

Dinosaur extinction: closing the '3 m gap'

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Modern debate regarding the extinction of non-avian dinosaurs was ignited by the publication of the Cretaceous–Tertiary (K–T) asteroid impact theory and has seen 30 years of dispute over the position of the stratigraphically youngest *in situ* dinosaur. A zone devoid of dinosaur fossils reported from the last 3 m of the Upper Cretaceous, coined the '3 m gap', has helped drive controversy. Here, we report the discovery of the stratigraphically youngest *in situ* dinosaur specimen: a ceratopsian brow horn found in a poorly rooted, silty, mudstone floodplain deposit located no more than 13 cm below the palynologically defined boundary. The K–T boundary is identified using three criteria: (i) decrease in Cretaceous palynomorphs without subsequent recovery, (ii) the existence of a 'fern spike', and (iii) correlation to a nearby stratigraphic section where primary extraterrestrial impact markers are present (e.g. iridium anomaly, spherules, shocked quartz). The *in situ* specimen demonstrates that a gap devoid of non-avian dinosaur fossils does not exist and is inconsistent with the hypothesis that non-avian dinosaurs were extinct prior to the K–T boundary impact event.

Keywords: dinosaurs; extinction; 3 m gap; Cretaceous–Tertiary boundary; Ceratopsidae; Hell Creek Formation

1. INTRODUCTION

The temporal mode of the Cretaceous–Tertiary (K–T) extinction, during which many groups of organisms, including non-avian dinosaurs, went extinct, has been hotly debated since Alvarez *et al.* [1] proposed the extraterrestrial impact hypothesis. Whereas the presence of an impact is now generally accepted [2], it remains unclear whether non-avian dinosaurs gradually went extinct prior to the impact, as the result of climate or sea-level change [3], or suddenly went extinct as the direct, catastrophic result of the impact (e.g. [4]).

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Numerous studies have reported a terrestrial vertebrate fossil-barren zone in the uppermost Cretaceous of the Western Interior of North America, although they differ in their interpretations of whether this is a real phenomenon [5–8] or owing to the incomplete nature of the fossil record [4,9–11]. This barren zone, coined the '3 m gap' [12], lies directly below the K–T boundary. The lack of dinosaur fossils in this zone has been used by some [5,12–15] as evidence for gradual extinction of non-avian dinosaurs.

Identification of the K–T boundary requires elaborate laboratory analyses. Therefore, most surface-collecting studies, with the exceptions of Pearson *et al.* [10,11], lack precise stratigraphic control relative to the K–T boundary. Traditionally, most studies plot dinosaur localities relative to the time-transgressive top of the Hell Creek Formation. However, recent palynological studies have demonstrated that the K–T boundary actually lies anywhere from –5 to +3 m relative to the contact and, therefore, rarely coincides with the formation contact [16–18]. The only Hell Creek studies with precise stratigraphic control [10,11] were able to constrain the fossil-barren zone using a non-avian dinosaur fossil found 1.76 m below the palynologically identified K–T boundary. Although these studies reduced the size of the gap, a fossil-barren zone below the K–T boundary still persists.

Several explanations have been put forth for the putative presence of a fossil-barren zone directly below the K–T boundary. Retallack [19] argued it was the result of a diagenetic overprint caused by impact-derived acid rain that dissolved bones below the K–T boundary. Others (e.g. [20]) attributed the gap to the Signor–Lipps effect [21], and concluded that extinction patterns could not be accurately resolved (see also [22]). The gap has also been used to infer that dinosaurs were already extinct before the K–T boundary [5,12–15]. This putative gap continues to fuel debate regarding the extinction of non-avian dinosaurs at the end of the Cretaceous [4,9,10,14,23,24].

2. METHODS

A brow horn, approximately 45 cm long, from a horned dinosaur (Ceratopsidae), was found in the latest Cretaceous (Maastrichtian) Hell Creek Formation of southeastern Montana (figure 1a) along a hill informally called Camel Butte. A stratigraphic section (Section no. 190) was dug less than 2 m from the specimen where all pertinent sedimentological information was recorded (figure 1b). To determine the placement of the K–T boundary, palynological samples were collected above and below the ceratopsian horn at sub-decimetre resolution from individual lithological units separated by noticeable sedimentological changes (figure 2). Samples were sent to Global Geolabs Ltd., Alberta, Canada for preparation. A series of three palynomorph counts were performed on each sample: relative abundance, presence/absence and characterization of palynofacies (see Bercovici *et al.* [25] for details). Individual palynomorph taxonomic count results are provided as electronic supplementary material, table S1.

3. RESULTS

A ceratopsian brow horn was found 125 cm below the Hell Creek–Fort Union Formation contact in poorly rooted, silty mudstone interpreted as an overbank deposit (figure 2). Earliest Palaeocene, Puercan 1 mammals (e.g. arctocyonid condylarths) and a rich assemblage of other vertebrates (e.g. turtles, crocodylians, osteichthyans) occur 29 cm above the formation contact. The relative abundance of typical Cretaceous palynomorphs

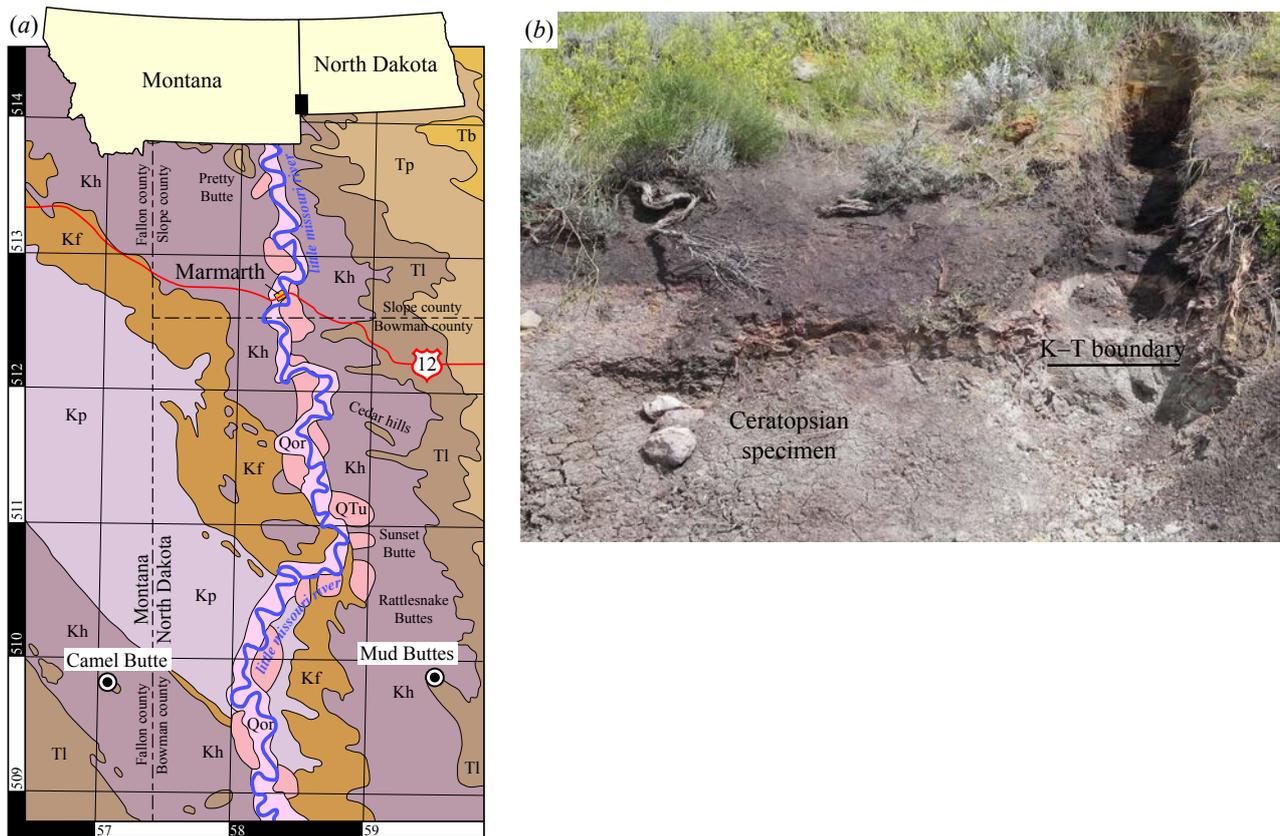


Figure 1. (a) Geological map showing the placement of the two localities discussed in the text. (b) Photo of the Camel Butte K–T boundary section showing the position of the palynologically defined K–T boundary and the *in situ* non-avian dinosaur (Ceratopsidae) brow horn. Abbreviations: Kp: Pierre Shale Fm., Kf: Fox Hills Fm., Kh: Hell Creek Fm., Tl: Fort Union Fm., Tp: Slope Fm., Tb: Bullion Creek Fm., QTu: Quaternary and upper Tertiary, Qor: Holocene. Geographic coordinates are given as a 10 km UTM grid.

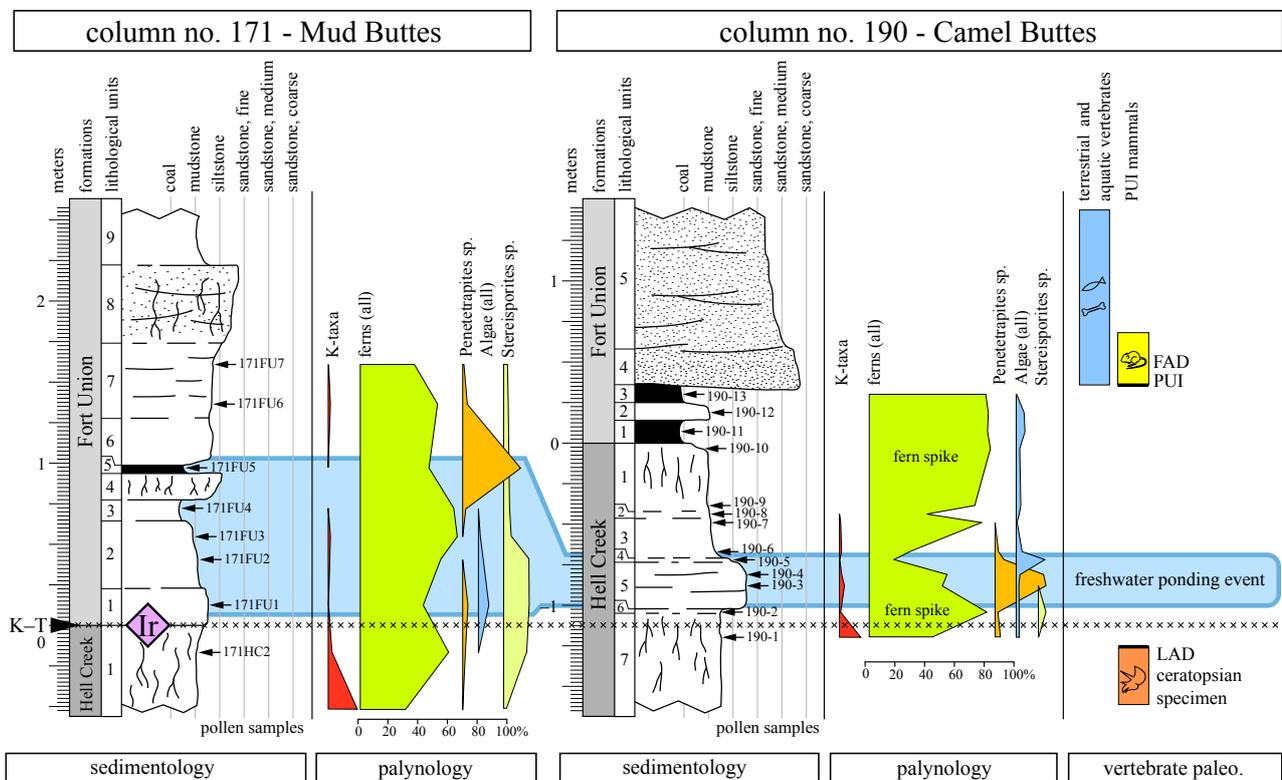


Figure 2. Sedimentological, palynological and vertebrate palaeontological data from the Mud Buttes (no. 171) and Camel Butte (no. 190) K–T boundary sections. The non-avian dinosaur specimen was found 13 cm below the Camel Butte K–T boundary section (see §4 for justification of the placement of the boundary). Arrows indicate levels where palynological samples were collected. Appearance data (first—FAD; last—LAD) for vertebrates are indicated for the Camel Butte section. Abbreviations: Ir: iridium anomaly; PUI: Puercan 1.

(K-taxa) drops significantly from 14% in sample 190-1 to 1–3% in the overlying samples. A ‘fern spike’ is also identified starting at sample 190-2, where the assemblage consists of as much as 80% ferns (figure 2; electronic supplementary material, table 1). Based on these measurements, placement of the K–T boundary is not higher than 13 cm above the non-avian dinosaur specimen.

4. DISCUSSION

Placement of the K–T boundary at Camel Butte is inferred using three lines of evidence (figure 2). First, a major decrease in Cretaceous palynomorph taxa without subsequent recovery [25] indicates the demise of Mesozoic floras. Second, the correlated development of a ‘fern spike’, as described from K–T boundary sections worldwide and interpreted as the recovery by pioneering plants of terrestrial ecosystems devastated by the asteroid impact [26]. Third, the K–T boundary at Camel Butte is established through correlation to the nearby Mud Buttes (Section no. 171), from which an iridium anomaly has been reported [17]. Few K–T boundary sections in the Western Interior preserve the primary markers (e.g. iridium anomaly, spherules, shocked quartz) of the Chicxulub impact event [2], and correlation to such sections is necessary. Correlation between the Camel Butte and Mud Buttes sections is made possible by the identification of a freshwater ponding event in the lowermost Palaeocene at both sections, which is characterized by a 1–2 m thick series of massive mudstones devoid of vertebrate fossils and by the proliferation of freshwater taxa (algal cysts such as *Pediastrum* sp., *Schizophacus* sp. and the aquatic monocot *Penetetrapites* sp., which are often preceded by mosses, *Stereisporites* sp.).

The dinosaur specimen was found 13 cm below the K–T boundary in a poorly rooted mudstone overbank deposit, indicating that it was not reworked, but autochthonous; unlike channel sands, which commonly rework and concentrate vertebrate specimens, fossils found in overbank deposits are unlikely to have been re-deposited from older sediments [27,28]. This, along with the placement of the boundary, indicates the ceratopsian brow horn represents the stratigraphically youngest *in situ* non-avian dinosaur.

Discovery of this dinosaur locality demonstrates that a Cretaceous ‘3 m gap’ does not exist and is inconsistent with the hypothesis that non-avian dinosaurs were extinct prior to the K–T boundary impact event. Although channel deposits must have been deposited during the K–T event, we are confident that it is highly improbable to find a boundary section in this facies and to recover the dinosaurian fossils strictly associated with such deposits [29]. We therefore predict that future fieldwork will identify additional overbank-associated dinosaur faunas near the top of the Cretaceous, but this facies bias will prohibit finding channel-associated faunal elements close to the boundary. While our data indicate that an Upper Cretaceous gap does not exist, an approximately 125 cm section post K–T impact in the lowermost Palaeocene completely devoid of fossils is present. Additional fieldwork and high-resolution stratigraphic analyses

are needed for this important time interval to reconstruct the conditions on Earth immediately after the asteroid impact.

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	190-1	190-2	190-3	190-4	190-5	190-6	190-7	190-8	190-9	190-10	190-11	190-12	190-13
Bryophytes	2,0 %	5,3 %	0,2 %	0,3 %	0,0 %	0,1 %	0,0 %	0,0 %	0,4 %	0,0 %	0,2 %	0,0 %	0,0 %
<i>Foraminisporis undulatus</i>	7	1		1									
<i>Stereisporites</i> spp.	1	34	1	1		1			1		1		
<i>Zlivisporites novomexicanum</i>	1								1				
Quillworts	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	1,8 %	0,2 %	0,0 %	0,0 %	0,0 %	0,0 %	0,1 %	5,2 %
<i>Palaeoisoetes subengelmannii</i>						13	1					1	17
Lycopods	0,4 %	0,5 %	0,4 %	0,5 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %
<i>Hamulatisporis hamulatis</i>		3	2	4									
<i>Retitriteles</i> sp.	2												
Ferns	42,5 %	78,8 %	49,0 %	52,2 %	16,6 %	27,1 %	75,2 %	38,7 %	70,7 %	81,2 %	79,3 %	79,8 %	78,1 %
<i>Azolla circinata</i>		1		24	11	33		23	22				
<i>Azolla cretacea</i>	1	2		3	2	1			1				
<i>Azolla microspore</i>	7		1	14	8	3	1			1			
<i>Cicatricosisporites</i> spp.	2												
<i>Cyathidites</i> spp.	62	64	29	32	3	23	30	13	84	16	3	4	
<i>Deltoidospora</i> sp.	5	8	2	8	2	7		1		1			35
<i>Echinisporites</i> sp.	3					1							
<i>Ghoshispora bella</i>		4	5	5	18	3							
<i>Gleicheniidites</i> spp.	16	174	82	67	14	40	38	10	50	64	1	2	
<i>Laevigatosporites</i> spp.	87	227	90	167	23	65	391	179	154	208	347	637	167
<i>Leptolepidites tenuis</i>	1	1				1		1		3			2
<i>Osmundacidites stanleyi</i>					1		2			1			
<i>Polycingulatisporites</i> sp.	4		1										
<i>Reticuloidosporites pseudomurii</i>		43	39	61	8	14	5	10	7	8	1		53
<i>Toroisporis major</i>	2		1	1		1							
Gymnosperms	11,0 %	6,5 %	6,9 %	5,5 %	17,1 %	18,4 %	7,7 %	13,9 %	12,0 %	9,1 %	6,1 %	1,6 %	3,6 %
<i>Cycadopites</i> spp.	11	4	8	3	1	6	3	4	1	3		4	4
<i>Ephedripites ovatus</i>	1												
<i>Inaperturopollenites</i> spp.								9	3		6		
<i>Pityosporites</i> spp.	36	35	27	36	90	104	39	71	47	29	21	9	8
<i>Podocarpites</i> spp.					1		1	1					
<i>Taxodiaceapollenites</i> spp.	1	4		1	1	20	5		3	2			
Monocotyledon	5,4 %	2,3 %	35,1 %	32,9 %	16,4 %	10,2 %	3,7 %	26,3 %	6,2 %	2,4 %	1,8 %	0,0 %	0,6 %
<i>Arecipites</i> sp.	3	1	5	2	4	4	6	139	19	5	8		2
<i>Dyadonapites reticulatus</i>						3							
* <i>Liliacidites altimurus</i>	1												
* <i>Marsypiletes cretaceus</i>	1												
<i>Pandaniidites typicus</i>	2	1		1	53	48	16	22	9	3			
<i>Penetetrapites</i> sp.	16	13	174	238	32	16	1			1			
Dicotyledons	36,5 %	4,8 %	6,5 %	6,1 %	30,8 %	38,4 %	12,6 %	19,1 %	7,6 %	4,8 %	6,8 %	13,0 %	12,2 %
<i>Aquilapollenites attenuatus</i>	2												
* <i>Aquilapollenites collaris</i>	5	2	9	3	1								
* <i>Aquilapollenites conatus</i>	2		1	2									
* <i>Aquilapollenites marmarthensis</i>									1				
* <i>Aquilapollenites quadrilobus</i>	29	2	4	3		2							
* <i>Aquilapollenites reductus</i>	10												
* <i>Cranwellia edmontonensis</i>	1												
<i>Ericacepollenites</i> sp.	4	1		2	2	4		31		1		1	
<i>Inaperturotetradites scabratus</i>					14	5							
<i>Kurtzipites trispissatus</i>	18	1		1	57	92	7	1	1		1	14	1
* <i>Leptopocopites pocockii</i>	1		1	1									
<i>Nyssapollenites</i> spp.						1							
<i>Simplicepollis rallus</i>	1				1			20	3	5			
* <i>Striatellipollis striatellus</i>	4	1	1										
<i>Striatopollis tectatus</i>	8	4	2		2								
* <i>Styxpollenites calamitas</i>						1							
<i>Tricolpites</i> spp.	5		2	1	2	7		23	1	2			
* <i>Tricolpites microreticulatus</i>	6			2		6	4		1				
<i>Tripoporipollenites</i> spp.	11	16	9	25	69	135	61	14	24	10	3	11	36
* <i>Tschudypollis</i> spp.	3		1				1						
<i>Ullmipollenites krempii</i>	49	5	2	4	16	15	5				26	79	3
<i>Wodehouseia spinata</i>	4		1	1	3	4		28	3				
Algae	2,0 %	2,0 %	1,8 %	2,5 %	19,2 %	4,0 %	0,6 %	2,1 %	3,1 %	2,4 %	5,9 %	5,3 %	0,3 %
<i>Ovoidites</i> sp.				2	11	3							
<i>Pediastrum</i> sp.			1	3	1							1	
<i>Tetraporina</i> sp.		2		1	14	7	1	5	3	6	5	3	
<i>Schizophacus</i> sp.	6	8	6	8	72	14	2	7	9	3	19	39	1
4-14		1		1									
4-17	2	2	2	3	1				1		2		
4-22					5	4	1	1	1				
4-26	1												
Dinoflagellates	0,2 %	0,0 %	0,2 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %	0,1 %	0,0 %
<i>Dinoflagellates</i>	1		1									1	
Total	447	665	510	732	543	708	621	613	450	372	444	806	329