

## New Estimates of Area and Mass for the North American Tektite Strewn Field

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The exact extension of the North American tektite strewn field, the oldest known tektite strewn field, is not well established. Past estimates have ranged from an area including most of the eastern part of the United States and a large part of the Pacific Ocean to smaller areas centered at the Caribbean Sea. New and revised estimates about the extension of the North American tektite field are based on: (1) the recent discoveries of tektites in Barbados and at a DSDP site off the coast of New Jersey; (2) the verification of the genuineness of the Cuban tektite; and (3) the recognition that the microtektites in the Pacific core are of different origin. The discovery of impact ejecta at the New Jersey DSDP site, the possible Muong-Nong-type nature of the tektites found at that location, and isotopic and chemical arguments support the view that the source crater for the North American field has to be somewhere on the continental shelf, probably underwater. Although the recently discovered submarine impact crater Montagnais (close to Nova Scotia) has about the required geographical location, it seems to be too old compared with the North American tektites. A revised estimate is given for the total mass of the North American tektite material, which is based on a concept of patches or rays of distribution rather than on a continuous tektite and microtektite blanket. This concept yields a total mass of about  $3.10^{14}$  g, which is less than a third of previous estimates. The shape of the North American tektite strewn field is in agreement with other tektite strewn fields, e.g., the Australasian tektite strewn field. Also, discontinuous ejecta blankets are known from most impact craters.

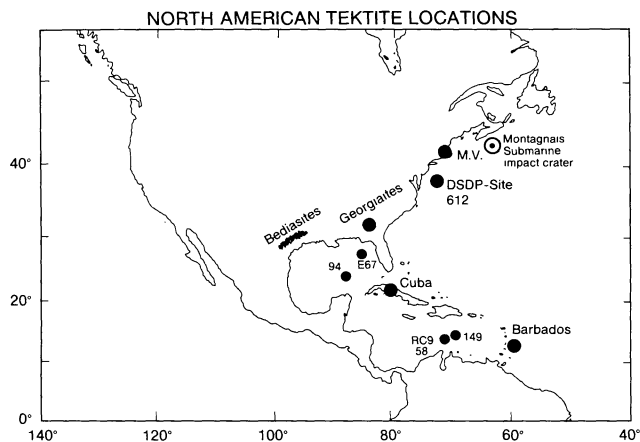
### INTRODUCTION

The major tektite occurrences in the North American tektite strewn field are in Texas, where numerous bediasites (named after a common place name in Grimes County) have been recovered since 1936 (Barnes, 1940). Only in 1959 was the existence of another substrewn field of tektites in Georgia confirmed, although the first Georgia tektite came to the Smithsonian Institution as early as 1938 (Clarke and Carron, 1961). Numerous tektite specimens have been found at both places since then (e.g., Povenmire, 1985). In 1959 a tektite fragment was found at Martha's Vineyard, Massachusetts (Kaye et al., 1961), but no additional specimens have since been found. This fragment was found among assorted rock debris in an erosional gully on a well-traveled tourist location, and it is probable that Martha's Vineyard is not its original location. Another individual tektite, reportedly from Cuba, was described by Garlick et al. (1971). This very large tektite (the complete piece must have been in excess of 100 g) was found in a mineral cabinet at Columbia University, and a scrap of paper found with the tektite was the only hint that it may be from Cuba. A recent reanalysis of the Cuban tektite in the view of new information on the North American tektite locations was reported by Koeberl (1988a), who concluded that the Cuban tektite is (1) a North American tektite, and (2) probably really originated from Cuba. No more tektites, however, have been recovered from Cuba thus far.

Microtektites have been reported from a number of drill cores, many of them obtained by the Deep Sea Drilling Project (DSDP) in the Gulf of Mexico and in the Caribbean Sea. On the basis of stratigraphic, chemical, isotopic, and age data these microtektites have been classified as belonging to the North American tektite strewn field (e.g., Donnelly and Chao, 1972; Glass et al., 1973; Glass and Zwart, 1979). It was mainly on the basis of the geographical distribution of the microtektite

locations that the extension of the North American tektite strewn field was outlined. For some time it was believed that microtektite-like spherules, which have been found in cores from DSDP sites across the Pacific, in the Indian Ocean, and the Caribbean region, are part of the North American strewn field (Glass et al., 1979). Later it was recognized that the Pacific and Indian Ocean spherules, as well as some of the Caribbean spherules, were mostly clinopyroxene-bearing spherules (cpx spherules) and that they belong to an event different from the North American tektite event (Glass et al., 1985). The cpx spherules are associated with an iridium anomaly (Ganapathy, 1982; Asaro et al., 1982; Alvarez et al., 1982) and occur stratigraphically slightly below the North American microtektite layers (John and Glass, 1974; Glass and Zwart, 1979; Glass et al., 1985). Although they are of impact origin as well, the cpx spherules are different from normal microtektites (Glass and Burns, 1987) and probably originated from an earlier impact event (Glass et al., 1985); therefore, they do not need to be taken under consideration for the extension of the North American tektite strewn field.

The discovery of tektite fragments together with microtektites in deep sea deposits (on land) on Barbados (Saunders et al., 1984; Glass et al., 1984; Sanfilippo et al., 1985) was of great importance. First, this was the first time that microtektites and tektites have been found together in one layer, thus finally eliminating doubts about stratigraphic tektite ages and the link between splash-form tektites and microtektites. Second, on the basis of chemical (Glass et al., 1984; Nagasawa et al., 1986; Koeberl and Glass, 1986), isotopic (Ngo et al., 1985), and age data (Glass et al., 1986a), these tektites were identified as belonging to the North American tektite strewn field. Thus the number of tektite locations within the North American strewn field was increased to three, covering a much larger area than previously known. Chemically



**Fig. 1.** Map of all known North American tektite locations. Large dots mark locations of tektites (or tektites and microtektites); smaller dots mark locations with only microtektites. Abbreviations: Bedia bediasites; Georg. =georgiites; M.V. = Martha's Vineyard. Numbers mark DSDP core locations. The dot with the circle northeast of Martha's Vineyard is the Montagnais impact crater.

the microtektites were quite similar to occurrences already known in the Gulf of Mexico and the Caribbean Sea (Nagasawa *et al.*, 1986).

#### THE IMPORTANCE OF DSDP SITE 612

Recently a layer containing tektite fragments, microtektites, and other probable impact debris was discovered in a core from DSDP Site 612, which was drilled on the upper continental slope off New Jersey in a water depth of 1404 m (Thein, 1987). This layer contains centimeter-long glass fragments of varying color, ranging from grey to olive-green to dark brown, as well as numerous microtektites. The mass of the microtektites is, however, not important compared to the mass of the tektite fragments. Microtektites are concentrated in the upper part of the tektite-bearing layer (Thein, 1987; Keller *et al.*, 1987). In addition, the layer, which is 20 cm thick (Thein, 1987), contains detrital mineral grains like quartz, coesite (or mixtures thereof, plus glass), feldspar, and

garnet (Thein, 1987; Bobor *et al.*, 1988). All these mineral grains show more or less distinct indications of shock such as multiple sets of shock lamellae (planar features) (Thein, 1987; Bobor *et al.*, 1988). The occurrence of these features together with coesite and lechatelierite (the latter apparently forming from melting of coesite) throughout the sediment layer (Glass, 1987; Bobor *et al.*, 1988) is indicative of an impact event.

Stratigraphically and chemically the tektites, microtektites, and impact debris have been identified as belonging to the North American tektite strewn field (Thein, 1987; Keller *et al.*, 1987; Koebel and Glass, 1988), although there seem to be some interesting differences. This raises the number of tektite occurrences within the North American strewn field to four, omitting the singular occurrences of Cuba and Martha's Vineyard. Figure 1 gives an overview of the North American tektite locations, together with DSDP core locations where only microtektites have been found. Occurrences of cpx spherules are omitted because they most probably do not belong to the North American tektite event. Chemically the DSDP Site 612 tektites are similar to normal North American tektites, although there are some significant differences. One of the most important differences is the content of the alkalis. Table 1 gives the chemical composition of tektites from all over the North American strewn field, and if the DSDP 612 tektites are compared with those from other locations it is evident that they have much lower sodium, but higher potassium contents. Figures 2a and 2b give the ranges of the North American tektites from the four major locations, plus the compositions of the two tektites from Cuba and Martha's Vineyard, respectively. In most cases the DSDP 612 tektites are well within the range outlined by the bediasite tektites, although they have slightly higher MgO contents. Magnesium is also most variable in tektites from Barbados, maybe indicating a small admixture of ultramafic or mafic material (which would be consistent with Cr and Mg enrichments observed in these tektites; Koebel and Glass, 1988) in the parent material.

The tektite fragments from the DSDP 612 site have an appearance different from normal North American tektites. They have numerous vesicles and change color within single specimens. They also show flow structures like schlieren as

TABLE 1. Major element compositional data for North American tektites from all known location.

	Bediasites		Georgiites		Martha's Vineyard (1)	Cuban Tektite (1)	Barbados Range (18)	DSDP 612 Range (8)	Montagnais Crater Impact Melts	
	Average (30)	Range (30)	Average (8)	Range (8)					(1)	(1)
SiO <sub>2</sub>	76.05	71.9 - 80.2	81.4	79.8 - 83.6	80.50	75.00	76.9 - 85.6	71.9 - 77.8	74.7	75.1
TiO <sub>2</sub>	0.78	0.59 - 1.05	0.49	0.42 - 0.60	0.53	0.81	0.40 - 0.71	0.55 - 0.85	0.50	0.72
Al <sub>2</sub> O <sub>3</sub>	13.92	11.2 - 17.6	10.75	9.50 - 11.7	11.20	15.50	7.97 - 14.8	13.0 - 15.1	12.8	12.5
FeO	4.07	2.29 - 5.75	2.44	1.83 - 3.14	2.69	4.30	1.37 - 3.98	2.7 - 5.0	3.70	3.45
MnO	0.04	0.01 - 0.07	0.04	0.02 - 0.07	0.05	0.04	-	-	-	-
MgO	0.65	0.37 - 0.98	0.56	0.37 - 0.69	0.69	0.54	0.13 - 1.13	0.7 - 1.4	1.32	1.26
CaO	0.62	0.35 - 0.96	0.50	0.40 - 0.69	0.69	0.40	0.52 - 0.87	0.8 - 1.0	1.63	2.06
Na <sub>2</sub> O	1.53	1.20 - 1.98	1.17	1.00 - 1.53	1.00	1.17	1.15 - 1.52	0.2 - 0.6	2.32	2.11
K <sub>2</sub> O	2.03	1.42 - 2.43	2.39	2.22 - 2.51	2.37	2.09	1.73 - 2.54	3.0 - 3.8	2.97	2.75

Data after compilations by Koebel (1988 a,b) and Koebel and Glass (1988). Montagnais data from Jansa and Pe-Piper (1987). All data in wt.%, and all Fe as Fe. Montagnais data have been included to show the similarity to North American tektites. Even if the Montagnais crater is too old to be the source crater for the North American tektites, an impact in similar (shelf) material seems very probable.

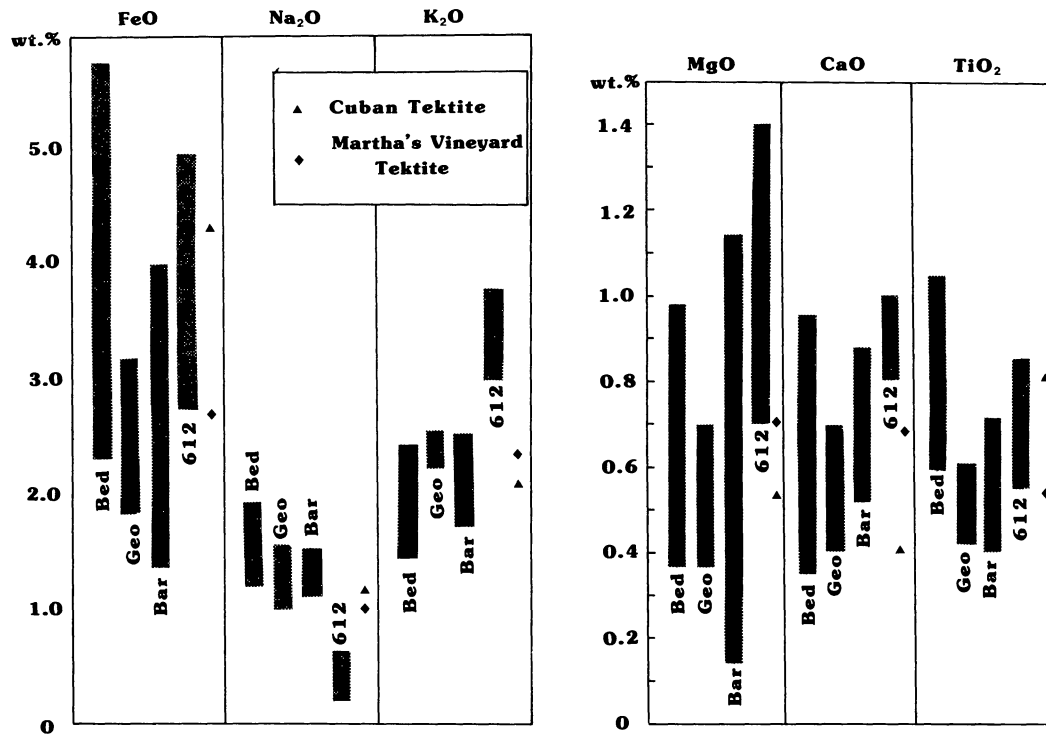


Fig. 2. Major element ranges for tektites in the four major North American tektite locations (BED = bediasites, GEO = georgiaites, BAR = Barbados tektites, 612 = DSDP Site 612 tektites), and data for the two singular occurrences at Martha's Vineyard and Cuba (data after compilations by Koeberl, 1988a,b; and Koeberl and Glass, 1988).

well as layers of different composition and color (Thein, 1987), and they are somewhat enriched in volatile elements (Koeberl and Glass, 1988). These features are consistent with their being Muong-Nong-type tektites. Muong-Nong-type tektites are well known from the Australasian tektite strewn field, where they occur in Indochina in the form of large, inhomogeneous, layered chunks of tektite glass enriched in volatile elements. Although there have been occasional reports about Muong-Nong-type tektites from other strewn fields, they have not been substantiated with analytical data (e.g., volatile element enrichments or measurements of the inhomogeneity of samples), and therefore Muong-Nong-type tektites have been known unambiguously only from the Australasian strewn field (Koeberl, 1986). This has now changed with the discovery of the DSDP 612 tektites, which not only fulfill the criteria for Muong-Nong type (Koeberl, 1986), but also contain quartz grains partially melted to lechatelierite (Glass *et al.*, 1986b). All these points are forceful arguments for a closer proximity of DSDP Site 612 to the source crater of the North American tektites than any other site. This, however, is valid only if the DSDP 612 tektites are really part of the North American tektite strewn field, which may be doubted in view of some of the chemical differences.

One important diagram for distinguishing North American tektites is the soda-potash diagram (King, 1966) given in Fig. 3. Georgiaites and bediasites occupy separated areas of the diagram. The Cuban tektite plots in-between the space

separating the bediasite and georgiagate compositions, which was one of the arguments for the genuineness of this tektite (Koeberl, 1988a). The tektite from Martha's Vineyard is indistinguishable from Georgia tektites. If the new Barbados tektites are added, the distinction between the bediasites and the georgiaites disappears. It appears, however, as if the Barbados tektites (including the Cuban tektite) occupy mostly the field between the other two major groups, thus maybe creating (or demonstrating) their own Caribbean substrewn field. The DSDP 612 tektites plot in another part of the diagram, characterized by low Na and high K contents. Although there is a gap left between the DSDP 612 tektites and the tektites from the rest of the strewn field, microtektite compositions (e.g., Glass *et al.*, 1973, 1985) do not show such a distinction and would fill up the field in-between. Assuming that the positions of different types of tektites in the Na/K diagram reflect some kind of mixing trend, then the DSDP 612 tektites seem to belong to the North American field.

Isotopic data (Steber *et al.*, 1988) show a similar behaviour. In a Rb/Sr-Sm/Nd diagram the DSDP 612 tektites are not identical with other North American tektites but also seem to lie on a mixing line. Thus it seems that both chemical and isotopic evidence are in favor of an association between the other North American tektites and the tektites (and microtektites) from DSDP Site 612.

Of further importance is the fact that real impact ejecta, in the form of shocked quartz and other shocked minerals, are

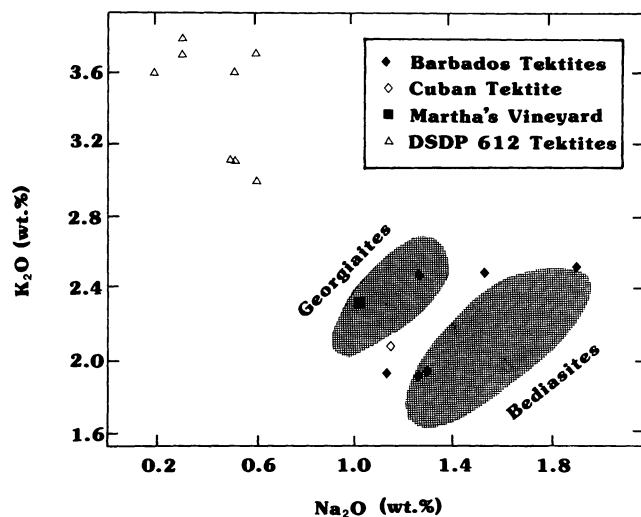


Fig. 3. Soda-potash diagram for tektites of the North American tektite strewn field. The separation between the bediasites and georgiites disappears if tektites from Barbados are also plotted. Tektites from DSDP Site 612 plot in a different region of the diagram, but seem to be consistent with a mixing trend over the total strewn field.

present in the same layers as the tektites. Together with the Muong-Nong-like character of the tektite glass, this is another argument for a close source crater.

#### SHAPE AND SIZE OF THE NORTH AMERICAN TEKTITE STREWN FIELD

With the exclusion of microtektite locations in the Pacific Ocean, only four major tektite locations and a number of microtektite occurrences in the eastern part of the United States, the Gulf of Mexico, and the Caribbean Sea remain to define the North American field. The north-south extension is considerably longer than was thought before the discovery of the DSDP 612 tektites. Some forceful isotopic arguments have been used by *Shaw and Wasserburg* (1982) to argue for a source crater at the eastern or southeastern part of the U.S., most probably on the continental shelf. The data from DSDP Site 612 implies a similar location. For these reasons the recent discovery of the Montagnais submarine meteorite crater (*Jansa and Pe-Piper*, 1987), which is in the right area and at the right distance in relation to the North American tektite strewn field, led *Glass* (1988) to suggest that this crater may be the source crater for the North American tektites. Although this would be a perfect solution, the crater does not seem to have the right age; its age is closer to 50 m.y. than to 34 m.y. (*Jansa et al.*, 1988).

Since there are a number of arguments in favor of a source crater at a similar location, it is suggested that if Montagnais crater is not the source crater for the North American tektites, there has to be another large submarine impact crater close by (i.e., within several hundred kilometers), most probably also on the continental shelf.

If we assume the crater to be somewhere close to DSDP Site 612, we may take the general area of DSDP Site 612 as the upper boundary of the North American tektite field. It is well known from other tektite strewn fields (such as the Australasian field, or the moldavite field) that tektite strewn fields are asymmetrical, with the crater on one side (or Muong-Nong-type tektites indicating the proximity of crater), and tektite locations occur only on one side from the crater (this statement is based on the assumption that the Ries crater is the source crater for the moldavites, Bosumtwi crater is the source for the Ivory Coast tektites, and a yet unknown crater near Indochina is responsible for the Australasian tektites). From the known tektite locations in North America and the analogy with other strewn fields, it is concluded that the field extends from the approximate area of DSDP Site 612 to the southern boundary of the Caribbean Sea. The tektites at the southern border of the strewn field would be the ones that have traveled furthest from the source crater, being perfect splash-form tektites, which is in agreement with the observations (*King*, 1964).

The best approximation of the outline of the strewn field would be a triangular figure defined by DSDP Site 612, the bediasite locations, and Barbados. Practically all other occurrences are within these boundaries. We purposely exclude Martha's Vineyard from the outline of the strewn field, because aside from the unusual location in which this tektite was found, and the georgiite chemistry, there are other indications that this may be a misplaced Georgia tektite (*E. A. King*, personal communication, 1988). These assumptions lead to an approximate area of 8.8 million square kilometers for the total strewn field as outlined above. The total area calculated here differs from other calculations, such as that of *Glass* (1988), who estimates 9.7 million square kilometers because of the inclusion of the tektite of Martha's Vineyard.

#### AREAL DISTRIBUTION OF TEKTITES WITHIN THE STREWN FIELD

To determine the total mass of tektites within the North American strewn field, the area is usually multiplied by the estimated mass of tektite material per unit area. Using an average density of 0.042 g tektite material per square centimeter, *Glass et al.* (1979) calculated about  $10^9$  tons of tektite material for the whole strewn field. Using a larger area in a subsequent estimate, *Glass* (1988) calculates  $4 \times 10^9$  tons of tektite material.

It is argued here that these estimates are too high because the average mass per unit area used is too high and the area estimates are also too large. Tektites do not show a uniform distribution over the area of a strewn field. Instead, there are areas within each strewn field where abundant tektites are found, and others where tektites, despite intensive searches, are completely absent. The Australasian tektite or strewn field is a very good example. Australites are known to occur in certain places, while others are completely devoid of them (e.g., *Chapman*, 1971; *Chalmers et al.*, 1976). The same is true for indochinites in Vietnam (*E. K. Izokh*, personal communication, 1986) and is demonstrated by the distribution of the

moldavites in the Czechoslovakian strewn field. It should be noted, however, that this argument applies only to the geographical and not the geological distribution, since later changes in the geological setting of tektites (e.g., moldavites) may provide an altered stratigraphical position of the tektites. It is unlikely that redeposition changes the large-scale geographical distribution.

In addition, chemical differences between tektites from different locations, again prominently displayed in the Australasian strewn field, are well documented (*Chapman and Scheiber, 1969*) and in agreement with a nonuniform tektite occurrence within one strewn field. The same chemical/geographical "zoning" may be observed in the case of the North American tektites. The absence of tektites in the continental United States in areas in-between the well-known occurrences is taken as further evidence for a real effect, and not just specific erosion preservation, or redistribution, or other secondary processes.

Observations from impact craters also show that ejecta are deposited as more or less continuous ejecta only in the near vicinity of the crater (<2.5 crater diameters), while further away all ejecta are discontinuous. It is known from photogeologic studies (e.g., *Moore et al., 1974*) that at larger distances the ejecta became more lobate, and only rays of material are thrown out. Tektites, on the other hand, are not like normal crater ejecta but probably require a slightly different process similar to jetting, allowing their ejection in the form of rays of material to one side of the crater only. The impact debris at DSDP 612 may, however, qualify as being part of the real crater ejecta (but it is not known if it belongs to the continuous or the discontinuous part).

This picture emerging for the distribution of tektites within the North American strewn field is shown in Fig. 4. In this model tektites have varying areal densities, leading to a concept of patches, or rays of tektite distributions. Between these patches there are chemical differences present in the composition of tektites, like between georgiites and bediasites. Furthermore, the area density of tektites may not be uniform, but it is dependent on the distance from the source crater, unlike the simplifying assumptions made for the earlier estimates discussed previously.

If our new estimates are adopted to that model, the total area covered by tektite material is reduced by at least 30% (since here it is assumed that it is not the total area outlined by DSDP 612-Barbados-bediasite locations that actually contains tektites). Also, the areal density is allowed to vary in a very simple way as a function of the distance from the source crater (which is assumed to be in the vicinity of DSDP Site 612). This would be an improvement over previous estimates of an average areal density. For an estimate of the total mass, the upper (DSDP 612; 2.22 g/cm<sup>2</sup>) and lower (Barbados; 0.008 g/cm<sup>2</sup>) limits of the areal densities (*Glass, 1988; Sanfilippo et al., 1985*) are taken as boundary values, together with the average from Caribbean Sea cores (0.042 g/cm<sup>2</sup>; *Glass and Zwart, 1979*). A simple exponential curve is fitted to these three points, with a steep initial slope close to the crater (thus the areal density at the crater is assumed to equal the density at DSDP 612). This leads to a smaller average areal

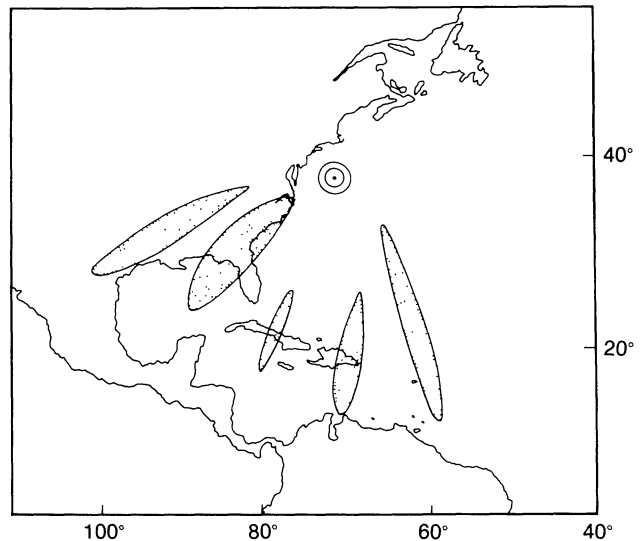


Fig. 4. Map of the North American strewn field showing the concept of nonuniform areal tektite distribution leading to patches or rays of tektite occurrences. This model yields a smaller total mass of tektites in the strewn field than previous estimates. The circles in the center are drawn around DSDP Site 612, which contains impact ejecta and Muong-Nong-type tektites and is thus close to the crater site.

density than earlier estimates (*Glass, 1988*), since the low density at the Barbados site is not excluded. The empirical curve fitting leads (together with a smaller initial area) to an estimate of  $3 \times 10^{14}$  g, or about  $3 \times 10^8$  tons of tektite material. This is lower than previous estimates of about  $10^9$  tons (*Glass et al., 1979; Glass, 1988*) but seems more realistic, following the assumption of a discontinuous tektite distribution pattern. Although the absolute numbers are highly uncertain due to many unknown variables and several simplifying assumptions, the difference to previous models (using similar assumptions) results mainly from the reduced area ("patches" of tektite occurrence) and the lower areal density.

## CONCLUSIONS

We have presented evidence for a more realistic outline and mass of the North American tektite strewn field. These new estimates reflect the crucial discovery of tektites, together with microtektites and impact debris, at DSDP Site 612 at the continental slope off New Jersey, far from other tektite locations. Chemical, stratigraphic, and isotopic arguments may be used to show that the tektites from DSDP 612 are in fact part of the North American strewn field. The tektite from Martha's Vineyard is not regarded as genuine and is probably a misplaced Georgia tektite. By contrast, the so-called Cuban tektite is, in the view of recent analytical work and the discovery of tektites at Barbados (which also stretches the strewn field further to the south than assumed earlier), genuine and perhaps part of a Caribbean substrewn field.

The revised shape of the North American tektite strewn field, produced by including the DSDP 612 and Barbados locations, is taken as a starting point for calculating a more realistic total mass of tektite material within the strewn field. Using the concept of a nonuniform (patchy) distribution of tektites within the strewn field (Fig. 4) and the dependence of the areal density of tektite material on the distance from the source crater (assumed to be close to DSDP Site 612), we arrive at a total mass of about  $3.10^{14}$  g tektite material (tektites and microtektites) for the North American strewn field, about one third of that estimated earlier. Due to age differences the submarine meteorite crater Montagnais does not seem possible as a source crater of the North American tektites, but the source crater is most probably located in that general area, preferably on the continental shelf.

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