Accretion Rate of Extraterrestrial Matter: Iridium Deposited 33 to 67 Million Years Ago

FRANK T. KYTE AND JOHN T. WASSON

Iridium measured in 149 samples of a continuous 9-meter section of Pacific abyssal clay covering the time span 33 to 67 million years ago shows a well-defined peak only at the Cretaceous/Tertiary boundary. In the rest of the section iridium ranges from a minimum concentration near 0.35 nanograms per gram in the Paleocene to a maximum near 1.7 in the Eocene; between 63 and 33 million years ago the mean iridium accumulation rate is approximately 13 nanograms per square centimeter per million years. Correction for terrestrial iridium leads to an extraterrestrial flux of 9 ± 3 nanograms of iridium per square centimeter per million years, and an estimated annual global influx of 78 billion grams of chondritic matter, consistent with recent estimates of the influx of dust, meteorites, and crater-producing bodies with masses ranging from 10^{-13} to 10^{18} grams. Combining the recent flux of objects ranging in mass from 10^6 to 10^7 grams with the flux of 10^{14}- to 10^{15}-gram objects indicates that the number of objects is equal to 0.54 divided by the radius (in kilometers) to the 2.1 power. Periodic comet showers should increase the cometary iridium flux by a factor of 200 to 600 on a time scale of 1 to 3 million years; the predicted iridium maxima (more than 30 times background) are not present in the intervals associated with the Cretaceous/Tertiary boundary or the tektite-producing late Eocene events.

THE EARTH FORMED BY THE ACCRETION OF BODIES WITH masses ranging from tiny fractions of a gram up to about 10^{26} g. Although most accretion occurred during the first 100 million years (m.y.) after the birth of the solar system about 4.5 billion years ago, it continues at the present time.

During the past century a number of techniques have been used to estimate the influx of interplanetary matter. Each technique applies to a limited range of particle sizes. The first quantitative estimates were based on the observation of visual meteors corresponding to projectiles ranging in size between 10^{-2} and 10^{1} g (*1*). These were augmented in the 1950's by radio observations extending the range down to 10^{-6} g and in the 1960's and 1970's by satellite data of objects as small as 10^{-13} g (*2*). The fall rate of meteorites 10^2 to 10^6 g in size is estimated from their recovery rates in highly populated regions.

The accretion rate of large ($>10^8$ g) objects is not historically observable, but can be determined by counting craters and inferring the size of the meteoroid from the diameter of the crater. Ancient craters are preserved on the earth (for example, in eastern Canada) and, more legibly, on the moon, but the integration periods are very long ($\geq 3.2\ 10^9$ years), and the flux may show temporal variations on a shorter time scale. One can also calculate an influx of large objects from the observed earth-crossing asteroid population. Rates based on crater counts (*3*) and asteroid populations agree to within a factor of 2 (*4*). Crater counts offer information on objects between 10^{13} and 10^{20} g in size; asteroid observations cover those from 10^{16} to 10^{20} g.

The technique we use spans a much greater mass range than others; measurement of a noble-metal tracer in sediments integrates all masses up to that of the largest objects that fall during the sampled time span; during the 30-m.y. interval that we investigated the largest objects were 10^{17} to 10^{18} g. If we accept Hughes' (*2*) lower limit of 10^{-13} g, our sampled mass range covers 30 to 31 orders of magnitude. The work of Barker and Anders (*5*) using this technique was confined to sediments less than 1 m.y. in age, and thus a mass interval about two orders of magnitude smaller (*6*) was sampled.

Samples and Techniques

For practical reasons, we studied a core from a region with a low accumulation rate. Giant piston core 3 (GPC-3) was recovered from an abyssal clay section from the central North Pacific (*7*). Figure 1 shows the core's location relative to the location of the Hawaiian hot spot through time. In 24 m, the core contains a nearly complete record of sedimentation for more than 70 m.y. (*7*). The major sediment source at this locality is windblown dust (*8*) from the Asian mainland (*9*) although Leinen and Heath (*7*) suggested a predominantly North American source before 25 million years ago. Authigenic minerals (primarily iron-manganese oxides) precipitated from seawater are a volumetrically minor but important component. We used neutron-activation analysis to determine iridium (*10*) and 25 other elements in a continuous 9-m section (12 to 21 m in depth) representing approximately 34 m.y. [from 33 to 67 million years ago (*11*)]. Iridium was analyzed radiochemically; the other elements by counting gamma rays from the neutron-activated whole samples. This is the most extensive published set of Ir data on a single core both in terms of the number of analyses and the length of the deposition interval.

Iridium Profile in Giant Piston Core 3

The Ir content as a function of depth is shown in Fig. 2. In the large and well-defined Ir peak at the Cretaceous/Tertiary (K/T) boundary, concentrations reach 12 ng of Ir per gram of sample; the continuum Ir concentration on either side of the peak is 0.3 to 0.4 ng/g. After subtraction of the continuum, the net fluence of the Ir in

The authors are at the Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024.

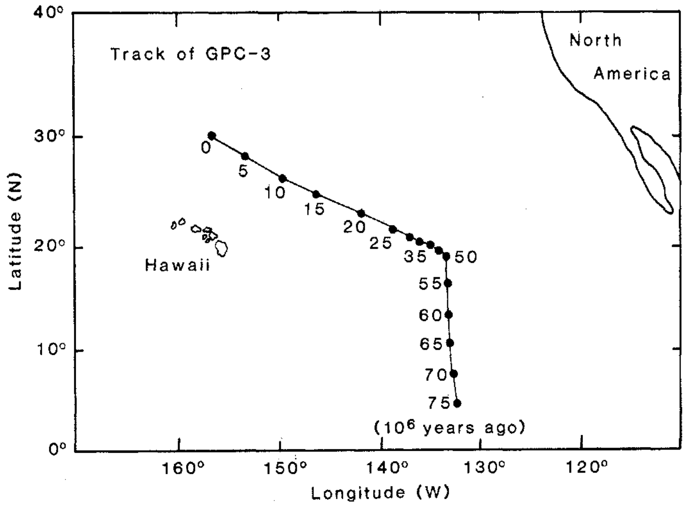

Fig. 1. The path of the Pacific plate has been generally northward during most of the 70-m.y. history of the GPC-core. Adapted from Corliss and Hollister (*7*).

the K/T peak is about 70 ng cm^{-2}. As has been reported (*12*), the siderophile element pattern and the presence of sanidine- and spinel-bearing (*13*) spherules indicate that we have sampled the same horizon identified at numerous localities around the world. The most probable source for this horizon is a major accretionary event at the end of the Cretaceous. The boundary occurs near the base of a homogeneous, nonlaminated unit extending from 2067 to 2010 cm. The breadth of the congruent Ir and sanidine-spherule profiles, and the homogeneous texture of the clay indicate that this portion of the section was, like much of the core, reworked by bioturbation. Thus we are unable to examine the boundary depositional record on a fine scale.

The K/T peak is distinct; although small Ir maximums occur elsewhere, they generally represent only one or two samples (Fig. 2). Analysis of smaller vertical intervals may show whether any of the other peaks are enough above the continuum to imply accretionary events. Although no definite Ir peak corresponding to the late Eocene microtektite event can be resolved, the Ir continuum in this region is high, resulting in poor sensitivity for small events. Either of the potential peaks at about 12.3 and 13.6 m could represent this event; upper limits on the excess Ir above the continuum are approximately 9 and 12 ng cm^{-2}, respectively, not inconsistent with reported fluences (*14*).

Away from the K/T, Ir concentrations are lowest (~0.35 ng/g) in the Paleocene and highest (~1.7 ng/g) in a broad plateau extending from the mid-Eocene to the earliest Oligocene. If one neglects small irregularities, the variation by a factor of five describes a rather smooth curve across a 30-m.y. interval. A key problem is to define the process or processes responsible for this variation.

Figure 3 shows that the profiles of Ir and cobalt are quite similar (*15*). The nickel profile is also similar; it is not plotted because the precision of the data is not as good. The manganese profile reported by Corliss and Hollister (*7*) also varies by a factor of 5 across this interval. Kadko (*16*) observed similar profiles in late Cenozoic sediments of elements such as Mn, Co, Ni, and Cu and showed that these variations were consistent with a constant depositional flux of authigenic (chemically precipitated) minerals as discussed by Krishnaswami (*17*); the variations reflect differences in the degree of dilution of this minor component by detrital sediment. Halbach *et al.* (*18*) have shown that authigenic Co accumulation in Mn-rich crusts and nodules is relatively constant, averaging 2.95 mg cm^{-2} m.y.$^{-1}$. The measured Co accumulation rate in GPC-3 of 2.5 mg cm^{-2} m.y.$^{-1}$ is similar to this, and leaching experiments (*19*) have shown that the Co is enriched in the hydrogenous authigenic component (that is, in ferromanganese oxides) in this portion of GPC-3.

We conclude that most and perhaps all of the observed factor of 5 variation in the Ir concentration above the K/T results from differences in sediment accumulation rates. High concentrations of Ir and Co roughly coincide with low sediment accumulation rates inferred by Rea *et al.* (*8*). In a study of the eolian dust contents of GPC-3 and Deep Sea Drilling Project hole 576, they inferred very low eolian sediment accumulation rates in the Oligocene and Eocene, and higher rates in the Paleocene and Cretaceous. They noted that the mid-Pacific eolian dust deposition rate is inversely correlated with inferred rates of continental meteoric precipitation. High aerosol deposition rates are associated with larger grain sizes, which indicated dryer conditions and stronger tropospheric circulation in the late Cretaceous and Paleocene.

Terrestrial and Extraterrestrial Components

The mean Ir deposition rate for the GPC-3 interval between 12 and 20 m (which does not include the K/T) is about 13 ng cm^{-2} m.y.$^{-1}$. To determine the influx of extraterrestrial matter, we must subtract the fraction of Ir that is terrestrial. Potential sources include continental weathering and volcanism.

The most relevant and precise data on the Ir content of continental rocks appear to be those on Mississippi delta sediments of Fenner and Presley (*20*); their means of five samples are 0.046 ng of Ir and 12.2 μg of Co per gram of sample (*21*). This implies a maximum detrital contribution of 13% of the Ir in Paleocene sediments and 2.7% in the mid- to late Eocene sediments. On the average, detrital Ir probably does not account for more than 7% of the total in the section.

The role of leaching from fluvial (or to a lesser extent, volcanic) particles to produce dissolved Ir is difficult to estimate but the amount should be relatively small. Because of its tendency to be present as insoluble noble-metallic grains or to occupy high (+3 or +4) oxidation states, we expect Ir to be less easily leached than Co. If so, the product of the crustal Ir/Co ratio and the authigenic Co concentration yields an upper limit on the authigenic Ir derived

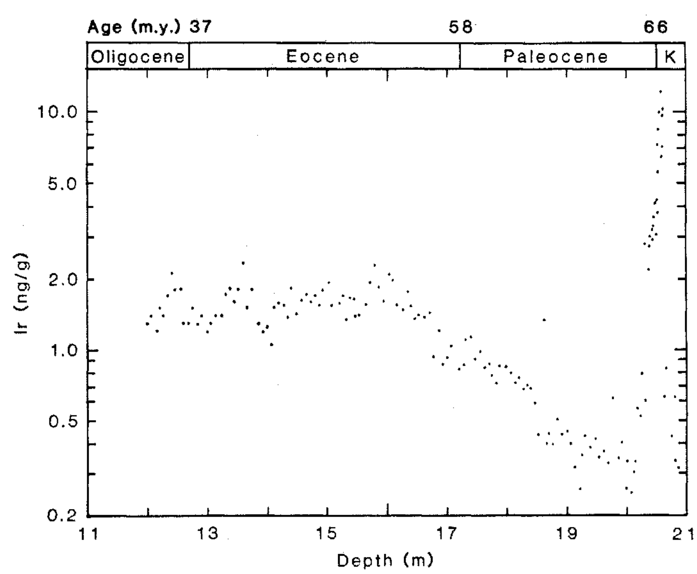

Fig. 2. Profile of Ir concentrations in a 9-m section of piston core GPC-3 from the central Pacific gyre. The only anomalously high Ir peak is observed at the K/T boundary.

from continental weathering. Using the Fenner-Presley (*20*) ratio and assuming that 95% of the Eocene Co is authigenic, we estimate a maximum authigenic Ir concentration of approximately 0.92 ng/g, about 55% of the observed concentration.

Some extraterrestrial Ir undoubtedly enters the ocean as oxides produced by vaporization and as relatively large (>0.1 mm) dense particles that are rapidly transported to the sea floor. Since this Ir flux is probably constant, it yields concentration variations similar to those expected for a constant authigenic precipitation rate.

It seems doubtful that volcanism contributes appreciable Ir to this section. Andesitic and silicic volcanic solids are probably similar to, and represented by, our continental estimate. The amount of Co or Ir introduced into solution by submarine volcanism is not known. However, it is known that Fe-Mn oxides form at high rates in the immediate vicinity of spreading centers and it seems likely that these would sequester the bulk of the Co and Ir. Submarine volcanism probably contributes only a small fraction of the dissolved Ir removed by authigenic precipitation at sites distant from spreading centers. In any case, if the Ir/Co ratio in dissolved matter associated with submarine volcanism is less than or equal to that in Mississippi delta sediments, the above Co-based upper limit on the continental contribution (<55%) would encompass any volcanogenic Ir.

Zoller *et al.* (*22*) showed that Hawaiian hot-spot volcanism releases appreciable Ir into the atmosphere. However, no reliable estimates of the worldwide volcanic Ir flux are available; our rough calculations suggest that this flux is minor. The inferred gaseous iridium fluorides should be highly reactive with particulates, leading to deposition near the source. Only that fraction reaching the stratosphere should be deposited globally, and the fraction of the Hawaiian gaseous Ir that reaches the stratosphere must be trivial. We note that the GPC-3 site was about 2000 km east (far away and probably upwind) of the Hawaiian hot spot at the time that the sediments in this section were deposited.

Arsenic and antimony are highly enriched in volcanic aerosols (*22, 23*), whether or not Ir is enriched; they are probably also introduced into the ocean by submarine volcanism. We observe major fluctuations in antimony concentrations (Fig. 3) (arsenic trends are identical) which probably reflect the volcanic contribution but do not correlate with Ir or the authigenic Co. Thus, the bulk of the Ir probably has a nonvolcanic origin.

The terrestrial contribution to the 13 ng of Ir per square centimeter per million years must be between the 7% maximum eolian contribution and the 55% maximum authigenic estimate. We propose that the extraterrestrial fraction lies in the range of 6 to 12 ng cm^{-2} $m.y.^{-1}$, and that 9 ± 3 ng cm^{-2} $m.y.^{-1}$ is the best available value for the extraterrestrial influx in the size range sampled during our 30-m.y. integration (*24*). This mean value corresponds to an Ir/Co ratio in the terrestrial authigenic fraction of about 2×10^{-6}, about half the ratio in Mississippi delta sediments (*20*).

Other Studies

Barker and Anders (*5*) studied five Pleistocene abyssal clays having maximum ages of 1 m.y. and estimated an Ir influx of 7 ± 3 ng cm^{-2} $m.y.^{-1}$. Ku *et al.* (*25*) show that the sedimentation rates (*26*) used by Barker and Anders (*5*) are too low by factors averaging to about 2. Thus their flux should be increased to 14 ng cm^{-2} $m.y.^{-1}$, identical to our estimate of 13 ng cm^{-2} $m.y.^{-1}$ within estimated uncertainties. As a result of bioturbation, the Barker-Anders cores probably represent mean fluxes for the past 1 to 2 m.y. (*6*) which should include 10^{16}-g objects and possibly a 10^{17}-g object. Thus, there is evidence that, aside from punctuation by objects with radii of at least 4 km, the extraterrestrial influx has

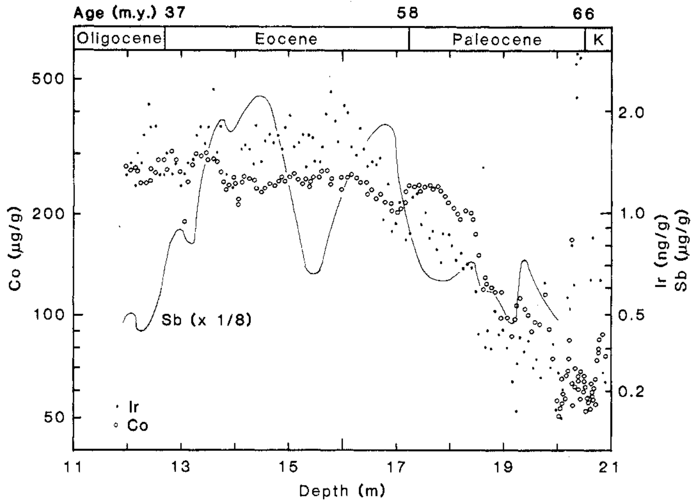

Fig. 3. Comparison of Ir, Co, and Sb profiles in GPC-3. In the section above the K/T boundary, Co is strongly correlated with Ir, having low concentrations in the Paleocene and high concentrations in the Eocene and Oligocene. This probably reflects an inverse correlation between concentration and sedimentation rate. The K/T Ir peak plots off scale. The Sb profile probably reflects volcanic activity and does not correlate with Ir or Co.

remained constant during the past 70 m.y. Our extraterrestrial Ir flux estimate is also in agreement with the value of 9 ng cm^{-2} $m.y.^{-1}$ calculated by Ganapathy (*27*) from analyses of Antarctic ice. However, Ganapathy noted that allowance for enhanced stratosphere-troposphere mixing at temperate latitudes leads to an estimated global flux 4 times as high, too high to be consistent with our result.

Our Ir accumulation rate of 13 ng cm^{-2} $m.y.^{-1}$ is not in agreement with values reported by Crocket and Kuo (*28*) ranging from 61 to 866 ng cm^{-2} $m.y.^{-1}$. They reported Ir concentrations near 0.3 ng/g in calcareous and siliceous oozes and in pelagic clay, considerably higher than continuum values (<0.1 ng/g) measured in similar materials (*14, 29*). Our substantially lower Ir accumulation rate is more likely.

Concentration and isotopic studies of osmium in sediments are consistent with our estimate of the extraterrestrial Ir. Osmium and Ir are similar in their geochemical and cosmochemical properties; in meteoritic samples they fractionate coherently, and the Os/Ir ratio rarely differs from the cosmic ratio of 1.2 by more than a factor of 2. Terrestrial samples show a somewhat larger range. Barker and Anders (*5*) found a strong Os-Ir correlation consistent with a constant ratio in deep-sea sediments, an indication that both are mainly extraterrestrial. Potentially more telling is the $^{187}Os/^{186}Os$ ratio; because ^{187}Os is partly produced by the decay of ^{187}Re, this ratio is sensitive to the age and Re/Os ratio of the source. In mean continental matter the $^{187}Os/^{186}Os$ ratio is expected to range between 13 and 26; in mantle and meteoritic samples it is near 1.0 (*30*). Luck and Turekian (*31*) leached Os from ferromanganese nodules from deep ocean basins and found $^{187}Os/^{186}Os$ ratios between 6 and 8. These are indicative of a continental fraction of 25 to 50% of the leached Os. The remainder is of mantle or extraterrestrial origin; their data offer no means for discriminating between these two possibilities, but arguments similar to those given above for Ir suggest that extraterrestrial Os is more abundant than mantle Os introduced by oceanic volcanism. In their experiment, only the ferromanganese oxides were leached; it is not known what fraction of the total Os was extracted. Their leach would not have attacked the Os in cosmic spherules (*32*) or other particulate matter that may be a major fraction of the Os in the nodules. Thus, these Os isotopic data support the idea that ~75% of deep-sea Ir and Os are of extraterrestrial origin. A more extensive Os study is highly desirable.

Other Accretion Rate Estimates

Our extraterrestrial Ir influx of 9 ± 3 ng cm^{-2} $m.y.^{-1}$ and an assumed Ir concentration of 592 ng/g in the infalling matter yields a mean accretion rate to the earth (*33*) of 78 billion grams (Gg) per year. Because of the long time interval involved in this estimate it should (with due allowance for stochastic effects) apply to bodies that fall at a rate of at least one per 30 m.y.

Hughes (*2*) used satellite, radar, and visual observations of meteors and meteorite fireballs to estimate a global influx of 16 Gg per year for objects with masses of 10^6 g or less; Grün *et al.* (*34*) support this estimate. A convenient way to discuss data on masses spanning so many orders of magnitude is to compare the mass influx per magnitude (Fig. 4). Maxima of 5 Gg per year occur at mass intervals of 10^{-6} to 10^{-5} and 10^{-5} to 10^{-4} g. The difference (62 Gg per year) between our global flux and that of Hughes must result from accretion of bodies having masses between 10^6 and 10^{18} g.

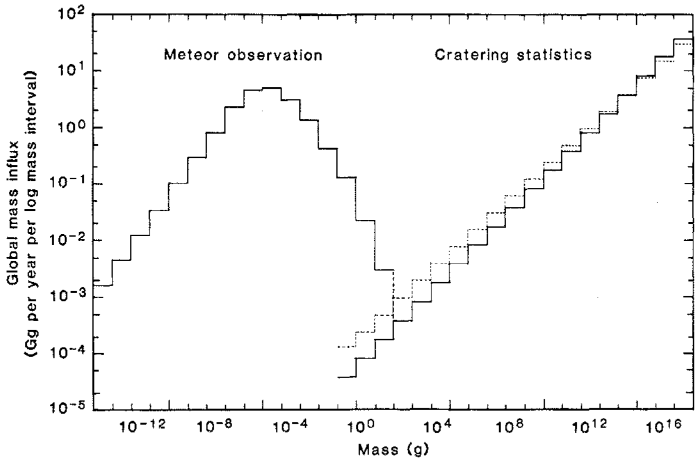

Fig. 4. The estimated influx of extraterrestrial matter shows a peak at low masses largely due to the accretion of cometary dust [adapted from (*2*)] and an exponential relation that increases with increasing size and is due to the accretion of fragments of asteroids and comets (*4*). The dashed exponential curve is a revision of the exponent in the number-radius relation from -2.0 to -2.1, determined by fitting the exponential relation to the observed flux of 10^6- to 10^7-g objects.

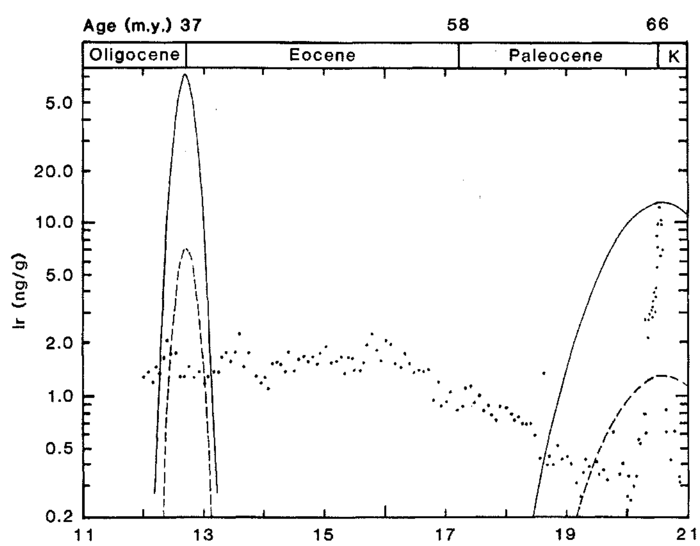

Fig. 5. Comparison of the Ir profile in GPC-3 to the increase in Ir sedimentation expected from dust produced by periodic comet showers. The solid curves represent the increase Ir accumulation expected during a 3-m.y. event. The dashed curves represent that expected from an ultraconservative model in which only 2% of extraterrestrial Ir is cometary.

Wetherill and Shoemaker (*4*) summarized available information on the flux of large, crater-forming objects. They report that the impact rate (N) of all bodies having radii (r) greater than r is roughly proportional to r^{-2}, that N is equal to 10 $m.y.^{-1}$ where r is 0.25 km. This led to the relation $N = 0.63\ r^{-2}$ where r is expressed in kilometers. We evaluated the mass accretion rate from this relation by assuming a density of 3 g cm^{-3}. The largest-sized body with an expected earth impact rate of one per 30 m.y. is about 10^{18} g, or a radius of 4.3 km. For $r_{max} = 4.3$ km, the calculated accretion rate is 68 Gg per year. If $r_{max} = 2.0$ km, corresponding to a mass of 10^{17} g, the rate is 31 Gg per year. Since uncertainties associated with this approach are at least a factor of 2, these estimates are remarkably close to the 62 Gg per year by which our accretion rate exceeds that estimated by Hughes (*2*) for bodies having masses of 10^6 g or less. The general agreement lends credence to both techniques for estimating accretion rates.

The Wetherill-Shoemaker relation is shown in Fig. 4. Since the largest meteoroids considered by Hughes should belong to the same population as the crater-producing objects, we would expect the histograms to merge in the kilogram to megagram range. In fact, the two models yield essentially the same influx for the interval 10^2 to 10^3 g. Wetherill and Shoemaker suggest a large uncertainty (± 0.5) in the exponent -2 in their equation. The general agreement of our Ir-based influx with that predicted by their model suggests a lower uncertainty. The fall rate (*35*) of large (10^6 to 10^7 g) meteorites is relatively well determined and yields a flux of about 0.015 Gg per year with an uncertainty of about a factor of 2. We suggest that the slope is very close to -2.1 and within an uncertainty of only ± 0.2. If the flux of 10 $m.y.^{-1}$ at $r = 0.25$ km is well determined, this uncertainty corresponds to a factor of 4 uncertainty in the flux of objects in the mass range 10^6 to 10^7 g. We show as a dashed line in Fig. 4 our recommended revision of the cumulative flux relationship to $N = 0.54\ r^{-2.1}$, where r is in kilometers.

One could argue that the K/T object corresponds to the 10^{18}-g object expected during a 30-m.y. period and that the largest objects in our section are approximately 10^{17} g. The absence of recognizable Ir peaks corresponding to objects having masses near 10^{17} g can be attributed to factors such as heavy dilution of the projectile material by terrestrial ejecta or accretion during the Eocene-Oligocene period when the low sedimentation rate lowered the signal-noise ratio.

Periodic Comet Showers?

The proposal that periodicities are recognizable in the biological extinction record (*36*) has stimulated models calling for periodic swarms of comets to invade the inner solar system (*37*). These models rely on periodic perturbations of the Oort Cloud by an eccentrically orbiting dark solar-companion star, by a tenth giant planet, or by giant molecular clouds in the galactic plane. Davis *et al.* (*37*) estimated that such a typical cometary swarm would consist of about 2×10^9 new long-period comets with perihelia of 1 astronomical unit or less—sufficient to result in about 25 terrestrial impacts of comets (presumably with radii of 0.5 to 5 km) during a 1-m.y. to 3-m.y.-long shower. Since the modern flux of long-period comets with perihelia of less than 1 AU is 16 per year, of which about 3 are dynamically new, the resultant increase in the comet flux would be by a factor of 200 if the duration of the shower is 3 m.y. (*38*). The dynamics of the planet-X model are not yet specified (*39*), but the results must be similar in order to ensure that there are enough large impacts to yield periodic extinctions.

In order to compare our results with predictions of these models we need to know what fraction of the extraterrestrial influx is cometary. There seems to be general agreement on a cometary source for a large fraction, perhaps essentially all, of the material having masses less than 10^{-2} g (Fig. 4). Hughes (*2*) estimates an annual influx of these materials of 15.7 Gg. There is also no doubt that an appreciable (5 to 20%) fraction of the meter- to kilometer-sized accreted bodies is also cometary. We will assume that at least 16 Gg, or 20% of our inferred influx of extraterrestrial matter, is cometary. This conservative lower limit (essentially including only the dust) corresponds to an Ir accumulation rate of 1.8 ng cm^{-2} $m.y.^{-1}$. The estimates cited above show that this should increase 200 times during the 3-m.y. period (or by 600 if the duration is 1 m.y.) when the perturbing planet or star is near perihelion. In Fig. 5 we indicate this increased flux with normal curves having a standard deviation of 0.75 m.y. and areas equal to 1080 ng of Ir per square centimeter. Not only is the predicted increase not observed, but it is apparent from the dashed curves that the late Eocene data rule out an increase one-tenth as large corresponding to the assumption that only 2% of the extraterrestrial Ir is of cometary origin. Even the distinct K/T event does not yield as much Ir as predicted by the ultraconservative 2% model.

The absence of evidence for Ir maximums spanning 1 to 3 m.y. at the predicted times is strong evidence against the occurrence of comet showers. This evidence confirms other arguments disputing their existence (*40*) and casts serious doubt on the existence of periodicities in catastrophe-induced extinctions.

REFERENCES AND NOTES

1. F. G. Watson, *Between the Planets* (Blakiston, Philadelphia, 1941).
2. D. W. Hughes, in *Cosmic Dust*, J. A. M. McDonnell, Ed. (Wiley, Chichester, 1978), p. 123.
3. R. A. F. Grieve, *Geol. Soc. Am. Spec. Pap.* **190**, 25 (1982).
4. G. W. Wetherill and E. M. Shoemaker, *ibid.*, p. 1.
5. J. L. Barker and E. Anders, *Geochim. Cosmochim. Acta* **32**, 627 (1968).
6. The actual range sampled in a young sediment is a running average covering a period at least as long as the longer of (i) the Ir residence time in the oceans and (ii) the interval mixed by bioturbation. In Barker and Anders' (*5*) most slowly deposited sediment, the bioturbation interval was probably about 1 m.y., corresponding to the largest expected object having a mass of about 10^{16} g.
7. B. H. Corliss and C. D. Hollister, *Nature (London)* **282**, 707 (1979); in *The Ocean Floor*, R. A. Scrutton and M. Talwani, Eds. (Wiley, New York, 1982), p. 277; P. S. Doyle and W. R. Riedel, *Micropaleontology* **25**, 337 (1979); M. Leinen and G. R. Heath, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **36**, 1 (1981).
8. D. K. Rea, M. Leinen, T. R. Janecek, *Science* **227**, 721 (1985).
9. R. A. Duce, C. K. Unni, B. J. Ray, J. M. Prospero, J. T. Merrill, *ibid.* **209**, 1522 (1980).
10. The interval 11.95 to 20.04 m was continuously sampled with 112 samples typically spanning 7 cm. The interval 20.0 to 20.9 m was determined in 37 samples spanning 1 to 5 cm each. Iridium was chemically purified by fusion in Na_2O_2, conversion to chlorides, adsorption onto Srafion NMRR resin, and elution with NH_4OH. Yields were determined by reactivation. Concentrations are relative to the sediment dried at 110°C. To obtain fluxes, bulk dry densities of the sediment were calculated from measured H_2O concentrations (*7*) and an assumed mineral density of 2.6 g cm^{-3}; values range from 0.37 to 0.42 g cm^{-3} except near the K/T boundary where values as high as 0.48 g cm^{-3} occur.
11. Stratigraphic age is based on ichthyolith assemblages [P. S. Doyle, in *Subseabed Disposal Program Annual Report*, K. R. Hinga, Ed. (Sandia National Laboratory, Albuquerque, NM, 1981), p. 327]. Absolute location of the boundaries between Cenozoic epochs shown in Figs. 2, 3, and 5 are subject to a possible error of a few million years. Ages assigned to the boundaries are taken from A. R. Palmer, *Decade of North American Geology Geologic Time Scale* (Geologic Society of America, Boulder, CO, 1983).
12. F. T. Kyte, thesis, University of California, Los Angeles (1983); F. T. Kyte and J. T. Wasson, in preparation.
13. F. T. Kyte and J. Smit, *Geology*, in press.
14. R. Ganapathy (*27*); F. Asaro, L. W. Alvarez, W. Alvarez, H. V. Michel, *Geol. Soc. Am. Spec. Pap.* **190**, 517 (1982); A. Sanfilippo, W. R. Riedel, B. P. Glass, F. T. Kyte, *Nature (London)* **314**, 613 (1985); B. P. Glass, C. A. Burns, J. R. Crosbie, D. L. DuBois, *J. Geophys. Res.* **90**, D175 (1986). Reported Ir fluences in seven of nine localities are less than 10 ng cm^{-2}.
15. We have distinctive concentration profiles for different element sets, probably reflecting variable contributions from several components. Of the 25 elements measured, only Ni and Co closely correlate with Ir. We did not determine Cu or Mn.
16. D. Kadko, *Geochim. Cosmochim. Acta* **49**, 651 (1985).
17. S. Krishnaswami, *ibid.* **40**, 425 (1976).
18. P. Halbach, D. Puteanus, F. T. Manheim, *Naturwissenschaften* **71**, 577 (1984).
19. M. Leinen, personal communication.
20. F. D. Fenner and B. J. Presley, *Nature (London)* **312**, 260 (1984).
21. A mean continental Ir value of 0.046 ng/g is consistent with backgrounds measured in nonmarine sediments around the K/T boundary by J. S. Gilmore, J. D. Knight, C. J. Orth, C. L. Pillmore, R. H. Tschudy [*Nature (London)* **307**, 222 (1984)]; C. J. Orth, J. S. Gilmore, J. D. Knight, C. L. Pillmore, R. H. Tschudy, J. E. Fassett [*Science* **214**, 1341 (1981)]; C. J. Orth, J. S. Gilmore, J. D. Knight, C. L. Pillmore, R. H. Tschudy, J. E. Fassett [*Geol. Soc. Am. Spec. Pap.* **190**, 423 (1982)]; in Devonian shales by G. R. McGhee, Jr., J. S. Gilmore, C. J. Orth, E. Olsen [*Nature (London)* **308**, 629 (1984)], and Ir contents of U.S. Geological Survey standard rocks (J. T. Wasson, unpublished data).
22. W. H. Zoller, J. R. Parrington, J. M. P. Kotra, *Science* **222**, 1118 (1983). A more extensive study [I. Olmez, D. L. Finnegan, W. H. Zoller, *J. Geophys. Res.* **91**, 653 (1986)] gives similar results that also yield no evidence that volcanism could produce a thin, worldwide Ir-rich layer.
23. C. B. Officer and C. L. Drake, *Science* **227**, 1161 (1985).
24. F. T. Kyte and J. T. Wasson, *Lunar Planet. Sci.* **13**, 411 (1982). In a preliminary report we incorrectly estimated a flux of 30 ng cm^{-2} $m.y.^{-1}$; this value, based on a smaller interval of GPC-3, was too high because we used bulk dry densities and sedimentation rates that were too high.
25. T. L. Ku, W. S. Broecker, N. Opdyke, *Earth Planet. Sci. Lett.* **4**, 1 (1968).
26. E. D. Goldberg and M. Koide, *Geochim. Cosmochim. Acta* **26**, 417 (1962).
27. R. Ganapathy, *Science* **220**, 1158 (1983).
28. J. H. Crocket and H. Y. Kuo, *Geochim. Cosmochim. Acta* **43**, 831 (1979).
29. M. Kastner, F. Asaro, H. V. Michel, W. Alvarez, L. W. Alvarez, *Science* **226**, 137 (1984); M. Kuslys and U. Krähenbühl, *Radiochim. Acta* **34**, 139 (1983); P. E. Playford, D. J. McLaren, C. J. Orth, J. S. Gilmore, W. D. Goodfellow, *Science* **226**, 437 (1984); C. J. Orth, J. D. Knight, L. R. Quintana, J. S. Gilmore, A. R. Palmer, *ibid.* **223**, 163 (1984).
30. C. J. Allegre and J. M. Luck, *Earth Planet. Sci. Lett.* **48**, 148 (1980); K. K. Turekian, *Geol. Soc. Am. Spec. Pap.* **190**, 243 (1982).
31. J. M. Luck and K. K. Turekian, *Science* **222**, 613 (1983).
32. R. B. Finkelman, *Marine Tech. J.* **6**, 34 (1972).
33. J. T. Wasson, W. V. Boynton, C.-L. Chou, *Moon* **13**, 121 (1975); G. W. Kallemeyn and J. T. Wasson, *Geochim. Cosmochim. Acta* **45**, 1217 (1981). Studies of lunar mare soil suggest that the most common type of interplanetary material has a composition similar to that of type CM chondrites, which have an Ir concentration of 592 ng/g in samples dried at 150°C.
34. E. Grün, H. A. Zook, H. Fechtig, R. H. Giese, *Icarus* **62**, 244 (1985).
35. R. E. McCrosky, C. Y. Shao, A. Posen, *J. Geophys. Res.* **76**, 4090 (1978); G. W. Wetherill and D. O. ReVelle, *Icarus* **48**, 308 (1981); I. Halliday, in *Evolutionary and Physical Properties of Meteoroids*, C. L. Hemenway, P. M. Millman, A. F. Cook, Eds. (NASA, Washington, DC, 1971), p. 1; Z. Ceplecha, *Bull. Astron. Instit. Czech.* **28**, 328 (1977). Since 1945 at least four objects (the Allende, Jilin, Norton County, and Sikhote-Alin meteorites) greater than 10^6 g (1*t*) have accreted to the continental portion of the earth between 25° and 55°N latitude, an area that accounts for 9.5% of the earth's surface, implying a fall rate of $1.1 > 1 - t$ objects per year. Several other objects have physically determined preatmospheric masses greater than 1*t* but smaller masses were recovered; the Revelstoke type CI chondrite is the commonly cited example. At least three for which no mass was recovered were recorded by meteor camera networks. Fireballs 39470 and 40503 observed in 1966 and 1969 by the Prairie Network had preatmospheric masses of 1 and 3*t* even after reducing the calculated masses by a factor of 13 as recommended by Wetherill and ReVelle. European Network fireball 041275 yields a mass of about 1*t*. The Prairie Network covered an area of about 11.4×10^5 km^2 during an 11-year period, and the European Network an area of about 10.8 10^5 km^2 during a 26-year period; thus these three objects imply a flux of 3.9 per year over the earth's surface. We use an influx of four per year over the earth. The $N \propto r^{-2}$ distribution yields a mean mass of 2.8×10^6 g for objects in the range 10^6 to 10^7 g, and thus a mass accumulation rate of 0.011 Gg per year.
36. D. M. Raup and J. J. Sepkoski, *Proc. Natl. Acad. Sci. U.S.A.* **81**, 801 (1984).
37. M. Davis, P. Hut, R. A. Muller, *Nature (London)* **308**, 715 (1984); M. R. Rampino and R. B. Stothers, *ibid.*, p. 709; R. D. Schwartz and P. B. James, *ibid.*, 712; D. P. Whitmire and A. A. Jackson, IV, *ibid.*, p. 713; D. P. Whitmire and J. J. Matese, *ibid.* **313**, 36 (1985).
38. P. Hut and P. R. Weissman, *Bull. Am. Astron. Soc.*, in press.
39. D. P. Whitmire and J. J. Matese, *Nature (London)* **313**, 744 (1985).
40. P. R. Weissman, *ibid.* **314**, 517 (1985); R. A. F. Grieve, V. L. Sharpton, A. K. Goodacre, *Lunar Planet. Sci.* **16**, 296 (1985); C. J. Orth, J. S. Gilmore, J. D. Knight, *ibid.*, p. 631.

41. Supported by NSF grant OCE 84-10177. We thank P. S. Doyle and M. Leinen for discussions that improved our understanding of the stratigraphy and chemistry of this core.