emboli and the timing of drug administration to increase the likelihood of demonstrating therapeutic efficacy. The apparent safety of the drug in these experimental conditions does not prove that tPA will be safe in cases where larger emboli lodge in the cerebral circulation and hemorrhagic complications may arise after the onset of ischemia. Until such preliminary studies are completed, trials with human patients will be premature. However, the potency ratio for tPA of 1.7 (*15*) suggests that this drug may be beneficial for such urgent medical problems as frequent transient ischemic attacks with threatened infarction and stroke in evolution. Whether further benefits may be derived from treatment with tPA after more severe ischemic damage has already been done remains to be determined.

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14. We are currently engaged in a number of further investigations to examine such factors as the length of time after embolization over which tPA therapy can reduce neurological damage, the effects of varying the size of emboli, and the determination of whether hemorrhagic complications will develop after cerebral ischemic damage is produced. All of these questions can be experimentally approached with the embolic stroke model we have described here.
15. The potency ratio is the ED_{50} of the treated animals divided by the ED_{50} of the controls.

16. We thank Genentech, Inc., for supplying the tPA.

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Cretaceous-Tertiary Extinctions: Alternative Models

Officer and Drake (*1*) appear to present a valid alternative to the large impact model for the Cretaceous-Tertiary extinctions. Their basic premise is that the distribution of iridium (Ir) in some sections can only be explained by an event of relatively long duration. This proposal is supported by a model which suggests that Ir distribution extending beyond an interval expected by bioturbation requires a noninstantaneous source for the siderophiles. They further suggest that evidence favors a mantle (volcanic) origin for these elements. We find that (i) the bioturbation model is inaccurately applied and inadequately explains possible sedimentary effects for any given section, (ii) there is no evidence of prolonged Ir sedimentation at any site, and (iii) the volcanic model, although not positively excluded by the data, is not easily reconciled with the data and remains at best a very low probability alternative to the impact hypothesis.

The bioturbation interval of 11 cm (5 to 6 cm after compaction) used by Officer and Drake applies only to the homogenization interval for surface sediments. As deposition (and burial) proceeds, older sediments continue to be mixed upward. Sediments that are deposited instantaneously (like microtektites or ash) can be spread over tens of centimeters (*2*). Table 1 shows the observed distribution of microtektites (*3*), which are spread over a minimum of 35 cm and an average of 59 cm. Bioturbation is only one process that will affect Ir distribution after a presumed impact. Other potentially important processes include diagenetic mobilization, secondary deposition after transport by bottom currents, and

Table 1. Observed distribution of microtektites in eight piston cores (*3*). The duration of the microtektite zones indicates the time interval represented by the length of sediment across which the microtektites have been smeared by bioturbation.

Core	Sedimentation rate (m/10^6 years)	Microtektite zone	
		Length (cm)	Duration (years)
RC8-52	5.6	80	145,000
RC8-53	2.6?	40?	155,000?
RC9-137	6.4	40	63,000
RC9-143	5.1	50	98,000
V16-70	2.2	70	320,000
V16-76	15.1	~50	~33,000
V19-153	7.5	35	47,000
V19-297	7.0	90	130,000
Average	7.0	59	130,000

delayed deposition of siderophiles in solution, which have relatively long residence times.

Because there is no independent evidence for prolonged deposition of Ir-rich sediment at the four sites cited by Officer and Drake, the bioturbation argument may not be relevant.

1) Site 465A was grossly disturbed by drilling, and Cretaceous and Tertiary sediments are mixed over an interval of at least 100 cm (*4*). The published profile for this locality does not in any way reflect the original stratigraphy, which cannot be determined in this section.

2) Anomalously high concentrations of Ir have been reported in only 10 cm of the core at site 524 (*5*); the 43 cm cited by Officer and Drake is the distance to the first background analysis.

3) High Ir concentrations below the fish clay in Stevns Klint, Denmark, rely on correction for more than 99 percent $CaCO_3$, but the significance of the procedure is not clear. The highest concentrations measured outside the fish clay are approximately 0.1 ng/g Ir and probably amount to only a few percent of the total Ir in the section at best. It is reasonable to expect some diffusion of siderophiles out of the clay during diagenesis, and there is no evidence for prolonged deposition of large amounts of siderophiles. Moreover, Stevns Klint is a prime example of a lithologic discontinuity, which Officer and Drake state "preclude[s] precise geologic time discrimination." In fact, every known K/T boundary section has a lithologic discontinuity, and that, if we follow the criteria of Officer and Drake, invalidates their time interval estimates.

4) The Brazos River, Texas, section shows irregular peaks of significant amounts of Ir over about 45 cm on top of a thick turbidite-like sediment at the K/T boundary (*6*). This is a shallow shelf environment where lateral transport, reworking, and winnowing of sediments by storm waves is common. The Ir distribution is easily explained in terms of these mechanisms and by bioturbation.

With regard to characteristics of the event that suggest a mantle rather than meteoritic source, we make the following points.

1) The discovery of Ir-bearing particulates from Kilauea (*7*) is important. However, such particulates would be deposited near the source; we cannot imagine a volcanic event capable of worldwide distribution of the spheroidal material common to KT sediments (*8*).

2) Isotopic systematics (*9*) of the boundary clay that indicate mantle affinities are likely to represent terrestrial impact ejecta. The impact hypothesis predicts an exotic terrestrial component. We note that only the basal layer (<3 mm) at Caravaca, Spain, is highly enriched in this exotic isotopic component.

3) Spherules found by Vannucci *et al.* (*10*) outside the boundary at Gubbio, Italy, are texturally and compositionally different from those in the boundary clay. In particular the siderophile-rich spherules with skeletal magnetite (*11*) described in Italy and the North Pacific are characteristic of the KT boundary.

4) The lamellar quartz can easily be distinguished from coesite, which forms under high static pressures.

5) Iridium concentrations do not correlate with clay concentrations. Measurements within the boundary clay (*12*) at Stevns Klint and Caravaca show a decrease in the ratio of Ir to clay by a factor of 3 to 5. Extrapolations into the nearly pure carbonates at Stevns Klint are not appropriate unless one first demonstrates that the Ir actually resides in the silicate fraction. In other localities (for example, Caravaca), where backgrounds contain a substantial clay fraction, Ir is not observed.

6) We question the use of the data of Wezel *et al.* (*10*) on Ir in clays below the K/T boundary from Gubbio. Why was the data of Alvarez *et al.* (*13*) on the same clays, which indicates no excess Ir below the K/T boundary, ignored?

We agree that the available data do not exclude a volcanic source for the siderophiles or the boundary clay. However, the shocked quartz and the global spherule distribution would appear to limit it to extremely violent events. A statistically probable impact is a more likely explanation than a poorly defined mantle event resulting in worldwide simultaneous volcanic eruptions of an unprecedented magnitude.

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The statement by C. B. Officer and C. L. Drake (*1*, p. 1164) that "the presence of lamellar quartz features does not in and of itself demonstrate a meteor impact origin" for the shock-metamorphosed quartz grains discovered at several widespread locations in the Cretaceous-Tertiary (K/T) boundary layer (*2*) gives a misleading impression of the relative evidence for the impact and nonimpact interpretations of such features. The impact interpretation rests on a solid and extensive base of theoretical, experimental, and observational studies, whereas such unspecified alternative mechanisms as "intense volcanic or tectonic overpressure events" (*1*, p. 1164) are not supported by field evidence or by the establishment of a testable mechanism.

The use of these lamellar features (shock lamellae) in quartz, together with other shock-deformation effects, to indicate meteorite impact has been justified in studies of the earth (*3–5*) and other planets (*6*).

1) It is generally accepted, even by some proponents of nonimpact mechanisms (*7*) that certain unusual deformation features in rocks and minerals are produced only by intense transient shock waves that have peak pressures as high as 5 to 100 GPa (50 kbar to 1 Mbar). These features include (*8*): (i) distinctive shock lamellae in quartz and other minerals, which are clearly different in both appearance and orientation within the host grain from conventional metamorphic deformation lamellae; (ii) amorphous (diaplectic) glassy forms of minerals; (iii) shatter cones; (iv) high-pressure minerals such as coesite and stishovite, when found in low-pressure, high-level crustal rocks. The formation of these features by shock waves has been recorded in laboratory experiments (*9*) and after chemical and nuclear explosions (*10*). Other distinctive features, such as extensive brecciation and the melting of refractory minerals such as quartz and zircon at temperatures above 1700°C, are produced by shock waves, but they may also be produced in nonshock environments.

2) Hypervelocity meteorite impacts on the surface of the earth can and do generate shock pressures adequate to form these distinctive features. Evidence for this view comes from both theoretical studies of the impact process (*4, 11*) and from the occurrence of shock-metamorphic features in young structures of undoubted meteorite impact origin, for example, Meteor Crater, Arizona (*12*).

3) The resulting hypothesis, that any geological structure which exhibits shock-metamorphic effects has been formed by meteorite impact, has not been disproved in the more than 20 years since it was first proposed. Shock-metamorphic effects have been found only in so-called "cryptoexplosion" structures that are circular (or nearly so), localized, and characterized by sudden and extensive deformation—generally consistent with the expected effects of large meteorite impacts.

4) No shock-metamorphic effects have been observed in undisputed volcanic or tectonic structures. The coesite found in deep-seated rocks (*1*) apparently formed stably at high lithostatic pressures and is not accompanied by any characteristic shock effects.

5) Despite much speculation (*13, 14*), no mechanism to explain the generation of shock waves within the earth has been developed to a point that permits critical evaluation and prediction.

Officer and Drake (*1*) correctly point out that ambiguities and controversies exist in the intepretation of shock-metamorphic effects in large and complex structures like those in Vredefort, South Africa (*15, 16*), and Sudbury, Canada (*14, 17*). However, there is evidence for an impact origin of both structures (*15, 17*), which is consistent with observations at other impact structures. In view of the evidence for the impact mechanism, it is probable that these ambiguities are caused by our ignorance about the details of how impact structures with diameters of 100 km are formed rather than by flaws in the impact theory itself.

Suggestions that the K/T extinctions have a volcanic origin should include evidence that the shock-metamorphosed quartz grains are unrelated to the K/T event or that there was volcanism that could have produced both global iridium anomalies and shock-metamorphic features.

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We welcome the commentary by Smit and Kyte (*1*) and by French (*2*) related to our article (*3*). Their criticisms fall into five categories: (i) bioturbation; (ii) temporal extent of the iridium signature; (iii) iridium enhancements in the clays at Gubbio, Italy; (iv) microspherules; and (v) shock deformation features.

Bioturbation. The statement by Smit and Kyte (*1*) that "the bioturbation interval of 11 cm (5 to 6 cm after compaction) used by Officer and Drake applies only to the homogenization interval for surface sediments" is incorrect. They refer to an article on microtektites by Glass (*4*), but do not note that the result quoted in our article (*3*) of a mixing depth of 11 ± 5 cm for microtektite, ash, and pumice distributions was based on determinations by Officer and Lynch (*5*) from 16 piston cores, six from the same article by Glass (*4*), one reported by Glass *et al.* (*6*), and nine more recent observations by Ruddiman *et al.* (*7*). The analyses followed analytic and computer parameter optimization procedures developed by Officer and Lynch (*8*) and Lynch and Officer (*9*). All showed a characteristic bioturbation distribution expected for an instantaneous flux input. Glass (*4*) reported two additional cores, RC8-52 and RC8-53, for which the microtektite distribution did not follow this pattern, but showed an irregular and erratic distribution over a depth interval of 40 to 80 cm. As we noted in our article (*3*), this is to be expected at some locations where there can be extreme physical disturbance of deep sea sediments (*10*). Glass (*11*) also furnished microtektite distributions for 17 other cores. We have analyzed them for the purpose herein. Sixteen have a characteristic bioturbation distribution with an average mixing depth of 12 ± 3 cm (table 1). The other core, V19-171, shows an irregular distribution over 40 cm. In summary, of 35 cores with microtektite, ash, and pumice distributions, 32 show a well-defined bioturbation characteristic with a mixed layer thickness of 11 to 12 cm; three show a distribution reflecting more extreme physical mixing processes.

For compacted K/T sediments the bioturbation interval will be reduced to about 5 to 6 cm (*3*). It is necessary to examine each K/T section to determine the extent of bioturbation smearing. For example, at DSDP site 516F in the southwest Atlantic there is essentially no bioturbation in the K/T core (*12*), and at DSDP sites 525 and 529 along the Walvis Ridge bioturbation smearing varies from 1 to 5 cm (*13*).

Temporal extent of the iridium signature. Smit and Kyte (*1*) comment on the drilling disturbance at DSDP site 465A, which we also noted (*3*). Specifically, for the K/T core at this site there is a "white stringer of Cretaceous material which has spread into the Paleocene section during the drilling process" (*14*, figure 6). We consider that the observed distribution of iridium and other associated elements over an extended depth interval corresponding to the pyrite portion of the Paleocene gray ooze (*3*, figure 1) correctly represents K/T conditions at this site. Smit and Kyte (*1*) also criticize our citation of data from Stevns Klint, Denmark (*15*), because it is corrected for carbonate. In most models the iridium is associated with the noncarbonate fraction and is not related to the nannofossil and microfossil remains of biogenic origin in these sediments. For sections in which there are substantial variations in the fraction of bulk sediment that these remains represent, it is appropriate to make comparisons on a carbonate-free basis.

For DSDP site 557B in the northwest Pacific, there is no clay layer and little variation in the carbonate fraction through the K/T transition. A broad peak for iridium and other associated elements including iron occurs over 50 cm at the K/T transition corresponding to a time interval of approximately 50,000 years (*16*). In addition there are satellite peaks at 40 and 230 cm below the main peak and 270 cm above the main peak. The satellite peaks have concentrations of iron and associated elements comparable to those of the K/T peak but lower concentrations of iridium. In particular the Ir/Fe ratio shows a gradual increase (by two orders of magnitude) to the K/T peak followed by a gradual decrease over a total core depth interval of 300 cm. It is difficult to explain the extended iridium distribution for the K/T peak in terms of a single asteroid impact. It is equally difficult to explain the gradual change in the Ir/Fe ratio in terms of a series of impacts. We suggest that these variations are best explained in terms of volcanic activity and that the change in the Ir/Fe ratio represents a deeper mantle plume source of volcanism.

Iridium enhancements in the clays at Gubbio, Italy. Smit and Kyte (*1*) question our use of the data from Wezel *et al.* (*17*) and Vannucci *et al.* (*18*) on iridium in the clays below the K/T boundary clay at Gubbio and ask why we ignored the Alvarez *et al.* (*19*) data on the same clays which indicate no excess iridium. One, we did not use the Wezel *et al.* (*17*) and Vannucci *et al.* (*18*) data, although their reports prompted our own investigations. The data presented in table 2 of our article (*3*) were from samples collected by G. D. Johnson and analyzed by J. H. Crocket (*20*). Two, there are no data on iridium determinations for the Gubbio clays in the article by Alvarez *et al.* (*19*).

Wezel *et al.* (*17*) and Vannucci *et al.* (*18*) reported iridium anomalies in clay layers other than the K/T as well as an anomaly of around 10 ppb at the Bonarelli level, of Turonian age, approximately 240 m below the K/T boundary layer clay. Alvarez *et al.* (*19*) report that they find no iridium enhancement in the Bonarelli layer, but do not mention the other Gubbio clay layers. Crocket *et al.* (*20*) also find no iridium anomaly in the Bonarelli layer, but do find iridium enhancements above background in clay layers and the alternating limestones extending 2 m on both sides of the anomaly in the reference K/T clay.

Microspherules. Smit and Kyte (*1*) state that we have essentially ignored the significance of microspherules at the boundary. This is not the case. Microspherules are, indeed, a feature of the K/T transition, and it is generally agreed that their present composition is secondary (*21*). Naslund *et al.* (*22*) have shown that while the microspherules are 10 to 50 times more abundant in the K/T layer, they also occur in clay layers at Gubbio extending over an age span of 22 million years. Many of the microspherules are hollow with a smooth outer surface, and the size and gross morphology of these hollow spherules is similar to that reported for silicate glass spherules formed during volcanism (*23*).

Shock deformation features. French (*2*) argues that the shock metamorphic features of lamellar quartz or shatter cones, or both, that are associated with the Vredefort and Sudbury intrusives and some of the cryptovolcanic structures must be of impact origin. Recent studies at Vredefort and Sudbury contradict this conclusion. For the Vredefort and Sudbury intrusives one hypothesis assumes that a single asteroid impact triggered the intrusion, in which case the shock metamorphic features must be contemporaneous with or predate the intrusion deformation and static (high-temperature) metamorphic features. The other hypothesis assumes that there is a large overpressure event, or events, associated with the intrusion, in which case the shock metamorphic features will postdate the onset of the intrusion. Schreyer (*24*) has shown that dynamic, or shock, metamorphic events at Vredefort postdate the onset of the static, or high-temperature, metamorphic events; the investigations by Lilly (*25*) have shown that there were two shock metamorphic events; and the investigations by Simpson (*26*) have shown that the shatter cone features cut across and postdate indurated fault breccia associated with the structure. All three of these findings are not in accord with an impact origin for the Vredefort dome. At Sudbury, Fleet (*27*) has shown that the shatter cones postdate the emplacement of the nickel intrusive, again contrary to an impact origin.

Table 1. Mixed layer thicknesses determined for an additional 16 microtektite distributions in deep sea piston cores. Microtektite data supplied by Glass (*11*). Mixed layer thicknesses in centimeters.

Core	Mixed layer thickness
V20-138	18.6
RC12-327	8.9
RC12-328	14.1
E35-9	11.6
E45-71	8.1
E45-89	12.9
E49-4	9.0
E49-50	9.2
MSN-48G	14.9
V16-75	12.6
V16-169	15.4
V20-18	11.8
V28-239	9.6
K9-57	7.1
V27-237	6.4
LSDH236	15.1
Average 12 ± 3 cm	

French (*2*) also states that "no shock-metamorphic effects have been observed in undisputed volcanic or tectonic structures." In a recent investigation Carter *et al.* (*28*) have found shock metamorphic features including lamellar quartz in rock samples associated with the Toba eruption. Toba is the largest known volcanic eruption of the recent past, occurring about 75,000 years ago with a total eruption magnitude of 400 times that of Krakatoa (*29*). Microstructures in the Toba rocks record shock stress levels greater than 10 GPa. Carter *et al.* (*28*) conclude that peak shock stresses from explosive volcanism at K/T time could account for the microstructures observed (*30*).

Smit and Kyte (*1*) conclude that "a statistically probable impact is a more likely explanation than a poorly defined mantle event resulting in worldwide simultaneous volcanic eruptions of an unprecedented magnitude." We submit that evidence for the impact is thin and the crater has yet to be found, while massive volcanism is indicated by the geological record. In any event, the question is not whether impacts occurred, it is whether they are related to extinctions. The selective pattern of extinctions is not the stuff of a global dust cloud.

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