

Reports

Multiple Microtektite Horizons in Upper Eocene Marine Sediments: No Evidence for Mass Extinctions

Abstract. *Microtektites have been recovered from three horizons in eight middle Eocene to middle Oligocene marine sediment sequences. Five of these occurrences are coeval and of latest Eocene age (37.5 to 38.0 million years ago); three are coeval and of early late Eocene age (38.5 to 39.5 million years ago); and three are of middle Oligocene age (31 to 32 million years ago). In addition, rare probable microtektites have been found in sediments with ages of about 36.0 to 36.5 million years. The microtektite horizon at 37.5 to 38.0 million years can be correlated with the North American tektite-strewn field, which has a fission track age (minimum) of 34 to 35 million years and a paleomagnetic age of 37.5 to 38.0 million years. There is no evidence for mass faunal extinctions at any of the microtektite horizons. Many of the distinct faunal changes that occurred in the middle Eocene to middle Oligocene can be related to the formation of the Antarctic ice sheet and the associated cooling phenomena and intensification of bottom currents that led to large-scale dissolution of calcium carbonate and erosion, which created areally extensive hiatuses in the deep-sea sediment records. The occurrence of microtektite horizons of several ages and the lack of evidence for faunal extinctions suggest that the effects of extraterrestrial bolide impacts may be unimportant in the biologic realm during middle Eocene to middle Oligocene time.*

Microtektites are believed to be the residue of large extraterrestrial bolide impacts. These sand-sized, glassy objects, which are predominantly spherical, teardrop-, or dumbbell-shaped, range from transparent colorless, yellow, and bottle green to translucent black (Fig. 1). They generally have smooth surfaces, but many are pitted and some exhibit star-shaped impact craters. Microtektites consist predominantly of SiO_2 with varying contents of MgO , Al_2O_3 , FeO , CaO , K_2O , Na_2O , and TiO_2 (1).

Microtektites found in upper Eocene cores from Deep-Sea Drilling Project (DSDP) sites have been associated with the North American tektite-strewn field, which has a fission track age (minimum) of 34 to 35 million years ago. This association is based on appearance, petrography, chemistry, and apparent age (1–3). A fission track age of 34.6 ± 4.2 million years was reported for microtektites in a piston core (RC9-58) from the Caribbean Sea (2), and the disappearance of four radiolarian species was noted at this microtektite horizon (1, 2). An age of

32.2 ± 0.9 million years has been suggested for the Eocene-Oligocene boundary; this age was based solely on upward extrapolation of sedimentation rates from the microtektite horizon in several DSDP cores in which the presence of microtektites in late Eocene sediments was assumed to be part of the North American tektite-strewn field (3).

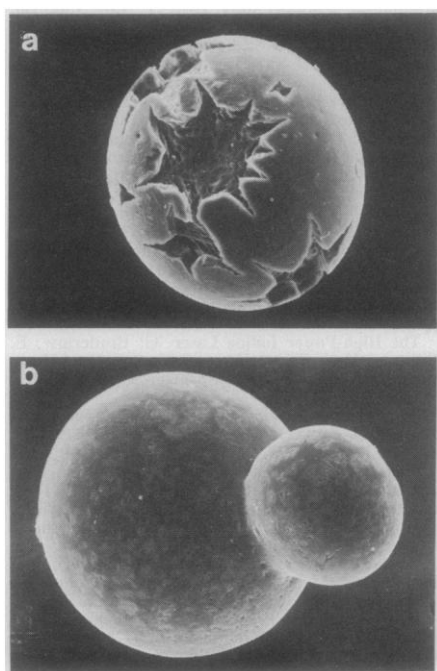


Fig. 1. (a) Microtektite with star-shaped impact craters (yellow) from site RC9-58 (240 to 243 cm). (b) Microtektite consisting of two-fused spheres (black) from DSDP site 292, core 38-2 (1 mm in diameter).

The discovery of an iridium anomaly associated with microtektite occurrences in two deep-sea cores (RC9-58 and site 149) in the Caribbean Sea (4, 5), the suggested extinctions of four radiolarian species, and the major mammal extinctions that apparently occurred within 4 million years of the supposed bolide impact led to the conclusion that catastrophic extinctions occurred near the Eocene-Oligocene boundary (5), similar to the proposed catastrophic scenario of the terminal Cretaceous extinctions (4, 5).

Our data suggest that the ages of microtektite horizons and the suspected associated mass extinctions in the marine and terrestrial records have been misinterpreted. Microtektite occurrences in many deep-sea sequences (Table 1) reveal that the microtektite horizon presumed to belong to the North American tektite-strewn field is restricted to the latest Eocene (P15/P16 planktic foraminiferal zone boundary) with a paleomagnetic age of 37.5 to 38.0 million years (Fig. 2). There appears to be at least one other microtektite horizon ~ 1 million years older and other probable microtektite occurrences at the Eocene-Oligocene boundary and in the mid-Oligocene, but these need further study to determine their petrographic and chemical properties.

No major extinctions of marine or terrestrial faunas and floras are associated with any of the microtektite horizons. Hence there appears to be no cause-and-effect relation between microtektite occurrence, iridium anomaly, and faunal turnover.

We have examined the biostratigraphic record in 18 middle Eocene to middle Oligocene deep-sea sequences; our examination was based on quantitative population studies of planktic foraminifers and nannofossil stratigraphy. This combined approach yields a high-resolution age control and permits accurate dating of microtektite horizons within these sediments. In addition, quantitative population studies illustrate the nature of faunal turnover that has taken place in the marine environment during the time of "mass extinctions" claimed by some workers (4, 5).

We have found microtektites in eight middle Eocene to middle Oligocene deep-sea sequences (Table 1 and Fig. 2); in five of these sequences (DSDP sites 292, 167, 242, 94, and E67-128) the microtektite horizons are stratigraphically coeval, occurring at the latest Eocene P15/P16 planktic foraminiferal zone boundary (within *Isthmolithus recurvus* nannofossil subzone). The *Thyrsocyrtis*

bromia radiolarian zone was used by earlier workers (1-3) to identify the microtektite horizon ranges throughout the late Eocene and hence cannot provide good biostratigraphic control for this microtektite horizon. In two Caribbean Sea sequences, site 149 and piston core RC9-58, biostratigraphic control at the microtektite horizon is poor because of severe CaCO₃ dissolution, mixing, and the probable presence of a hiatus. The sediments underlying the microtektite horizon in these cores are of late middle Eocene age, *Discoaster saipanensis* nanofossil subzone (CP14b) (6), whereas the dissolution-affected sediments containing the microtektite horizon are of either latest middle Eocene or late Eocene age. The late early Oligocene *Sphenolithus predistentus* zone (CP17) overlies the dissolved interval in site 149, an indication that the early Oligocene *Helicosphaera reticulata* zone (CP16) is removed by a hiatus. The microtektite horizon in these Caribbean sequences are thus most likely of late Eocene age, and on the basis of their common occurrence and chemical and optical similarities with microtektites of site 94 (1), earlier investigators concluded that they are part of the North American tektite-strewn field; therefore, they may be coeval with those in the other five, well-dated horizons.

This microtektite horizon is now well dated on the basis of microtektite horizons in the five deep-sea sequences with excellent biostratigraphic control. The microtektite horizon in these sequences coincides with the P15/P16 planktic foraminifer zone boundary (*Globigerinatheka semiivoluta*-*Globorotalia cerroazulensis* zone boundary), which correlates to the upper part of magnetic anomaly 16 (7) (Fig. 2). Recent magnetostratigraphic studies have provided radiometric dates for the tops of anomalies 12 and 13 of 32.4 and 34.6 million years, respectively (8). The lower part of anomaly 13 has a date of 36.1 million years, and the reversed interval above anomaly 15 has a date of 37.4 to 37.7 million years (8-10). These dates provide tight geochronologic constraints for the microtektite horizons and are consistent with the magnetic time scale of Ness *et al.* (11) for the Oligocene and of LaBrecque *et al.* (12) for the late Eocene. Using these magnetic time scales, we find that the age of the microtektite horizon is 37.5 million years

(11) or 38.0 million years (12). This age is considerably older than the fission track date of 34 to 35 million years; the difference may be attributable in part to the bias toward younger dates of the fission

track method. The standard error margin of the fission track ages are 34 to 35 ± 2 to 4 million years (3); the older range of these dates is well within the paleomagnetic age of 37.5 million years.

Table 1. Biostratigraphic zonation and core depth of microtektite occurrences in marine sediment sequences. The following DSDP sites were also investigated, but no microtektites were found: sites 219, 217, 253, and 237 (Indian Ocean); sites 77, 277, 163, and 69A (Pacific Ocean). Abbreviations: SSQ, St. Stephen quarry, Alabama.

Site	Depth of microtektites (core-section, depth)	Foraminifer zone	Nannofossil zone
<i>Pacific Ocean</i>			
292	29, core-catcher	P20/P21	CP18
292	36-2, 36-4 (3)	P16	CP15b, top
292	38-2 (35 cm)	P15, middle	CP15b, near base
167	28-1 (35 cm) (3)	P15/P16	CP15b
<i>Indian Ocean</i>			
242	10-4, 10-5 (99 cm)	P20, top	CP18
242	15-1 (62 cm), 15-3 (100 cm)	P17/P18	CP16a
242	18-1 (60 cm)	P15, top	CP15b
242	19-3 (60 cm)	P15, middle	CP15b
<i>Caribbean Sea</i>			
149	31-1 (46 cm)		{Below CP17 Above CP14 (6)}
RC9-58	Peak at 240 to 258 cm		{Below CP16 Above CP14 (6)}
<i>Gulf of Mexico</i>			
94	14-1 (109 cm)	P16	CP15b, top
94	15-4 (68 cm)	P15/P16	CP15b
E67-128	5198 feet	P15/P16	CP15b
E67-128	5206, 5209 feet	P15, middle	CP15b
SSQ	SSQ 2, 3	P16	
SSQ	SSQ 15	P20	

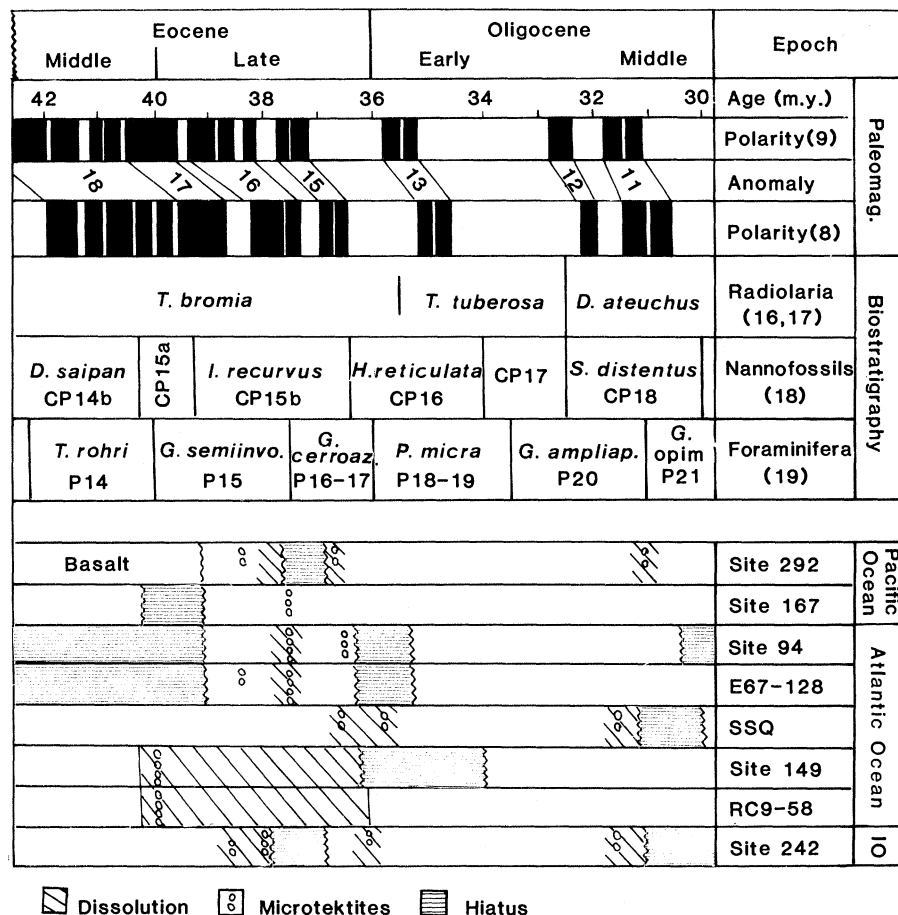


Fig. 2. The occurrences of microtektite horizons in marine sediment sequences in the biostratigraphic and magnetostratigraphic time scale; SSQ, St. Stephen quarry; IO, Indian Ocean; m.y., millions of years.

There are two other, although less well-defined, microtektite occurrences present in upper Eocene marine sediments at about 38.5 million years (sites 292, 242, and E67-128) and near the Eocene-Oligocene boundary at about 36.0 million years [sites 242 and 94 and St. Stephen quarry (Fig. 2)]. The stratigraphic occurrences of these microtektites indicate events separate from the North American tektite-strewn field of 37.5 to 38.0 million years ago; no major reworking or bioturbation is evident at these intervals.

In addition, rare microtektites have been found at stratigraphic levels estimated to have an age of 31 to 32 million years [sites 292, 242, and St. Stephen quarry (Table 1; Fig. 2)]. Chemical analyses will be necessary to determine whether these glassy microspheres are indeed microtektites and to differentiate these from the microtektite horizon at 37.5 million years ago.

Sediments in which microtektites were found are affected by CaCO_3 dissolution, and in many sections a short hiatus is present (Fig. 2). Microtektites are most abundant in the radiolarian ooze of sites 149 and RC9-58 where, incidentally, the iridium anomalies were found (4, 5). Most of the CaCO_3 in these sediments has been dissolved. This suggests that microtektites, and perhaps iridium, are selectively concentrated at dissolution intervals.

The extinction of five radiolarian species at the microtektite horizon appears to be due to the hiatus that is commonly present at this interval. The terrestrial mammal extinctions which Alvarez and his colleagues refer to as "mass extinctions" occur in the mid-Oligocene at 32.4 million years (13), that is, 5 million years after the supposed bolide impact. Berggren *et al.* have pointed out (10) that this faunal turnover is not interpreted by vertebrate paleontologists in terms of catastrophism.

Quantitative population analyses of nannofossils (14) and planktic and benthic foraminifers (15, 16) reveal no major extinctions in the marine records. Five distinct faunal assemblage changes do occur, however, in the marine plankton record between middle Eocene and middle Oligocene time at 43 to 42, 41 to 40, 38 to 37, 36 to 35, and 31 to 30 million years ago. These faunal changes coincide with paleoclimatic cooling episodes as determined by $\delta^{18}\text{O}$ studies (15). During these cooling episodes, faunal turnover occurred gradually; as a result, there was a reduction in the relative abundance of some species and increased dominance of others (15). There

is no evidence, however, for a catastrophic event at any of the faunal assemblage changes. Climatic cooling in the interval from the middle Eocene to the middle Oligocene appears to have been induced by the growth of a major Antarctic ice sheet. These climatic changes were presumably triggered by the separation and northward movement of India and Australia from Antarctica and the subsequent development of the circum-Antarctic current (17).

The conclusions of Glass and his co-workers (1-3) should be reevaluated since (i) all middle Eocene to middle Oligocene microtektite horizons are not coeval and (ii) no faunal extinctions can be correlated with any of the microtektite horizons or with the late Eocene bolide impact (4, 5) that occurred in the late Eocene about 37.5 to 38.0 million years ago.

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Nitrogen Fixation by Floating Diatom Mats:

A Source of New Nitrogen to Oligotrophic Ocean Waters

Abstract. *Nitrogen fixation, apparently by bacterial endosymbionts, is associated with intertwining chains of two species of the diatom Rhizosolenia. In situ fixation rates were enhanced by incubation in the dark, whereas concurrent shipboard experiments either underestimated or did not detect nitrogen fixation. This is the first example of nitrogen fixation associated with a bacteria-diatom symbiosis in the pelagic zone, and it indicates that these systems may contribute a significant amount of "new" nitrogen to oligotrophic waters.*

Although oligotrophic central oceanic regions such as the North Pacific Gyre and the Sargasso Sea are traditionally viewed as biological deserts, more recent evidence indicates that they may in fact be highly productive (1, 2). Researchers seeking explanations for high productivity in waters that often lack measurable amounts of nitrogenous nutrients have hypothesized processes ranging from salt-fingering (3) and small-scale nutrient pulses produced as a result of zooplankton excretion (2) to remineralization (4) and nitrogen fixation (5). Although current models describing inputs of "new" nitrogen to oligotrophic waters consider nitrogen fixation unimportant (6), our work suggests that the

fixation rates may have been underestimated and that this process may introduce significant amounts of nitrogenous nutrients into these waters.

One notable example of high primary production under nutrient-limited conditions is demonstrated by free-floating diatom mats composed of *Rhizosolenia castracanei* and *R. imbricata* var. *shrubsolei* (7) (Fig. 1A). These mats have been noted in surface waters of the Sargasso Sea (8), the North Pacific Gyre, and the California Current (7). On a recent cruise to the eastern Pacific (9), we found *Rhizosolenia* mats in great abundance (up to 4.4 m^{-3}). The aggregations are large (average length, 7 cm) and conspicuous to scuba divers, yet they are often not