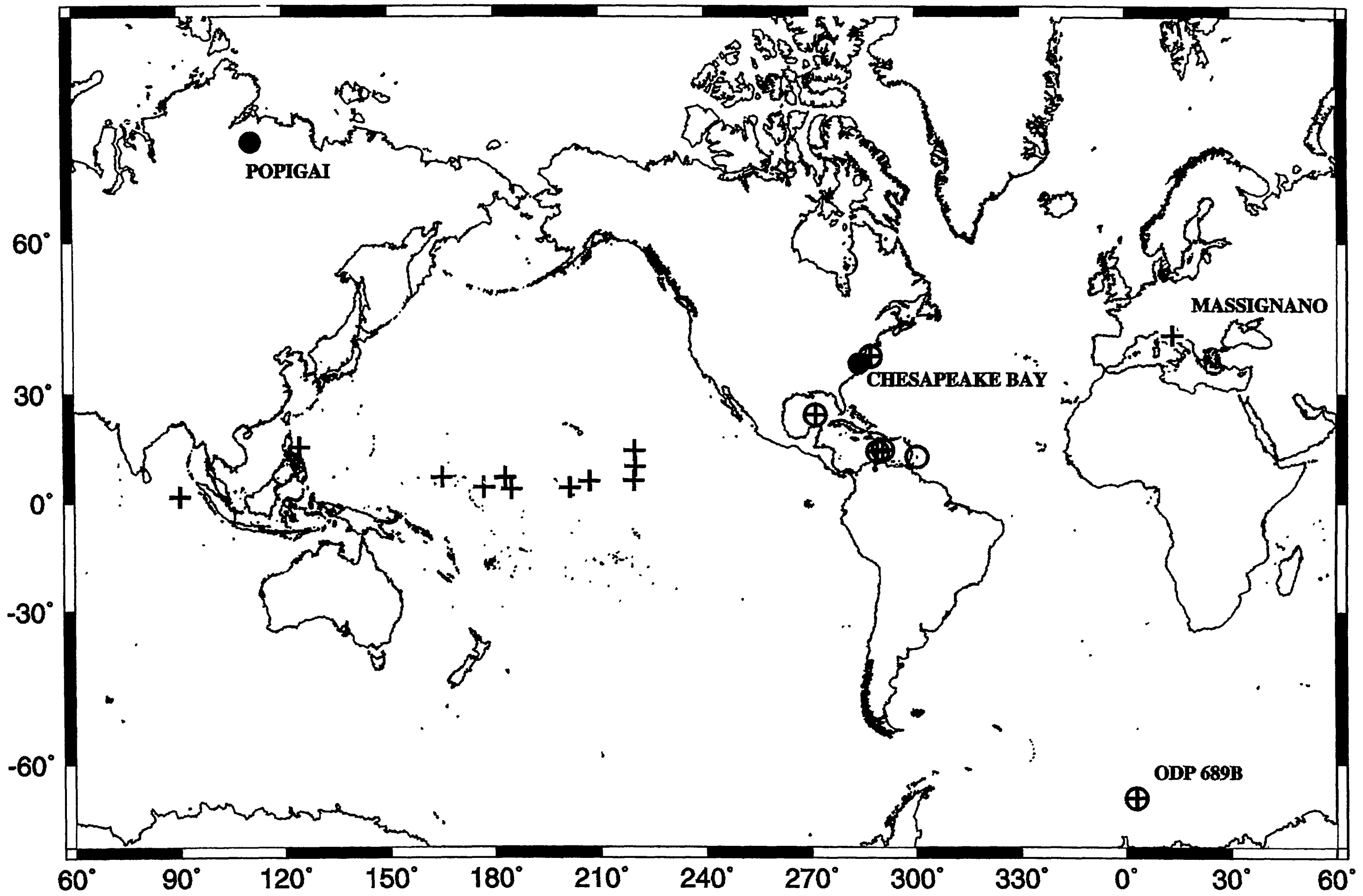

FIG. 1. World map showing location of late Eocene impact structures (solid circles), cpx spherule-bearing sites (plus signs), North American microtektite-bearing sites (open circles), and sites containing both cpx spherules and North American microtektites (open circles with a plus sign inside).

spherule-bearing sites. The North American microtektites do not contain Ni-rich spinels, and the North American microtektite layer does not appear to be associated with an Ir anomaly. On the other hand, the North American microtektite layer is associated with shocked quartz, shocked feldspar, coesite, and stishovite (Glass and Wu, 1993).

Montanari *et al.* (1993) reported the discovery of a positive Ir anomaly in upper Eocene sediments from Massignano, Italy, and in upper Eocene sediments from Ocean Drilling Project (ODP) Hole 689B on the Maud Rise in the Southern Ocean. Clymer *et al.* (1996) and Langenhorst (1996) showed that there is shocked quartz associated with the Ir anomaly at Massignano. Furthermore, Pierrard *et al.* (1998) found Ni-rich spinels associated with the Ir anomaly and the shocked quartz. In addition, Vonhof and Smit (1996) and Vonhof (1998) reported microtektites and cpx spherules associated with the Ir anomaly at Hole 689B. They suggested that the microtektites might belong to the North American strewn field.

In this paper, we present the results of a detailed study of the stratigraphic relationship between the microtektites and cpx spherules at Hole 689B. We also present major and trace element data for the microtektites and major element data for the cpx spherules. We agree with Vonhof (1998) that the microtektites at Hole 689B probably belong to the North American strewn field and we conclude that the slightly older cpx spherule strewn field is probably global in geographic extent. We discuss the possibility that the cpx spherules may have come from the 100 km diameter Popigai structure in Northern Siberia. (Poag *et al.*, 1998, suggests that the Popigai structure may only be 85 km in diameter).

METHODS

Samples were obtained at 2 cm intervals, through the spherule layer at ODP Hole 689B and at 5 to 10 cm intervals above and below the layer. The samples were disaggregated in water using ultrasonics and sieved into 63–125 and >125 μm size fractions. Spherules and other impact ejecta were then searched for in the >63 μm size fractions using a binocular microscope with up to 50× magnification. X-ray diffraction patterns were obtained for two of the cpx spherules using a Gandolfi camera. Selected spherules were mounted on 1" diameter glass discs, ground down to expose an interior surface, and then polished for study using a petrographic microscope and a scanning electron microscope (SEM) (Cambridge S90B). Major oxide compositions were determined using energy dispersive x-ray analysis (EDS) (Princeton Gamma Tech System 4) in combination with the SEM (Glass, 1989). A glass with tektite composition, prepared by Corning, and whose composition was determined by the U. S. Geological Survey (using wet chemistry) was used as a standard. Fragments of the standard were mounted on each disc along with the tektite fragments and analyzed at the same time as the tektite fragments. All the spectra were corrected for background, atomic number effects, absorption, and fluorescence using a computer algorithm provided by Princeton Gamma Tech. Each analysis is the average of five spot analyses. The standard was analyzed twice before and after each tektite fragment. The standard and tektite analyses were normalized to 100%. Correction factors were determined for each element by dividing the known weight percent of each element in the standard by the weight percent obtained by the above analysis. The normalized elemental compositions of the tektite fragments were then standardized by multiplying the weight percent of each element by the correction factor. Trace element contents of eight microtektites from Hole 689B were determined using instrumental neutron activation analysis (INAA) (see Koeberl, 1992, and Koeberl *et al.*, 1997, for details). The major element compositions of these eight microtektites were determined after completion of the INAA as discussed above.

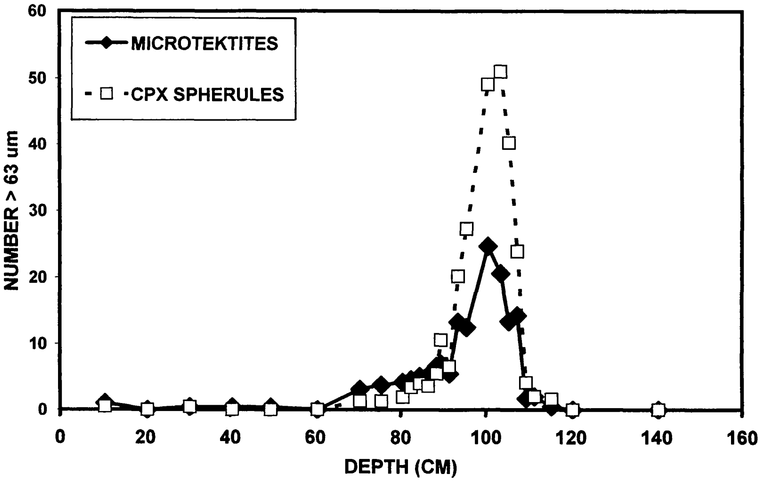

FIG. 2. Vertical distribution of number of microtektites and cpx spherules per gram of sediment in Hole 689B, Core 14H, Section 6.

HOLE 689B SPHERULES

Vertical Distribution

Hole 689B (latitude 64.52° S; longitude 3.10° E) is on the Maud Rise, Southern Ocean (Fig. 1). We searched for spherules in 27 samples that bracket the spherule layer. A total of 386 microtektites and 667 cpx spherules were recovered. Both the microtektites and cpx spherules were concentrated in an ~20 cm-thick layer between 90 and 110 cm in Core 14H, Section 6 (128.6–128.8 m below the sea floor). Thus, the spherule layer at this site correlates with the Ir anomaly centered at 128.7 m below the sea floor, which was reported by Montanari *et al.* (1993).

The spherule layer is not associated with any obvious change in sediment lithology or with any change in abundance of the microfossils (*e.g.*, planktic foraminifera, benthic foraminifera, Radiolaria, icthyoliths). Detailed study indicates that the peak abundance of cpx spherules is ~2 cm below the peak abundance of microtektites (Fig. 2). Furthermore, the microtektites are more abundant than the cpx spherules in samples more than 10 cm above the peak abundance and less abundant than cpx spherules below the peak abundance. This suggests that the cpx spherule layer may be slightly older. The estimated sedimentation rate in this section of the core is between 4 and 6 m/Ma (Barker *et al.*, 1988). Using this range in sedimentation rate, we calculate that the cpx spherule layer may be about 3000–5000 years older than the microtektite layer. This is at the low end of the estimated age difference between the North American microtektite and cpx spherule layers at other sites (Glass *et al.*, 1998).

Description and Composition

Microtektites–The Site 689B microtektites are transparent and colorless to pale brown in color. They are mostly splash forms (Fig. 3) with spherical shapes being the most abundant (~72%). Many of the spherical ones are oblate. Teardrop, disc, oval, and dumbbell shapes (in decreasing abundance) make up ~15%, and fragments make up ~13% of the microtektites. The largest microtektite is a very oblate spherule with a diameter of 920 μm; ~13% are >125 μm. Most have shiny smooth surfaces, but some are pitted (Fig. 3). Several contain obvious vesicles and a few exhibit flow structure. They are devoid of crystalline material. Lechatelierite particles were not observed; but during EDS analysis, one microtektite was found to contain a silica-rich (~99 wt% SiO_2) area that could be lechatelierite. Most of the microtektites have SiO_2 contents >74 wt% (Table 1; Fig. 4). The MgO, CaO, and Na_2O contents are low, usually <1 wt%. Some microtektites contained <0.1 wt% Na_2O. The Al_2O_3 and FeO contents vary widely; with one exception, the Al_2O_3 content varies between 8 and 21 wt% and the FeO content between 0.2 and 7 wt%. The FeO contents generally vary inversely with the Al_2O_3 content, the exception being when the SiO_2 content is high (>80 wt%), in which case both the Al_2O_3 and FeO contents are low. The microtektites with higher FeO contents are generally pale brown in color, whereas those with lower FeO contents are generally colorless. One microtektite has low SiO_2 (~47 wt%) and high Al_2O_3 (~36 wt%) (Table 1).

The trace element contents of eight of the Site 689B microtektites were determined using INAA (Table 2). Like some of the major elements, the concentrations of some of the trace elements vary by up to an order of magnitude or more: Ni ranges between 10 and 153 ppm, Zn between 4 and 64 ppm, Ga between 0.8 and 10.6 ppm, As between 0.2 and 9.8 ppm, Sb between 0.03 and 4.5 ppm. The chondrite-normalized rare earth element (REE) patterns (Fig. 5) are similar to post-Archean average sediment. Ocean Drilling Project Hole 689B microtektites have high Ir contents (up to 0.3 ppb) and some have high Ni contents (up to 153 ppm), but the Ir and Ni contents are not positively correlated. In fact there is no correlation between any of the siderophile elements (Table 2).

Clinopyroxene-Bearing Spherules–The Hole 689B cpx spherules range from translucent to opaque. The translucent spherules are generally yellow in color with an opalescent appearance and are birefringent under crossed polarizers. The opaque cpx spherules range from white to black in color, but most are some shade of tan to dark brown. Most of the cpx spherules are spherical, but ~40% are fragments. A few appear to be agglutinates with two or more spherules fused together (Fig. 3d). All of the cpx spherules are smaller than 125 μm. The surfaces range from shiny to dull and some have obvious crystalline textures (Fig. 3). X-ray diffraction patterns made of two of the cpx spherules indicate that the most abundant crystalline phase is clinopyroxene (probably diopside). Scanning electron microscope and EDS studies of polished interior surfaces indicate the presence of Ni-rich spinels in addition to the clinopyroxene.

In general, the Hole 689B cpx spherules have lower SiO_2, Al_2O_3, and TiO_2 and higher CaO, MgO, Na_2O, Cr_2O_3, and NiO contents than the Hole 689B microtektites (Table 1; Fig. 6); one microtektite, however, has a composition more similar to the cpx spherules than to the other microtektites (Fig. 6). The Hole 689B cpx spherules have major oxide compositions indistinguishable from cpx spherules at other sites (Vonhof, 1998).

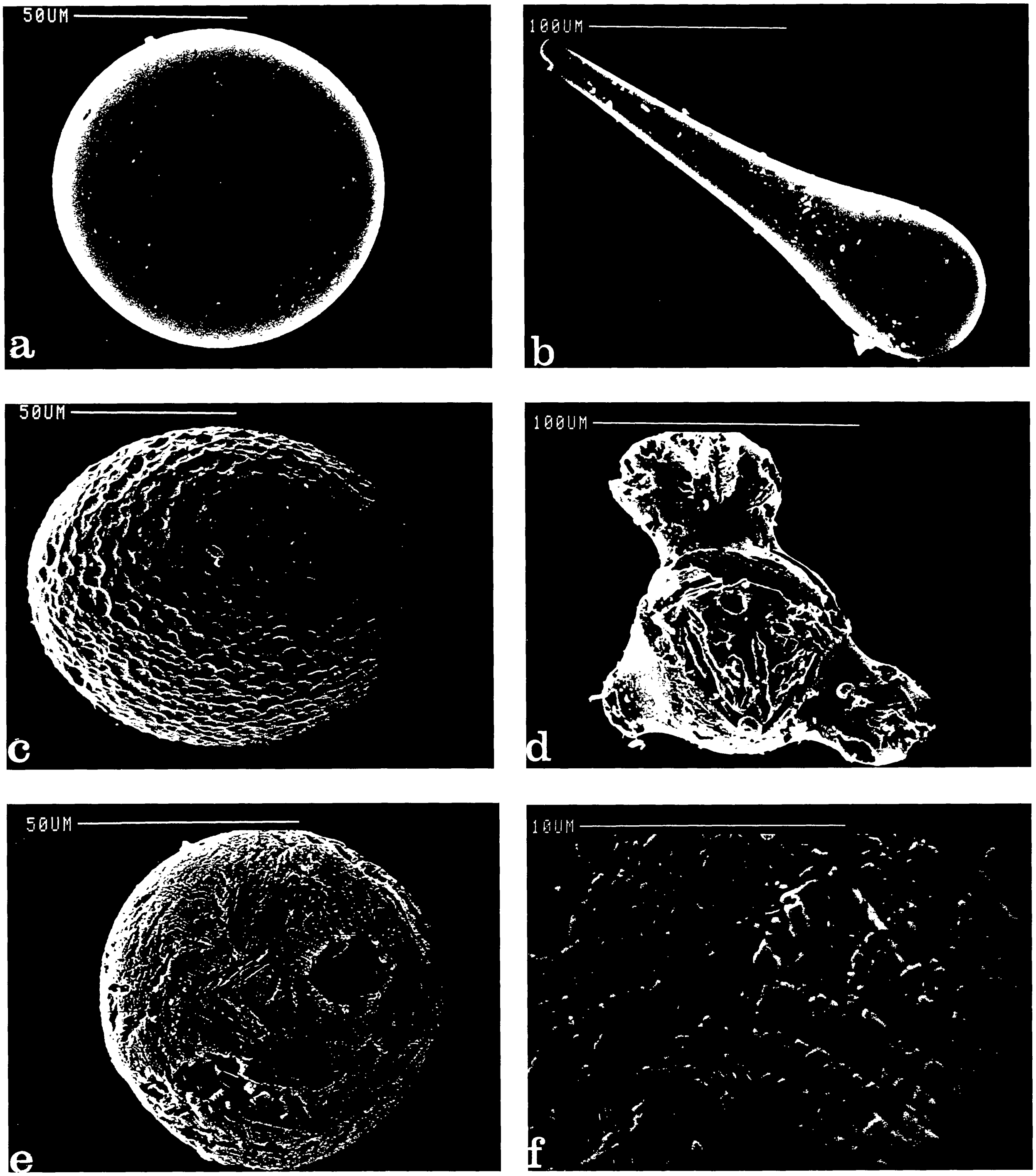

FIG. 3. Scanning electron microscope photomicrographs of Hole 689B microtektites and cpx spherules. (a) Transparent colorless spherical microtektite. (b) Transparent colorless teardrop microtektite. (c) Transparent colorless pitted microtektite with oblate spherical shape. (d) Irregular cpx grain composed of four fused spherules. Note crystalline texture due to solution of more soluble mineral phases (olivine?). (e) Clinopyroxene-bearing spherule with crystalline texture. (f) Enlargement of crystalline texture on the surface of the spherule in (e). The crystalline phase (probably clinopyroxene) is above the surface of the more soluble glass matrix.

The Ni contents of the Hole 689B cpx spherules exhibit a weak positive correlation with the FeO, MgO, and Cr_2O_3 contents (Table 1; Fig. 7) suggesting meteoritic contamination. A similar relationship was observed in cpx spherules from other sites (Glass *et al.*, 1985). In an earlier unpublished study, Ganapathy (pers. comm., 1983) found roughly chondritic ratios for various siderophile elements in a bulk sample of cpx spherules from Core RC9-58 taken in the Caribbean Sea (Table 3).

STREWN FIELDS AND SOURCE CRATERS

North American

The source crater for the North American microtektite strewn field is believed to be the Chesapeake Bay structure (Poag *et al.*, 1994; Koeberl *et al.*, 1996). At DSDP Site 612 and ODP Site 940, the ejecta layer containing North American microtektites and fragments of tektites is approximately 8 and 5 cm thick, respectively.

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TABLE 1. Major oxide compositions (wt%) of Hole 689B microtektites and cpx spherules.

Sample	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	Cr_2O_3	NiO	Total
Microtektites											
740-16	75.2	14.7	4.78	0.86	0.50	0.20	2.65	0.57	–	–	99.46
740-17	78.4	17.1	1.25	0.76	0.13	0.01	1.18	0.63	–	–	99.46
740-25	77.8	10.8	7.11	0.62	0.62	0.00	1.98	0.41	–	–	99.34
740-26	76.3	15.0	3.54	0.89	0.45	0.06	2.51	0.62	–	–	99.37
740-27	78.9	17.8	0.24	0.49	0.07	0.00	1.26	0.57	–	–	99.33
740-29	77.4	17.4	1.35	0.76	0.14	0.02	1.56	0.64	–	–	99.27
740-30	83.5	12.8	0.34	0.41	0.12	0.02	1.67	0.41	–	–	99.27
740-32	77.3	12.6	4.73	0.74	0.50	0.08	2.83	0.55	–	–	99.33
735-10	79.4	13.7	3.52	0.60	0.31	0.04	1.33	0.52	–	–	99.42
735-12	75.6	11.6	7.09	0.85	1.07	0.29	2.60	0.39	–	–	99.49
735-13	75.4	12.5	6.97	0.76	0.87	0.16	2.43	0.34	–	–	99.43
735-14	78.8	12.9	2.92	0.91	0.69	0.08	2.53	0.54	–	–	99.37
735-15	74.5	21.7	0.67	0.77	0.08	0.00	0.94	0.71	–	–	99.40
741-1	46.7	35.6	1.32	4.43	9.18	0.09	0.18	1.80	–	–	99.31
741-2	83.3	13.6	0.24	0.39	0.11	0.00	1.19	0.49	–	–	99.24
741-3	79.1	15.8	0.90	0.65	0.17	0.01	1.96	0.66	–	–	99.29
741-4	75.6	12.9	5.64	0.60	0.32	0.44	3.26	0.63	–	–	99.33
741-5	76.5	13.9	4.69	0.72	0.39	0.14	2.46	0.54	–	–	99.38
741-7	78.7	12.3	4.39	0.50	0.38	0.02	2.63	0.50	–	–	99.41
741-8	76.5	18.8	0.78	0.64	0.14	0.00	1.88	0.66	–	–	99.38
741-9	74.4	17.3	4.28	0.85	0.38	0.04	1.40	0.74	–	–	99.40
741-10	80.0	16.1	0.45	0.52	0.13	0.00	1.65	0.56	–	–	99.32
741-11	66.9	12.4	7.86	7.05	4.06	0.21	0.62	0.41	–	–	99.43
741-12	78.0	14.1	4.09	0.73	0.29	0.02	1.56	0.62	–	–	99.38
766-1	81.5	12.8	0.58	0.47	0.08	0.03	3.39	0.54	–	–	99.39
765-2	78.8	14.8	0.92	0.44	0.14	0.05	3.34	0.82	–	–	99.31
765-3	82.8	13.7	0.25	0.42	0.08	0.02	1.78	0.45	–	–	99.50
765-4	89.5	8.0	0.21	0.40	0.17	0.02	0.82	0.28	–	–	99.40
766-5	77.8	10.3	6.82	0.44	0.46	0.52	2.68	0.37	–	–	99.39
766-6	83.0	12.9	0.34	0.38	0.08	0.00	2.16	0.49	–	–	99.35
766-7	77.6	13.6	3.60	0.68	0.26	0.22	2.84	0.58	–	–	99.38
766-8	81.6	13.5	0.96	0.52	0.13	0.02	2.22	0.46	–	–	99.41
Cpx Spherules											
735-16	66.1	9.94	8.37	3.17	7.36	1.11	2.86	0.45	0.05	0.01	99.38
735-17	61.7	6.19	8.01	8.25	11.65	0.90	1.96	0.31	0.19	0.19	99.31
735-18	61.2	7.04	3.49	8.58	16.10	0.41	2.30	0.23	0.06	0.05	99.41
735-19	59.8	6.01	5.96	10.45	14.26	0.57	1.87	0.22	0.08	0.20	99.38
735-20	62.1	6.19	4.17	8.95	15.65	0.43	1.64	0.21	0.05	0.02	99.43
735-21	66.9	7.37	7.62	4.93	8.76	0.79	2.59	0.24	0.08	0.10	99.38
740-2	64.3	7.32	4.31	7.83	12.40	0.78	2.17	0.26	0.00	0.08	99.45
740-6	61.4	5.98	5.62	9.12	13.10	1.05	2.60	0.28	0.15	0.18	99.48
740-12	61.8	6.59	4.95	9.74	13.50	0.60	1.75	0.24	0.20	0.16	99.53
740-14	53.9	5.70	9.86	8.72	18.00	1.13	1.35	0.31	0.14	0.11	99.22
740-15	65.5	5.38	8.75	8.43	6.91	1.38	2.11	0.24	0.21	0.54	99.45
740-21	62.5	6.52	15.80	5.71	4.25	1.28	2.42	0.23	0.25	0.42	99.38
740-22	62.0	7.48	8.49	8.76	9.05	0.80	2.26	0.27	0.09	0.17	99.37
740-24	60.6	5.43	8.81	7.76	13.40	0.86	1.90	0.27	0.16	0.18	99.37

Note: Samples 765-2, 765-3, 765-4, 766-5, 766-6, 766-7, and 766-8 are samples T2, T3, T4, T5, T6, T7, and T8, respectively, in Table 2.

In the Gulf of Mexico, Caribbean Sea, and Barbados, the concentration of North American microtektites ranges between roughly 900 and 8000 (>125 μm)/cm^2 (Glass *et al.*, 1997). The lowest concentration is in Barbados, which (other than Hole 689B) is farthest from the Chesapeake Bay structure. The high concentration at these sites suggests that they are not near the edge of the strewn field. In the Australasian strewn field, sites with comparable concentrations of microtektites are more than 5000 km from the edge of the strewn field assuming that the source crater is in Indochina (Glass and Pizzuto, 1994; Glass *et al.*, 1997); and the Australasian event appears to have been smaller than the North American event (see below). Based on the data shown in Fig. 2, we estimate that the number of microtektites (>125 μm)/cm^2 at Hole 689B is ~52 (see Glass and Pizzuto, 1994, for method of calculating microtektite concentrations).

Although the source crater of the Australasian tektite strewn field is not known, most authors believe it is somewhere in Indochina. Glass and Pizzuto (1994) found a well-defined linear relationship between the log of Australasian microtektite concentration *vs.* the log distance from a site in Cambodia (Fig. 8). A similar linear relationship (although not as well defined) was found for the Ivory Coast (IVC) microtektite concentration *vs.*

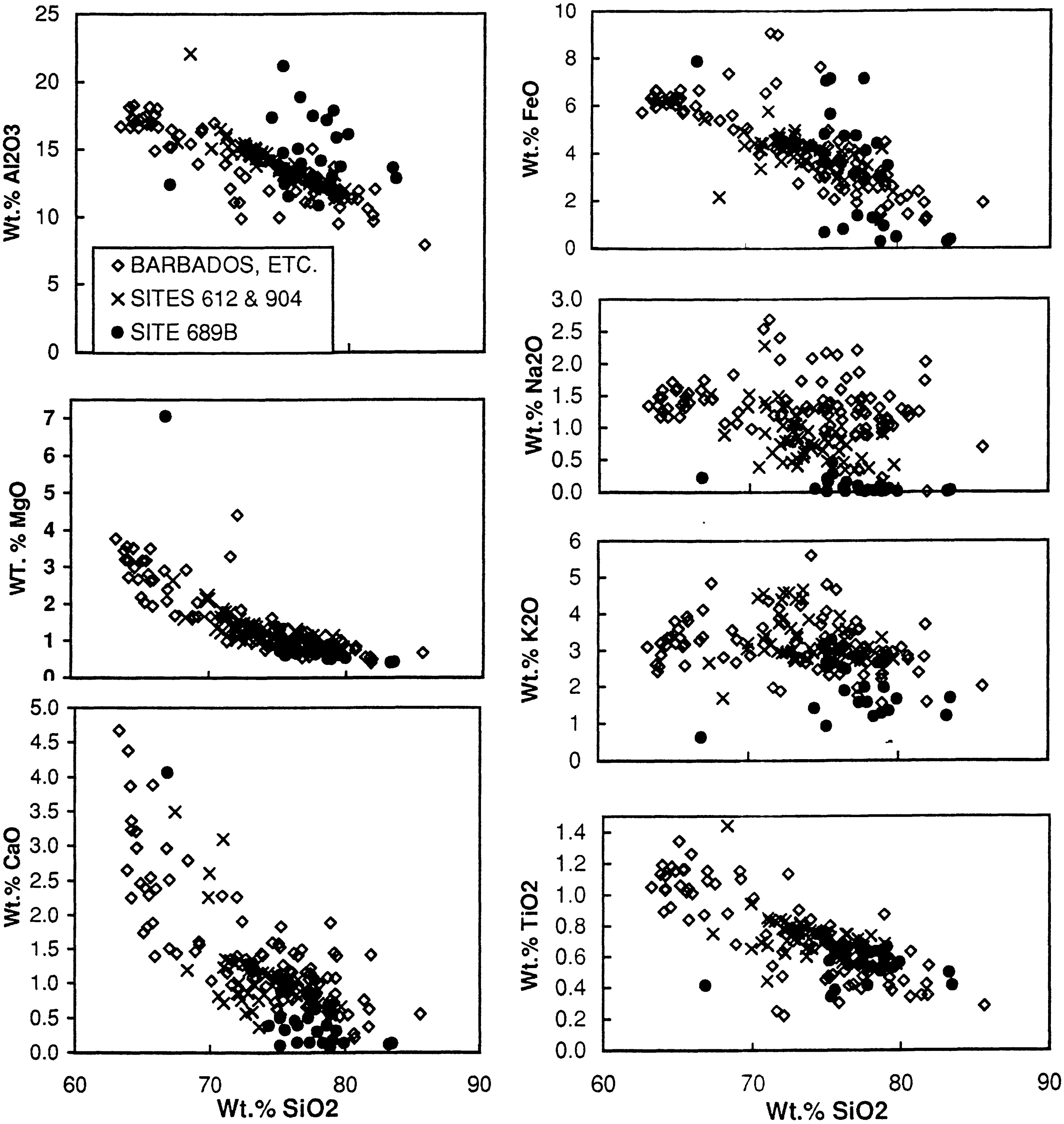

FIG. 4. Major element oxide plots for Hole 689B microtektites and North American microtektites from other sites. "Barbados, *etc.*" refers to Core RC9-58, DSDP sites 94 and 149, as well as to Barbados.

distance from the 10.5 km diameter Bosumtwi crater (Fig. 8). The slope of the trend line is similar, but the IVC microtektites have a lower concentration for a given distance from the proposed source region. This is to be expected because the IVC strewn field, and therefore (presumably) the source crater, is much smaller. The North American microtektite data plot slightly above the Australasian data, which suggests that the North American event was larger than the Australasian event. The trend line for the North American strewn field is based on only three sites: Barbados, Core RC9-58, and DSDP Site 149.

The concentrations of microtektites at sites 612 and 904 are not known (there are too many to reasonably count, and the average size is much larger than at the more distal sites), but we estimated the number based on the thickness of the layers and the relative abundance of tektite glass in each layer. We estimate a concentration of ~550 000 (>125 μm)/cm^2 for Site 612. This value falls close to the extrapolated trend line for the North American microtektite data (Fig. 8). The estimated value for Site 904 (*i.e.*, ~240 000/cm^2) falls below the extrapolated trend line. The sites 612 and 904 data points are not shown in Fig. 8 because to do so would

TABLE 2. Bulk composition of ODP 689B microtektites (as determined by INAA), average georgiaite, average bediasite, and average DSDP Site 612 tektites.*

Sample†	T1	T2	T3	T4	T5	T6	T7	T8	Average (T1–T8) N=8	Std. Dev.	Average Georgiaite	Average Bediasite	Average DSDP-612
Weight (mg)	0.0178	0.0402	0.369	0.2248	0.5027	0.1222	0.2297	0.3293					
Depth (cm)	70–71	88–89	89–90	91–92	93–94	103–104	105–106	105–106					
Na (wt%)	0.179	0.027	0.026	0.12	0.592	0.051	0.308	0.073	0.17	0.19	0.69	1.16	0.71
K (wt%)	3.45	0.57	1.29	3.3	2.6	2.34	2.7	2.25	2.31	0.97	1.84	n.d.	2.9
Sc	10.8	1.63	6.76	7.86	5.39	6.15	9.94	7.98	7.06	2.85	6.92	13	10.2
Cr	125	17 7	20.8	55.3	27.1	31.8	45.4	28.5	44	35	23.7	49	110
Fe (wt%)	0.85	0.19	0.27	0.59	6.73	0.35	3.77	1.08	1.73	2.33	1.56	3.33	3.5
Co	15.2	1.77	1.54	13.1	7.21	8.94	10	7.33	8.14	4.84	7.43	13.5	8
Ni	153	20.1	19.9	40	9.73	25.9	20	8.73	37.2	47.8	18	n.d.	20
Zn	64.3	4	7.48	37	3.75	9.7	6	4.99	17.2	22	13	n.d.	10
Ga	3.95	0.80	10.6	3.19	21.4	1.69	15	4.25	7.61	7.36	8	n.d.	n.d.
As	9.76	0.71	0.34	5.72	0.24	0.38	<0.8	<0.50	2.14	3.99	0.2	n.d.	0.8
Br	0.05	<0.27	<0.46	<0.30	<0.28	0.05	0.28	0.04	0.05	0.12	0.17	n.d.	0.2
Rb	98.2	18.8	50.8	98.5	79.5	66.6	94	78.9	73.2	27.5	73	66	90
Sr	145	19.6	135	130	205	100	195	185	139	60.4	173	125	110
Zr	485	150	410	420	240	370	355	305	342	107	201	230	200
Sb	0.56	0.18	0.13	0.35	4.59	0.09	0.03	0.03	0.75	1.56	0.07	n.d.	0.9
Ba	1385	225	940	1235	1045	1125	1180	1445	1073	381	377	470	650
La	66.9	12.7	55.5	51.5	36.1	51.6	49.7	48.5	46.6	16.1	21.7	35	29.5
Ce	111	18.7	98.5	91.5	68.1	77.6	87.1	80.9	79.2	27.7	41.2	76	55
Nd	61	7.24	39.5	37.3	24.5	36.4	41.6	37.8	35.7	15.3	21.6	n.d.	34
Sm	8.99	1.39	5.27	7.07	4.8	6.95	6.87	6.57	6	2.25	4.28	7.2	8.3
Eu	1.93	0.25	1.27	1.51	1.09	1.34	1.46	1.5	1.29	0.49	0.93	1.58	0.9
Gd	7.72	1	4.79	5.89	4.14	4.97	6.03	5.58	5	1.94	4.05	6.4	7
Tb	1.24	0.17	0.77	0.9	0.6	0.67	0.75	0.74	0.73	0.3	0.63	0.97	1.1
Tm	0.72	0.1	0.36	0.46	0.29	0.33	0.36	0.37	0.37	0.17	0.28	n.d.	0.6
Yb	4.78	0.7	2.46	3.18	2.05	3.02	3.19	2.89	2.78	1.16	1.89	3	4
Lu	0.65	0.11	0.34	0.52	0.33	0.46	0.48	0.43	0.42	0.16	0.26	0.47	0.38
Hf	13.2	4.97	11.3	11.2	6.18	10.8	9.32	7.97	9.37	2.81	3.88	6.7	6.1
Ta	1.44	0.48	0.95	0.95	0.59	1.1	0.95	0.87	0.92	0.3	0.64	n.d.	0.9
Ir (ppb)	0.1	0.33	0.33	0.2	0.1	0.33	0.2	0.17	0.22	0.1	0.03	n.d.	<1
Au (ppb)	0.6	0.1	0.3	0.4	0.3	0.2	0.6	0.4	0.36	0.18	1.3	n.d.	<6
Th	11.9	3.78	9.87	9.7	6.09	8.52	10.5	8.8	8.65	2.59	5.21	7.6	9.5
U	4.99	1.08	1.82	3.37	0.95	2.6	2.56	1.69	2.38	1.33	1.7	2	3.5
K/U	6914	5278	7088	9792	27368	9000	10547	13314	11163	7005	10804	5800	8286
Th/U	2.38	3.50	5.42	2.88	6.41	3.28	4.1	5.21	4.15	1.4	3.06	3.8	2.71
La/U	13.4	11.8	30.5	15.3	38	19.8	19.4	28.7	22.1	9.32	4.17	4.61	3.11
Zr/Hf	36.7	30.2	36.3	37.5	38.8	34.3	38.1	38.3	36.3	2.85	51.8	34.3	32.8
La_n/Yb_n	9.46	12.3	15.2	10.9	11.9	11.5	10.5	11.3	11.7	1.69	7.77	7.88	4.98
Eu/Eu*	0.708	0.645	0.772	0.715	0.747	0.697	0.698	0.757	0.717	0.04	0.685	0.713	0.361

All values are in ppm, except as indicated.
n.d. = no data.
*For data of average bediasite, georgiaite, and DSDP-612 tektites, see Glass *et al.* (1998).
†The major oxide compositions of these microtektites (T2–T8) are given in Table 1.

result in the other data points being crowded together in one corner of the figure. Note that the Hole 689B microtektite concentration plots close to the extrapolated trend line for the North American microtektites (Fig. 8), which is thus consistent with the Hole 689B microtektites belonging to the North American strewn field.

The major oxide compositions of the Hole 689B microtektites are similar to the major oxide compositions of the North American tektites and microtektites, but there are some differences (Fig. 4). For a given SiO_2 content, the Hole 689B microtektites have similar MgO, K_2O, and TiO_2 contents compared with North American microtektites. The Al_2O_3, CaO, and K_2O contents overlap those of the North American microtektites, but the Hole 689B microtektites have higher average Al_2O_3 contents and lower average CaO and K_2O contents for a given SiO_2 content. The average FeO content of the Hole 689B microtektites is about the same as for North American microtektites, but the Hole 689B microtektites have a slightly greater range in FeO content than North American microtektites for a given SiO_2 content. The biggest difference exists for the Na_2O contents of the Hole 689B microtektites, which are generally lower than those of the North American microtektites.

The Hole 689B microtektites also have similar trace element contents compared with North American tektites and microtektites (Table 2). The main differences are the Zr, Ba, and Ir contents which are generally higher. The high Ir contents of the Hole 689B microtektites, along with the high Ni content (153 ppm) of one of the microtektites (Table 2), may be due to meteoritic contamination. Vonhof (1998) found that the Hole 689B microtektites have $^{87}Sr/^{86}Sr$ ratios intermediate between those of North American tektites from Texas, Georgia, and Barbados, and North American tektites from DSDP Site 612.

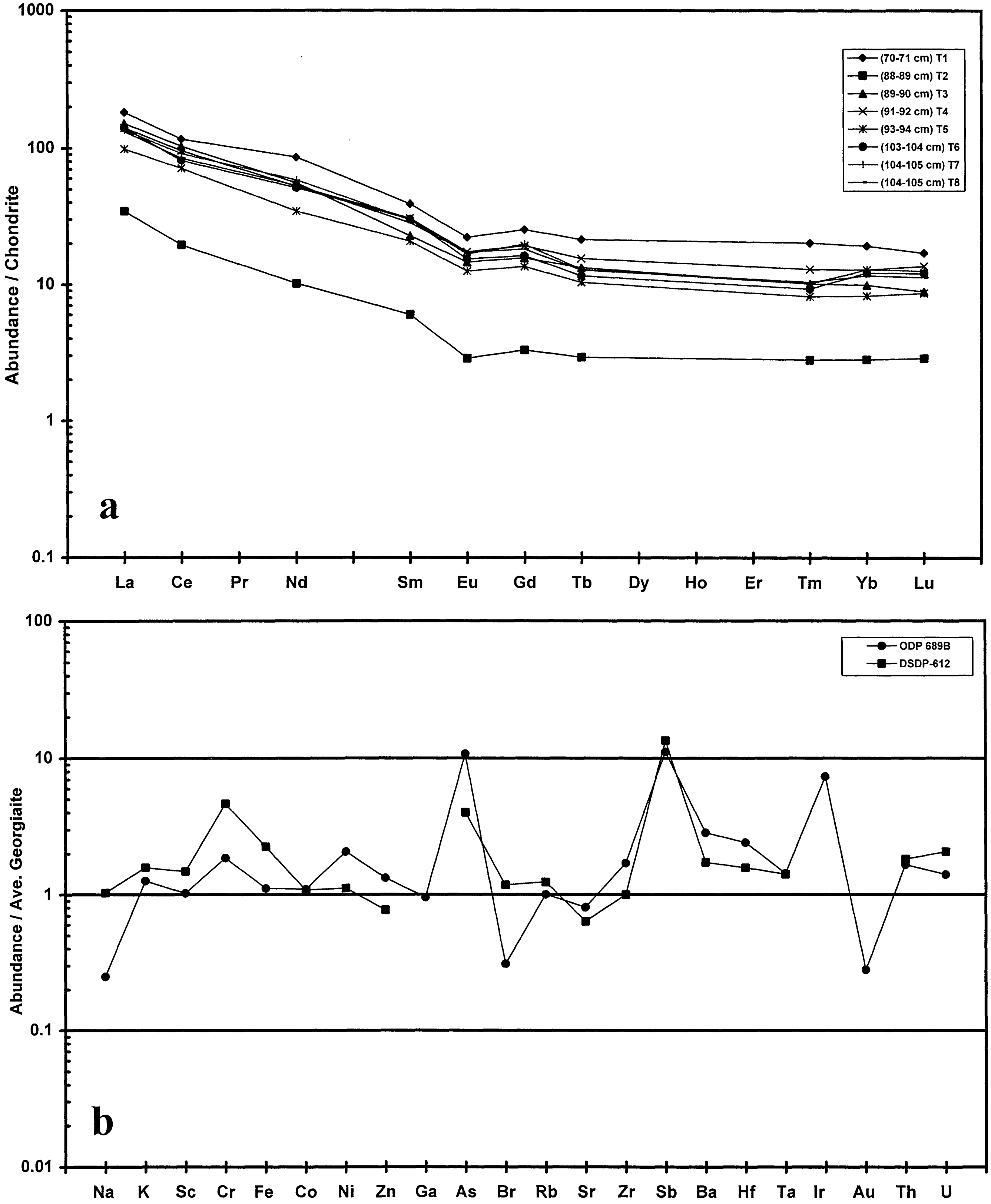

FIG. 5. Chondrite-normalized rare earth element (REE) abundance patterns. (a) Hole 689B microtektites. (b) Trace element abundances for Site 612 and Site 689B tektites/microtektites normalized to the average georgiaite. The CI chondritic REE normalizing factors are from Taylor and McLennan (1985).

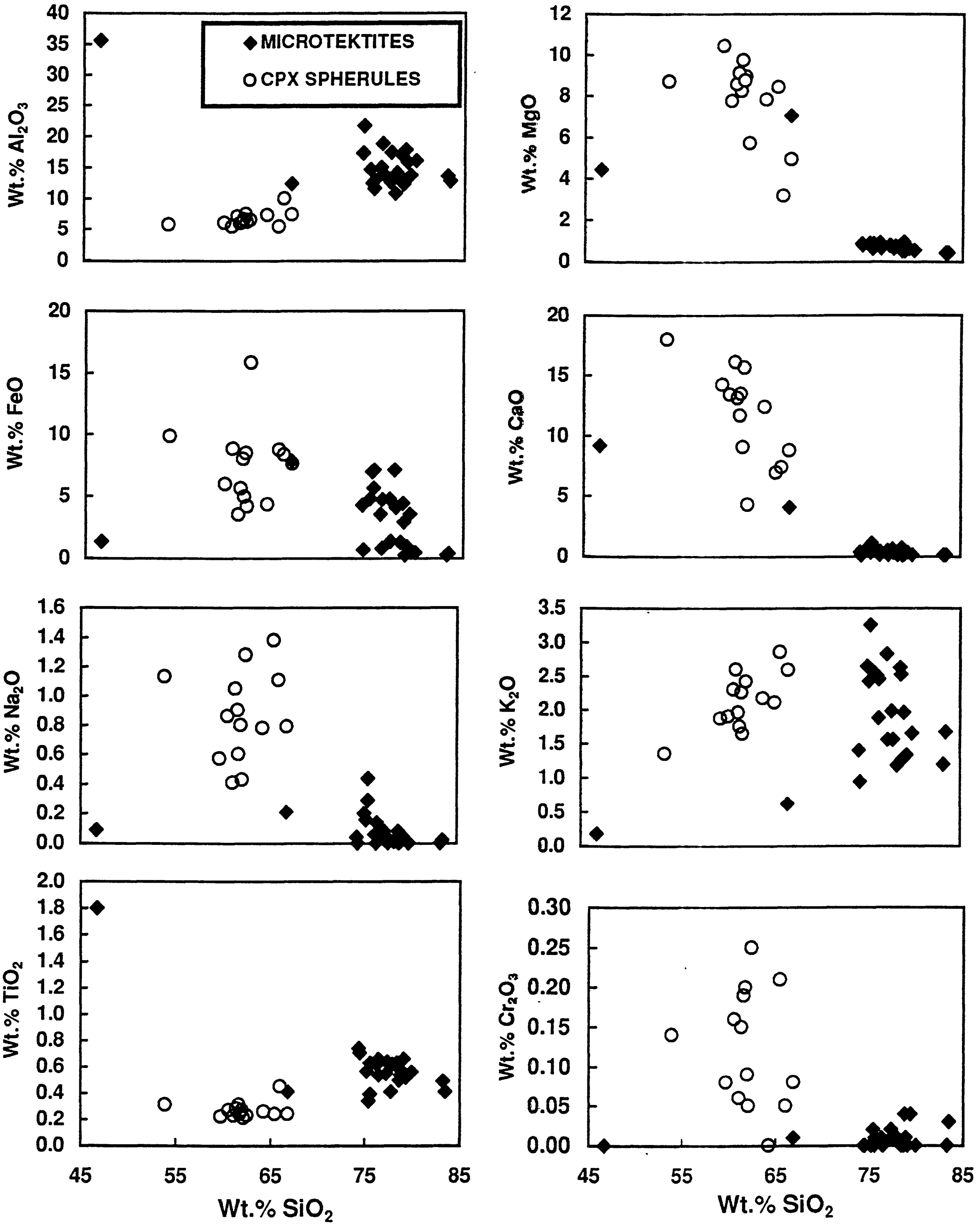

FIG. 6. Major element oxide plots for Hole 689B microtektites and cpx spherules.

The stratigraphic relationship between the Hole 689B microtektites and cpx spherules, the concentration of microtektites, and their compositions suggest that they are North American microtektites. The differences in composition between the Hole 689B microtektites and North American tektites and microtektites may be due in part to their greater distance from the source crater (Chesapeake Bay structure) and, thus, their derivation from a shallower depth in the target material. The lower alkali content (especially Na_2O) may be the result of greater fractionation due to higher temperature of formation, again because of their derivation from a shallower depth.

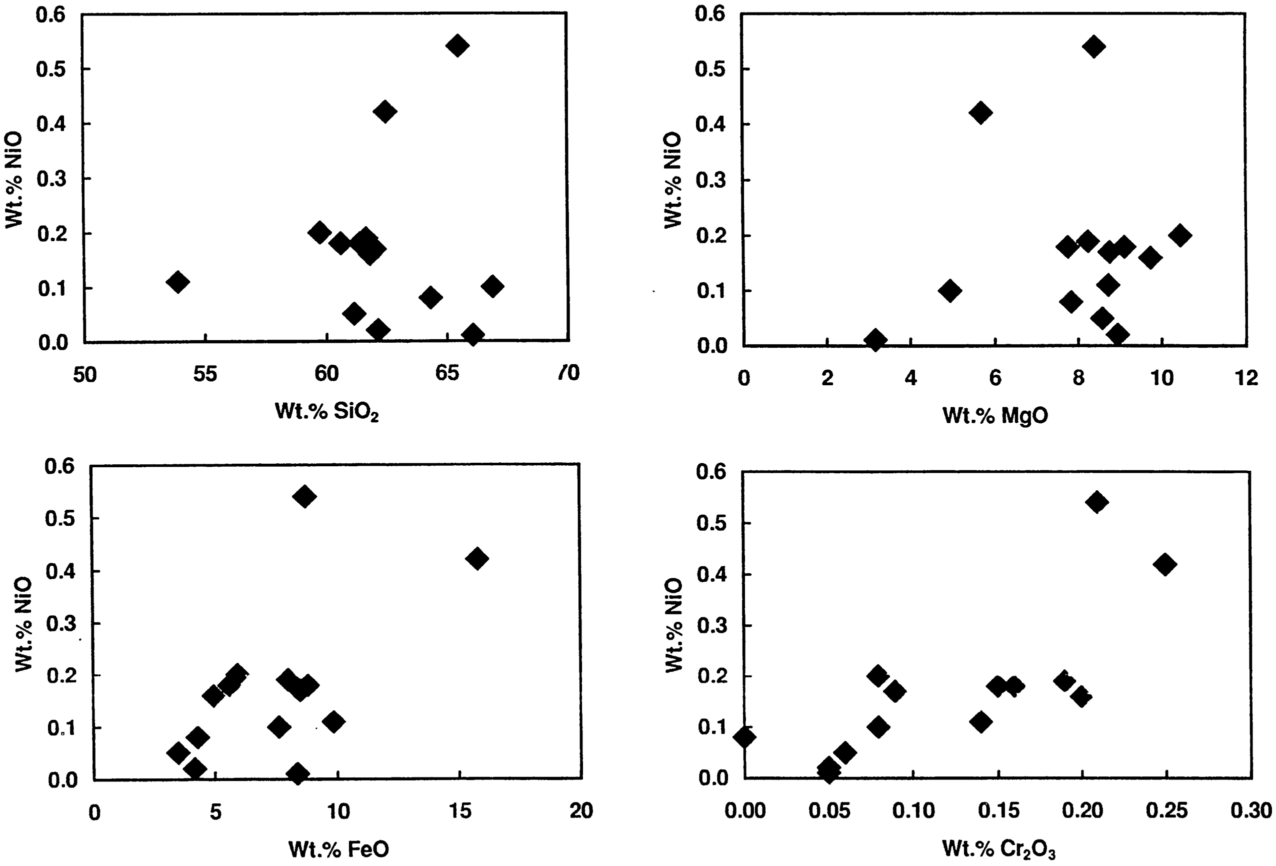

FIG. 7. Nickel *vs.* Si, Fe, Mg, and Cr for Hole 689B cpx spherules.

The low Br content of the Hole 689B microtektites is also consistent with the proposal that the Hole 689B microtektites may have experienced greater vapor fractionation than North Amercian tektites (Table 2). The higher Ir and Ni contents of the Hole 689B microtektites are also consistent with their greater distance from the source crater and, therefore, derivation from shallower depths in the target rock and greater contamination by the impacting body. On the other hand, all of the compositional differences between the Hole 689B microtektites and North American microtektites found at other sites could be due to heterogeneity of the target rocks.

If the Hole 689B microtektites are North American microtektites, then the North American strewn field is at least four times larger than has previously been mapped (Fig. 1). It also implies that North American tektites may have fallen on Central and South America.

TABLE 3. Siderophile element and Cr/Zn ratios in cpx spherules.*

	Average Upper Cont. Crust†	Average CI Chondrite‡	Average Dark Cpx Spherule§
Ni/Co	2	21	16
Au/Ir	90	0.3	0.7
Ni/Ir	1×10^6	2.3×10^4	5.3×10^4
Cr/Zn	0.5	8.5	21

*From Core RC9-58 compared with average upper continental crust and average CI chondrite.
†Taylor and McLennan (1985).
‡Wasson (1985).
§R. Ganapathy, pers. comm. (1983).

Clinopyroxene-Bearing Strewn Field

Clinopyroxene-bearing spherules have been found in the northwest Atlantic, Caribbean Sea, Gulf of Mexico, equatorial Pacific, and the eastern equatorial Indian Ocean. An Ir anomaly found below the North American microtektite layer on Barbados may indicate the former presence of the cpx layer at that site. Diagenetically altered cpx spherules appear to be associated with Ni-rich spinel crystals found in association with the Ir anomaly at Massignano, Italy (Pierrard *et al.*, 1998). Hole 689B is the first site where cpx spherules have been found south of the equator (Fig. 1).

Although the average major oxide compositions of cpx spherules from different sites are slightly different, there is a great deal of overlap, and the cpx spherules from all the sites have similar compositions, as well as petrographies (Glass and Burns, 1987). Thus, we conclude that all the cpx spherules are the result of a single impact and that the cpx strewn field is probably global.

The source crater for the cpx strewn field is not known, but the 100 km diameter Popigai crater in northern Siberia has the same age (Bottomley *et al.*, 1997) and is a strong possibility. However, the cpx spherules have lower Al_2O_3 and higher FeO, MgO, and CaO contents than Popigai impactites (Table 4). This could be because the near surface rocks at the Popigai impact site are more carbonate rich than the deeper rocks, which would have been the source of the impactites found in and immediately adjacent to the crater. The concentration of cpx spherules does not exhibit a clear inverse correlation with distance from Popigai (Fig. 8). On the other hand, DSDP Site 216, which is one of the closest to Popigai, has the highest concentration; and ODP Hole 689B, which is farthest from

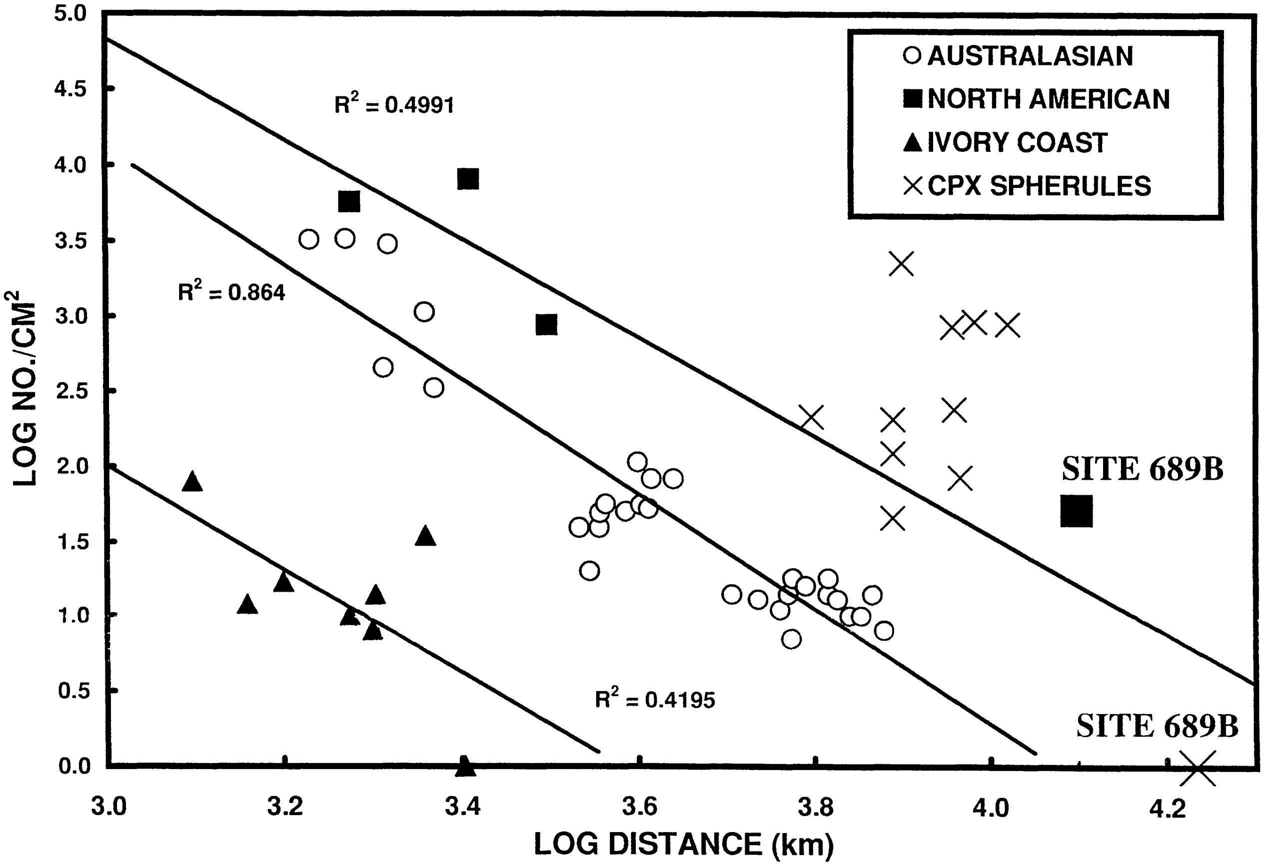

FIG. 8. Log number microtektites and cpx spherules (>125 μm)/cm^2 *vs.* log distance from proposed source crater or source area. Source craters for the Ivory Coast and North American strewn fields are Bosumtwi (6.53° N, 1.42° W) and the Chesapeake Bay structure (37.25° N, 76.08° W), respectively. The source area used for the Australasian strewn field is 12° N and 106° E (see Glass and Pizzuto, 1994). Distances for the cpx spherule-bearing sites are from Popigai crater (71.5° N, 111° E).

Popigai, has the lowest concentration. Furthermore, the log concentration *vs.* log distance from Popigai data for the cpx spherule sites are generally above the extrapolated trend line for the North American microtektites (Fig. 8). Therefore, the cpx spherule concentration data are consistent with a source crater somewhat larger than the Chesapeake Bay structure and located at or near Popigai. Furthermore, although there is a great deal of scatter in the data, a location in northern Siberia (between 110° to 180° E longitude and 55° to 75° N latitude) explains the geographic variation in concentration of cpx spherules better than any other location on the Earth's surface; assuming that the log number of cpx spherules/cm^2 decreases linearly with increasing log distance from the source crater. This location was determined by doing a regression analysis and determining the r^2 value of the log number of cpx spherules/cm^2 *vs.* log distance in kilometers to each spherule-bearing site from hypothetical crater locations all around the globe. We started with a 40° grid and then narrowed down to a 10° grid in the area with the higher r^2 values (see Glass and Pizzuto, 1994, for a more detailed description of this method). The assumption is that the location that gives the highest r^2 value (and therefore explains the geographic variation in concentration the best) must be closest to the source crater. We note that the Popigai structure is located in the extreme western part of the area that gives the high r^2 values (>0.3). Using the late Eocene latitudes and longitudes of Popigai crater and the cpx spherule-bearing sites does not improve the correlation; in fact, it makes it worse. The area that gives the best correlation is still in northern Siberia, but it is farther to the east and the r^2 values fall below 0.3. In summary, the present data, regarding the possibility that Popigai may be the source crater for the cpx spherules, are ambiguous.

The average number of cpx spherules (>125 μm)/cm^2 is 414. If the strewn field is global and if 414 spherules/cm^2 is a good average for the entire strewn field, then we calculate a total mass of 2.5×10^{16} g (or 25 billion metric tons) for the mass of cpx spherules in this strewn field (assuming an average size of 200 μm for the cpx spherules >125 μm in diameter and a density of 2.8 g/cm^3). This is equivalent to ~9 km^3 of cpx spherules, which is ~0.1% of the estimated volume of material ejected from Popigai crater or less than 1% of the estimated melt produced by the impact.

TABLE 4. Composition of cpx spherules and Popigai impactites.

	Average Cpx Spherule† (n = 158)	Popigai impactites‡ Suevites (n = 58)	Impact-melt rocks (n = 163)
SiO_2	64.4	65.41	63.17
Al_2O_3	8.1	13.11	14.54
FeO	7.4	5.76	6.74
MgO	6.8	2.77	3.38
CaO	9.0	2.60	3.70
Na_2O	1.2	1.88	2.29
K_2O	2.3	2.73	2.70
TiO_2	0.3	0.63	0.73

†Glass *et al.* (1985), D'Hondt *et al.* (1987), Glass (1989).
‡Masaitis *et al.* (1994).

CONCLUSIONS

Microtektites and cpx spherules are associated with a positive Ir anomaly in upper Eocene sediments in Hole 689B, Maud Rise, Southern Ocean (Vonhof, 1998; this study). We find that the cpx spherules at this site appear to be slightly older (3000–5000 years) than the microtektites.

The microtektites are compositionally similar to the North American tektites and microtektites. The differences in composition may be due to a combination of heterogeneity of the target rock and variations in degree of vapor fractionation and meteoritic contamination. Based on their composition, abundance, and stratigraphic relationship to the cpx spherules, we conclude (in agreement with Vonhof, 1998) that the Hole 689B microtektites probably belong to the North American strewn field. If so, the North American strewn field may be at least four times larger than previously mapped.

The cpx spherules are petrographically and compositionally similar to upper Eocene cpx spherules previously found in the northwest Atlantic, Caribbean Sea, Gulf of Mexico, equatorial Pacific, and eastern Indian Ocean. We conclude that the Hole 689B cpx spherules belong to the same strewn field as the other previously reported upper Eocene cpx spherules and that this strewn field is probably global in extent. The total mass of cpx spherules is calculated to be ~25 billion metric tons. The Popigai crater in northern Siberia may be the source crater for this strewn field, based on its age, size, and geographic location; but additional studies are required in order to test this hypothesis.

Acknowledgments–Hole 689B core samples were provided by the Ocean Drilling Program. Critical reviews by Wylie Poag and Shyam Prasad greatly improved the paper. We thank Takako Nagase (University of Delaware) and Hailemeskel Awoke (University of Vienna) for help with the SEM/EDS and INAA work, respectively. James D. Black (University of Delaware) helped prepare Figure 1. Christian Koeberl was supported by the Austrian FRW, project Y58-GEO.

Editorial handling: S. R. Taylor

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