instantaneous destruction of a unique macrohabitat, the immediate effect of which was the extinction of faunal groups that were specialized and restricted to the chalk substrate, such as the chalk brachiopods. The surviving species included forms that could survive in well-aerated shallow marine waters in other types of substrate.

When chalk deposition eventually resumed, adaptive radiation within surviving groups led to a rapid restoration of the chalk macrohabitat. The Maastrichtian and Danian chalks had uniform properties as substrates for benthic animals. Sedimentologically they are, however, quite different. The Danian chalk is composed of the remains of a whole new plankton flora and fauna. The shelly benthos is almost totally different on the species level as regards the most specialized groups, whereas other groups with wider substrate tolerance continue less changed across the boundary.

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Terminal Cretaceous Extinctions in the Hell Creek Area, Montana: Compatible with Catastrophic Extinction

Abstract. *Inaccurate stratigraphic correlations in the Hell Creek area, Montana, have led to the assumption that transitional vertebrate faunas (Bug Creek Anthills) exist in the latest Cretaceous, refuting a catastrophic turnover at the Cretaceous-Tertiary boundary. Establishment of the transitional faunas in Paleocene channels that cut down through the Cretaceous-Tertiary boundary renders the terrestrial faunal record compatible with the marine record and with catastrophic extinction.*

Since the discovery of iridium abundance anomalies at the Cretaceous-Tertiary (K/T) boundary at various sites (*1*) and the subsequent verification of the presence of an iridium anomaly at others (*2*), many investigations have been undertaken, culminating in several symposia (*3, 4*). Although not all investigators agree with the asteroid-impact theory (*5–8*), the evidence in its favor has steadily increased (*4, 9*). The marine fossil record across the K/T boundary appears to be in accord with an impact-induced mass mortality and mass extinction and with a subsequent recovery, as demonstrated by the planktonic foraminiferal record (*10*).

Some vertebrate paleontologists and paleobotanists studying the terrestrial sequence of the western interior of the United States (*6–8*) have presented a different picture of the K/T boundary turnover, which is inconsistent with a catastrophic impact model. They argue that the record shows gradual replacement of the latest Cretaceous vertebrate faunal communities by new faunas already below the K/T boundary. However, new data that we collected on a field trip to Montana, as guests of W. A. Clemens and his co-workers, show otherwise. We argue here that the terrestrial record, on the contrary, is consistent with the model of catastrophic turnover and that both terrestrial and marine extinctions are probably due to the same catastrophe.

Smit and ten Kate (*9*) presented a scenario for marine plankton extinctions (shown slightly modified in Fig. 1). A succession of five phases is hypothesized in a catastrophic faunal turnover resulting from an asteroidal impact:

1) Before the impact equilibrium conditions existed for several million years at the end of the Cretaceous.

2) An asteroidal impact led to mass mortality and mass extinctions and to the deposition of an iridium-enriched fallout stratum.

3) This was followed by a period of indirect and delayed effects, leading to a period of stressed ecological conditions, in which secondary extinctions took place. These extinctions continued for 1,000 to 15,000 years after impact, during deposition of the so-called boundary clay (*10*). No new species are known to have appeared in this period.

4) The origination of new species and the radiation of pioneering faunas, dominated by short-living opportunistic spe-

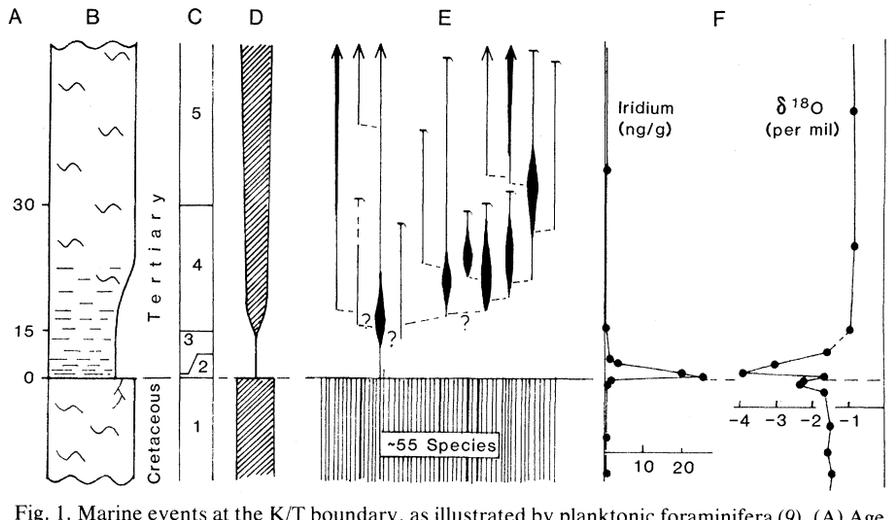

Fig. 1. Marine events at the K/T boundary, as illustrated by planktonic foraminifera (*9*). (A) Age (in 10^3 years) from the K/T boundary. (B) Lithology. (C) Subdivision in phases of the faunal events. (D) "Biomass" estimated on the basis of species and specimen density. (E) Lineages and relative abundances of planktonic foraminiferal species (*10*). (F) Iridium profile and $\delta^{18}O$ isotope profile relative to the Pee Dee belemnite standard (*9, 10*).

cies, took place during the next 15,000 to 100,000 years.

5) A new equilibrium condition was then established.

The duration of the successive intervals is estimated on the basis of sedimentation rates of the Caravaca, Spain, section (*10*). Figures 8 and 9 of Birkelund and Hakansson (*11*) show a very similar picture of the marine macrofossil change in the Nye Kløv section in Denmark, consistent with the plankton change.

An essential difference between this sudden scenario and gradual scenarios is that in the catastrophic scenario the massive radiation and diversification of new species take place after the mass extinction and not during the extinction, or below the iridium-enriched level, as reported in the terrestrial sequence of Montana.

Clemens and Archibald and others (*7–9*) have repeatedly stressed that the vertebrate record across the K/T boundary in terrestrial strata is best preserved and observed in the Hell Creek (upper Cretaceous) and Tullock (lower Paleocene) formations of northeastern Montana. Traditionally, the K/T boundary is drawn at the lowest persistent coal seam (the Z-coal) above the highest dinosaur remains. This definition is still useful as a general field criterion but can lead to confusion if used as the chronostratigraphic K/T boundary, as the Z-coal locally consists of several discontinuous coal seams, spaced some meters apart (*12*). In this respect the 63.9 × 10^6 year date of Baadsgaard and Lerbeckmo (*13*) cannot be accepted for the chronostratigraphic K/T boundary as the dated bentonite occurs in one of the younger Z-coals.

In the Raton basin of New Mexico, a well-defined iridium anomaly is associated with a sharp pollen change (*14*). Figure 2 shows that in the Hell Creek area also the sudden disappearance of several pollen taxa (*Aquilapollenites*) occurs exactly at the iridium anomaly in the basal Z-coal. This level is used as K/T boundary in this report.

The vertebrate fauna occurs in two different sedimentary facies (Fig. 3) and is said to consist of two different faunal communities: the Hell Creek faunal facies and the Bug Creek faunal facies (*6, 7*). The Hell Creek faunal facies consists of, among others, dinosaurs and Cretaceous mammals and can be found in the floodplain deposits throughout the Hell Creek Formation (below the K/T boundary). It changes slowly, if at all, and terminates abruptly. The Bug Creek faunal facies is found in fluvial channels and sandy point bars only and is consequently reworked or transported. This faunal facies is composed of a Cretaceous mammal fauna and dinosaur bone fragments and is outnumbered already in the oldest channels by a rapidly evolving mammal fauna of new, so-called "Paleocene aspect" mammals. Among these are the first representatives of ungulate and primate groups. The stratigraphically lowest sites of the Bug Creek faunal facies

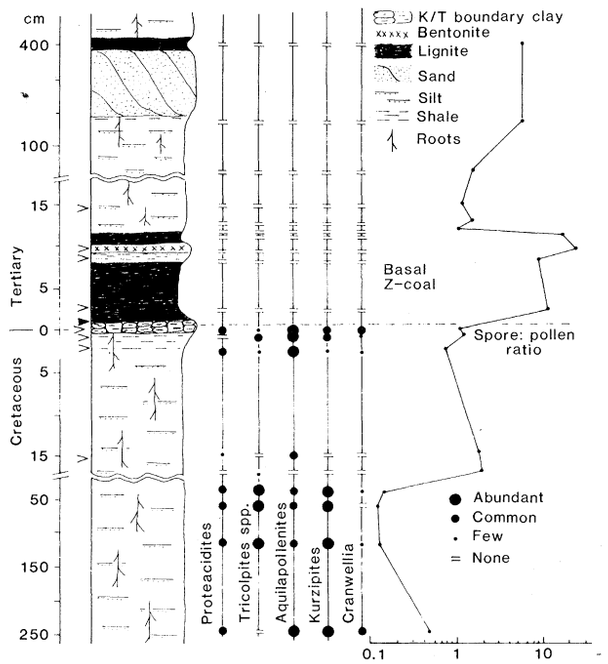

Fig. 2. Stratigraphic section at Herpijunk Promontory (*16*), Snow Creek area, Montana, showing the distribution of important pollen taxa; (>) samples analyzed for iridium. The iridium abundance in the top of the K/T boundary clay layer (▶) is 11.7 ng/g (± 10 percent); the iridium concentrations of the other samples are below the detection limit (1 to 2 ng/g).

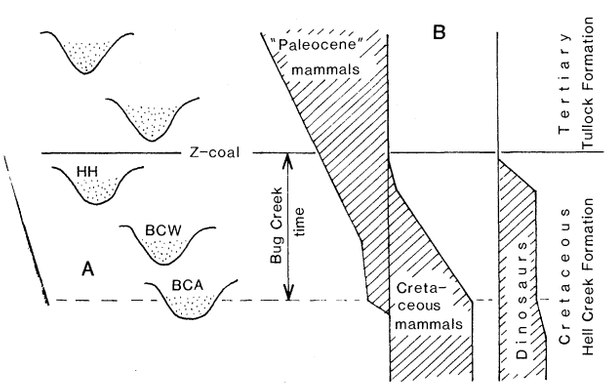

Fig. 3. Earlier reported stratigraphic position of faunal communities in the Hell Creek area, Montana. [(A) After Clemens and Archibald (*7*); (B) after Van Valen and Sloan (*6*)] Abbreviations: *HH*, Harbicht Hill; *BCA*, Bug Creek Anthills; *BCW*, Bug Creek West.

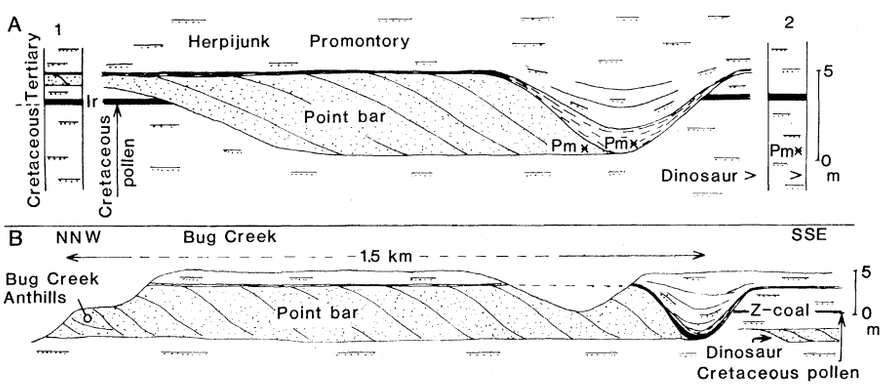

Fig. 4. Reconstructions of point bar and abandoned channels in the Hell Creek field, Montana, cutting through the K/T boundary (after photographs). The vertical scale is exaggerated. (A) Snow Creek area. 1, Section of Fig. 2. 2, Composite section [after (*15*)] of the same general area, suggesting a Cretaceous age for "Paleocene aspect" mammals (*Pm*); (>) approximate position of unreworked highest dinosaur remains. (B) Bug Creek area.

reportedly occur in the uppermost part of the Hell Creek Formation, below the K/T boundary. In this view the new Paleocene mammalian groups thus seem to appear and diversify before the extinction of dinosaurs and Cretaceous mammals. This would imply a gradual faunal turnover, inconsistent with the prediction of our model that new explosive radiation follows the elimination of dominant faunal elements. However, the evidence is almost exclusively based on these lowermost channels, and very little is known about the sedimentological framework and stratigraphic relations.

Recently, the group headed by W. Alvarez, in collaboration with W. A. Clemens and his co-workers, discovered an iridium-enriched level in the Snow Creek area of Montana, in the lower Z-coal of an isolated hill, dubbed the Iridium Hill (*15*). Our analyses of another outcrop of the Z-coal, about 1 km east-southeast of Iridium Hill, confirmed the iridium anomaly (Fig. 2) and showed that it occurs in the top of a thin clay layer at the base of the Z-coal in this outcrop (Herpijunk Promontory). If this clay is the equivalent of the iridium-rich fallout stratum in marine rocks (*10*), then it will presumably be preserved only in coal swamps. In the other, strongly dominating siltstones, shales, and sandstones, the chance of removal by erosion is much greater, as testified to by the observation that the numerous thin bentonites in the Hell Creek area occur only in coals. Some 200 m southeast of Iridium Hill, on another isolated hill, is an outcrop of an abandoned-channel fill that contains "Paleocene aspect" fossils [Morales-1 (*16*)]. Topographic projection of beds resulted in a composite stratigraphic section (2, in Fig. 4A), which suggests evidence of "Paleocene aspect" fossils below the iridium-enriched level (*15*). However, the more extensive outcrops around Herpijunk Promontory allow another reconstruction of stratigraphic relations (1, in Fig. 4A). Figure 4 shows the simplified cross section of a fluvial point bar with associated abandoned channel that was active in Paleocene time but partly cuts through Cretaceous deposits, including the Z-coal with the iridium-rich clay of Fig. 2. The abandoned channel is similar in shape, size, and lithology to the abandoned channel at Morales-1 and contains the same pollen association. A correlation made on the basis of intermediate outcrops suggests that both channels were cut by the same river, and that the stratigraphic position of the Morales-1 fossils is not below but above the Z-coal with the iridium anomaly.

One of the richest bonanzas of mammalian fossils ever found is located at the Bug Creek Anthills (BCA) sites, some 80 km east of Snow Creek. This site and the nearby, faunistically younger sites at Harbicht Hill and Bug Creek West have been interpreted by Van Valen and Sloan (*6*) as occurring in the upper part of the Hell Creek Formation, in the uppermost Cretaceous. This interpretation has been cited many times (*6*) as a major argument for a gradual faunal turnover at the K/T boundary. The channel in which the BCA fauna is found forms part of a large point-bar system, which can be traced in the field over about 1.5 km (Fig. 4). Abundant, poorly sorted floating bone fragments and clay pebbles in a sand matrix without the typical tabular fluviatile cross-bedding suggest deposition as a debris flow, a rare event deposit, possibly resulting from a hard rainstorm. Although a small gap exists between outcrops in the field, here too the point-bar system appears to terminate in an abandoned channel filled with fine carbonaceous shale. In the field it can clearly be seen that the cutting margin of this fluvial system has removed deposits of both Cretaceous and Paleocene age, as the K/T pollen break occurs within these cutout sediments. Consequently, the abandoned channel and point-bar system are Paleocene in age, as are the BCA sites within it. Considering the large amount of Cretaceous sediments eroded by this meandering river, the occurrence of outwashed dinosaur bone fragments and other Cretaceous fossils is not surprising.

Until now, a gradual transition has been postulated in the vertebrate turnover at the K/T boundary. The transition fauna would represent a time span, termed Bug Creek time (Fig. 3), in which the diversity of dinosaurs decreased and the diversity of mammals increased simultaneously. The results of our study suggest that this Bug Creek time did not exist, and that all Bug Creek faunas are Paleocene in age, apart from the reworked Cretaceous fossils. In our interpretation a gradual faunal change is not justified. On the contrary, the evidence appears to underscore a catastrophic scenario as outlined for the marine record. Extinction and new radiation are separated in time, in accord with the predictions of the catastrophic scenario. The Cretaceous Hell Creek dinosaur and mammal faunas disappear, overlain by an iridium-rich level associated with a sharp pollen break. After a certain time (it is difficult to determine how long because of the great range in sedimentation rates in a fluviatile environment), the explosive radiation of new mammalian groups followed. In view of the close association of the iridium-enriched level and mass extinction both on land and in the sea, it seems logical to assume that both have been caused by the same event—a large impact. Moreover, it is easier to understand that the origin and early development of the new mammalian groups, including the "Paleocene aspect" mammals of the Bug Creek channels, took place in the early Paleocene, because the disappearance of their main predators and competitors, the dinosaurs, opened up to them the ecological opportunity to diversify and radiate.

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