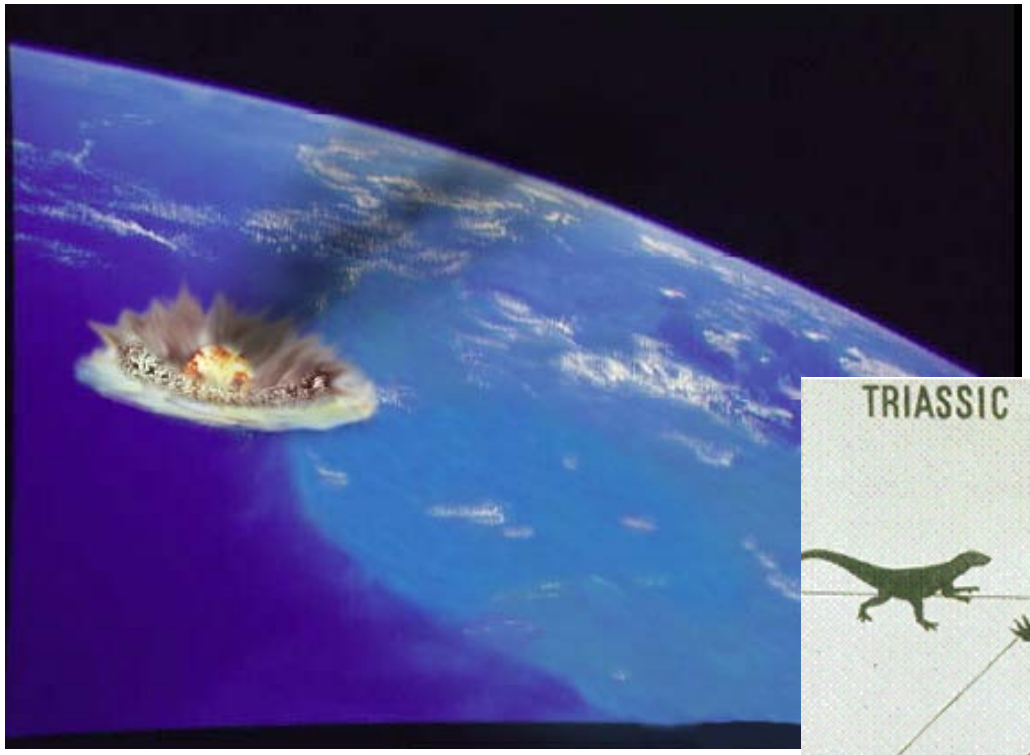
12.007 Geobiology
Spring 2009

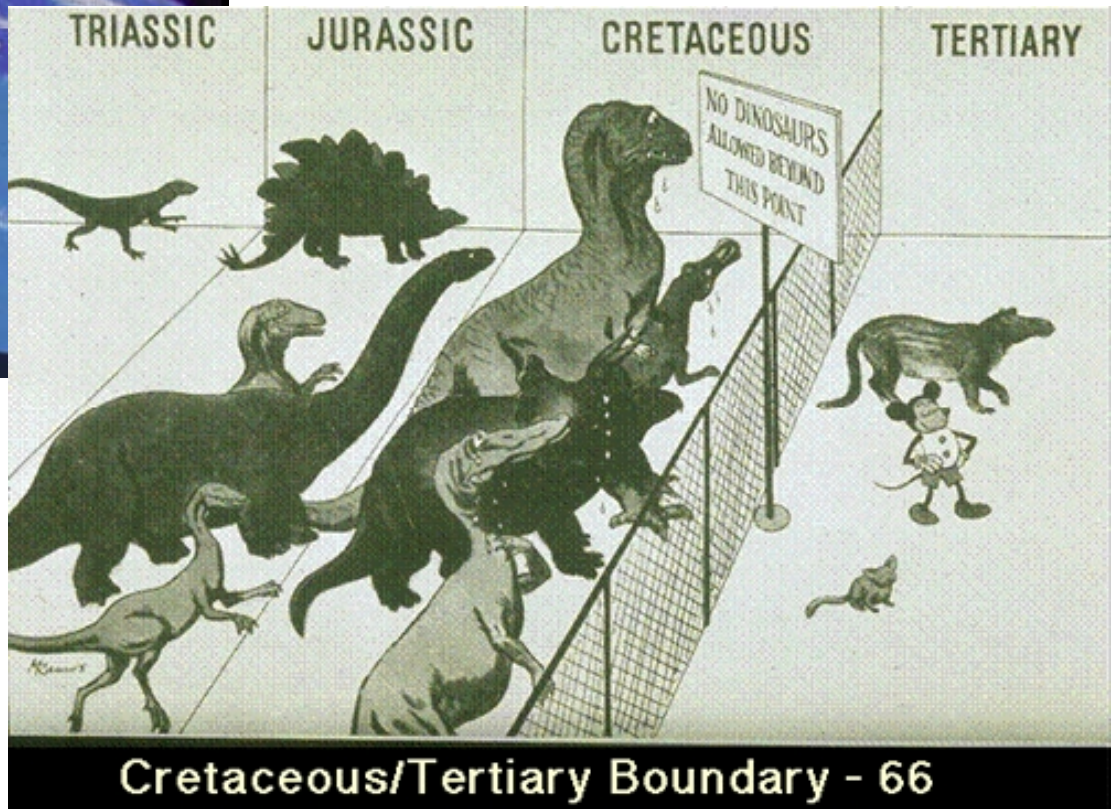
Geobiology Lecture 18
Mass Extinctions in the Geological Record

- Alvarez, L.W., Alvarez, W., Asaro, F., and Michel, W.V., 1980. Extraterrestrial cause of the Cretaceous-Tertiary extinctions. *Science* 208, 1095-1108.
- D'Hondt, S., Donaghay, P., Zachos, J.C., Luttenberg, D., and Lindinger, M., 1998, Organic carbon fluxes and ecological recovery from the Cretaceous-Tertiary mass extinction. *Science* 282, 276-279.
- *Zachos et al., Science*, Vol 302, Issue 5650, 1551-1554, 28 November 2003
- **Rapid Acidification of the Ocean During the Paleocene-Eocene Thermal Maximum**

James C. Zachos, *et al. Science* ***308, 1611 (2005)***

K-T Boundary





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K-T Boundary

Two seconds before the impact

One minute after the impact

This view is based on laboratory experiments and computer simulations of giant impacts. Some debris is being blown out of the atmosphere into space, only to fall back minutes later.

One month after the impact

Earth is covered by a hazy layer of dust blown out by the impact and smoke from forest fires. This blocked sunlight, killed much plant life and plankton, and disrupted the food chain.

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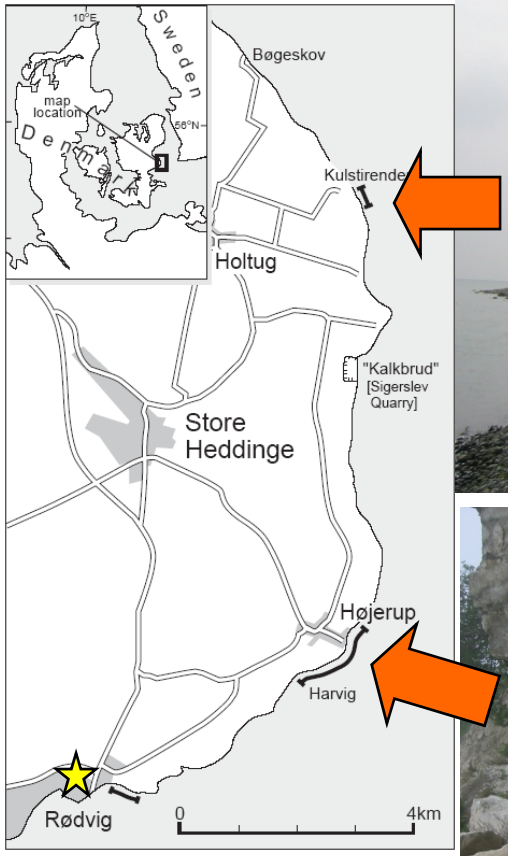
1 ky after the impact

The dust has cleared and a large crater is revealed. Dinosaurs and many other species have mostly died out, and species such as small mammals are beginning to fill the empty environmental niche.

http://www.psi.edu/projects/ktimpact/ktimpact.html

K~T Boundary at Stevns Klint (Fish Clay) in Denmark

Stevns Klint



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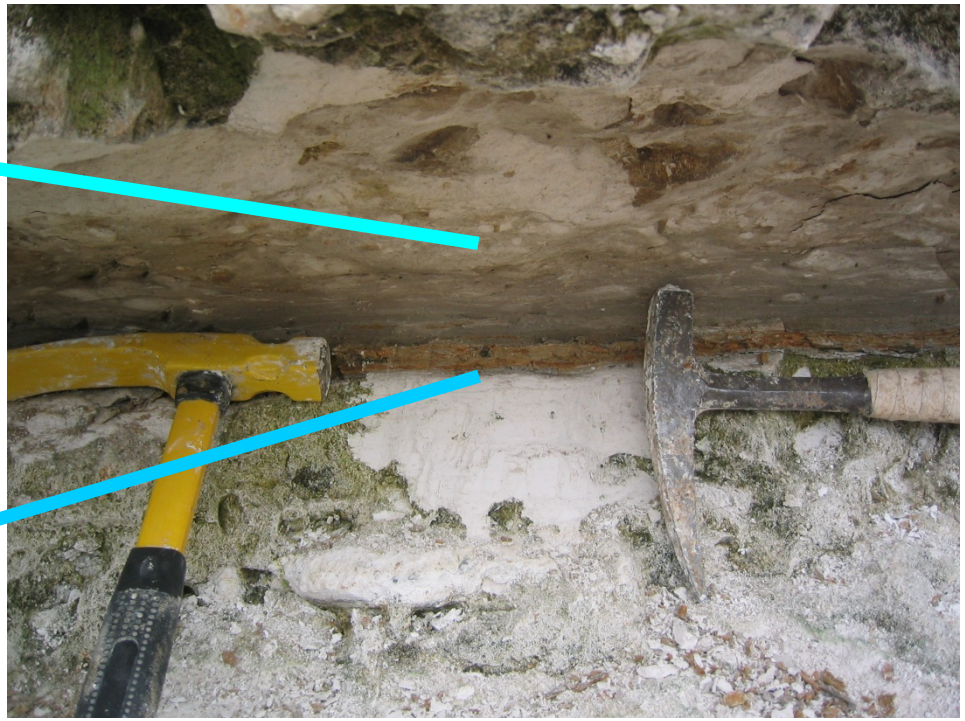
Stevns Klint



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Comet or Asteroid??

Comets are sometimes called **dirty snowballs** or "icy mudballs". They are a mixture of ices (both water and frozen gases) and dust that for some reason didn't get incorporated into planets when the solar system was formed. This makes them very interesting as samples of the early history of the solar system.

Comets are invisible except when they are near the Sun. Most comets have highly eccentric orbits which take them far beyond the orbit of Pluto; these are seen once and then disappear for millennia. Only the short- and intermediate-period comets (like Comet Halley), stay within the orbit of Pluto for a significant fraction of their orbits.

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KT Boundary

Science 291, 1952 (2001)

A Short Duration of the Cretaceous-Tertiary Boundary Event: Evidence from Extraterrestrial Helium-3

S. Mukhopadhyay,1* K. A. Farley,1 A. Montanari2

Analyses of marine carbonates through the interval 63.9 to 65.4 million years ago indicate a near-constant flux of extraterrestrial helium-3, a tracer of the accretion rate of interplanetary dust to Earth. This observation indicates that the bolide associated with the Cretaceous-Tertiary (K-T) extinction event was not accompanied by enhanced solar system dustiness and so could not have been a member of a comet shower. The use of helium-3 as a constant-flux proxy of sedimentation rate implies deposition of the K-T boundary clay in (10 ± 2) × 103 years, precluding the possibility of a long hiatus at the boundary and requiring extremely rapid faunal turno

Fig. 1. (**A**) [3He]Et, (**B**) [4He], and noncarbonate fraction (solid black line) in the Gubbio sediments. Points are individual values and are averages of leached replicates (if replicated). ( ) indicates the K-T boundary clay. He concentrations are per gram of bulk sediment. The shaded envelope represents the 1 uncertainty of the three-point running mean calculated from the uncertainties of individual data points (18). The K-T boundary sample was not included in the running mean. C29N and C29R refer to magnetic polarity chrons, and the chron boundary ages are from (33).

Chicxulub impact predates the K-T boundary mass extinction
Gerta Keller * , Thierry Adatte , Wolfgang Stinnesbeck , Mario Rebolledo-Vieyra ¶, Jaime Urrutia Fucugauchi ||, Utz Kramar ** and Doris Stüben ** PNAS 101, 3753-3758

Since the early l990s the Chicxulub crater on Yucatan, Mexico, has been hailed as the smoking gun that proves the hypothesis that an asteroid killed the dinosaurs and caused the mass extinction of many other organisms at the Cretaceous-Tertiary (K-T) boundary 65 million years ago. Here, we report evidence from a previously uninvestigated core, Yaxcopoil-1, drilled within the Chicxulub crater, indicating that this impact predated the K-T boundary by 300,000 years and thus did not cause the end-Cretaceous mass extinction as commonly believed. The evidence supporting a pre-K-T age was obtained from Yaxcopoil-1 based on five independent proxies, each with characteristic signals across the K-T transition: sedimentology, biostratigraphy, magnetostratigraphy, stable isotopes, and iridium. These data are consistent with earlier evidence for a late Maastrichtian age of the microtektite deposits in northeastern Mexico

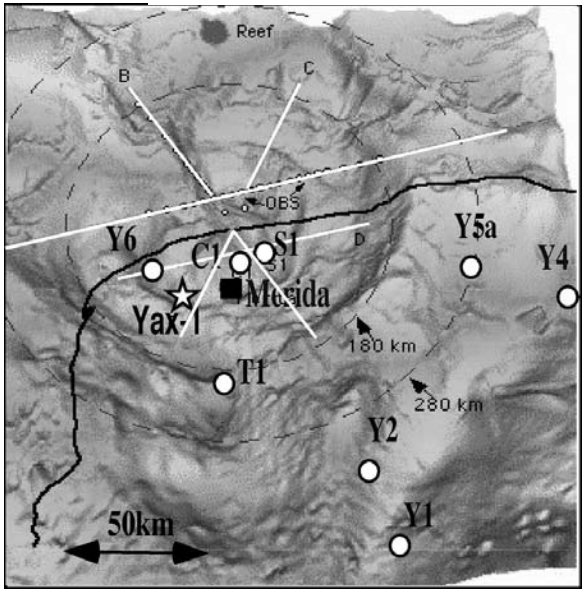
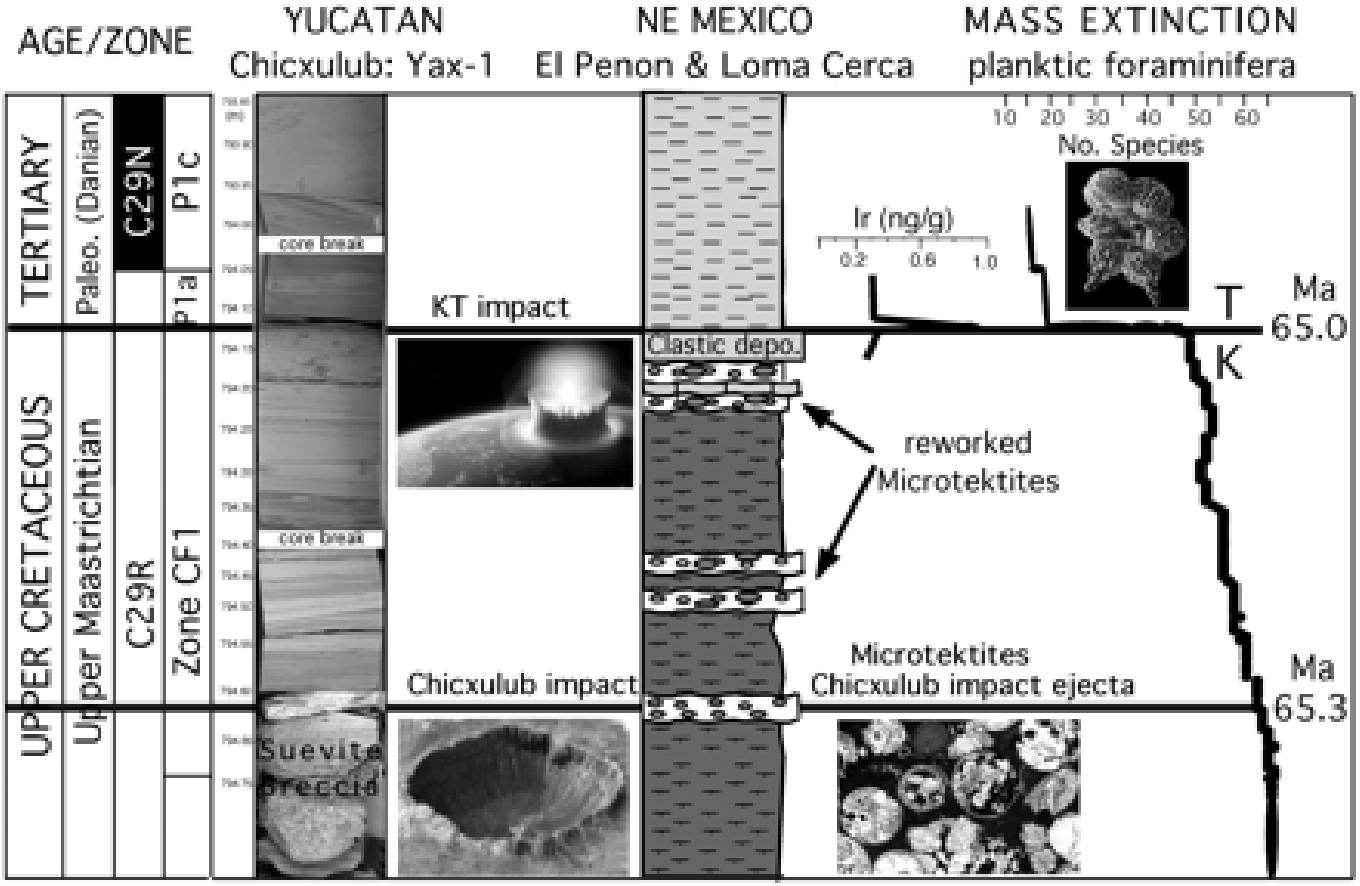
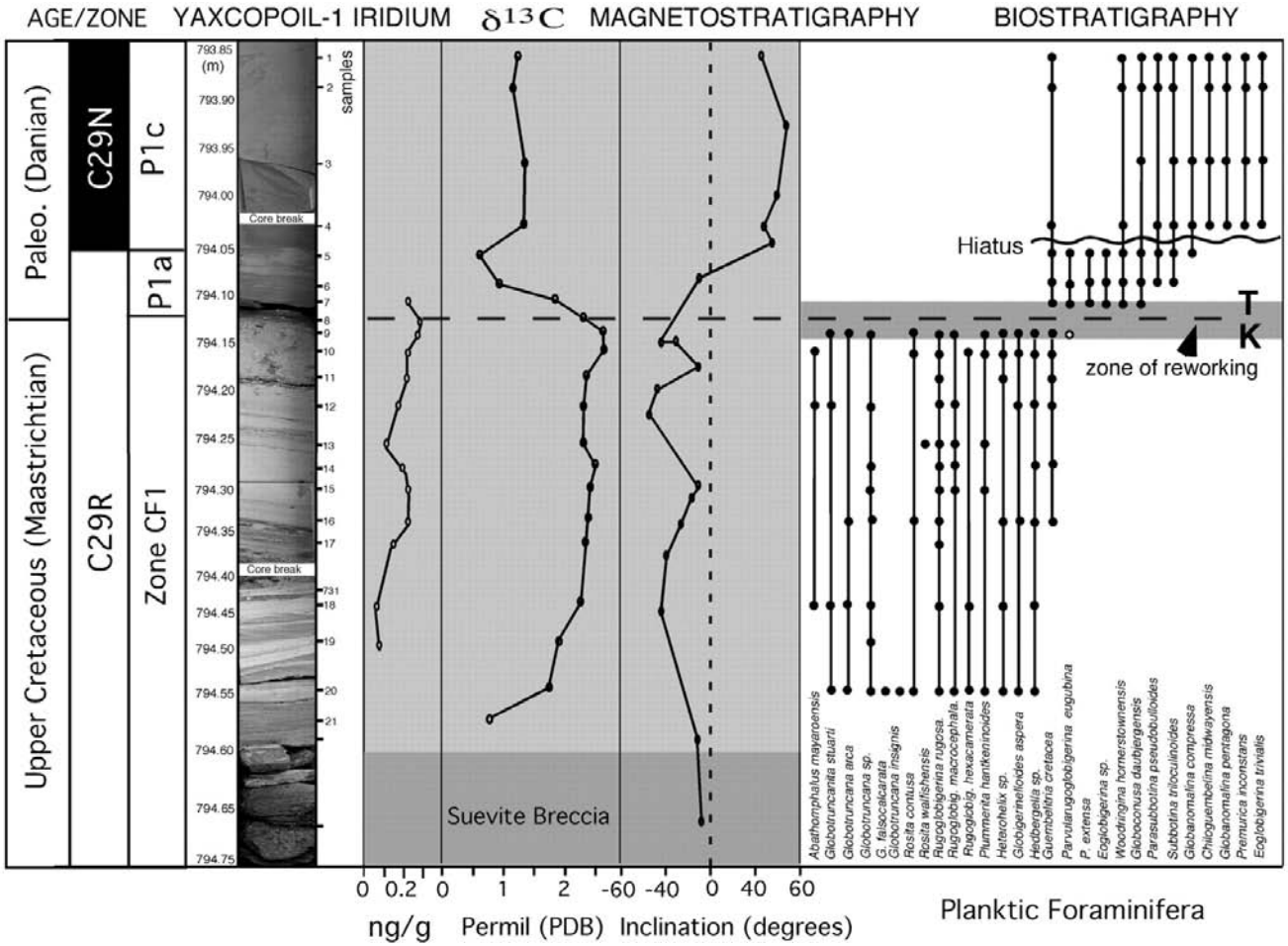


Fig. 6. Proposed correlation of Chicxulub impact breccia in core Yax-1 with the oldest microtektite layer in Late Maastrichtian marls of the Mendez Formation at El Penon and Loma Cerca in northeastern Mexico (22, 24). (We consider the younger microtektite layers that are interbedded in marls to be reworked.) The Ir anomaly in northeastern Mexico is at the K-T boundary



Keller et al., PNAS 101, 3753-3758

Fig. 2. Five sediment and age-related proxies reveal Late Maastrichtian pelagic sediments overlying the impact breccia in the Chicxulub core Yax-1. Note that zones P0, most of Pla, and probably the uppermost part of zone CF1 are missing. In addition, the hiatus at 794.05 m marks the loss of zone Plb and the lower part of Plc. The absence of the Ir anomaly is likely due to the hiatus that spans the K-T boundary.



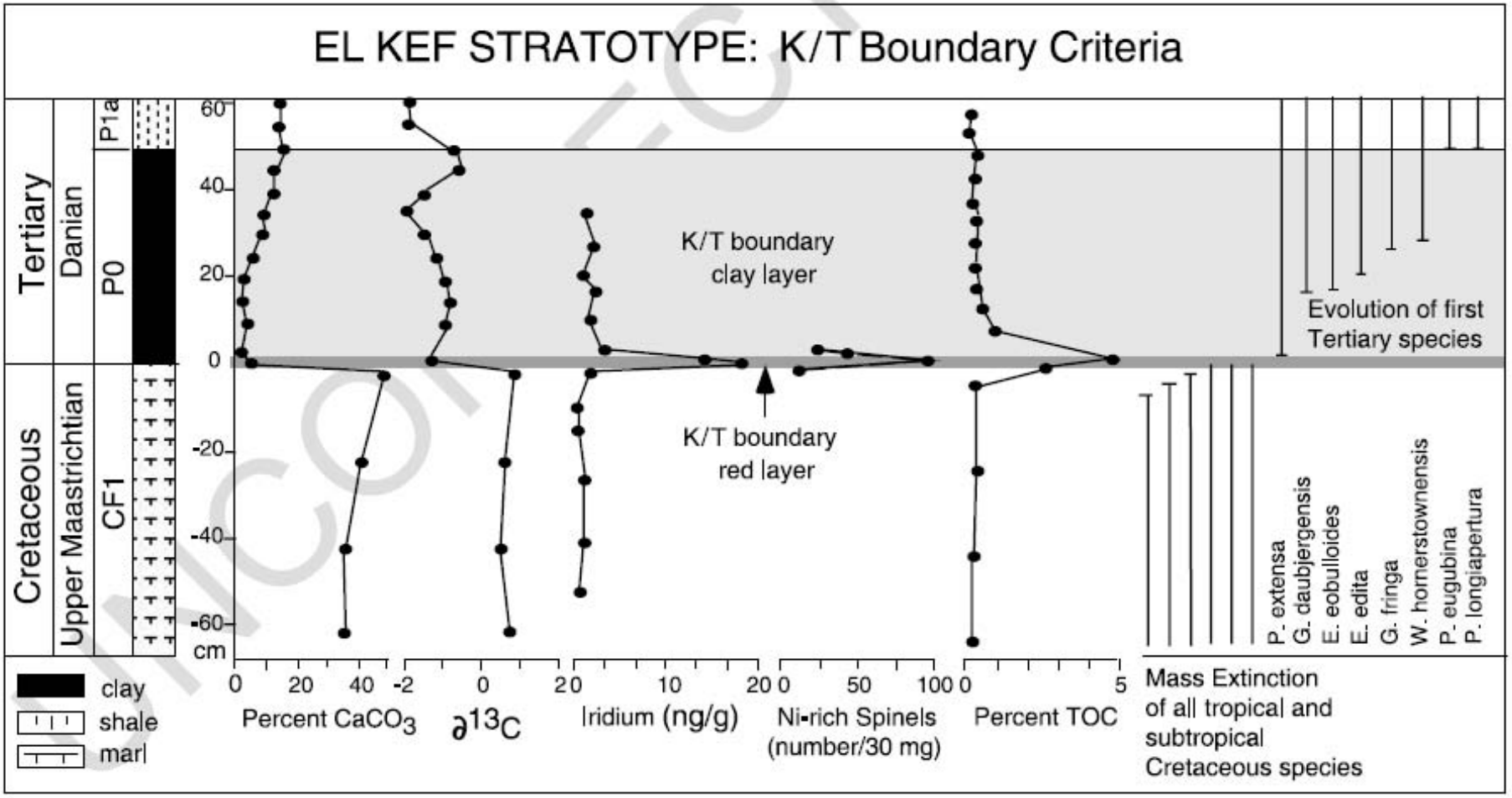
Courtesy of National Academy of Sciences (PNAS). Used with permission.

Keller et al., PNAS 101, 3753-3758

Multiple impacts across the Cretaceous–Tertiary boundary

G. Keller[a,*], W. Stinnesbeck[b], T. Adatte[c], D. Stüben[d]

Earth-Science Reviews 1283 (2002) 1–37



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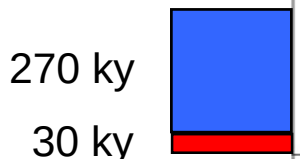
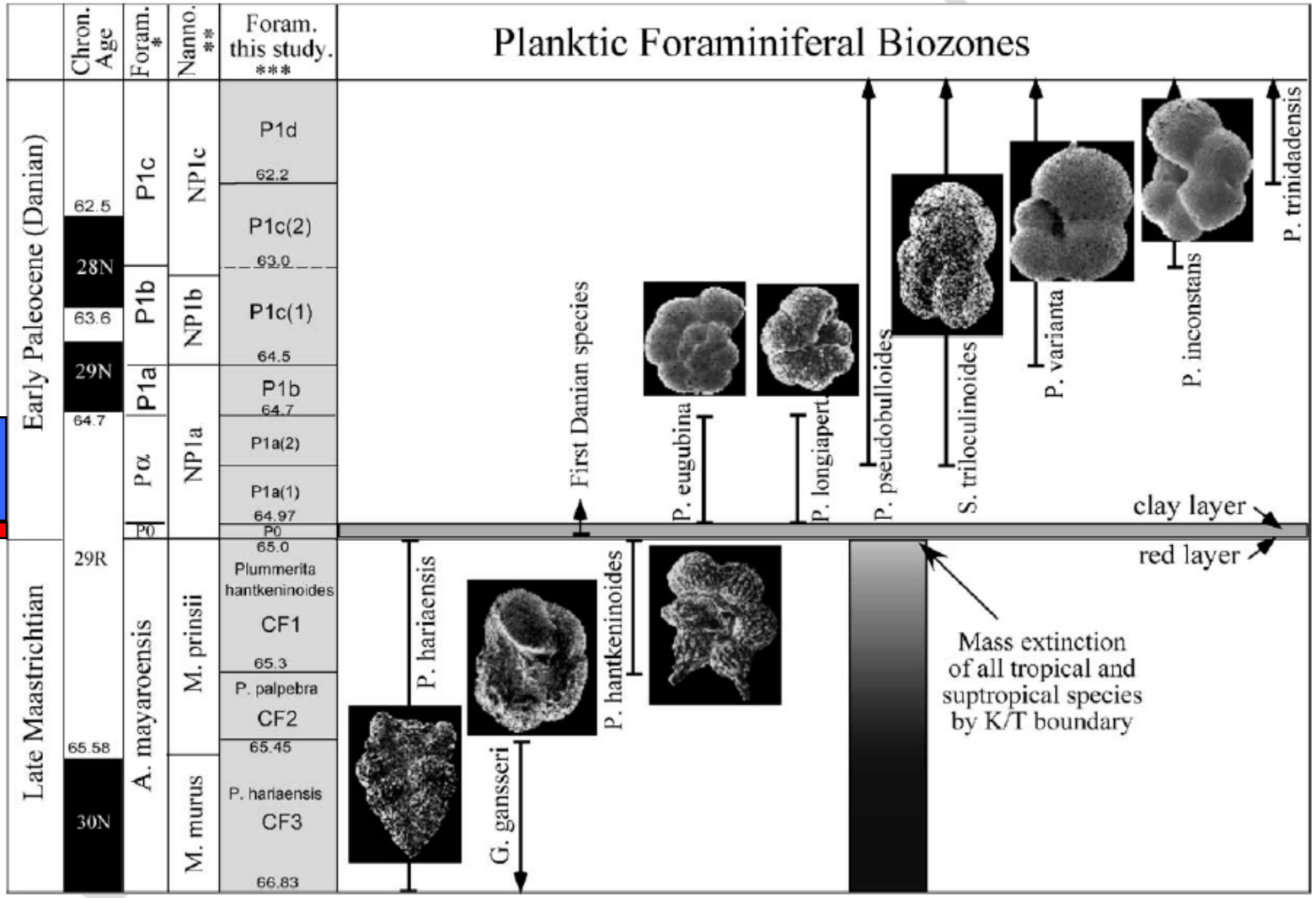


270 ky

30 ky



Organic Carbon Fluxes and Ecological Recovery from the Cretaceous Tertiary Mass Extinction

Steven D'Hondt, Percy Donaghay, James C. Zachos, Danielle Luttenberg, Matthias Lindinger

Differences between the carbon isotopic values of carbonates secreted by planktic and benthic organisms did not recover to stable pre-extinction levels for more than 3 million years after the Cretaceous-Tertiary mass extinction. These decreased differences may have resulted from a smaller proportion of marine biological production sinking to deep water in the postextinction ocean. Under this hypothesis, marine production may have recovered shortly after the mass extinction, but the structure of the open-ocean ecosystem did not fully recover for more than 3 million years.

Closed symbols = benthic

Image removed due to copyright restrictions.

Open symbols = planktic

Figure 1. Cretaceous-Tertiary 13C records from South Atlantic DSDP site 528. magnetostratigraphy; Ma, million years ago; mbsf, meters below sea floor. (**A**) 13C records of benthic foraminifera (*Gavelinella* and *Nuttallides*) (solid circles) and fine (<25 µm) carbonate (open circles) (23). (**B**) 13C records of benthic foraminifera (solid circles), fine (<25 µm) carbonate (open circles), and planktic foraminifera. Open symbols represent near-surface planktic foraminifera: *Morozovella angulata* (right-pointing open triangles), *Praemurica taurica* (left-pointing open triangles), and *Rugoglobigerina rotundata* (open squares). Gray symbols represent deeper-dwelling planktic foraminifera: *Eoglobigerina eobulloides* (gray circles), *Parasubbotina pseudobulloides* (right-pointing gray triangles), and *Pseudotextularia ultimatumida* (gray squares). Hatched areas represent intervals with insufficient data to assign magnetic polarity. White "core recovery" intervals mark missing sections

The presence or absence of the drastic K-T decrease in planktonic-to-benthic $\delta^{13}C$ differences does not depend on the planktonic and benthic species examined (although its magnitude does) (1–4). Hence, the reduction in these differences appears to document a real decrease in the $\delta^{13}C$ gradient between TCO2 in the surface ocean and that in the deep ocean. The latter decrease in turn indicates that much less organic carbon was oxidized in the deep sea after the KT extinction event

Oxygen Isotope Systematics

$\delta^{18}O\ (‰) = (R_x - R_{std} / R_{std}) \times 1000$

where R_x is sample ratio $^{18}O/^{16}O$ & R_{std} is standard ratio $^{18}O/^{16}O$

International standards are:

Standard Mean Ocean Water SMOW for water and most rocks and PDB for carbonate rocks

- Water vapor is depleted in ^{18}O (ie 'light') compared to residual water
- Oxygen and hydrogen both fractionated by evaporation so can be cross-correlated through the MWL = meteoric water line
- ^{18}O-depleted (light) water accumulates in ice sheets sending the ocean 'heavy'. Continental water also tends to be 'light'.
- The $\delta^{18}O$ signature of biogenic carbonates integrates water temperature, ice volume, salinity and vital effects. The latter three can be deconvoluted to provide an accurate paleothermometer in the skeletons of foraminifera

Planktonic foraminifera shell chemistry as proxy for sea surface temperatures

Globigerina bulloides

Mg/Ca = sea surface temperature

$Mg/Ca = 0.474\ e^{0.107\ T}$ (*G. bulloides*)

$\delta^{18}O_c$- $\delta^{18}O_w$= shell $\delta^{18}O$ minus seawater $\delta^{18}O$ related to sea surface temperature

$T^oC = 13.3 - 4.89\ (\delta^{18}O_c - \delta^{18}O_w)$

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(Mashiotta *et al*., 1999)

(Bemis *et al*., 1998)

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Mechanisms of Climate Warming at the End of the Paleocene

Santo Bains, 1* Richard M. Corfield, 1 Richard D. Norris 2

An abrupt episode of global warming marked the end of the Paleocene epoch. Oxygen and carbon isotope records from two widely separated sites support the notion that degassing of biogenic methane hydrate may have been an important factor in altering Earth's climate. The data show evidence for multiple injections of methane, separated by intervals in which the carbon cycle was in stasis. Correlations between the two sites suggest that even these small-scale events were global in nature

Science 284, 724 (1999)

Mechanisms of Climate Warming at the End of the Paleocene
Santo Bains, 1* Richard M. Corfield, 1 Richard D. Norris 2
Science 284, 724 (1999)

A. Praep & Subbotina = plantonic
B. N. truempyi = benthic

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Mechanisms of Climate Warming at the End of the Paleocene
Santo Bains, 1* Richard M. Corfield, 1 Richard D. Norris 2
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Fig. 2. The 13C and 18O records of marine bulk carbonate, planktonic foraminifera *Acarinina praepentacamerata* and *Subbotina*, and the benthic foraminifer *Nuttallides truempyi* across the LPTM interval in ODP sites 690B and 1051B (6). Labels a through i are used to denote events across the LPTM and are referred to in the text. Ma, million years ago. (**A**) Changes in 13C across this interval record a number of small-scale global carbon isotope fluctuations. The stepped fall in values suggests multiple injections of light carbon from dissociated methane or some other source. (**B**) The 18O records from these two sites are very similar across the LPTM; however, the oxygen isotope values may have been more strongly affected than the carbon isotope records by latitudinally dependant temperature-forcing mechanisms (for example, cyclic variation of Earth's orbit) and are thus less correlative than the 13C records. Features x and y probably represent enhanced episodes of low-latitude cooling associated with precessional periods. Temperatures were calculated with the method of Shackleton (31)

Late Paleocene Thermal Maximum & the PEB

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Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present

James Zachos,1* Mark Pagani,1 Lisa Sloan,1 Ellen Thomas,2, 3 Katharina Billups4 Science 292, 686 (2001)

Since 65 million years ago (Ma), Earth's climate has undergone a significant and complex evolution, the finer details of which are now coming to light through investigations of deep-sea sediment cores. This evolution includes gradual trends of warming and cooling driven by tectonic processes on time scales of 105 to 107 years, rhythmic or periodic cycles driven by orbital processes with 104- to 106-year cyclicity, and rare rapid aberrant shifts and extreme climate transients with durations of 103 to 105 years. Here, recent progress in defining the evolution of global climate over the Cenozoic Era is reviewed. We focus primarily on the periodic and anomalous components of variability over the early portion of this era, as constrained by the latest generation of deep-sea isotope records. We also consider how this improved perspective has led to the recognition of previously unforeseen mechanisms for altering climate.

Late Paleocene Thermal Maximum & the PEB

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Fig. 5. The LPTM as recorded in benthic 13C and 18O records (**A** and **B**, respectively) from Sites 527 and 690 in the south Atlantic (73), and Site 865 in the western Pacific (26). The time scale is based on the cycle stratigraphy of Site 690 (30) with the base of the excursion placed at 54.95 Ma. The other records have been correlated to Site 690 using the carbon isotope stratigraphy. Apparent leads and lags are artifacts of differences in sample spacing. The oxygen isotope values have been adjusted for species-specific vital effects (118), and the temperature scale on the right is for an ice-free ocean. The negative carbon isotope excursion is thought to represent the influx of up to 2600 Gt of methane from dissociation of seafloor clathrate

The Source and Fate of Massive Carbon Input During the Latest Paleocene Thermal Maximum

Miriam E. Katz, 1* Dorothy K. Pak, 2 Gerald R. Dickens, 3 Kenneth G. Miller 1

Lithologic, faunal, seismic, and isotopic evidence from the Blake Nose (subtropical western North Atlantic) links a massive release of biogenic methane ~55.5 million years ago to a warming of deep-ocean and high-latitude surface waters, a large perturbation in the combined ocean-atmosphere carbon cycle (the largest of the past 90 million years), a mass extinction event in benthic faunas, and a radiation of mammalian orders. The deposition of a mud clast interval and seismic evidence for slope disturbance are associated with intermediate water warming, massive carbon input to the global exogenic carbon cycle, pelagic carbonate dissolution, a decrease in dissolved oxygen, and a benthic foraminiferal extinction event. These events provide evidence to confirm the gas hydrate dissociation hypothesis and identify the Blake Nose as a site of methane release.

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A Transient Rise in Tropical Sea Surface Temperature During the Paleocene-Eocene Thermal Maximum

James C. Zachos,1* Michael W. Wara,1 Steven Bohaty,1 Margaret L. Delaney,1 Maria Rose Petrizzo,2 Amanda Brill,3 Timothy J. Bralower,4 Isabella Premoli-Silva2

The Paleocene-Eocene Thermal Maximum (PETM) has been attributed to a rapid rise in greenhouse gas levels. If so, warming should have occurred at all latitudes, although amplified toward the poles. Existing records reveal an increase in high-latitude sea surface temperatures (SSTs) (8° to 10°C) and in bottom water temperatures (4° to 5°C). To date, however, the character of the tropical SST response during this event remains unconstrained. Here we address this deficiency by using paired oxygen isotope and minor element (magnesium/calcium) ratios of planktonic foraminifera from a tropical Pacific core to estimate changes in SST. Using mixed-layer foraminifera, we found that the combined proxies imply a 4° to 5°C rise in Pacific SST during the PETM. These results would necessitate a rise in atmospheric pCO2 to levels three to four times as high as those estimated for the late Paleocene.

Science, Vol 302, Issue 5650, 1551-1554, 28 November 2003

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Fig. 1. Hole 1209B was drilled at a water depth of 2387 m (*17*). The sampled 80-cm interval was recovered at a subbottom depth of 195.95 to 196.6 m. The sediment is calcareous nannofossil ooze. The sharp color contact lies just above the Paleocene-Eocene boundary at 1.35 m in this section. (**A**) Percent CaCO3 of bulk sediment. (**B**) Bulk magnetic susceptibility. (**C**) Percent fragmentation of planktonic foraminifera. (**D** and **E**) The 13C and 18O of individual specimens of *M. velascoensis* (blue circles) and *A. soldadoensis* (red triangles). (**F** and **G**) Mg/Ca and Sr/Ca of *M. velascoensis* and *A. soldadoensis.* The lower age listed on the right represents the assigned age of the boundary (55.0 Ma) and is placed at the base of the excursion. The upper age (54.85 Ma) is based on the estimated duration of the event as determined from orbital cycles (*23*) and He isotopes (*24*).

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With modern foraminifera, an exponential relation is observed between calcification temperature and shell Mg/Ca

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Fig. 2. In the Hole 1209B PETM section, the 18O and Mg/Ca anomalies were both calculated with respect to the sample at 1.485 m (sample 1209B-22H-1, 148 to 149 cm), the lowest pre-event sample in the data set. (**A**) The Mg/Ca temperature anomalies were derived with the following equation: where T is the relative change in temperature (°C), *m* is an assumed temperature sensitivity (i.e., exponential constant), and C is the percentage change in Mg/Ca (with respect to the baseline Mg/Ca value) (see note S1 for full derivation). The calculated Mg/Ca temperature anomaly field assumes a range of exponential constant values between 0.085 and 0.107, within a range characteristic of most modern planktonic taxa (*26*, *27*). The 18O temperature anomalies were calculated with a 18Ocalcite/ T relationship of –0.213 /°C. (**B**) The salinity anomaly calculations assume that the discrepancy between the 18O and Mg/Ca temperature anomalies results from a local surface-water 18O increase during the PETM due to a shift in the precipitation-evaporation balance. For these calculations, an intermediate exponential constant value of 0.09 was used to obtain the Mg/Ca temperature anomalies. These anomalies were then converted to expected 18O anomalies (with the –0.213 /°C relationship), and the observed 18O anomalies were subtracted from 18O anomalies. The resulting 18O "residual" ( ) was then assumed to reflect changes corresponding to surface-water salinity changes. The salinity anomaly fields represent a range of 18Oseawater/ salinity relationships between 0.50 /salinity unit and 0.25 /salinity unit.

Rapid Acidification of the Ocean During the Paleocene-Eocene Thermal Maximum

James C. Zachos,[1]* Ursula Ro¨ hl,[2] Stephen A. Schellenberg,[3]
Appy Sluijs,[4] David A. Hodell,[6] Daniel C. Kelly,[7] Ellen Thomas,[8,9]
Micah Nicolo,[10] Isabella Raffi,[11] Lucas J. Lourens,[5]
Heather McCarren,[1] Dick Kroon[12]

The Paleocene-Eocene thermal maximum (PETM) has been attributed to the rapid release of 2000 x 10^9 metric tons of carbon in the form of methane. In theory, oxidation and ocean absorption of this carbon should have lowered deep-sea pH, thereby triggering a rapid (G10,000-year) shoaling of the calcite compensation depth (CCD), followed by gradual recovery. Here we present geochemical data from five new South Atlantic deep-sea sections that constrain the timing and extent of massive sea-floor carbonate dissolution coincident with the PETM. The sections, from between 2.7 and 4.8 kilometers water depth, are marked by a prominent clay layer, the character of which indicates that the CCD shoaled rapidly (G10,000 years) by more than 2 kilometers and recovered gradually (9100,000 years). These findings indicate that a large mass of carbon (d2000 10_9 metric tons of carbon) dissolved in the ocean at the Paleocene-Eocene boundary and that permanent sequestration of this carbon occurred through silicate weathering feedback.

Fig. 1. Digital core photos and weight % $CaCO_3$ content plotted versus meters of composite depth (MCD) across the P-E boundary interval at ODP sites 1262 (hole A), 1263 (hole C/D), 1265 (hole A), 1266 (hole C), and 1267 (hole B) on Walvis Ridge (fig. S1) (*18*). Records are plotted from left to right in order of increasing water depth. The core photos for each site represent composites of the following sections: 1262A-13H-5 and -6; 1263C-14H-1 and core catcher (CC); 1263D-4H-1 and -2; 1265A-29H-6 and -7; 1266C-17H-2, -3, and -4; 1267B-23H-1, -2, and -3.

Fig. 3. Bulk sediment d13C and weight % carbonate content (gCaCO3/gTotal 100) plotted versus age for ODP sites 1262, 1263, 1265, 1266, and 1267. Age (ky) relative to the P-E boundary is plotted on the left axis and absolute age (Ma) along the right. Age models (table S4) are based on correlation to site 690 (8) using the carbon isotope stratigraphy as verified with the nannofossil events in Fig. 2 and with the Fe and MS cycles in fig. S2. Transferring the 1263 age model to deeper sites with carbon isotopes could only be achieved where sufficient carbonate was present. Ages within the clay layers for sites 1266, 1267, and 1262 were derived through linear interpolation from tie points E and A. Paleodepths (È55 Ma) are provided for sites 1263 (1500 m), 1266 (2600 m), and 1262 (3600 m). Key events in the evolution of south Atlantic carbonate chemistry were (i) the rapid drop in content to G1% for all sites with the exception of site 1265, where the lowermost Eocene is absent (marked I); (ii) the return of the CCD to site 1263 roughly 5 ky after the excursion (marked II); (iii) the return of the CCD to site 1262 at 60 ky (marked III); and (iv) the lysocline descending to a point below the deepest site at 110 ky after the excursion (marked IV). PEB, Paleocene-Eocene boundary.

Science 295, 2062 (2002) Mammalian Dispersal at the Paleocene/Eocene Boundary

Gabriel J. Bowen,1* William C. Clyde,2 Paul L. Koch,1 Suyin Ting,3,4 John Alroy,5 Takehisa Tsubamoto,6 Yuanqing Wang,4 Yuan Wang4

A profound faunal reorganization occurred near the Paleocene/Eocene boundary, when several groups of mammals abruptly appeared on the Holarctic continents. To test the hypothesis that this event featured the dispersal of groups from Asia to North America and Europe, we used isotope stratigraphy, magnetostratigraphy, and quantitative biochronology to constrain the relative age of important Asian faunas. The extinct family Hyaenodontidae appeared in Asia before it did so in North America, and the modern orders Primates, Artiodactyla, and Perissodactyla first appeared in Asia at or before the Paleocene/Eocene boundary. These results are consistent with Asia being a center for early mammalian origination

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Fig. 2. Carbon isotope and magnetostratigraphy of the P/E transition in the Hengyang Basin, and the proposed intercontinental correlation of late Paleocene/early Eocene mammal faunas.

uintatheres
Large, extinct hippo-like mammals

Rodents = squirrel-like mammals

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Hyaenodontids= hyaena-like predatory mammals

East of Eden. Phylogenetic data suggest that Asia was the geographic source for many mammalian groups that later spread to Europe and North America. The fossil record implies that Asian mammals invaded North America at least three times near the P/E boundary. The three waves of Asian mammals included uintatheres (order Dinocerata), which dispersed to North America 57 million years ago (Late Tiffanian); rodents, which first appeared in North America 56.3 million years ago (Early Clarkforkian), and hyaenodontids, which migrated to North America 55 million years ago at the P/E boundary (or Early Wasatchian). New geochronological evidence from China supports this iterative biogeographic model.
CREDIT: MARK A. KLINGLER/CARNEGIE MUSEUM OF NATURAL HISTORY