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Stratigraphic aspects of the Cretaceous-Tertiary boundary in the Bug Creek area of eastern Montana, U.S.A.

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Abstract. — Stratigraphical and palynological analysis of the Hell Creek and Tullock formations in the Bug Creek area of Eastern Montana show that dinosaur extinction and mammal turnover is consistent with a large impact model. The rapid evolutionary radiation of ungulate mammals in particular [Sloan *et al.*, 1986] in a short stratigraphic sequence above the iridium anomaly, in which possibly remnants of a dinosaur population occur as well [Rigby, 1984], underscores an extinction model which is modified after Smit & Ten Kate [1982]. Four localities which show this dinosaur extinction simultaneous with new mammal radiation were previously thought to occur in the Upper Cretaceous. Three out of four are now unquestionably Paleocene in age (BCW, HH and FR). The fourth, Bug Creek Anthills (BCA), is close in age to the Cretaceous-Tertiary (K/T) boundary, but cannot be conclusively shown to be either Cretaceous or Paleocene. Its highly unusual fossil abundance and taphonomy may document the initial adaptations to the terminal Cretaceous large impact event. We review stratigraphic data and explore an extinction model in which the impact initially produced a short but very profound floral change and a severe reduction of the populations of dinosaurs, mammals, and other biota. The final extinctions of dinosaurs and other vertebrates documented in the Bug Creek faunas, but, more important, the beginnings of the Paleocene explosive radiation of placental mammals, may be a direct consequence of this reduction or mass mortality. This initial radiation of the Bug Creek faunas is shown to occur entirely within the Z-Coal interval, or in less than 50 000 years.

Aspects stratigraphiques de la limite Crétacé-Tertiaire dans la région de Bug Creek, Montana oriental, Etats-Unis

Résumé. — L'étude stratigraphique et palynologique des Formations Hell Creek et Tullock dans la région de Bug Creek (Montana oriental) montre que l'extinction des dinosaures et le renouvellement des mammifères sont compatibles avec un modèle d'impact de grande ampleur. La présence d'une courte séquence stratigraphique au-dessus de l'anomalie en iridium [Rigby, 1984; Sloan *et al.*, 1986], dans laquelle les mammifères ongulés, en particulier, connaissent une rapide radiation, avec peut-être les restes d'une population de dinosaures, conforte un modèle d'extinction modifié d'après Smit & Ten Kate [1982]. Quatre gisements montrant cette extinction des dinosaures simultanément à une nouvelle radiation mammalienne étaient auparavant placés dans le Crétacé supérieur. Trois de ceux-ci peuvent maintenant être rapportés sans conteste au Paléocène (BCW, HH et FR). Le quatrième, Bug Creek Anthills (BCA), est proche de la limite Crétacé-Tertiaire, mais on ne peut le rapporter avec certitude soit au Crétacé, soit au Paléocène. Sa taphonomie et sa composition faunique très inhabituelles illustrent peut-être les adaptations initiales au grand impact de la fin du Crétacé. Nous passons en revue les données stratigraphiques et nous proposons un modèle d'extinction dans lequel l'impact a initialement produit un changement de flore bref mais très profond et une sévère réduction des populations de dinosaures, mammifères, et autres organismes. L'extinction finale des dinosaures et d'autres vertébrés, indiquée par les faunes de Bug Creek, mais aussi, chose plus importante, les débuts de la radiation explosive des mammifères placentaires du Paléocène peuvent être une conséquence directe de cette réduction ou mortalité de masse. Cette radiation initiale des faunes de Bug Creek se place entièrement à l'intérieur de l'intervalle chronologique du "Z-Coal", c'est-à-dire en moins de 50 000 ans.

INTRODUCTION.

Dinosaur extinction has always played a major role in the Cretaceous-Tertiary extinction discussion, not the least in the public opinion. Numerous causes for their extinction have been suggested, ranging from scenarios such as climatic deterioration [e.g. Tappan, 1968] and community evolution [Van Valen & Sloan, 1977] or competition of mammals with dinosaurs to less plausible ones such as the standing room in Noah's ark. Most of these theories stress gradual earthbound processes underlying the extinctions.

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The discovery of widespread iridium anomalies and microtektites in marine rocks precisely at the Cretaceous-Tertiary boundary [Alvarez *et al.*, 1980; Smit & Hertogen, 1980; Smit & Klaver, 1981; Montanari *et al.*, 1984] provided evidence for a catastrophic extinction mechanism, a large asteroid impact. Whether the extinctions themselves were "catastrophic" (sudden) or relatively gradual, is immaterial for and independent from the discussion whether the impact directly or indirectly caused these extinctions. Moreover, the term "catastrophic extinction" is momentarily interwoven with memories of Cuvierian catastrophes from the past to such an extent, that we will avoid the term in this discussion entirely. The semantics of this term apparently lead to aversion and misunderstanding as discussed later. However, if one wishes to discuss hypothesized causes of extinction ranging from long term environmental changes to extremely short as an asteroid impact, one has to determine the exact position of the Cretaceous-Tertiary boundary. This may seem a moot point [Archibald, 1984; Unwin, 1986] if one *a priori* accepts only gradual or stepwise changes when indications for gradual extinction have been found. Indeed, then the definition of the Cretaceous-Tertiary boundary would just be an artifact of human classification [Russell, 1982]. But, we are faced with the fact that a sharp level with probable extraterrestrial remains has been found. If the postulated impact is in any way connected with the extinctions, one has to test whether the evidence for impact pre- or post-dates the extinctions, be these gradual or not. It is thus of crucial interest to determine the Cretaceous-Tertiary boundary level with respect to any extinction record.

Of course, it may be argued that evidence of events in the order of days or 100 years have little chance of being preserved in the sedimentary record [Dingus, 1984] and it may thus be futile to search for these. However, even a 1 % preservation chance of a 100 yr sedimentary interval becomes almost a certainty when a 100 or so complete sections are analysed. This number has already been approached for marine pelagic sections and the bedding-plane — iridium anomaly coupled — extinction levels of planktonics still remains valid [Smit & Romein, 1985]. Extinction levels of planktonics and pollen, co-occurring with iridium anomalies and microtektite/shocked quartz grains, are found worldwide, essentially confined to a bedding plane when smearing processes are taken into account. In the classical stratotypes of the Maastrichtian and Danian in Europe this horizon occurs at the defined (type)level of the Cretaceous-Tertiary boundary. Also in areas where vertebrate (dinosaur) extinction is documented, these sharp iridium anomalies and a sharp pollen break have been found [Bohor *et al.*, 1984; Smit and Van Der Kaars, 1984; Tschudy *et al.*, 1984]. Their temporal relation with the vertebrate extinction record should be established first before one can infer whether the extinctions were independent (in time) from the impact or not. Previous research in these areas delineated the Cretaceous-Tertiary boundary for practical reasons at a useful lithological marker, the Z-coal. As discussed later, this marker is not identical with the (chronostratigraphic) Cretaceous-Tertiary boundary, nor has its relation to crucial fossil locations been well established. We will argue below that terminal Cretaceous extinctions, and the following acceleration of the evolution of placental mammals, are in time intimately related to the largely unknown effects of a large impact. This scenario is more or less independent of earth bound, longterm environmental changes. But, of course, these continue to play a role, presumably in the background. The authors agree on most what is presented here. However, Rigby allows also more gradual processes to play a role in the extinctions.

Vertebrate turnover.

Alvarez *et al.* [1980] speculated that also terrestrial (dinosaur) extinction was caused by the effects of the same large impact which caused marine extinctions. Soon after, however, doubts were expressed whether this was the case [Archibald, 1981; Archibald & Clemens, 1982; Clemens, 1982; Kent, 1981; Van Valen, 1984]. Later on an iridium anomaly was discovered at the palynological Cretaceous-Tertiary boundary in New Mexico [Orth *et al.*, 1982]. Subsequently the iridium anomaly [Alvarez, 1983; Smit & Van Der Kaars, 1984] and shocked minerals [Bohor *et al.*, 1984] were shown to occur in dinosaur and mammal bearing fluvial beds at the same sharp palynological break. However, the relation between the proposed large impact, and dinosaur extinction, and mammal turnover remained largely obscure.

Several authors stress [e.g. Van Valen & Sloan, 1977; Clemens & Archibald, 1980; Archibald & Clemens, 1984] that the only record which documents the terrestrial vertebrate transition from the Cretaceous to the Tertiary in some detail can be found in eastern Montana, in the Hell Creek field south and east of Fort Peck Lake (fig. 1). Here vertebrate remains are found in fluviatile sediments of two formations; the (largely) Late Cretaceous Hell Creek Formation and the Early Paleocene Tullock Formation. These formations are separated by the (Upper) Z-coal. Many dinosaur and in particular mammal bearing fossil localities are found and new sites continue to be found [Sloan *et al.*, 1986; Rigby *et al.*, in press] below and above the Cretaceous-Tertiary boundary. Some additional information comes from the Upper Cretaceous (Lance Formation) of Wyoming [Clemens, 1965] and from Saskatchewan [Johnston, 1980].

One of the first more detailed accounts of dinosaur extinction in Montana was given by Sloan & Van Valen [1965] and Van Valen & Sloan [1977]. They described a sequence of three faunas, here termed Bug Creek faunas, in the upper Hell Creek Formation of the Bug Creek/Sand Arroyo area in McCone County east of the Fort

Peck Lake. With the term "fauna" is meant here a fossil microvertebrate assemblage, consisting of among others dinosaur and mammal fragments. Such a "fauna" is found in a, horizontally as well as vertically, restricted locality, usually at the base of a stream channel or point-bar. These Bug Creek faunas document a gradual transition from faunas with dinosaurs and typical Late Cretaceous mammals to faunas where Paleocene mammals dominate without any dinosaur remains [Hell's Hollow; Archibald, 1981]. Later mostly smaller supplementary faunas (KA, SMP, FR, BG) to the Bug Creek faunas were found. The three original faunas are in ascending order Bug Creek Anthills (BCA), Bug Creek West (BCW) and Harbicht Hill (HH). Within these biostratigraphically ordered series of faunas, dinosaurs (fig. 2) and mammals typical of the Late Cretaceous decrease, and among others ungulate mammals increase and diversify. Clemens and Archibald [1980] [see also Archibald & Clemens, 1984] extended and corroborated Van Valen and Sloan's work by discovering numerous additional sites mainly in Garfield County south of Fort Peck lake (Hell's Hollow, Flat Creek). However the main body of information still comes from the Bug Creek area.

Van Valen & Sloan [1977] inferred from the Bug Creek faunas three communities living contemporaneously in the general area; two terrestrial ones, one of which consists of dinosaurs and typical Cretaceous mammals dominated by marsupials and multituberculates (the *Triceratops* community), and the other of new incoming (invading) new mammal groups (the *Protungulatum* community). The third community is aquatic (among others fish, amphibians, crocodile/turtles, shore birds) and does not change appreciably across the Cretaceous-Tertiary boundary. This fresh-water community is apparently relatively unaffected by whatever event occurred at the Cretaceous-Tertiary boundary because most of its constituents continue unchanged. [Van Valen & Sloan, 1977]. The aquatic community has been cited [Van Valen, 1984] in disfavour of an impact event. This implies we know enough about

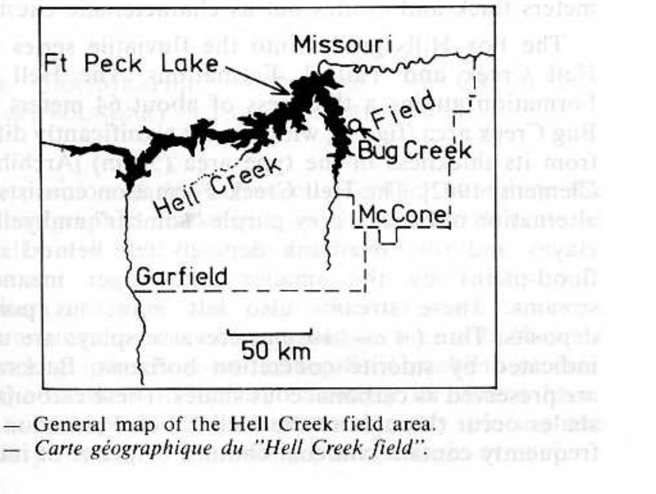


FIG. 1. — General map of the Hell Creek field area.
FIG. 1. — *Carte géographique du "Hell Creek field".*

impact effects to infer with certainty it should have affected the freshwater community, which we don't. Clemens & Archibald [1980] refer to the different kind of faunas believed to co-occur in the Uppermost Cretaceous Hell Creek Formation in a descriptive sense as microvertebrate assemblages. They distinguish a Hell Creek faunal facies, which occurs throughout the Hell Creek Formation and is more or less comparable to the *Triceratops* community but with the aquatic members. The second is the Bug Creek faunal facies which includes all three communities in the Bug Creek faunas. The *Triceratops* community existed for millions of years and evolved slowly [Van Valen & Sloan, 1977]. Archibald & Clemens [1984] indicate that mammals within the Hell Creek faunal facies show little if any evolutionary change throughout the Hell Creek Formation. This is in great contrast to the developments in the Bug Creek faunas where the *Protungulatum* community evolves rapidly within little time. This "little time" is hard to quantify, but is used as comparison to the total duration of the Hell Creek formation as given by Sloan *et al* [1986] as 2.5 myr. The Hell Creek Formation has a total thickness of a 64 meters in the Bug Creek area, and Sloan & Van Valen [1965] estimated the stratigraphic distance between the three Bug Creek faunas in the top of the Hell Creek at 12.2 meters (40 ft), or 0.5 myr assuming that sedimentation rates do not differ appreciably. As we will see later, the duration of the interval of the Bug Creek faunas is probably closer to 50 000 years or even less.

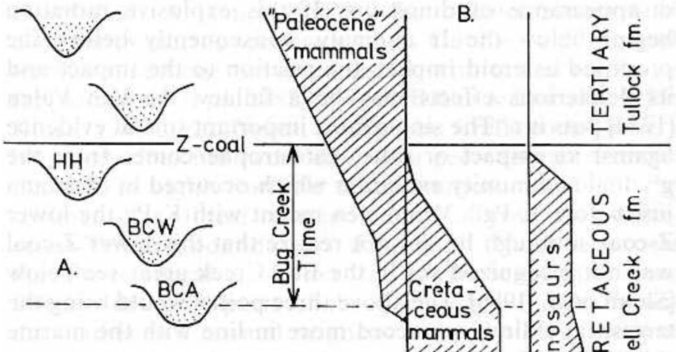


FIG. 2. — Interpretation of extinctions in the Hell Creek field by A) Clemens & Archibald [1980] and B) Van Valen & Sloan [1977]. In both interpretations only one (the upper) Z-coal is indicated. In Clemens & Archibald's reconstruction the faunas involved are shown as channels, which occur below the Z-coal, equated with the Cretaceous-Tertiary boundary. Also Van Valen & Sloan thought the Z-coal to represent the Cretaceous-Tertiary boundary. However, the Cretaceous-Tertiary boundary is closer to the beginning of "Bug Creek time". Cm = Cretaceous mammals, Pm = Paleocene type mammals, D = dinosaurs.

FIG. 2. — *Interprétation des extinctions des vertébrés dans la Formation Hell Creek. D'après A) Clemens & Archibald [1980] et B) Van Valen & Sloan [1977]. Seulement un chenal des "Z-coal" a été indiqué par ces auteurs.* Cm = *mammifères du Crétacé.* Pm = *mammifères "type" Paléocène.* D = *Dinosaures.*

tent forest fires, and locally pieces of amber. Lignite deposition starts in the middle of the Hell Creek Formation with a 10 cm thick persistent lignite, the so-called Null coal [Rigby *et al.*, in press]. The Null coal (fig. 3-5) crops out over most of the Bug Creek area, but is locally eroded by the Toadstool Park sandstone point-bar complex, among others just below BCW. It contains abundant charcoal and characteristic amber fragments. A 1-2 cm thick bentonite is intercalated just below the charcoal fragments, which suggests that volcanic eruptions led to forest fires. This bentonite is ubiquitous in the Null coal and shows that the Null coal is an isochron [see also Fastowski & Dott, 1986]. The Null coal serves to establish the stratigraphic positions of important faunal localities.

Petrographically the different point-bar deposits are almost indistinguishable; all consist of chert and volcanic lithic clasts [Fastowski & Dott, 1986]. Variable amounts of silt, depending apparently of stream gradients of the various smaller and larger streams, are mixed in. The boundary between the Hell Creek Formation and Tullock Formation is defined by the upper (or formational) Z-coal, both south and east of Fort Peck Lake. Nowhere, however, is this upper Z-coal equivalent to the Cretaceous-Tertiary boundary (see below). Although coal deposition starts already in the middle of the Hell Creek Formation, the Upper Z-coal marks an important facies change. The Tullock Formation contains numerous thicker coal seams (Z through U coals) and is generally multi-coloured opposite the monotonous, somber Hell Creek beds. The first beds directly upon the Upper Z-coal show highly characteristic, evenly and parallel interbedded silt and clay layers, clearly the result of suspension settling. This indicates a ponded environment. These finely bedded layers can be traced over a large area in both Garfield and McCone Counties [Fastowski & Dott, 1986]. We infer that this relatively rapid facies change could have been more or less synchronous over the Hell Creek field, because it was probably due to the eustatic sea level rise, which made the Cannonball sea. This, in turn, may imply that the Upper Z-coal, directly underlying the swamp facies, is also almost synchronous over a large distance.

THE STRATIGRAPHIC POSITION OF THE CRETACEOUS-TERTIARY BOUNDARY IN THE HELL CREEK FIELD.

The position of the Cretaceous-Tertiary boundary, the time-stratigraphic markerline, in the terrestrial strata of the Hell Creek field has been the source of many complications and errors. As Archibald & Clemens [1984] correctly remark : "...regrettable for work in Montana has been the entanglement of concepts based on time with those of rock stratigraphy. Beyond the legalistic problem of defining the Cretaceous-Tertiary boundary in eastern Montana, is the problem of more accurately placing the boundary for use in discussing paleontologic events".

Relevant for the present discussion is the temporal relation of the Cretaceous-Tertiary boundary to the informally defined local "Cretaceous-Tertiary boundary" markers in the literature. In Europe the proposed Cretaceous-Tertiary boundary stratotype is at Stevns Klint, Denmark (where the stratotype of the lowermost stage of the Tertiary, the Danian, is exposed). At Stevns Klint a bedding plane extinction of e.g. ammonites and coccoliths-planktonic foraminifera occurs exactly at the iridium anomaly. Other marine sections are concordant with Stevns Klint [Smit & Romein, 1985]. Since a first order biostratigraphic correlation of marine fossils with terrestrial fossils within one section does not exist yet, the definition of the Cretaceous-Tertiary boundary in terrestrial strata relies on indirect methods such as comparison of absolute ages, comparison of magnetozonations and by worldwide isochronous markers such as the iridium anomaly.

Absolute ages are not sufficiently accurate for precise correlation. For instance, two different numbers of absolute Cretaceous-Tertiary boundary ages circulate in the literature : one of Lerbeckmo *et al.* [1984] of 63.9 myr and another of 66.7 myr [Obradovitch & Cobban, 1975]. Which of these is correct is an open question. Moreover, a radiometric age for the Cretaceous-Tertiary boundary has not yet been determined in marine rocks [Van Valen, 1984].

The Cretaceous-Tertiary boundary occurs in a reversed geomagnetic zone, identified as sea floor anomaly (Chron) 29R in all sections where a magnetostratigraphy has been established. A comparison of the magnetozonation of continuous marine sections such as Gubbio, with those of terrestrial sections has been tested, with mixed results so far [Archibald *et al.*, 1982, (but see Butler & Lindsay, 1985; Klute, 1986); Van Valen, 1984]. The Cretaceous-Tertiary boundary does not occur close to a geomagnetic reversal. Because of highly variable sedimentation rates in fluvial sediments, a linear extrapolation towards the Cretaceous-Tertiary boundary is dangerous. Thus we expect that the temporal resolution will not be better than some 100 kyr or so. Reports of the Cretaceous-Tertiary boundary either in a normal magnetic zone [Wolberg, 1984] or in the next higher reversed magnetic zone 28R [Lindsay *et al.*, 1981] have been revoked. [Butler & Lindsay, 1985; Shoemaker *et al.*, 1984].

The worldwide iridium anomaly has the potential of a powerful and accurate time — stratigraphic Cretaceous-Tertiary boundary marker. As far as now known it occurs as a narrow spike or zone, and coincides invariably with a sharp marine biological extinction level [Smit & Romein, 1985]. Assuming the Cretaceous-Tertiary Ir anomaly in terrestrial strata to be the same as in marine rocks (one has to be aware of circular reasoning here, but the assumption has not been falsified), it may also there define the Cretaceous-Tertiary boundary accurately. Some practical problems remain. For instance, within a region where terrestrial strata are exposed, one has to rely on indirect

In conclusion, the Bug Creek faunas were reported to occur in the top 25 meters of the Hell Creek Formation below a Z-coal thought to represent the Cretaceous-Tertiary boundary. These Bug Creek faunas document a gradual or stepwise, relatively rapid evolution of new mammalian groups synchronous with a reduction in abundance of typical Cretaceous mammals and dinosaurs.

Smit & Van Der Kaars [1984] questioned this interpretation on the basis of three observations. — 1) The "Z-coal", as recognized in the Hell Creek field, is not coeval with the Cretaceous-Tertiary boundary. — 2) The Cretaceous-Tertiary boundary should be placed at or close to an older lignite, earlier not recognized as such in McCone County and recognized as the lower Z-coal in a number of localities in Garfield County [Archibald, 1982; Archibald & Clemens, 1984]. The lower Z-coal contains in Garfield County an iridium anomaly within an unusual clay layer, a "tonstein", and shows the extinction of several important Cretaceous palynomorphs *(Aquillapollenites)* within centimeters of the Ir anomaly. — 3) Two channels with reported Bug Creek faunas (Herpijunk Promontory and Bug Creek Anthills) would cut through the Cretaceous-Tertiary boundary, assuming the lower Z-coal to be the Cretaceous-Tertiary boundary.

The impulse for Smit & Van der Kaars' [1984] research was the earlier reported occurrence of substantial mammalian evolution below the reported Cretaceous-Tertiary boundary. This would be in conflict with the marine extinction record. The great explosive radiation of placental mammals in the Paleocene is generally ascribed to the disappearance of dinosaurs. If this explosive radiation begins below the Ir anomaly, consequently before the proposed asteroid impact, the relation to the impact and its deleterious effects may be a fallacy. As Van Valen [1984] puts it : "The single most important sort of evidence against an impact or other catastrophe comes from the gradual community evolution which occurred in Montana just before K-Pg". Van Valen meant with K-Pg the lower Z-coal, although he did not realize that this lower Z-coal was not recognized yet in the Bug Creek area; see below [Sloan *et al.*, 1986]. The above three points would bring the terrestrial extinction record more in line with the marine record.

Smit & Van Der Kaars' [1984] account met with strong opposition [Rigby, 1984, 1985; Archibald, 1984, 1985; Van Valen, 1984; Fastowski & Dott, 1986; Sloan *et al.*, 1986]. Some of the criticism was directed against the stratigraphic relationships in a reconstruction of the Bug Creek Anthills-Big Bugger point-bar position with respect to the Cretaceous-Tertiary boundary [Fastowski & Dott, 1986; Sloan *et al.*, 1986] which was somewhat oversimplified, so that BCA was mistakenly incorporated within the Big Bugger point-bar. However, their basic conclusions still stand : three out of the four Bug Creek faunas are now definitely Paleocene in age (BCW, FR and HH; Rigby *et al.*, in press). Fastowski & Dott [1986], Rigby *et al.* (in press), conclude that it cannot be shown whether the BCA fauna is either Cretaceous or Paleocene in age. This conclusion is already fundamentally different from a BCA stratigraphic position 25 meters below the Cretaceous-Tertiary boundary, as generally accepted before Smit & Van der Kaars' [1984] report.

Another raised point comes out of a misunderstanding. Smit & Van der Kaars [1984] assumed that (mass)extinction starting from a catastrophic event like an asteroid impact should be termed a "catastrophic extinction", irrespective of the fact whether the extinctions following it were sudden gradual or stepwise in character. This is in line with Van Valen [p. 122, 1984]. Archibald [1984, 1985], however, disagreed and stated that the gradual or stepwise extinction record, apparently irrespective of what happened, should be termed a "gradual extinction", and that it was a "moot point" whether this gradual extinction record occurred before, during or after the Cretaceous-Tertiary event [Unwin, 1986]. Clemens [1982] essentially said the same, when he accepts catastrophic extinction only if complete within one generation time (100 years). Because of the above misunderstandings we refrain from the term catastrophe as much as possible, for to quote Ken Hsü : "...one man's catastrophe is nothing out of the ordinary to another" [Hsü *et al.*, 1982].

Geological setting.

The Late Cretaceous (Maastrichtian) in the Hell Creek field of eastern Montana consists of a regressive sequence which documents a withdrawal of epicontinental seas from the interior seaway. The Bearpaw Shale represents an open sea facies haunted by ammonites and mosasaurs. Where exposed, the youngest zone of the Bearpaw Shale is of Middle Maastrichtian age, (the *Baculites clinolobatus* Zone) [Sloan *et al.*, 1986]. The Bearpaw Shale grades into the Fox Hills Sandstone, a near-shore facies of beach-sands and tidal channels with conspicuous ophiomorph burrows. The Fox Hills is usually some ten to twenty meters thick and erodes out as characteristic cuestas.

The Fox Hills grades into the fluviatile series of the Hell Creek and Tullock Formations. The Hell Creek Formation attains a thickness of about 64 meters in the Bug Creek area (fig. 3), which is not significantly different from its thickness in the type area (58 m) [Archibald & Clemens, 1982]. The Hell Creek Formation consists of an alternation of banded grey-purple "somber" and yellowish clayey and silty overbank deposits left behind on the flood-plains by the smaller and larger meandering streams. These streams also left numerous point-bar deposits. Thin (+/— 10 cm) crevasse splays are usually indicated by siderite concretion horizons. Backswamps are preserved as carbonaceous shales. These carbonaceous shales occur throughout the Hell Creek Formation. They frequently contain charcoal chunks, evidence of intermitcorrelations because an iridium anomaly is not directly visible in the field. Fortunately, where an iridium anomaly has been identified, it co-occurs with a sharp extinction level of some Cretaceous palynomorphs [Tschudy, 1985; Smit & Van der Kaars, 1984; Nichols *et al.*, 1984]. This palynological Cretaceous-Tertiary boundary is easier to determine in the field, by quick methods of slide preparation [Van der Kaars & Smit, 1985]. Also fortunate, the Ir anomaly is apparently associated with a typical clay layer (a "tonstein") of about one cm thickness. This "tonstein" is different from the numerous volcanic tuffs, now altered to bentonites, by the practical absence of phenocrysts. Unfortunately, this "tonstein" has only been preserved in backswamp deposits, lignites. In the Hell Creek field the "tonstein" has been observed over 30 km from Seven Blackfoot Coulee to Brownie Butte south of Fort Peck Lake within the so-called lower Z-coal. In the Bug Creek area, however, the iridium anomaly and the associated tonstein are incorporated in flood-plain silts 10-20 cm below the Lower Z-coal and escape visual identification. Carl Orth [see Smit & Van der Kaars, 1984; Fastowski & Dott, 1986] found a slight Ir enrichment in Russell basin, 1.5 km ESE of BCA, at the palynological Cretaceous-Tertiary boundary.

The Z-coals and the Cretaceous-Tertiary boundary problem.

Traditionally, the Cretaceous-Tertiary boundary has been equated with the "Z-coal" (complex) in the Hell Creek field. Coal geologists have labelled the numerous persistent coal and lignite seams with the letters Z- (the lowest) through to U-coal (the boundary between the Tullock and Lebo Formations). R. Brown [1952] defined for practical reasons the Cretaceous-Tertiary boundary as "the first lignite above the highest dinosaur remains". As apparently coal deposition in the Hell Creek field starts at about the Cretaceous-Tertiary boundary, it may have been a useful approximation. For years this "first" lignite became known as "the Z-coal bed" and somehow the notion of a Z-complex, with numerous seams, became lost and was replaced by a single "Z-coal" [Van Valen & Sloan, 1977; Norton & Hall, 1969; Oltz, 1969]. This thick, persistent, now termed Upper Z-coal forms the clearly distinguishable boundary between the Hell Creek and Tullock Formations. However, the Cretaceous-Tertiary boundary occurs from 0.5 up to 11 meters, on the average 5 m, below this Upper Z-coal (fig. 6), usually close to a very thin discontinuous coal, the Lower Z-coal of Archibald & Clemens [1982].

The entanglement of upper and lower (in the Bug Creek area even four) Z-coal beds with the Cretaceous-Tertiary boundary has led to confusion [Sloan *et al.*, 1986]. For instance, an extinction of dinosaurs is believed to occur about 3 m below the Cretaceous-Tertiary boundary [Archibald & Clemens, 1982]. As it is not clear which Z-Coal is meant as Cretaceous-Tertiary boundary, this number should be reevaluated and the stratigraphic position of the highest dinosaurs related to the correct Cretaceous-Tertiary boundary (usually the lower Z-coal). Reports of decreasing pollen abundance [Sloan *et al.*, 1986] and increasing winter temperatures [Van Valen & Sloan, 1977] occurring in the "Late Cretaceous" are questionable, as these records are from that part of the Hell Creek formation which has been shown to be Paleocene in age (see palynology). Similarly, the rough calculation by Sloan *et al.* [1986] of dinosaur abundance decrease in the Hell Creek formation is questionable. Sloan *et al.* [1986] suggest that the number of dinosaur specimens per square kilometer of outcrop per 9 m interval of stratigraphic section (exclusive of washing localities as BCA, BCW, HH) decreased significantly in the upper 9 m interval. Sloan *et al.* [1986] used data of Bell [1969] who used the upper, formational Z-coal as the Cretaceous-Tertiary boundary on his map. Figure 6 shows that the difference in distance between the Cretaceous-Tertiary boundary (within 10 cm of the Lower Z-coal) and the formational Upper Z-coal varies in Russell basin from 3.5 to 11 m. At FR the distance is about 6.1 m and at HH 5.7 m [Rigby Jr. *et al.*, in press]. The average distance between the Cretaceous-Tertiary boundary (the Lower Z-coal) and the formational Z-coal is thus estimated at 5.3 m, rounded to 5 m. As non-reworked dinosaur specimens are found exclusively below the lower Z-coal, the upper 9 meter interval should be reduced to 4. Recalculating the dinosaur specimen abundance over the Hell Creek Formation with this corrected interval, no progressive reduction is shown (table I), although the numerical data base remains woefully small.

TABLE I. — Number of dinosaur specimens per km^2 of outcrop per 9 meter interval of stratigraphic section (exclusive of washing localities) after Sloan *et al.* [1986]. The upper 9 m interval is recalculated to 4 m in the column at right.

TABL. I. — *Nombre de restes de dinosaures recueillis par km^2 et par intervalle stratigraphique de 9 mètres (à l'exclusion des localités des microvertébrés), d'après Sloan* et al. *[1986]. L'intervalle supérieur à 9 mètres a été recalculé à 4 mètres pour incorporer la distance entre le "Z-coal" supérieur et le "Z-coal" inférieur, sans aucun reste de dinosaures.*

Stratigraphic interval below Z-coal (m)	No. of dinosaur specimens	Area prospected per km^2	Dinosaurs per km^2	Corrected no. dinosaurs per km^2(* = x9/4)
0-9 (5-9)*	6	4.18 (1.86)*	1.44	3.22*
10-18	13	4.18	3.1	3.1
19-27	9	3.93	2.29	2.29
28-36	14	2.76	5.07	5.07
37-45	4	2.31	1.71	1.71
46-54	6	2.42	2.48	2.48

Geological setting of faunal localities in the Bug Creek area.

Mostly discrete microvertebrate fossil localities play a role in the reconstruction of the Cretaceous-Tertiary vertebrate turnover. The larger skeletons and other large remains from the flood-plains are in this question of less importance. The Bug Creek faunas, Bug Creek Anthills (BCA), Bug Creek West (BCW) and Harbicht Hill (HH) are the most famous and were used in the extinction scenario as outlined by Van Valen & Sloan [1977] and Clemens and co-workers [Archibald & Clemens, 1984]. Recently J. Keith Rigby Jr. found numerous additional localities, of which Ferguson Ranch (FR) is the most prolific and important [Sloan *et al.*, 1986; Rigby *et al.*, in press]. Additional (old and new) localities with microvertebrate assemblages are Kens Saddle (KS), Ken's Apex (KA), Scmenge Point (SMP), Carnosaur Flat (CF), and By George (BG). All these localities and numerous smaller ones, except HH and FR, are located in the small area of the Bug Creek drainage (fig. 3). Useful additional information comes from Flat Creek and Hell's Hollow localities in Garfield County, south of Fort Peck Lake [Archibald & Clemens, 1984].

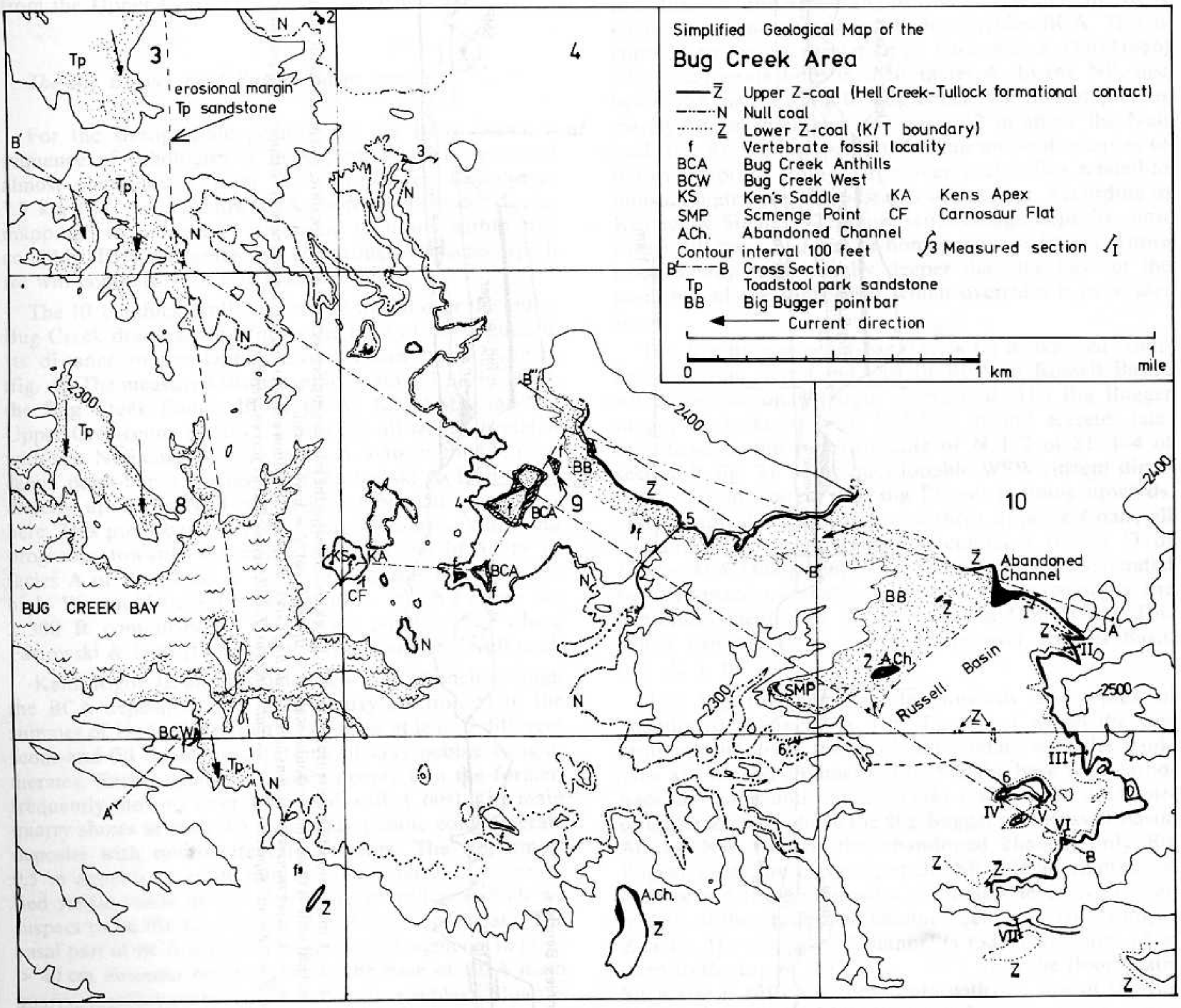


FIG. 3. — Simplified geological map, showing the relevant lithological units mentioned in the text.
FIG. 3. — *Carte géologique simplifiée de la région de Bug Creek.*

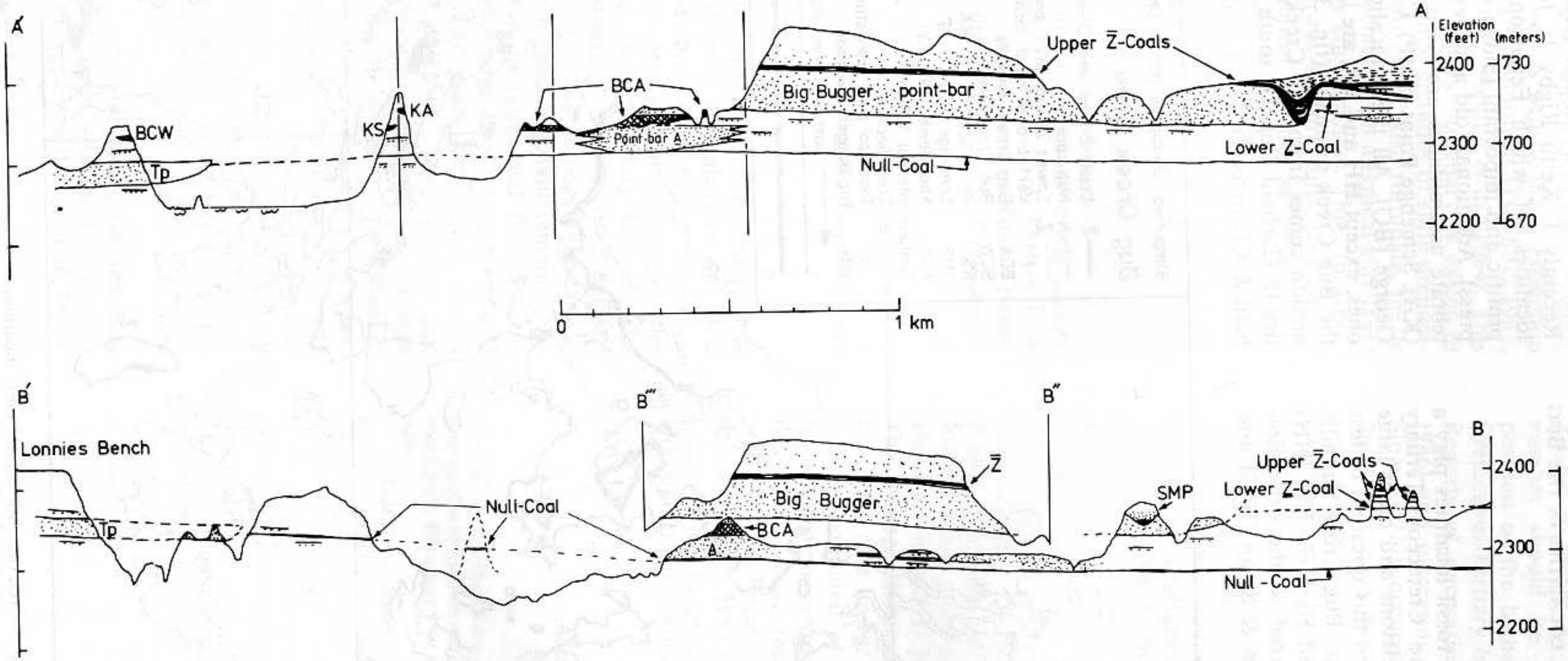


FIG. 4. — Cross section diagrams through the Bug Creek area, showing the relationship between important localities and marker coals mentioned in the text. The vertical scale is twice the horizontal scale. $\bar{\bar{Z}}$ = upper Z-coal, $\underline{Z}$ = lower Z-coal.

FIG. 4. — *Coupes transversales dans la région de Bug Creek, montrant la relation entre les localités fossilifères et les lithologies importantes, indiquées dans le texte. $\bar{\bar{Z}}$ = "Z-coal" supérieur. $\underline{Z}$ = "Z-coal" inférieur. Echelle verticale deux fois exagérée.*

These microvertebrate localities have one thing in common : they all occur at the base of larger and smaller stream channels and point-bars. They are also contained within typical clay-pebble ironstone lag-conglomerates. The conglomerate/microvertebrate localities do not occur over the entire length of a point-bar base, but apparently are filling in local scours, which originate during rainstorm induced, high flow-intensity conditions [Fastowski & Dott, 1986]. Typically, these lag-conglomerates are some tens of centimeters thick. Most of these localities appear to be deposited in one depositional event. BCW, one of the more productive fossil sites, shows two depositional events and is about 0.5 m thick. BCA, however, is the unique exception among all of the microvertebrate sites from the Upper Cretaceous or Lower Paleocene.

The Big Bugger-BCA-Russell Basin complex.

For the stratigraphic position of the BCA fauna, a sequence of lithologies is important, which is exposed almost continuously from BCA to Russell Basin over 1.5 km (fig. 3-5). Fastowski & Dott [1986] used "facies mapping" to unravel stratigraphic relations within this complex. They recognize five (A through E) facies which we will compare with our interpretations.

The 10 cm thick Null-coal can be traced over the entire Bug Creek drainage and forms the base of the sequence. Its distance to the Upper Z-coal varies from 28-30 m (fig. 4). The measured stratigraphic sections 1-6 (fig. 3, 5), the Bug Creek faunas BCA, BCW, KA, SMP and the Upper Cretaceous faunas CF and KS all were correlated with the Null-coal as base level. A 8-10 m thick Cretaceous point-bar A (facies A of Fastowski & Dott) rests directly upon the Null-coal, without breaching it anywhere. This point-bar A on the whole is fining-upward and progrades towards the east. The thickness of 17 m of facies A of Fastowski & Dott [1986] seems therefore too high. We could trace the Null-coal — which follows the 2 300 ft contour-below the entire point-bar A, where Fastowski & Dott [1986] show it breaching the Null coal.

Keith Rigby Jr. and his field crew dug a trench through the BCA deposit in the main quarry (section 5) in the summer of 1985. The trench walls show at least 6 different scour-and-fill depositional events of clay pebble conglomerates. Each higher one scours deeply into the former, frequently showing over-steepened walls (60°). The main quarry shows at least 4.5 m of clay pebble conglomerate deposits with microvertebrate remains. The uppermost 0.5 m appears to grade into medium coarse, cross-stratified sterile sands of the overriding point-bar (which we suspect to be the base of the Big Bugger point-bar). The basal part of BCA is rich in larger fossil fragments (a large > 40 cm dinosaur bone occurs at the base of BCA main quarry, together with 10 cm large claypebbles). Sloan *et al.* [1986] show that dinosaur remains at BCA-base are relatively frequent (fig. 7), approximately between the abundance of typical Late Cretaceous localities such as KS and CF, and the top of BCA and younger Bug Creek faunas (BCW, HH, FR). In the upper part of BCA, scouring is less conspicuous and trough cross-stratification is obvious. Unfortunately, we were not able to measure reliable current directions in the BCA deposits.

The BCA deposit occurs over an exceptionally wide area (fig. 3). At the main quarry, the base of BCA is about 8.5-9 m above the Null coal. It rests with an erosional contact upon point-bar A. Both deposits are separated by a discontinuous siderite concretion horizon. In the extreme NE and SW exposures of BCA, the BCA deposits rest upon the finer overbank and flood-plain silts (facies B) which cap point-bar A. This point-bar A belongs thus to a different and earlier depositional cycle than the BCA channel and the point-bar which overrides BCA. This is contrary to the interpretation of Fastowski & Dott [1986] who incorporate both in their facies A. In the NE, just below the road leading to Bug Creek, the BCA deposit is merely 50 cm thick and its base is 12 m above the Null coal (fig. 4). We interpret BCA as an unusual complex of thalweg deposits from a large river, each influx related to unusual high energy floodstages of the river. According to Reineck & Singh [1975] these scour-trough deposits show trough-fill cross-bedding or homogenous sediment. Those troughs may scour locally deeper than the base of the point-bar of the same river which overrides it in a later stage.

The Big Bugger point-bar (facies C) is exposed continuously from north and east of BCA to Russell Basin, where its erosional margin is exposed. The Big Bugger ranges in thickness from 15.4-16.2 m and accretes laterally towards the south (middle of N 1/2 of SE 1/4 of section 9, fig. 3). Some questionable WSW current directions were measured. The Big Bugger is fining upwards, and is capped by a complex of three upper Z-Coals, all containing Paleocene pollen assemblages (facies D of Fastowski & Dott [1986]. These three lignites are separated by carbonaceous shales and the middle contains the bentonites mentioned by Fastowski & Dott [1986]. This triplet can be traced continuously over Russell Basin (fig. 3, 5, 6).

The Big Bugger progrades towards a complex of abandoned channels (A. Ch., fig. 4), of which the easternmost preserves the erosional contact with the bank. This abandoned channel is filled at the base with carbonaceous shales and lignite streaks traceable to the triplet of upper Z-coals above the Big Bugger and Russell Basin. At the NW side of the abandoned channel only Big Bugger sands are exposed, at the SE side alternations of lignites and flood-plain silts. A shallow levee is exposed just SE of the abandoned channel, below the triplet upper Z-coals. The abandoned channel is 133 m wide and 12 m deep to the top of the levee or 10.5 m to the flood-plain. Such size is fully commensurate with the size of the Big Bugger point-bar, taking differential compaction between the sandy Big Bugger on the one hand and the shaly

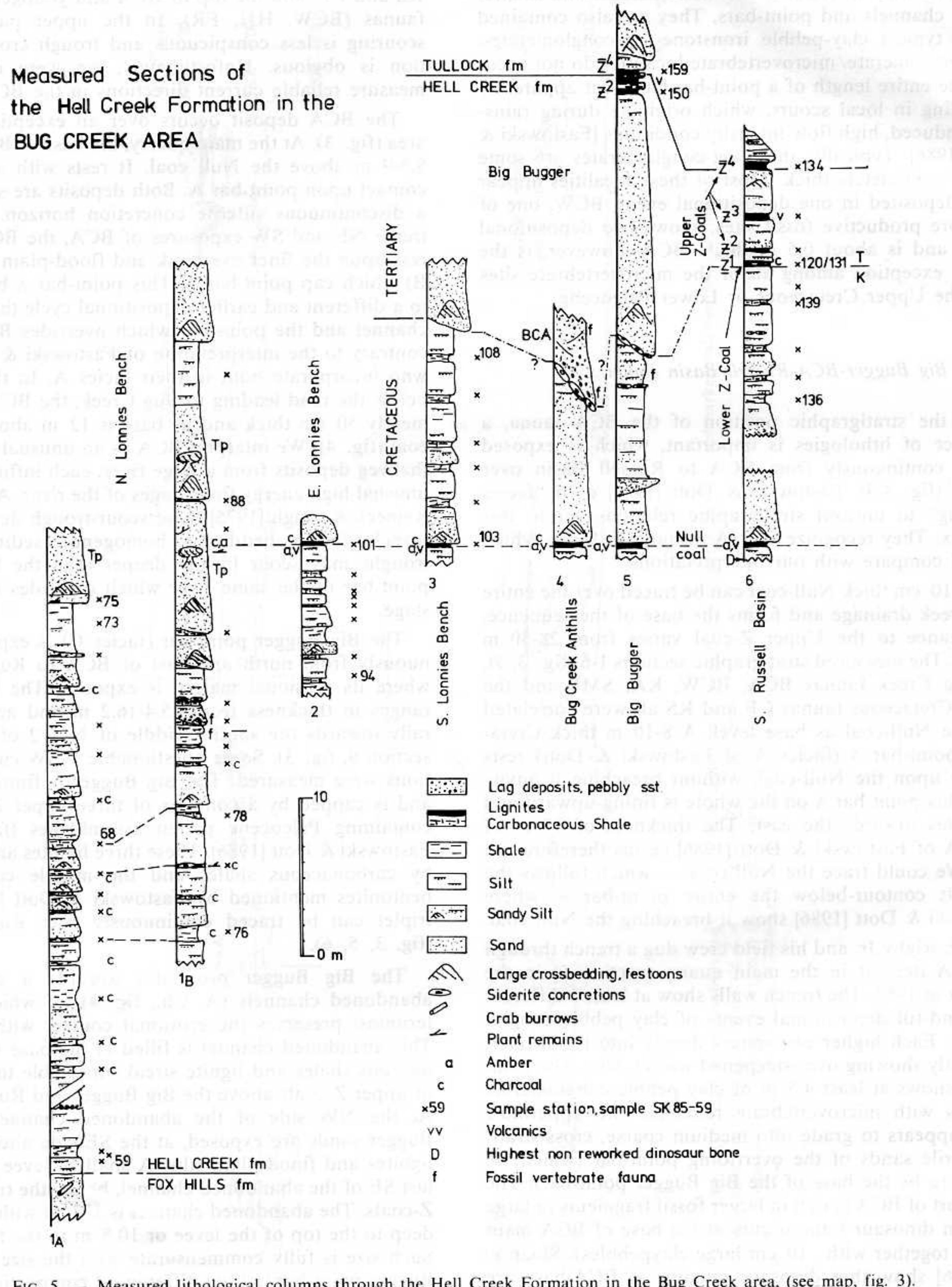


FIG. 5. — Measured lithological columns through the Hell Creek Formation in the Bug Creek area, (see map, fig. 3).

FIG. 5. *Coupes lithologiques de la Formation Hell Creek dans la région de Bug Creek (cf. fig. 3).*

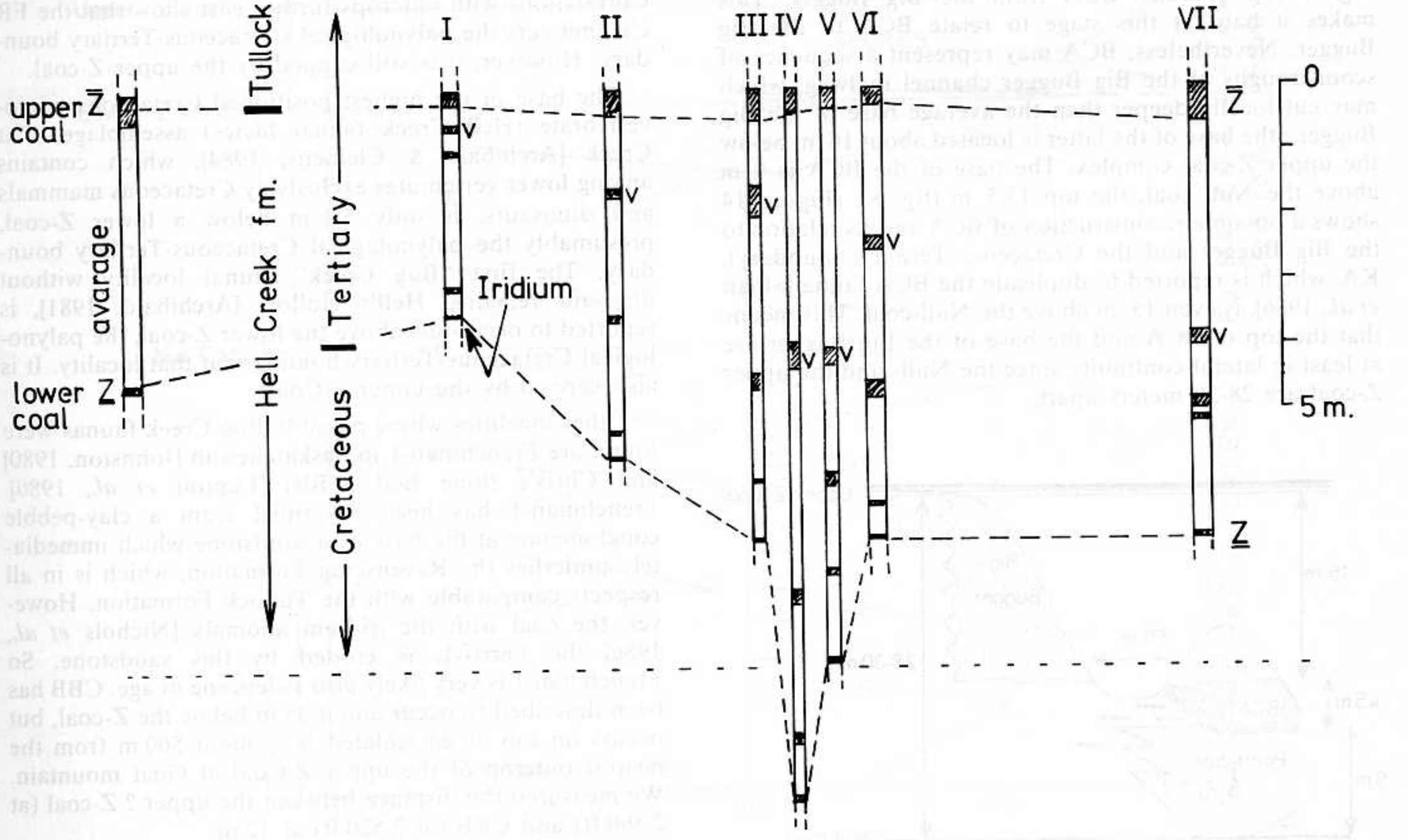


FIG. 6. — Diagram showing stratigraphic thickness of the Z-coal complex in Russell Basin at several measured sections (see map, fig. 3). The average distance between the lower Z-coal and upper Z-coal in the Bug Creek/Sand Arroyo area east of Fort Peck lake is 5.3 m (at left).

FIG. 6. — *Distances entre le "Z-coal" inférieur et le "Z-coal" supérieur dans le bassin Russell (cf. fig. 3).*

abandoned channel fill and banks on the other into account. This is at variance with Fastowski & Dott [1986] who indicate a thickness of only 5 m and erroneously interpret these fine grained carbonaceous shales as a thalweg (the line of maximum stream-gradient) deposit. The SE margin of the Big Bugger abandoned channel complex erodes the flood-plain silts containing the lower Z-coal with the palynological K/T boundary.

Localities	Number of dinosaur Genera	Dinosaur teeth per ton sediment	Number of ungulate mammal taxa	
				Upper Z-Coal
Hell's Hollow	0	0	8?	
Ferguson Ranch	7	18,3	8	
Harbicht Hill	10	27,9	5	
Bug Creek West	11	34,5	3	
Bug Creek-Anthills (top)	12	27,3	1	Approximate position of Lower Z-Coal
Bug Creek-Anthills (base)	12	70	1	
Kens Saddle	12	168	0	

FIG. 7. — Decrease of generic dinosaur abundance and number of dinosaur remains recovered per metric tonne of sediment. Ungulate mammals increase simultaneously in diversity [after Sloan *et al.*, 1986]. Indicated are also the previously assumed position of the Cretaceous-Tertiary boundary, and the Cretaceous-Tertiary boundary as indicated by a palynological break and iridium anomaly, the Lower Z-coal. The two numbers for BCA are for the base and top of the BCA main quarry deposit respectively.

FIG. 7. — *Décroissance des dinosaures et augmentation contemporaine des mammifères ongulés indiqué par le nombre des fossiles découverts dans chaque tonne de sédiment [d'après Sloan et al., 1986]. Les positions du "Z-coal" supérieur et du "Z-coal" inférieur sont indiquées et sont considérées ici comme étant la limite Crétacé-Tertiaire.*

Unfortunately, a gap in outcrops of about 50 m [Smit & Van der Kaars, 1984, erroneously not shown in their Figure 4b] separates BCA from the Big Bugger. This makes it hard at this stage to relate BCA to the Big Bugger. Nevertheless, BCA may represent a sequence of scour-troughs of the Big Bugger channel thalweg, which may cut locally deeper than the average base of the Big Bugger : the base of the latter is located about 16 m below the upper Z-coal complex. The base of the BCA is 9 m above the Null coal, the top 13.5 m (fig. 8). (Figure 14 shows a possible reconstruction of BCA and its relation to the Big Bugger and the Cretaceous-Tertiary boundary). KA, which is reported to duplicate the BCA fauna [Sloan *et al.*, 1986], is even 15 m above the Null-coal. This means that the top of BCA and the base of the Big Bugger are at least in lateral continuity since the Null- and the upper Z-coal are 28-30 meters apart.

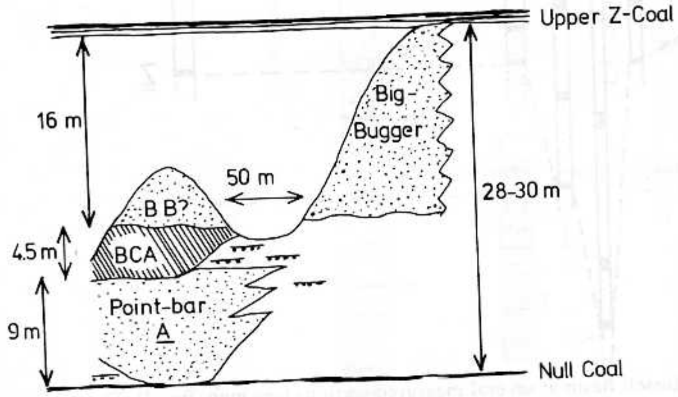


FIG. 8. — Stratigraphic position of BCA with respect to the Null coal, the Z-coals and the Big Bugger point-bar. Although 50 m separates the outcrops of BCA and the Big Bugger closest to each other, laterally the base of the Big Bugger and the top of BCA are at the same level.
FIG. 8. — *Position stratigraphique du "BCA", en relation avec le "Null-coal", les "Z-coals" et la "point-bar" Big Bugger. Le sommet du "BCA" et la base du Big Bugger sont au même niveau.*

Bug Creek West (BCW) occurs about 12 m above the inferred position of the Null-coal, which is eroded by the Toadstool park sandstone. Carbonaceous streaks within and above BCW contain Paleocene pollen assemblages, so BCW is Paleocene in age. The clay clasts in the BCW deposit contain Cretaceous assemblages.

By George (BG) and Scmenge Point (SMP) are 9 m and 12.5 m, respectively, above the Null-coal. These Bug Creek faunas have not been dated yet palynologically. The SMP channel is incised into the Big Bugger. The relationship of both BG and SMP to the Z-coal complex could not be established.

The Harbicht Hill (HH) channel has been interpreted by Rigby *et al.*, (in press) to cut the palynological Cretaceous-Tertiary boundary. No datable pollen samples, however, have been found within the HH channel.

The faunistically youngest Bug Creek fauna, Ferguson Ranch (FR), contains Paleocene pollen assemblages. Correlations with outcrops further east show that the FR channel cuts the palynological Cretaceous-Tertiary boundary. However, it is still capped by the upper Z-coal.

The base of the highest positioned Cretaceous microvertebrate (Hell Creek faunal facies) assemblage, Flat Creek [Archibald & Clemens, 1984], which contains among lower vertebrates exclusively Cretaceous mammals and dinosaurs, is only 5.2 m below a lower Z-coal, presumably the palynological Cretaceous-Tertiary boundary. The first "Bug Creek" faunal locality without dinosaur remains, Hell's Hollow [Archibald, 1981], is reported to occur just above the lower Z-coal, the palynological Cretaceous-Tertiary boundary at that locality. It is also capped by the upper Z-Coal.

Other localities where possible Bug Creek faunas were found are Frenchman-1 in Saskatchewan [Johnston, 1980] and Chris's Bone Bed (CBB) [Lupton *et al.*, 1980]. Frenchman-1 has been described from a clay-pebble conglomerate at the base of a sandstone which immediately underlies the Ravenscrag Formation, which is in all respects comparable with the Tullock Formation. However, the coal with the iridium anomaly [Nichols *et al.*, 1986] the Ferris-1, is eroded by this sandstone. So Frenchman-1 is very likely also Paleocene in age. CBB has been described to occur about 35 m below the Z-coal, but occurs on top of an isolated hill, about 500 m from the nearest outcrop of the upper Z-Coal at Goat mountain. We measured the distance between the upper ? Z-coal (at 2 560 ft) and CBB (at 2 520 ft) at 12 m.

PALYNOLOGY.

We have analysed the sporo-pollen content of the Hell Creek Formation in the Bug Creek area (fig. 9) and the interval of the Cretaceous-Tertiary boundary in particular (fig. 10a-c), qualitatively as well as quantitatively. The Cretaceous-Tertiary boundary interval was analysed in detail at Herpijunk Promontory in Garfield County because the critical Cretaceous-Tertiary interval in the Bug Creek area was barren. Also a well defined iridium anomaly which occurs within the lower Z-coal at a typical "tonstein" layer in Garfield County is absent at Bug Creek. At Bug Creek, as mentioned, only slightly enhanced Ir levels were found. Our results confirm the results of Norton & Hall [1969] and Smit & Van der Kaars [1984] in the type area of the Hell Creek Formation; Tschudy *et al.* [1985] in the Raton Basin and Nichols *et al.* [1986] in Saskatchewan. Figure 10a shows the abrupt extinction of the typical Cretaceous palynomorphs *Aquillapollenites* spp., *Proteacidites* sp., *Tricolpites* sp., *Tricolpites reticulatus (Gunnera),* and *Cranwellia* in a closely sampled section precisely at the iridium anomaly, assumed to represent the

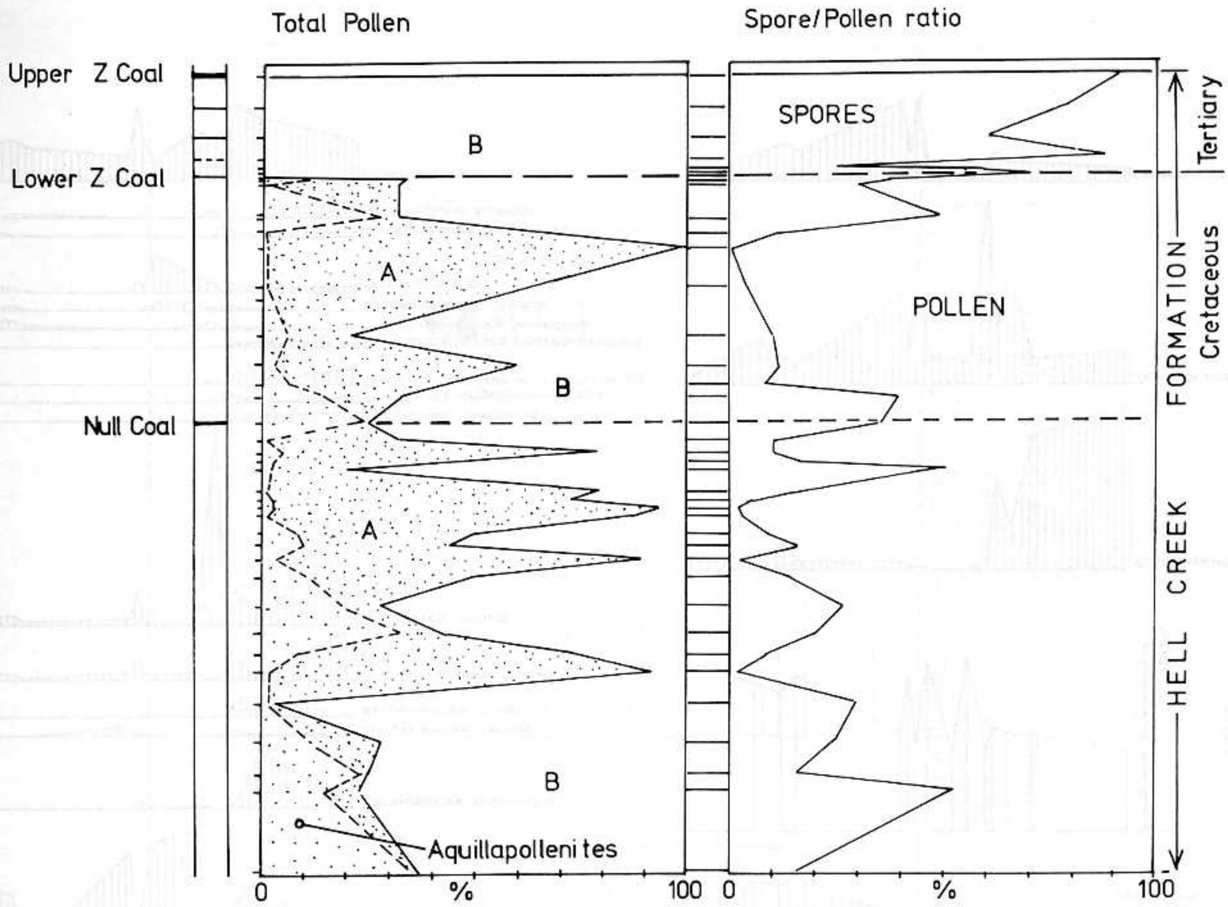
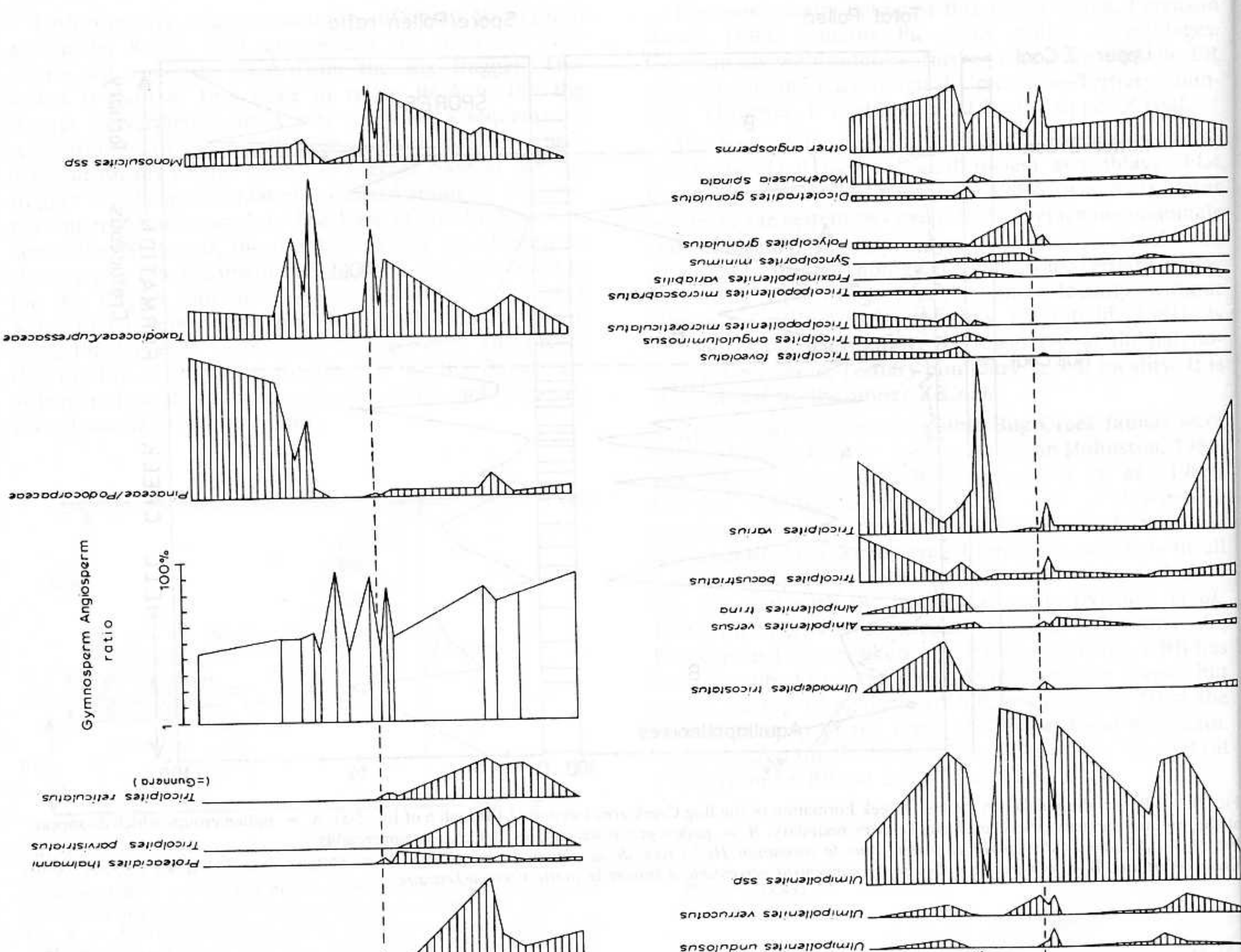


FIG. 9. — Pollen abundances in the Hell Creek Formation of the Bug Creek area (sections 1 through 6 of fig. 3-5). A = pollen groups which disappear at the iridium anomaly, the Cretaceous-Tertiary boundary. B = pollen group which does not change appreciably.

FIG. 9. — *Abondance des spores et pollen dans la formation Hell Creek de la région de Bug Creek.* A = *groupes de pollen disparus à la limite Crétacé-Tertiaire.* B = *groupes de pollen sans changement perceptible à travers la limite Crétacé-Tertiaire.*

Cretaceous-Tertiary boundary. Although in number these species may represent less than 10 % of all species, on average 50.7 % of all pollen specimens in the Late Cretaceous consist of these types (fig. 9). We assume therefore they represent an important constituent of Late Cretaceous floras in the Hell Creek area. At levels above the lower Z-coal at most a few corroded *Aquillapollenites* specimens were found in the sections (over 30 sample sites) analysed. Figures 9 and 10 show a significant increase of the spore/pollen ratio at the Cretaceous-Tertiary contact. The spore abundance reaches a maximum of over 90 % in the lower Z-coal but high spore levels last at least through the Z-coal complex. *Pinus-Podocarpus* gymnosperm pollen increase significantly in the Paleocene part of the Hell Creek Formation. Figure 9 demonstrates that assemblages do not change progressively in the Cretaceous part of the Hell Creek Formation. The considerable sample to sample variations are typical of pollen diagrams because samples analysed combine easily the wind blown pollen from different florules (swamp, riparian, flood plain floras) in different proportions, as noted by Norton and Hall [1969] and Tschudy [1984].

Our study does not support the gradual floral change before the Cretaceous-Tertiary boundary proposed by Van Valen & Sloan [1977], Sloan [1985] and Sloan *et al.*, studies based on the work of Norton & Hall [1969] and Oltz [1969]. Figure 9 does not show a significant reduction in sporopollen taxa through the Hell Creek Formation below the Cretaceous-Tertiary boundary. Both Oltz [1969] and Norton and Hall [1969] mention only "The Z-Coal bed" as Cretaceous-Tertiary boundary. This bed is the Upper or formational Z-Coal bed. However, it is not the Cretaceous-Tertiary time boundary (fig. 6). A few hundred meters east of the section locality of Norton & Hall [1969] at Brownie Butte, Bohor *et al.* [1983] found a lower Z-coal which contains the iridium anomaly and pollen extinction. At Norton and Hall's section this lower Z-coal was cut out


a)
b)
Cretaceous | Tertiary
cm
Aquilapollenites delicatus
Aquilapollenites quadrilobus
Aquilapollenites amplus
Aquilapollenites pyriformis
Aquilapollenites ssp.
Cranwellia striata
Orbiculapollis lucidus
Proteacidites thalmanni
Tricolpites parvistriatus
Tricolpites reticulatus (=Gunnera)
Gymnosperm Angiosperm ratio
100%
Pinaceae/Podocarpaceae
Taxodiaceae/Cupressaceae
Monosulcites ssp
Spinamonoporites typicus
Momipites parvus
Momipites circularis
Kurtzipites trispissatus
Kurtzipites annulatus
Triporopollenites coryloides
Triporopollenites rugatus
Triatriopollenites granilabratus
Ulmipollenites undulosus
Ulmipollenites verrucatus
Ulmipollenites ssp.
Ulmoideipites tricostatus
Alnipollenites versus
Alnipollenites trina
Tricolpites bacustriatus
Tricolpites varius
Tricolpites foveolatus
Tricolpites anguloluminosus
Tricolpopollenites microreticulatus
Tricolpopollenites microscabratus
Fraxinoipollenites variabilis
Syncolporites minimus
Polycolpites granulatus
Dicolcetradites granulatus
Wodehouseia spinata
other angiosperms

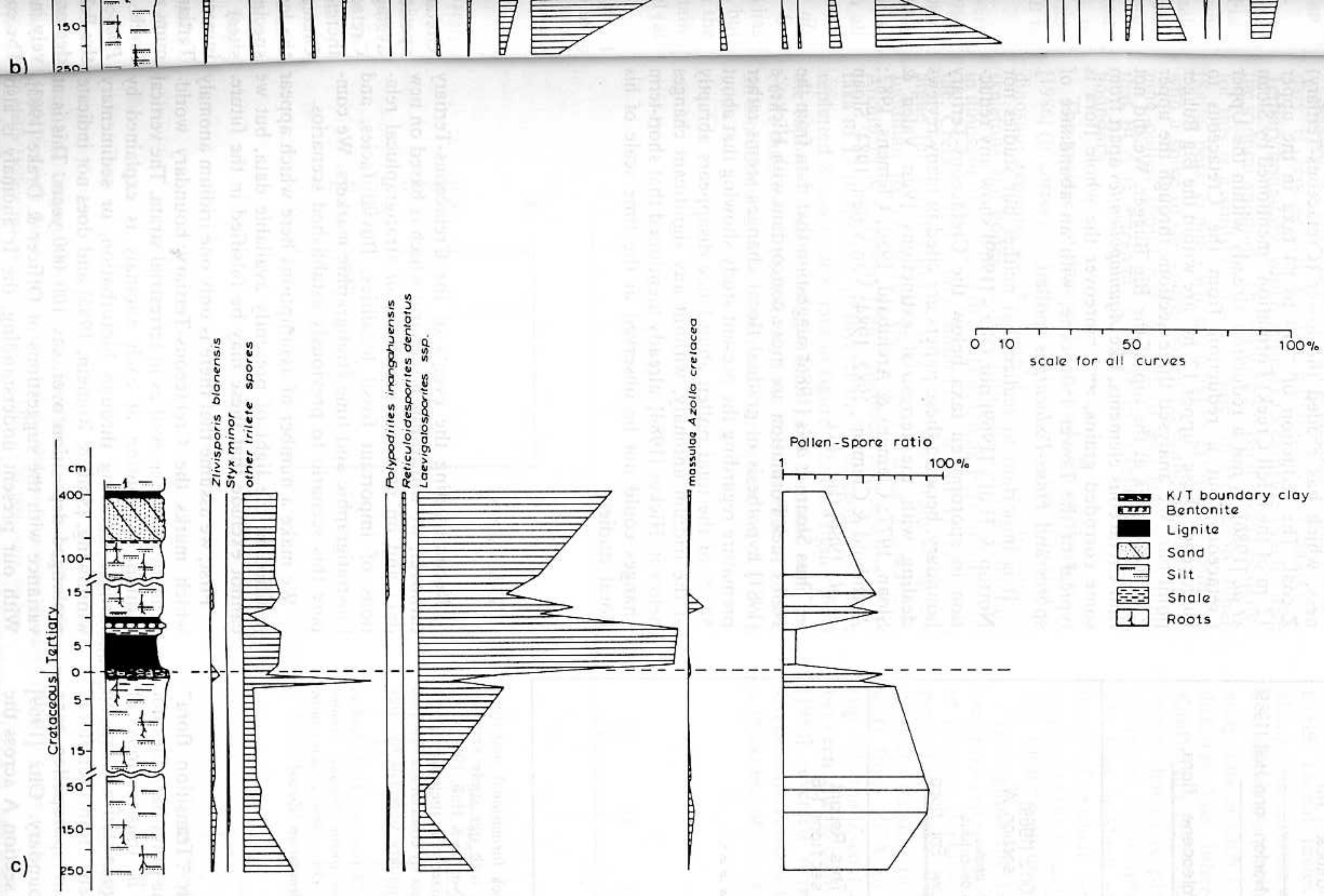


FIG. 10 a, b, c. — Spore and pollen abundances across the Cretaceous-Tertiary boundary at Herpijunk Promontory [Smit & Van der Kaars, 1984]. The maximum spore spike is confined to the lower Z-coal, although the spore levels in the entire Z-coal complex remain high. An iridium anomaly of 11.4 ng/g has been found at 0 cm. The coal at 400 cm is the local upper Z-coal. The scale is for the sum of the pollen (fig. 10 a, b), or the sum of the spores (fig. 10c).

FIG. 10 a, b, c. — *Abondance des spores et pollen à travers la limite Crétacé-Tertiaire, à Herpijunk Promontory [Smit & van der Kaars, 1984]. Le maximum de 100 % est soit pour les spores en total (10c), soit le total des pollen (10 a, b).*

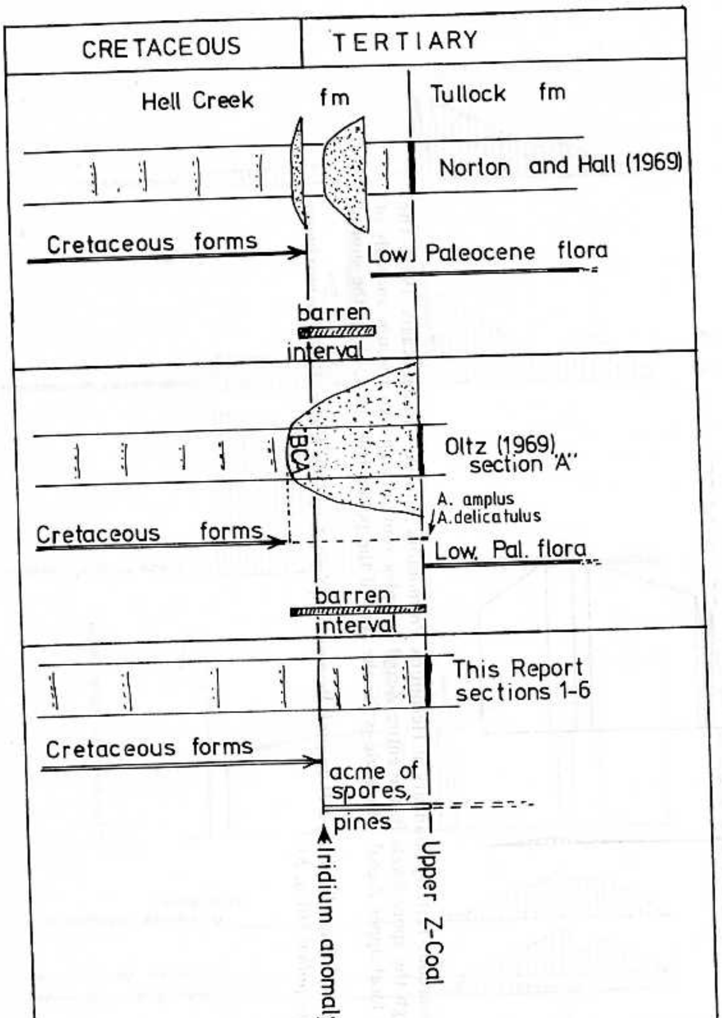


FIG. 11. — Comparison of Hell Creek-Tullock formational, and time-stratigraphic Cretaceous-Tertiary boundaries with our study and two palynological studies mentioned in the next [Norton & Hall, 1969; Oltz, 1969]. Both Oltz and Norton and Hall recognized only the upper Z-coal as Cretaceous-Tertiary boundary. This is correct by coincidence, because in both analyses the Cretaceous-Tertiary boundary were cut by large point-bars, sterile in pollen.

FIG. 11. — *Les relations entre les limites des formations Hell Creek et Tullock, et la limite Crétacé-Tertiaire chronostratigraphique, comme publiés antérieurement [Norton & Hall, 1969; Oltz, 1969], et dans notre étude. Oltz et Norton & Hall reconnaissent seulement un "Z-coal".*

by a large point-bar (fig. 11). Their "Transition flora" below the "Z-coal bed", but above the point-bar, does not contain Cretaceous elements and is thus entirely of Paleocene age. In addition, their quantitative work on pollen abundances below this Paleocene "transition flora" does not indicate any reductions in sporopollen taxa towards the Cretaceous-Tertiary boundary. Oltz [1969] analysed samples from Bell's [1969] section A across the BCA and Big Bugger localities. This section A contains only the upper three of the four Z-coal beds present in the Bug Creek area (fig. 6, 11). These three are underlain by the Paleocene Big Bugger point-bar of 15.4-16.2 m thickness, which has eroded the lower (Cretaceous-Tertiary) Z-coal. The reduction of "114 to 84 taxa in the upper 12 m of the (Hell Creek) Formation" mentioned by Sloan *et al.* [1986], is not a reduction already within the Upper Cretaceous, but a reduction from the Cretaceous to Paleocene. These "upper 12 m" are within the Big Bugger point-bar. We analysed three sections through the upper Z-coal complex at the top of the Big Bugger. We did not find Cretaceous elements, like *Aquillapollenites* apart from some corroded grains, and moreover the whole flora is typical of the Lower Paleocene, with an abundance of spores and *Pinus-Podocarpus* pollen.

It is important to realize that neither our studies nor Norton & Hall's [1969] nor Oltz's [1969] show any reduction in sporopollen taxa below the Cretaceous-Tertiary boundary, because these papers are cited in many reviews dealing with the terrestrial extinctions [Van Valen & Sloan, 1977; Clemens & Archibald, 1980; Clemens, 1982; Archibald & Clemens, 1982, 1984; Van Valen, 1984; Sloan *et al.*, 1986] (fig. 11).

Thus Sloan *et al.*'s [1986] suggestion that data from the Hell Creek Formation are more concordant with Hickey's [1981] hypothesis of gradual floral changes seems rather premature regarding the present study showing that about 50 % of the total pollen abundance disappears abruptly at the iridium anomaly, without any significant changes below it. Hickey [1984], already mentioned that short-term changes could not be observed at the time scale of his floral studies.

DISCUSSION.

Reconstructing the events of the Cretaceous-Tertiary turnover, we will follow a scenario which is based on new data and on new interpretations of stratigraphical relations of important fossil localities, fluvial facies, and biostratigraphic and time stratigraphic markers. We compare this scenario to previously established scenarios.

We make a number of assumptions here which appear justified in the light of presently available data, but we cannot exclude that these may be falsified in the future.

First, we assume that there is only one iridium anomaly which marks the Cretaceous-Tertiary boundary worldwide, in marine as well as in terrestrial strata. The vertical iridium distribution at each anomaly is explained by vertical smearing through bioturbation, or sedimentary winnowing, [Smit & Romein, 1985] and does not indicate prolonged deposition over, say 100 000 years. This is at variance with the suggestions of Officer & Drake [1983]. With our present understanding, the Ir anomaly is also synchronous, because at each locality it occurs in a reversed geomagnetic Chron, which we assume to be Chron 29R.

Second, we assume that the Cretaceous-Tertiary boundary is represented by the palynological Cretaceous-Tertiary boundary, which appears to coincide exactly with the iridium anomaly. The only direct (first order) evidence for this is a study of marine shales in Hokkaido, Japan (Saito, pers. comm.) where plankton extinctions coincide with a spike in the spore/pollen ratio and an increase in pine pollen abundance. And third and last, we assume that BCA is extremely close to the Cretaceous-Tertiary boundary.

The analyses of Alvarez [1983] and also of Sloan *et al.*, [1986] (if corrected, table I) of the vertical distribution of dinosaur remains on the flood-plains (large unreworked skeletons and bones) do not show any obvious reduction in dinosaur abundance in the Hell Creek Formation below the Cretaceous-Tertiary boundary. Sloan *et al.* [1986] argue for a reduction in dinosaur taxa from 30 in the Judithian to 19 in the Hell Creek/Lance Formations. Archibald & Clemens [1982] mention a reduction of 35 taxa to 17 in the last 10 myr of the Cretaceous. We have replotted Sloan *et al.*'s data in figure 12. This figure plots the reported number of dinosaur taxa constant over the entire duration of each formation. This assumes of course an evolutionary stasis within each formation, but that does not seem unreasonable regarding the data from the Hell Creek Formation given above and the inference of Archibald & Clemens [1984] that mammals of the Hell Creek faunal facies show "little, if any, evolutionary change" in contrast with the Bug Creek faunas. Figure 12 also shows the plotting of Sloan *et al.* [1986] who join the midpoints of each formation. This plot clearly shows the different bias inherent to graphic plots. Contrary to Kauffman's [1979] and Dingus [1984] remarks, figure 12 shows that these plots can also reduce the image of a biological catastrophe, instead of enhancing that image. The bias in Sloan *et al.* [1986] is clearly to enhance the image of gradual, be it accelerated, extinction, ours may emphasize the magnitude of the final dinosaur extinction. The future may decide which approach will be correct.

Throughout the Late Cretaceous the number of dinosaur taxa reduces by 11 in 7 myr [Sloan *et al.*,1986] [or 18 in 10 myr; Archibald & Clemens, 1982] or 1.6 (1.8) taxa per million years. The extinction sequence (assuming the dinosaur remains in the Bug Creek faunas are not reworked) from BCA to Hell's Hollow takes place within (fig. 13) the Z-coal complex. We averaged the distance between the Z-coals at 5 m (fig. 6). Archibald *et al.*'s [1982] reversed magnetic polarity zone straddling the Cretaceous-Tertiary boundary (Chron 29R, 500 kyr), has a thickness of 51 m. So 19 (17) dinosaur taxa disappear

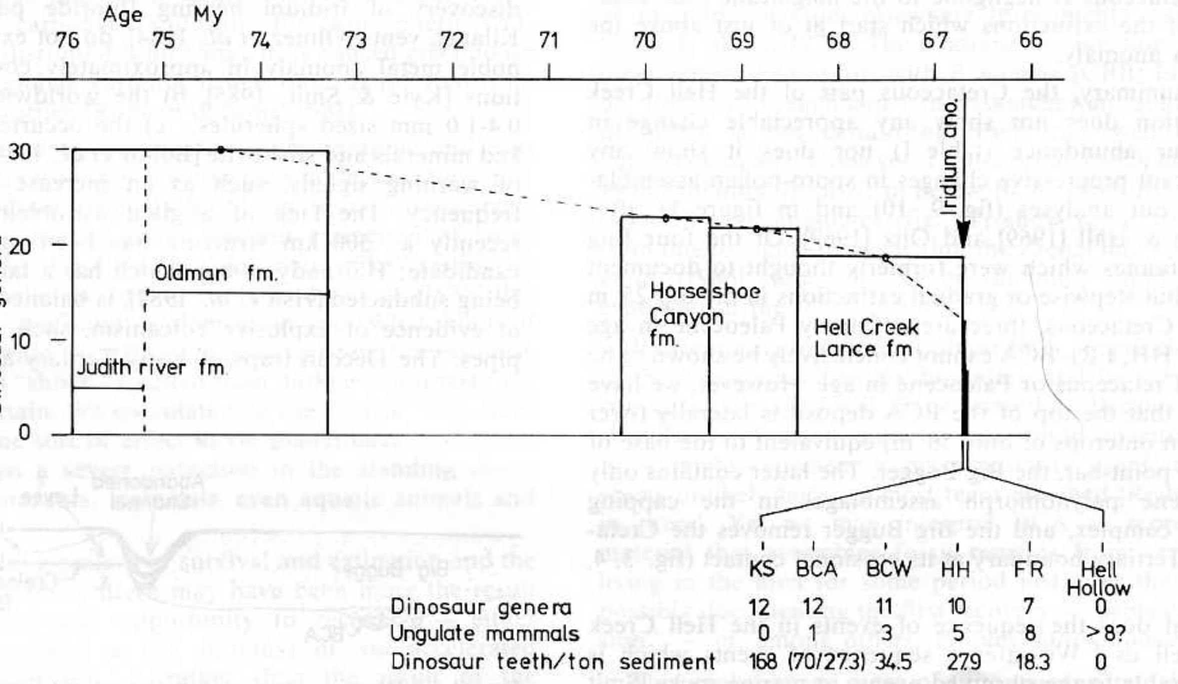


FIG. 12. — Diagram, replotting data from Sloan *et al.* [1986]. Plotted are the number of genera of dinosaurs, over the duration of each formation in which they were found. The Judith river and Oldman faunas are thought to be almost time equivalent and were combined by Sloan *et al.* The KS to Hell's Hollow sequence may cover as little as 50 000 years, or less.

FIG. 12. — *Abondance des genres de dinosaures dans le Crétacé supérieur [d'après Sloan* et al., *1986] redessiné. La séquence du KS jusqu'à "Hell's Hollow" comprend peut-être moins de 50 000 ans.*

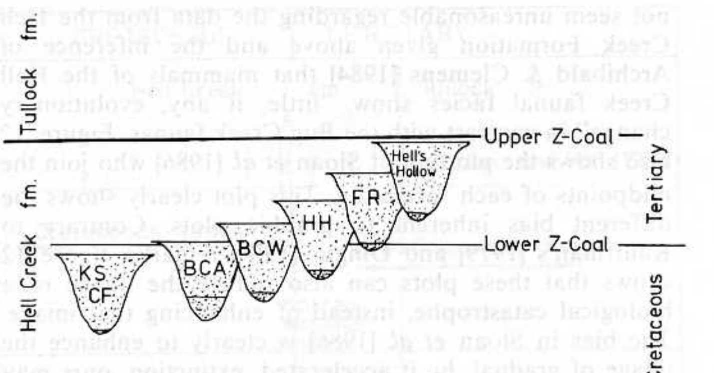


FIG. 13. — Diagram, showing the Bug Creek faunas and their relation to the Z-coals and the Cretaceous-Tertiary boundary. In contrast to figure 2, this diagram shows that all the Bug Creek faunas which document an increase in mammal species (especially ungulates), synchronously with a decrease in dinosaur abundance and Cretaceous mammals, are younger than the Cretaceous-Tertiary boundary.
FIG. 13. — *Diagramme montrant les faunes de Bug Creek, et leur relation avec les "Z-coals" et la limite Crétacé-Tertiaire.*

within 5/51x500 kyr = 50 000 years, or 380 (340) taxa per million years. Russell [1982] indicates that the decrease from 35 to 17 taxa is simply an artifact of sample size. However, even if a normalization to sample size will reduce, but not nullify this decrease, we feel that the 1.6 taxa/myr reduction through the final 7 million years of the Cretaceous is negligible to the magnitude (380 taxa/myr) of the extinctions which start at or just above the iridium anomaly.

In summary, the Cretaceous part of the Hell Creek Formation does not show any appreciable change in dinosaur abundance (table I) nor does it show any significant progressive changes in sporo-pollen assemblages in our analyses (fig. 9, 10) and in figure 11 after Norton & Hall [1969] and Oltz [1969]. Of the four Bug Creek faunas which were formerly thought to document rapid, but stepwise or gradual extinctions in the top 25 m of the Cretaceous, three are definitely Paleocene in age (BCW, HH, FR). BCA cannot conclusively be shown to be either Cretaceous or Paleocene in age. However, we have shown that the top of the BCA deposit is laterally (over a gap in outcrops of only 50 m) equivalent to the base of a large point-bar, the Big Bugger. The latter contains only Paleocene palynomorph assemblages in the capping Z-coal complex, and the Big Bugger removes the Cretaceous-Tertiary boundary at its erosional contact (fig. 3, 4, 14).

What does the sequence of events in the Hell Creek field tell us ? We infer a sequence of events which is comparable to the observed events in marine rocks [Smit & Romein, 1985].

The Upper Cretaceous in eastern Montana was a period of warm temperatures. A largely tropical, probably monsoonal climate with dry spells allowed flash-floods and forest fires [Rigby *et al.*, in press]. Vegetation shows similarities with the present Indomalaysian region [Nichols *et al.*, 1985]. Dinosaurs were the dominant animals, although the small mammals probably outnumbered them [Van Valen & Sloan, 1977]. There is no indication which might have foretold their doom. Minor changes (like the slight reduction in generic dinosaur abundance) may have been due to the slow regression of the interior seaway in the last 7 million years of the Cretaceous. The mammals showed relative evolutionary stasis; no invaders came in, some placental evolution took place. We see the same slowly changing environment in the marine realm; stable planktonic assemblages characterize the Campanian through Maastrichtian : the top-most Cretaceous sample of every analysed section shows the same assemblages as lower down in the section. The ammonites show a reduction of specialized forms, probably due to loss of habitats due to the same regression, but the "generalists", the deeper water forms like the Phylloceratids, range up to the iridium anomaly [Ward & Signor, 1983].

Suddenly these stable environments were perturbed by the consequences of an extremely forceful event.

Both lack of warning signals in the sedimentary record preceding the extinctions, and the co-occurrence of a noble metal anomaly, microtektite-like spherules and shocked quartz strongly suggest that an extraterrestrial event, an asteroid or cometary impact, took place. Earth-bound mechanisms, such as a gigantic volcanic eruption, which has been in the foreground lately due to the discovery of iridium bearing fluoride particulates in Kilauea vents [Olmez *et al.*, 1984], do not explain a) the noble metal anomaly in approximately cosmic proportions [Kyte & Smit, 1985], b) the worldwide spread of 0.4-1.0 mm sized spherules, c) the occurrence of shocked minerals and stishovite [Bohor *et al.*, 1984], d) the lack of warning signals, such as an increase in bentonite frequency. The lack of a giant astrobleme [although, recently a 300 km structure has been proposed as a candidate; Hartnady, 1986], which has a large chance of being subducted [Hsü *et al.*, 1982], is balanced by the lack of evidence of explosive volcanism, such as kimberlite pipes. The Deccan traps of Early Tertiary age are exten-

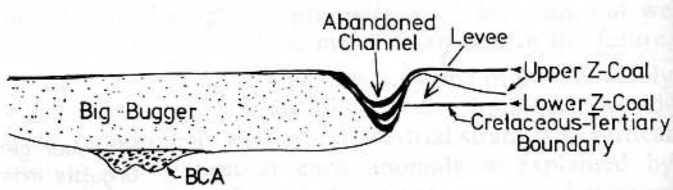


FIG. 14. — Diagram, showing hypothetical relations of BCA, Big Bugger, the abandoned channel and the Cretaceous-Tertiary boundary (the lower Z-coal). The drawing is not to scale.
FIG. 14. — *Relation stratigraphique hypothétique entre BCA, Big Bugger, le "Abandoned channel" de Big Bugger et la limite Crétacé-Tertiaire. Le dessin n'a pas une échelle horizontale réelle.*

sive, but are of an extremely non-explosive type. Recently active, explosive types of volcanism — which would be needed in order to explain the strewnfield of the spherules, or shocked minerals — do not produce such iridium rich fumes [Olmez *et al.*,1984]. Another argument which may argue against such earth bound mechanisms, is the apparent lack of long term (in the order of 1 Myr) climatic change across the Cretaceous-Tertiary boundary. Increased volcanism, or other mechanisms, would presumably cause climatic deterioration over longer timescales. ^{18}O records do not show such change [Boersma, 1984]]. Nichols *et al.* [1986] remark that pollen of *Arecipites* and *Pandaniidites* (Palms and screw pines) found below and above the Cretaceous-Tertiary boundary indicate essentially identical paleoclimates.

What this initial perturbation caused, is still open for speculation. One thing is clear, from the Ir-anomaly upwards, a variety of extinctions from semi-instantaneous, to stepwise or gradual are documented in the sedimentary record. In the marine record planktonics — foraminifers and coccoliths — suffer an almost complete annihilation, although some species were able to survive for some time in greatly reduced numbers [Smit & Romein, 1985]. This "mass-mortality" is testified by a detrital clay layer deposited worldwide upon the iridium anomaly (Hokkaido, Japan; T. Saito, pers. comm.; New Zealand; D.S.D.P. site 524, south Atlantic; El Kef, Tunisia; Caravaca, Spain; Jutland and Stevns Klint, Denmark). We speculate that during deposition of the clay (estimated at between 1 000 and 5 000 years [Smit & Romein, 1985], the marine carbonate and thus the atmospheric CO_2 cycles were disrupted, which may have caused greenhouse effects and global warming at that time, as inferred from some ^{18}O profiles [Romein & Smit, 1981].

In terrestrial environments the stratigraphic and thus the temporal resolution is worse than in the sea. Nevertheless, the iridium anomaly has been found co-occurring with a clay stratum and a sudden extinction of some palynomorphs. First clue is the "spore spike" resting on the Ir anomaly. According to Tschudy *et al.* [1985] this indicates a profound ecological shock. What kind of shock and what the effects may have been, for instance, whether this "shock" resulted from darkness or forest fires is still uncertain. We speculate that the "shock" may have had the same sort of effect as on planktonics in the sea; with perhaps a severe reduction in the standing abundance of dinosaurs, mammals, even aquatic animals and birds.

The resulting pattern of survival and extinction and the selectivity of this pattern may have been more the result of the ability and opportunity to recover — either immediately (after a few months) or *via* accelerated evolution later on — rather than the result of the postulated deleterious effects of an impact itself (of which we do know little).

Some data from the Hell Creek field support this view. The aquatic community apparently recovered unscathed [Van Valen & Sloan, 1977]. Dinosaurs did not survive their decimations. The Bug Creek faunas (assumed their remains are nor reworked) document an initial reduction already at BCA (fig. 12), which continues through BCW, HH and FR. Finally at Hell's Hollow, where the ungulates exhibit the same evolutionary stage as FR, no dinosaurs remain any more. On the flood-plains the dinosaurs had disappeared already, maybe partly due to diagenetic alterations. Not a single dinosaur bone has been found above the lower Z-coals in flood-plain sediments, as noted by Archibald & Clemens [1984] and others. Archibald & Clemens [1982, 1984] even note that the dinosaurs became extinct well below the upper Z-coal (on the average 3 m). At Russell Basin we found a large *Triceratops* vertebra in situ, 1.2 m below the Cretaceous-Tertiary boundary.

The mammals suffered extinction mainly in marsupial taxa, who remained subordinate in the Paleocene [Archibald & Clemens, 1984]. Multituberculates also suffered extinctions, but showed substantial evolutionary diversification in the Paleocene.

Placentals in particular took the opportunity to diversify and radiate. We suppose they underwent a similar decimation at the Cretaceous-Tertiary boundary as other mammal groups, but already in BCA time [Van Valen & Sloan, 1977] specimens of only four species of new mammals outnumbered specimens of all others. Especially *Protungulatum donnae* can be found in astounding numbers in BCA [Rigby *et al.*, in press]. We do not know if these mammals were already present in North America or migrated in from elsewhere [presumably Asia; Van Valen & Sloan, 1977]. The stratigraphic position of most other reported locations with *P. donnae*, [CBB; Lupton *et al.*, 1980 and Frenchman-1 in Saskatchewan; Johnston *et al.*, 1980] is not certain but they may well be also Paleocene in age. However, Lupton *et al.* [1980] described *Protungulatum* from 20 m below BCA. From BCA to FR especially the ungulates (fig. 12) show rapid speciation from one to eight species within the Z-coal interval. Sloan *et al.* [1986] stated this to be the most rapid rate of evolution in the fossil record.

It is tempting to speculate about BCA, its position close to the Cretaceous-Tertiary boundary and its exceptional concentration of fossil bone material. Because of its abundance of fossil material one could speculate that BCA might represent a mass-mortality event, but this seems unlikely because most teeth are shed [Rigby *et al.*, in press]. Yet we may interpret BCA as representing material that assembles fossil remains from vertebrates living in the area for some period just after the impact, possibly documenting the first recovery — acme or "invasion" — of, among others, *Protungulatum donnae.*

This evolutionary surge of (ungulate) mammals in the Bug Creek faunas just above the iridium anomaly, and apart from whether or not BCA is Paleocene in age, in our opinion documents the phenomenon of adaptative radiation as the result of the occupation of new habitats, which became vacant due to the decimation of the Cretaceous biota. This has its pendants in the marine fossil record, where planktonic foraminifera and coccoliths underwent rapid adaptative radiation and diversification into many new taxa only after the Cretaceous taxa had become fully extinct.

To us it is too much of a coincidence that these extinction-radiation patterns would be independent from the hypothesized impact, of which the evidence in the form of an iridium anomaly has now been placed at the beginnings of this radiation both in the sea and on land.

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References

ALVAREZ L. W. (1983). — Experimental evidence that an asteroid impact led to the extinction of many species 65Myr ago. — *Proc. Nat. Acad. Sci. U.S.A.*, 80, pp. 627-642.

ALVAREZ L. W., ALVAREZ W., ASARO F. & MICHEL H. (1980). — Extra-terrestrial cause for the Cretaceous-Tertiary extinction. — *Science*, 280, pp. 1095-1108.

ARCHIBALD J. D. (1981). — The earliest known Paleocene mammal fauna and its implications for the Cretaceous-Tertiary transition. — *Nature*, 291, pp. 650-652.

ARCHIBALD J. D. (1984). — Bug Creek Anthills (BCA), Montana : faunal evidence for Cretaceous age and non-catastrophic extinctions. — *Geol. Soc. Am., Abstr. Programs*, p. 465.

ARCHIBALD J. D. , BUTLER R. F., LINDSAY E. H., CLEMENS W. A. & DINGUS L. (1982). — Upper Cretaceous-Paleocene biostratigraphy and magnetostratigraphy, Hell Creek and Tullock Formations, northeastern Montana. — *Geology*, 10, pp. 153-159.

ARCHIBALD J. D. & CLEMENS W. A. (1982). — Late Cretaceous extinctions. — *Am. Sci.*, 70, pp. 377-385.

ARCHIBALD J. D. & CLEMENS W. A. (1984). — Mammal evolution near the Cretaceous-Tertiary boundary. — *In* : W. A. BERGGREN & W. VAN COUVERING Eds, Catastrophes and Earth history. — Princeton University Press, pp. 339-372.

BELL R. C. (1965). — Geology and stratigraphy of the Fort Peck fossil field northwest McCone County, Montana. — Unpubl. MS thesis, Univ. Minn.

BOERSMA A. (1984). — Campanian through Paleocene paleotemperature and carbon isotope sequence and the Cretaceous-Tertiary boundary in the Atlantic Ocean. — *In* : W. A. BERGGREN & W. VAN COUVERING Eds, Catastrophes and Earth history. — Princeton University Press, pp. 247-275.

BOHOR B. F., FOORD E. E., MODRESKI P. J. & TRIPLEHORN D. M. (1984). — Mineralogic evidence for an impact event at the Cretaceous-Tertiary boundary. — *Science*, 224, pp. 867-869.

BROWN R. (1952). — Cretaceous-Tertiary strata in eastern Montana and Western North and South Dakota. — *Billings Geol. Soc. Guidebook*, 3, pp. 89-92.

BUTLER R. F. & LINDSAY E. H. (1985). — Mineralogy of magnetic minerals and revised magnetic polarity stratigraphy of continental sediments, San Juan Basin, New Mexico. — *J. Geol.*, 93, pp. 535-554.

CLEMENS W. A. (1982). — Patterns of extinction and survival of the Terrestrial biota during the Cretaceous-Tertiary transition. — *Geol. Soc. Am., Spec. Pap.*, 190, pp. 407-414.

CLEMENS W. A. & ARCHIBALD J. D. (1980). — Evolution of terrestrial faunas during the Cretaceous-Tertiary transition. — *Mém. Soc. géol. France*, N. S., LIX, pp. 67-74.

CLEMENS W. A., ARCHIBALD J. D. & HICKEY L. J. (1981). — Out with a whimper, not a bang. — *Paleobiology (Paleontol. Soc)*., 7, pp. 293-298.

DINGUS L. (1984). — Effects of stratigraphic completeness on interpretations of extinction rates across the Cretaceous-Tertiary boundary. — *Paleobiology (Paleontol. Soc)*., 10, pp. 420-438.

FASTOWSKI D. E. & DOTT R. H. Jr. (1986). — Sedimentology, stratigraphy and extinctions during the Cretaceous-Paleogene transition at Bug Creek, Montana. — *Geology*, 14, pp. 279-310.

HICKEY L. J. (1981). — Land plant evidence compatible with gradual, not catastrophic, change at the end of the Cretaceous. — *Nature*, 292, pp. 529-531.

HICKEY L. J. (1984). — Changes in Angiosperm flora across the Cretaceous-Tertiary boundary. — *In* : W. A. BERGGREN & W. VAN COUVERING Eds, Catastrophes and Earth history. — Princeton University Press, pp. 279-310.

HSÜ K. J., HE Q., MCKENZIE J. A., WEISSERT H., PERCH-NIELSEN K., OBERHÄNSLI H., KELTS K., LABREQUE J., TAUXE L., KRÄHENBÜHL U., PERCIVAL S. F., WRIGHT R., KARPOFF A., PETERSEN N., TUCKER P. & POORE D. (1982). — Environmental and evolutionary consequences of mass-mortality at the end of the Cretaceous. — *Science*, 216, pp. 249-256.

JOHNSTON P. A. (1980). — First record of Mesozoic mammals from Saskatchewan. — *Can. J. Earth Sci.*, 17, pp. 512-519.

KAUFFMANN E. (1984). — The fabric of Cretaceous marine extinctions. — *In* : W. A. BERGGREN & W. VAN COUVERING Eds, Catastrophes and Earth history. — Princeton University Press, pp. 151-237.

KENT D. (1981). — Asteroid extinction hypothesis — *Science*, 211, pp. 648-653.

KLUTE M. A. (1986). — Sedimentology and sandstone petrography of the Upper Kirtland Shale and Ojo Alamo Sandstone, Cretaceous-Tertiary boundary, Western and Southern San Juan Basin, New Mexico. — *Am. J. Sci.*, 286, pp. 463-488.

KYTE F. T. & SMIT J. (1986) — Regional variations in spinel compositions : an important key to the Cretaceous-Tertiary event. — *Geology*, 14, pp. 485-487.

LERBECKMO J. F., EVANS M. E. & BAADSGAARD H. (1980). — Magnetostratigraphy, biostratigraphy and geochronology of Cretaceous-Tertiary boundary sediments, Red Deer Valley. — *Nature*, 279, pp. 26-30.

LINDSAY E. H., BUTLER R. F. & JOHNSON N. M. (1981). — Magnetic polarity of Late Cretaceous and Paleogene continental deposits, San Juan basin, New Mexico. — *Am. J. Sci.*, 281, pp. 390-435.

LUPTON C., GABRIEL D. & WEST R. M. (1980). — Paleobiology and depositional setting of a Late Cretaceous vertebrate locality, Hell Creek formation, McCone County, Montana. — *Contrib. Geol. Wyo. Univ.*, 18, pp. 117-128.

MONTANARI A., HAY R. L., ALVAREZ W., ALVAREZ L. W., ASARO F., MICHEL H. VV. & SMIT J. (1983). — Spheroids at the Cretaceous-Tertiary boundary are altered impact droplets of basaltic composition. — *Geology*, 11, pp. 668-671.

NICHOLS D. J., JARZEN D. M., ORTH C. J. & OLIVER P. Q. (1986). — Palynological and iridium anomalies at Cretaceous-Tertiary boundary, south-central Saskatchewan. — *Science*, 231, pp. 714-717.

NORTON N. J. & HALL J. W. (1969). — Palynology of the Upper Cretaceous and Lower Tertiary in the type locality of the Hell Creek Formation, Montana. — *Palaeontogr.* , Abt. B, 125, pp. 1-64.

OBRADOVITCH J. D. & COBBAN W. A. (1975). — A time scale for the Cretaceous of the Western Interior of North America. — *Geol. Ass. Can., Spec. Pap.*, 13, pp. 119-136.

OFFICER C. B. & DRAKE C. L. (1983). — The Cretaceous-Tertiary transition. — *Science*, 249, pp. 1383-1390.

OLMEZ I., FINNEGAN D. L. & ZOLLER W. H. (1986). — Iridium emissions from Kilauea volcano. — *J. Geophys. Res.*, 91, pp. 653-663.

OLTZ D. F. (1969). — Numerical analyses of palynological data from Cretaceous and Early Tertiary sediments in east central Montana. — *Palaeontogr.*, Abt. B., 128, pp. 39-42.

ORTH C. J., GILMORE J. S., KNIGHT J. D., PILLMORE C. L., TSCHUDY R. H. & FASSETT J. E. (1981). — An iridium abundance anomaly at the palynological Cretaceous-Tertiary boundary in northern New Mexico. — *Science*, 214, pp. 1341-1343.

PAYNE M. L., WOLBERG D. L. & HUNT A. A. (1982). — Magnetostratigraphy of the Raton and San Juan Basins, New Mexico; implications for synchroneity of Cretaceous-Tertiary boundary events. — *Geol. Soc. Am., Abstr. Programs*, 14, p. 584.

REINECK H. E. & SINGH I. B. (1975). — Depositional sedimentary environments. — Springer Verlag, Berlin-New York, 439 p.

RIGBY J. Keith Jr (1985). — Paleocene dinosaurs. The reworked sample question. — *Geol. Soc. Am., Abstr. Programs*, 17, p. 262.

RIGBY J. Keith Jr & CORRIGAN J. D. (1984). — Numeric methods, multituberculates (Mammalia) biostratigraphic implications for the Hell Creek Formation and the Cretaceous/Tertiary extinction event, Montana. — *Geol. Soc. Am., Abstr. Programs*, 16, p. 235.

RIGBY J. Keith Jr, NEWMAN K., SMIT J., SLOAN R. E., RIGBY J. Keith & VAN DER KAARS W. (in press). — Paleocene dinosaurs from the Hell Creek Formation, McCone County, Montana.

RUSSELL D. (1982). — A paleontological consensus on the extinction of dinosaurs ? — *Geol. Soc. Am., Spec. Pap.*, 190, pp. 401-406.

SHOEMAKER E. M., STEINER M., FASSETT J. E. & TSCHUDY R. H. (1984). — Magnetostratigraphy of Upper Cretaceous rocks at Mesa Portales, New Mexico. — *Geol. Soc. Am., Abstr. Programs*, 6, p. 255.

SLOAN R. E. & VAN VALEN L. (1965). — Cretaceous mammals from Montana. — *Science*, 148, pp. 220-227.

SLOAN R. E., RIGBY J. Keith Jr, VAN VALEN L. & GABRIEL D. (1986). — Gradual dinosaur extinction and simultaneous ungulate radiation in the Hell Creek Formation. — *Science*, 232, pp. 629-633.

SMIT J. & HERTOGEN J. (1980). — An extraterrestrial event at the Cretaceous-Tertiary boundary. — *Nature*, 285, pp. 198-200.

SMIT J. & TEN KATE W. G. H. Z. (1982). — Trace element patterns at the Cretaceous-Tertiary boundary. Consequences of a large impact. — *Cretaceous Research*, 3, pp. 307-332.

SMIT J. & VAN DER KAARS S. (1984). — Terminal Cretaceous extinctions in the Hell Creek area, Montana : compatible with catastrophic extinction. — *Science*, 223, pp. 1177-1179.

SMIT J. & KLAVER G. (1981). — Sanidine spherules at the Cretaceous-Tertiary boundary indicate a large impact. — *Nature*, 292, pp. 47-49.

SMIT J. & ROMEIN A. J. T. (1985). — A sequence of events across the Cretaceous-Tertiary boundary. — *Earth Planet. Sci. Lett.*, 74, pp. 155-170.

TAPPAN H. (1969). — Primary production, isotopes, extinctions and the atmosphere. — *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 4, pp. 187-210.

TSCHUDY R. H. (1984). — Palynological evidence for change in continental floras at the Cretaceous-Tertiary boundary. *In* : W. A. BERGGREN & W. VAN COUVERING Eds, Catastrophes and Earth history. — Princeton University Press, pp. 315-338.

TSCHUDY R. H., PILLMORE C. L., ORTH C. J., GILMORE J. S. & KNIGHT J. D. (1984). — Disruption of the terrigenous plant ecosystem after the Cretaceous-Tertiary boundary. — *Science*, 225, pp. 1030-1032.

UNWIN D. M. (1986). — Extinction-back to basics. — *Modern Geology*, 10, pp. 261-270.

VAN DER KAARS W. A. & SMIT J. (1985) — A palynological field preparation technique. — *Pollen et Spores*, 27, pp. 493-496.

VAN VALEN L. (1984). — Catastrophes, expectations, and the evidence. — *Paleobiology (Paleontol. Soc.)*, 10, pp. 121-137.

VAN VALEN L. & SLOAN R. E. (1965). — The earliest Primates. — *Science*, 150, pp. 743-745.

VAN VALEN L. & SLOAN R. E. (1977). — Ecology and the extinction of the Dinosaurs. — *Evol. Theory*, 2, pp. 37-64.

WARD D. W. & SIGNOR P. W. (1983). — Evolutionary tempo in Jurassic and Cretaceous Ammonites. — *Paleobiology (Paleontol. Soc.)*, 9, pp. 183-198.