orites (*7*). A calculation can be made of the minimum size of the impacting body from the following data: (i) the area of fallout for the North American microtektites is at least 36 million km^2; (ii) the excess Ir per square centimeter from 260 to 290 cm in depth is about 63×10^{-9} g; and (iii) the chondritic Ir content is 514×10^{-9} g/g (*8*). This calculation indicates that the impacting object weighed at least 50 billion tons and was 3 km in diameter. The estimate is a minimum because the size of the fallout field could be greater than has been assumed.

Although meteoritic Ir and impact-produced microtektites are near each other in this deep-sea core, their concentration profiles are not identical. The distribution peaks correspond to a separation of about 30 cm of sediment. However, in the Ir-rich region there are abundant dark, opaque microtektite spherules that have crystalline material in the glass. It has been suggested that these dark spherules are related to the other microtektites in the core (*5*). In this case, the fallout of microtektites, meteoritic debris, and dark spherules could have been contemporaneous, and the 30-cm displacement may have resulted from local factors such as bioturbation, turbidity currents, or density differences rather than a real time difference.

East Asian and Australian tektites, resulting from meteorite impact(s) on the earth about 0.70 to 0.83 million years ago, both contain a meteoritic component (*9*). The Ivory Coast tektites (1.3 million years) and the Czechoslovakian tektites (15 million years) are both associated with craters of the same ages. The origin of the North American tektites has long been disputed because of lack of direct evidence in the form of either a meteoritic component or a crater (*10*). Deep-sea sediments have now provided evidence for an impact origin for the North American tektites. Urey (*11*) had suggested earlier that the Eocene extinctions may have resulted from the impact that produced the North American tektites.

O'Keefe (*6*) has recently suggested that the Eocene extinctions might have been triggered by the formation of Saturn-like rings consisting of extraterrestrial tektites coming to the earth. Such an origin for North American tektites must now be regarded as remote, since their close association with a meteoritic component implies that they, like other tektites, were produced on the earth by a massive meteorite impact.

High concentrations of noble metals in terrestrial sediments have now been found at or near two major divisions in the stratigraphic record: the Cretaceous-Tertiary boundary (*3*) and the Eocene-Oligocene boundary. In both cases, there is evidence of extinctions among diverse fauna and flora. It is difficult to avoid the implication that major meteorite impacts have played a role in the evolution of life on the earth (*12*).

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5. B. P. Glass, personal communication; C. John and B. P. Glass, *Geology* **2**, 599 (1974). The data on microtektites per gram plotted in Fig. 1 were obtained from B. P. Glass. The question has been raised of whether there could have been a mix-up of samples at Lamont-Doherty, where the core samples are kept. Glass has checked some of my samples to ensure that there was no mixup; his examination confirmed abundant microtektites around 250 cm and dark, opaque glass spherules around 280 cm.
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7. The nickel and cobalt contents of the sample from 279.5 cm are 82 and 17 ppm. Background levels of these elements are 44 and 13 ppm. Abundance ratios relative to C1 chondritic meteorites are Ir, 7×10^{-3}; Co, 8×10^{-3}; and Ni, 4×10^{-3}.
8. The integrated excess Ir was calculated assuming a bulk density of 2 g/cm^3 for the sediment and a background correction of 0.4 ppb.
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12. Throughout this report I have indicated an age of 34 million years for the meteoritic impact at the terminal Eocene period. The fission track age of microtektites and the potassium-argon age of North American tektites are 34.6 and 34.2 million years. The close association of these microtektites with the disappearance of five major species of Radiolaria implies that the Eocene extinctions occurred 34.4 million years ago.
13. I am indebted to the following individuals for the successful completion of this work: J. W. Larimer for encouragement and assistance; O. K. Manuel for the reirradiation of Ir samples after chemical purification; A. Meyer and S. Gunn for neutron irradiation of samples; S. Mehtha for x-ray diffraction data; N. Trivedi for scanning electron micrographs; N. Arner, H. Kaufman, and K. Weber for encouragement; B. P. Glass for information on the microtektite distribution in deep-sea cores and for many helpful suggestions; F. McCoy for the core samples; and N. van Tyne for measuring the radioactivity in my samples while I was operating the plant during a worker's strike. Finally, my friend and colleague, R. T. Zahour, who died on 8 November 1981, provided invaluable assistance in setting up this laboratory.

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Iridium Anomaly Approximately Synchronous with Terminal Eocene Extinctions

Abstract. *An iridium anomaly has been found in coincidence with the known microtektite level in cores from Deep Sea Drilling Project site 149 in the Caribbean Sea. The iridium was probably not in the microtektites but deposited simultaneously with them; this could occur if the iridium was deposited from a dust cloud resulting from a bolide impact, as suggested for the anomaly associated with the Cretaceous-Tertiary boundary. Other workers have deduced that the microtektites are part of the North American strewn tektite field, which is dated at about 34 million years before present, and that the microtektite horizon in deep-sea cores is synchronous with the extinction of five radiolarian species. Mass extinctions also occur in terrestrial mammals within 4 million years of this time. The iridium anomaly and the tektites and microtektites are supportive of a major bolide impact about 34 million years ago.*

Iridium and other siderophile elements depleted in the earth's crust occur in anomalously high concentrations at the same stratigraphic level as the marine micropaleontological extinctions that define the Cretaceous-Tertiary boundary at about 66.7 million years ago. This anomaly has been documented at 12 sites in marine sediments (*1–6*) and one site in terrestrial sediments from New Mexico (*7*), and several other occurrences have been discussed (*8*). Stratigraphic information from southern Spain shows that the iridium-bearing level was deposited in an interval probably no longer than about 50 years (*9*). The anomaly has been interpreted as a result of the impact on the earth of an extraterrestrial object (*2, 8, 10, 11*), and it has been estimated that an impact of this magnitude should occur roughly every 100 million years (*12, 13*). Several mechanisms have been suggested for extinctions following a bolide impact (*2, 14–16*). The impact explanation for the terminal Cretaceous extinctions suggests that evidence for impact of an extraterrestrial object might be found at the stratigraphic horizons of other mass extinctions. In fact, there is already one case where there is evidence for an impact at or close to evidence for such an extinction.

Tektites are generally considered to have been formed by meteoritic or cometary impact on the earth, although a lunar origin (*17*) has also been suggested. Earlier references have been given by Glass *et al.* (*18*). The North American tektites on land and the associated microtektites studied in sea-bottom cores principally by Glass and co-workers (*18–20*) very likely provide direct evidence for a major impact. The strewn field extends halfway around the earth and contains at least 10^{10} metric tons of impact melt in the form of far-traveled glassy spherules (*18*). The best value for the fission track and K/Ar ages of North American tektites is 34.2 ± 0.6 million years (*21*), and the fission track age of microtektites is 34.6 ± 4.2 million years (*22*). Five radiolarian species die out at the microtektite level (*19*), but the event occurred about 2 million years before the Eocene-Oligocene boundary (age, 32.5 ± 0.9 million years) (*21*) as defined in the Deep Sea Drilling Project (DSDP) reports (*23*). The major turnover of mammalian taxa that defines the Eocene-Oligocene boundary in terrestrial sequences in North America, Europe, and Asia (*24*) has been assigned an age of 38.0 million years (*25*). The errors on the latter date were not given, and it is not known whether it differs significantly from that of the microtektite horizon.

The possible relation between the Eocene-Oligocene extinctions and a major impact has been considered by other workers (*18, 26*). In order to determine whether the impact that produced the North American strewn field also gave rise to an iridium anomaly, we measured 30 elements by high-precision techniques of neutron activation analysis in nine samples from DSDP site 149 in the eastern Caribbean. A preliminary report on this work has been presented (*27*).

Drilling at DSDP site 149 yielded a "Radiolaria-rich nannoplankton chalk" in the middle Oligocene of core 30 and a "semi-indurated calcareous-rich radiolarian ooze" in the upper Eocene of core 31 (*23*). The basal Oligocene may be missing between cores 30 and 31 (*23, 28*), a gap possibly amounting to 7 m (*19*). This was the discovery site for the North American microtektites (*29*), but the peak of microtektite abundance was apparently lost in the unrecovered interval between cores 30 and 31. The microtektite abundance rises rapidly at the top of core 31, but is back to nearly zero at the base of core 30 (Fig. 1). Despite the missing section, this DSDP site offered an opportunity to look for an extraterrestrial component.

Table 1 shows the stratigraphic levels and abundances of selected elements for the nine samples from cores 30 and 31 of DSDP site 149. Anomalously high iridium levels were found, coinciding with the highest abundance of microtektites, at the top of core 31. The two highest samples in core 31 have Ir concentrations of 0.41 ± 0.16 and 0.34 ± 0.10 parts per billion (ppb) as a fraction of the whole rock. The next sample below has a value for Ir that appears to follow the trend of the microtektite abundance but is also indistinguishable from zero. The other six samples, at levels where microtektites are very rare or absent, have a best value for the iridium abundance of 0.00 ± 0.05 ppb. We conclude that (i) the association of iridium anomalies with major impact events, inferred for the Cretaceous-Tertiary boundary, is strengthened by recognition of an iridium anomaly at a microtektite horizon; (ii) although not all impacts that produce detectable iridium enrichments are necessarily related to extinctions (*30*), the association of iridium anomalies with extinctions is strengthened by the disappearance of five species of radiolaria at the same level as the iridium and microtektite anomalies near the Eocene-Oligocene boundary; and (iii) detailed studies of the latest Eocene are needed to determine whether the terminal Eocene mass extinction of land mammals is synchronous with the tektite-iridium horizon.

Discovery of the late Eocene iridium anomaly raises a number of questions for further study. As seen in Fig. 1, the

Table 1. Selected DSDP 149 chemical data. The indicated precisions of measurement are standard deviations (S.D.) in gamma-ray counting. Calcium was calibrated against a $CaCO_3$ primary standard; Cr and Ni were calibrated against a secondary standard, "standard pottery" (*38*), with abundances of 102 ± 4 and 278 ± 7 ppm, respectively (*39*); and Ir was calibrated against a secondary standard, DINO-1 (prepared from the Danish Cretaceous-Tertiary boundary layer), with abundance 31.5 ± 0.6 ppb. The accuracies of the measurements are comparable to the precisions. When backgrounds comparable to gamma-ray peak intensities are subtracted, negative differences are sometimes obtained. If the difference is negative or if it is positive but smaller than 2 S.D., 2 S.D. plus any positive difference is given as the upper limit. The differences and standard deviations, in parts per billion, are also shown in parentheses.

Core	Section	Interval (cm)	Ca (%)	Cr (ppm)	Ni (ppm)	Ir (ppb)
30	2	20–21	25.1 ± .7	27.0 ± 0.9	56 ± 6	<0.36 (−0.06 ± 0.18)
30	2	100–101	23.5 ± .8	27.7 ± 0.5	53 ± 6	<0.21 (0.05 ± 0.18)
30	2	140–141	19.7 ± .7	34.0 ± 0.5	76 ± 8	<0.22 (0.02 ± 0.10)
31	1	1–2	5.4 ± .5	30.4 ± 1.1	86 ± 10	0.41 ± 0.16
31	1	3–4	3.6 ± .5	30.8 ± 1.1	98 ± 10	0.34 ± 0.10
31	1	14–15	2.6 ± .6	32.7 ± 1.1	103 ± 10	<0.42 (0.14 ± 0.14)
31	1	26–27	1.2 ± .4	29.7 ± 0.7	93 ± 9	<0.34 (0.06 ± 0.14)
31	1	40–41	6.1 ± .6	27.1 ± 0.7	77 ± 8	<0.24 (−0.01 ± 0.12)
31	1	84–85	6.9 ± .5	25.3 ± 0.9	75 ± 9	<0.26 (−0.15 ± 0.13)

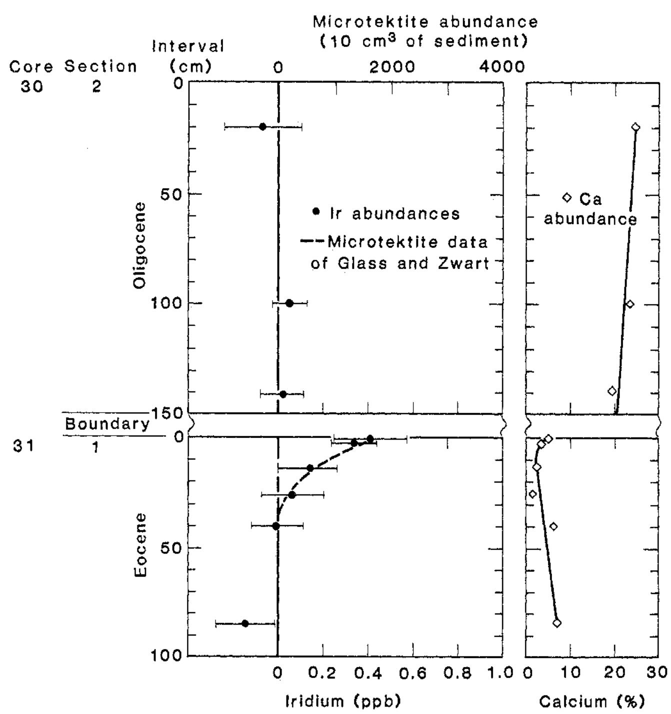

Fig. 1. Iridium and calcium whole-rock abundances in cores from DSDP site 149. Error bars in the Ir data are 1 S.D. In the Ca measurements 1 S.D. is smaller than the points.

iridium abundance pattern is quite different from that of calcium. It is also much different from that of the noncalcareous components of the sediments, which were determined by subtracting each of the calculated $CaCO_3$ abundances from 100 percent. The differences suggest that the Ir was not carried by the major components in the sediments, $CaCO_3$, silica, and clay (*23*), but by a minor component in the top of core 31, section 1, and perhaps in the lost interval between cores 30 and 31. The terrestrial component that would be most likely to contain sufficient Ir would be an ultramafic one. Such a terrestrial source should also contain detectable Cr and Ni, whereas a meteoritic source would not. Of the six late Eocene samples, the two that definitely contain Ir average 30.6 ppm Cr and 92 ppm Ni, and the other four average slightly less. From the differences in Cr and Ni abundances between the four Ir-poor and the two Ir-rich samples plus twice the root-mean-square deviations in the former, the maximum abundances of these elements which should be due to a separate component in the Ir-rich samples are 7 and 29 ppm, respectively. Ultramafic rocks contain Ir in even higher abundances than the observed anomaly, but estimates of their contribution can be made from their Cr and Ni contents. From 126 measurements of Ni and Ir abundances in ultramafic rocks (*31–33*) the Ni/Ir ratio is 0.65×10^6, and from 24 measurements of Cr and Ir abundances (*33*) the Cr/Ir ratio is 0.13×10^6. The expected Cr and Ni abundances in the Ir-rich samples due to such an intrusion (if marine fractionation is assumed to be negligible) would average 49 and 244 ppm, respectively; these values are much higher than the observed limits. If the intrusive component were due to a chondritic extraterrestrial source, the added Cr and Ni abundances would be 2 and 7 ppm (*34*), respectively, consistent with the observed limits.

Meteorite ablation debris is continually accumulating in deep-sea sediments. From Maurrasse's (*28*) value of 1.6 mm per 1000 years for late Eocene sedimentation in DSDP site 149 and Barker and Anders' (*35*) relation between Ir abundance and sedimentation rate, corrected for appropriate densities, the maximum expected Ir concentration would be 0.02 ppb. The observed value is 20 times higher, which agrees with the interpretation that the microtektites are evidence for a single large impact.

Iridium has not yet been measured in the microtektites, but estimates can be given. From the Os abundance of ≤ 1 ppb in the correlative bediasite tektites from Texas (*36*), the typical Ir/Os ratio of about one in chondritic material (*34*, pp. 451 and 463), and the maximum mass of microtektites (>125 μm in diameter) in core 31, 0.2 percent (*19*), the Ir abundance at the top of core 31 would be < 0.002 ppb. The much higher values observed indicate that the iridium was not carried primarily by the microtektites. This agrees with the interpretation that tektites are formed from shock-melted target rock, with only minor contamination by extraterrestrial material.

Even though terrestrial sources of Ir are rare, there are some which can cause serious errors. We stated in (*37*) that an Ir anomaly had been found associated with a continental Cretaceous-Tertiary deposit in Montana. We subsequently found that this attribution of the anomaly was erroneous and that the Ir was due to the platinum wedding or engagement ring worn by a technician who had prepared the samples for analysis. Platinum used for jewelry contains about 10 percent Ir, which is used as a hardening agent. If a platinum ring loses 10 percent of its mass in 30 years, the average loss per minute (if it all deposits on a sample) is about two orders of magnitude higher than our sensitivity of measurement. Thus the Ir anomaly measured near the Eocene-Oligocene boundary is comparable to the average amount lost from a platinum ring in ~ 2 seconds. Tests also demonstrated that gold impurities were introduced into samples if the sample preparer wore a gold ring. These effects are of concern because of the possibility of Pt, Ir, and Au contamination in the handling of deep-sea cores and other material collected in searches for geochemical anomalies. None of the published results of our group, except for the Montana comment discussed above, were affected by the wedding-ring anomalies.

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