Chapter 19

Ammonites on the Brink of Extinction: Diversity, Abundance, and Ecology of the Order Ammonoidea at the Cretaceous/Paleogene (K/Pg) Boundary

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19.1 Introduction

Ammonite shells are common fossils in marine Mesozoic deposits. Their disappearance in Cenozoic strata has intrigued naturalists from the early nineteenth century onward, and the cause of their extinction has been the subject of lively debate. Following the seminal publication of Alvarez et al. (1980), paleontologists have considered that the most plausible explanation for their disappearance was the impact of an asteroid, and its ensuing consequences (Gould 1995; Ward 1996). Today, the evidence for the Chicxulub impact in the Yucatán Peninsula, Mexico, is overwhelming (Schulte et al. 2010). Indeed, the stratigraphic layer of debris associated with the

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impact serves as the official base of the Danian Stage (= base of Cenozoic Erathem) (Molina et al. 2006). Yet, the diversity and geographic distribution of ammonites just prior to and at the moment of impact are still not well documented. Kiessling and Claeys (2002) provided an overview of localities where ammonites occur near or at the K/Pg boundary (KTBase project). However, only a handful of sections were described, leaving many blind spots. Thanks to renewed collecting efforts during the past decade to recover ammonites from close to the boundary, it is now possible to assemble a much more detailed picture of the health of this group at the brink of extinction.

19.2 Methods

We examined the stratigraphic distribution of ammonites at a total of 29 sites encompassing 14 regions around the world to tabulate the generic and specific diversity of these animals just prior to and at the K/Pg boundary. These sites include the Atlantic Coastal Plain of North America (New Jersey and Maryland); the Gulf Coastal Plain of North America (Missouri, Mississippi, and Texas); the La Popa Basin, northeastern Mexico; Denmark (Stevns Klint, Kjølby Gård, and the "*Dania*" Quarry); the Maastrichtian type area (the Netherlands and northeast Belgium); Poland (Nasiłów, Mełgiew, and Lechówka); Kyzylsay, Kazakhstan; the Sumbar River, Turkmenistan; the Bay of Biscay (Zumaya, Hendaye, and Bidart); Bjala (= Byala), Bulgaria; Tunisia (Kalaat Senan, El Kef, and Garn Halfaya) and Egypt (Dababiya Quarry Corehole); the Naiba River Valley, Sakhalin, Far East Russia; the Poty Quarry, Brazil; Lomas Colorados, Bajada de Jagüel, the Neuquén Basin, Argentina; and Seymour Island, Antarctica (Fig. 19.1, Appendix). We have arbitrarily focused on the last 0.5 million years of the Maastrichtian at each site (our target interval) because this is the shortest interval of time that still yields enough ammonite data from different environmental settings and geographic areas. However, it is worth noting that taphonomic bias and collection failure play a much larger role in the recovery of ammonite data than they do in the assembly of, for example, microfossil data.

We demarcated our target interval using biostratigraphy, magnetostratigraphy, and cyclostratigraphy, as well as data on fossil occurrences in relation to the K/Pg boundary in sections without any physical sign of a sedimentary break between the highest ammonites and the K/Pg boundary. In terms of biostratigraphy, many of our sites belong to, or can be correlated with, Calcareous Nannofossil Zone CC26b of Perch-Nielsen (1985), which is approximately equivalent to Zone UC20dTP of Burnett (1998), and extends from the FO of *Micula prinsii* to the LO of unreworked, non-survivor Cretaceous taxa, which starts 750 kyr (Hennebert 2012) to 530 kyr (Dinarès-Turell et al. 2013) before the end of the Cretaceous (see also Gardin et al. 2012). This interval is approximately equivalent to geomagnetic polarity Chron 29r, which starts 0.3 myr prior to the K/Pg boundary according to recent calculations (e.g., Husson et al. 2011). For planktic foraminifera, our 0.5 myr interval corresponds to the combined *Plummerita hantkeninoides* CF1 Zone, *Pseudoguembelina*

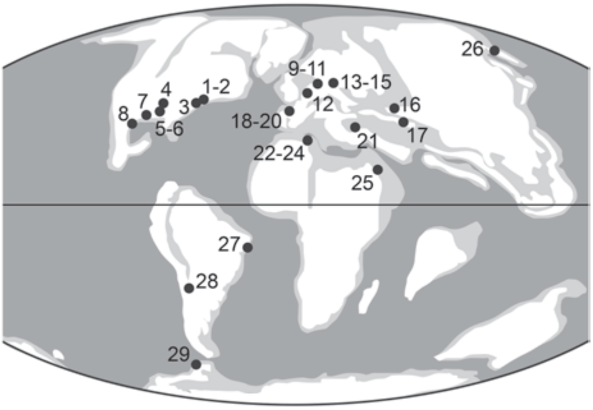


Fig. 19.1 Distribution of localities described in the text plotted on a paleogeographic map of the Earth at the K/Pg boundary (after Blakey 2011). *1* Central Monmouth County, New Jersey, *2* Northeastern Monmouth County, New Jersey, *3* Anne Arundel County, Maryland, *4* Stoddard and Scott Counties, Missouri, *5* Tippah County, Mississippi, *6* Chickasaw County, Mississippi, *7* Falls County, Texas, *8* Northeastern Mexico, *9* Stevns Klint, Denmark, *10* Kjølby Gård, Denmark, *11* Dania Quarry, Denmark, *12* Maastricht, the Netherlands, *13* Nasiłów, Poland, *14* Mełgiew, Poland, *15* Lechówka, Poland, *16* Kyzylsay, Kazakhstan, *17* Sumbar River, Turkmenistan, *18* Zumaya, Spain, *19* Hendaye, France, *20* Bidart, France, *21* Bjala, Bulgaria, *22* Kalaat Senan, Tunisia, *23* El Kef, Tunisia, *24* Garn Halfaya, Tunisia, *25* Dababiya Quarry core, Egypt, *26* Sakhalin Island, Russia, *27* Poty Quarry, Brazil, *28* Bajada de Jagüel, Argentina, *29* Seymour Island, Antarctica. (See Appendix for a description of the localities)

palpebra CF2 Zone, and possibly also the upper part of the *Pseudoguembelina fructicosa* CF3 Zone. The base of CF1 is approximately 0.23 myr prior to the K/Pg boundary, according to Hennebert and Dupuis (2003).

In evaluating the record of ammonites at the K/Pg boundary, it is important to distinguish between complete and incomplete sections. For example, in complete sections, e.g., in Tunisia, all of the impact markers are present, including a layer of fine clay (the so-called K/Pg boundary clay) with elevated concentrations of iridium. In such sections, the timescale of deposition is constrained by two points: the impact layer, which represents the same moment everywhere (isochronous), and the base of the highest biostratigraphic zone, which is possibly diachronous. This timescale can be further refined using cyclostratigraphic data, as in the Bay of Biscay, the Tunisian Trough Basin, and the Maastrichtian type area. In incomplete sections, e.g., at Nasiłów, central Poland, in contrast, the fallout layer (boundary clay) is not preserved, although it was undoubtedly deposited, and instead the boundary is marked by an erosional unconformity. The amount of time this unconformity represents is difficult to estimate using biostratigraphic indices and can include parts of the latest Maastrichtian and earliest Danian.

The authors of the ammonite species mentioned in the text are listed in Table 19.1. Some of the ammonites documented are in open nomenclature because the specimens are worn or consist of only fragments. For example, specimens of

Table 19.1 List of species that occur near the K/Pg boundary and the according localities (for abbreviations see Appendix).

	ATLANTIC COAST			GULF COAST					DENMARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMERICA		AN
Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
PHYLLOCERATINA																													
*Hypophylloceras (Neophylloceras) velledaeforme (*Schlüter, 1872)									1		1																		
Hypophylloceras (Neophylloceras) ramosum (Meek, 1858)																		1	1	1						1			
Hypophylloceras (Neophylloceras) hetonaiense Matsumoto, 1942																										1			
Hypophylloceras (Neophylloceras) surya (Forbes, 1846)											1								1										
Hypophylloceras (*Neophylloceras*) sp. of Goolaerts, 2010																						1							
Phyllopachyceras forbesianum (d'Orbigny, 1850)																		1	1	1		1							
LYTOCERATINA																													
GAUDRYCERATIDAE																													
*Gaudryceras kayei**																		1											

Table 19.1 (continued)

	ATLANTIC COAST			GULF COAST					DENMARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMERICA		AN
Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
(Forbes, 1846)																													
Gaudryceras hamanakense (Matsumoto and Yoshida, 1979)																										1			
Gaudryceras venustum Matsumoto, 1984																										1			
Anagaudryceras matsumotoi Morozumi, 1985																										1			
Anagaudryceras seymouriense Macellari, 1986																													1
Anagaudryceras politissimum (Kossmat, 1895)																		1	1	1	1								
Anagaudryceras cf. *politissimum* (Kossmat, 1895)																						1							
Anagaudryceras sp. of Ward and Kennedy, 1993																		1											
Zelandites varuna (Forbes, 1846)																						1	1			1			1

Table 19.1 (continued)

	ATLANTIC COAST			GULF COAST					DENMARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMERICA		AN
Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Zelandites japonicus Matsumoto, 1938																										1			
Zelandites sp. of Ward and Kennedy, 1993																		1											
*Vertebrites kayei** (Forbes, 1846)																					1								
TETRAGONITIDAE																													
Tetragonites (*Tetragonites*) sp. of Goolaerts, 2010																						1	1						
Saghalinites cala (Forbes, 1846)																						1							
Saghalinites wrighti Birkelund, 1965																				1									
Saghalinites n. sp. of Birkelund, 1993									1		1																		
Pseudophyllites indra (Forbes, 1846)																				1	1	1	1	1					
Pseudophyllites sp. of Goolaerts, 2010																							1	1					
Pseudophyllites loryi (Kilian and Reboul, 1909)																													1

Table 19.1 (continued)

	ATLANTIC COAST			GULF COAST					DENMARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMERICA		AN
Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
AMMONITINA																													
Desmophyllites larteti (Seunes, 1891)																		1											
Hauericeras rembda (Forbes, 1846)																						1	1	1					
Pseudokossmaticeras duereri (Redtenbacher, 1873)																				1									
Brahmaites (Brahmaites) brahma (Forbes, 1846)												1							1			1	1	1					
Grossouvrites gemmatus (Hupé, 1854)																													1
Maorites densecostatus (Kilian and Reboul, 1909)																													1
Kitchinites laurae Macellari, 1986																													1
Desmoceratoidea sp. of Goolaerts, 2010																						1	1						
Pachydiscus (*P.*) *riccardii* Macellari, 1986																													1
Pachydiscus (P.) neubergicus (von Hauer, 1858)																											1		

Table 19.1 (continued)

	ATLAN-TIC COAST			GULF COAST					DEN-MARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMER-ICA		AN
Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Pachydiscus (P.) neubergicus dissitus Henderson and McNamara, 1985																		1	1										
Pachydiscus (P.) gollevillensis (d'Orbigny, 1850)																			1										
Pachydiscus (*P.*) *ultimus* Macellari, 1986																													1
Pachydiscus (*P.*) *jacquoti jacquoti* (Seunes, 1890)							1					1	1					1		1									
Pachydiscus (*P.*) *armenicus* Atabekian and Akopian, 1969																		1	1	1									
Pachydiscus (*P.*) *noetlingi* Kennedy in Fatmi and Kennedy, 1999												1																	
Pachydiscus (P.) flexuosus Matsumoto, 1979																										1			
Pachydiscus (*P.*) sp. A of Goolaerts, 2010																						1	1	1					

Table 19.1 (continued)

	ATLANTIC COAST			GULF COAST					DENMARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMERICA		AN
Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Pachydiscus (*P.*) sp. indet. of Goolaerts, 2010																						1							
Pachydiscus (*P.*) sp. indet. of Ivanov and Stoykova, 1995																					1								
P.(*Neodesmoceras*) *snamensis* (Pervinquière, 1907)																						1	1	1					
P.(*Neodesmoceras*) *mokotibensis* Collignon, 1952	1			1																									
P. (Neodesmoceras) gracilis Matsumoto, 1979																										1			
Menuites terminus (Ward and Kennedy, 1993)									1		1	1	1					1	1	1	1								
Menuites sp. A of Goolaerts, 2010																						1	1	1					
Menuites sp. B of Goolaerts, 2010																						1		1					
Sphenodiscus binckhorsti Böhm, 1898												1	1																

Table 19.1 (continued)

	ATLANTIC COAST			GULF COAST					DENMARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMERICA		AN
Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Sphenodiscus lobatus (Tuomey, 1856)	1			1	1	1																							
Sphenodiscus pleurisepta (Conrad, 1857)		1		1	1	1		1																					
Sphenodiscus spp. of Landman et al., 2004b		1																											
ANCYLOCERATINA																													
NOSTOCERATIDAE																													
Nostoceras sp. of Van der Tuuk and Zijlstra, 1979												1																	
DIPLOMOCERATIDAE																													
Glyptoxoceras rugatum (Forbes, 1846)												1																	
Glyptoxoceras cf. *G. rugatum* (Forbes, 1846)							1																						
Glyptoxoceras sp. of Jagt, 1995												1																	
Glyptoxoceras sp. 1 of Jagt, 2012												1																	

Table 19.1 (continued)

	ATLANTIC COAST			GULF COAST					DENMARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMERICA		AN
Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Diplomoceras cylindraceum (Defrance, 1816)									1		1	1							1	1		1	1	1		1			
Diplomoceras lambi Spath, 1953																													1
Diplomoceras sp. of Stinnesbeck et al., 2012																											1		
Phylloptychoceras cf. *P. sipho* (Forbes, 1846) of Jagt et al., 2006												1																	
Phylloptychoceras cf. *P. sipho* (Forbes, 1846) of Goolaerts, 2010																						1	1	1					
Phylloptychoceras sp. of Birkelund, 1993									1																				
BACULITIDAE																													
Baculites anceps Lamarck, 1822												1	1																
Baculites ovatus Say, 1821								1																					
Baculites vertebralis Lamarck, 1801									1	1	1	1																	
Baculites cf. *B. vertebralis* Lamarck, 1801																	1												

Table 19.1 (continued)

	ATLAN-TIC COAST			GULF COAST					DEN-MARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMER-ICA		AN
Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Baculites cf. *B. claviformis* Stephenson, 1941 of Kennedy and Cobban (2000)					1																								
Baculites cf. *B. undatus* Stephenson, 1941 of Kennedy and Cobban, 2000					1																								
Baculites sp. A of Goolaerts, 2010																						1	1	1					
Baculites sp. C of Cobban and Kennedy, 1995				1	1	1																							
Baculites sp. of Naidin, 1987																1													
Baculites sp. of Machalski, 2005a														1															
Baculites sp. of Racki et al., 2011															1														
Baculitidae indet. of Goolaerts and Dupuis, 2012																									1				
Eubaculites carinatus (Morton, 1834)	1	1	1	1	1	1	1					1																	

Table 19.1 (continued)

	ATLAN-TIC COAST			GULF COAST					DEN-MARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMER-ICA		AN
Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Eubaculites cf. *E. carinatus* (Morton, 1834) of Landman et al., 2004a			1																										
Eubaculites latecarinatus (Brunnschweiler, 1966)	1	1		1	1	1						1																	
Eubaculites sp. ex. gr. *E. simplex* (Kossmat, 1895)																												1	
Fresvillia paradoxa (Pervinquière, 1907)																						1	1	1					
SCAPHITIDAE																													
Indoscaphites cunliffei (Forbes, 1846)																						1	1	1					
Indoscaphites pavana (Forbes, 1846)																						1	1	1	1				
Hoploscaphites constrictus (J. Sowerby, 1817)																1													
Hoploscaphites constrictus crassus Łopuski, 1911													1																

Table 19.1 (continued)

	ATLAN-TIC COAST			GULF COAST					DEN-MARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMER-ICA		AN
Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Hoploscaphites constrictus johnjagti Machalski, 2005b									1	1	1	1		1			1												
Hoploscaphites constrictus subsp. indet. of Racki et al., 2011															1														
Hoploscaphites felderi Kennedy, 1987									1			1																	
Hoploscaphites pungens (Binkhorst van den Binkhorst, 1862)												1																	
Hoploscaphites sp. ex gr. *waagei-angmartussutensis*												1	1																
Acanthoscaphites? sp. of Kennedy, 1987												1																	
Discoscaphites cf. *D. conradi* (Morton, 1834) of Kennedy and Cobban, 2000					1																								
Discoscaphites gulosus (Morton, 1834)	1	1																											

Table 19.1 (continued)

	ATLANTIC COAST			GULF COAST					DENMARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMERICA		AN
Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Discoscaphites cf. *D. gulosus* (Morton, 1834) of Kennedy et al., 2001							1																						
Discoscaphites iris (Conrad, 1858)	1	1	1	1	1	1	1																						
Discoscaphites cf. *D. iris* (Conrad, 1858) of Landman et al., 2004a			1																										
Discoscaphites jerseyensis Landman et al., 2007	1																												
Discoscaphites minardi Landman et al., 2004a	1	1		1	1	1																							
Discoscaphites cf. *D. minardi* Landman et al., 2004a of Landman et al., 2004a			1																										
Discoscaphites sphaeroidalis Kennedy and Cobban, 2000	1	1		1	1	1	1																						

Geographic distribution of ammonite species at 29 sites in the last 0.5 myr of the Cretaceous. Abbreviations: MA: Maastrichtian type area, The Netherlands and Belgium; KA: Kazakhstan; TR: Turkmenistan; BU: Bulgaria; EG: Egypt; FER: Far East Russia; AN: Antarctica; * = the two species may be synonymous, but further research is required.

Phylloptychoceras from Tunisia are small pyritic fragments of shafts and can, therefore, only be referred to as *Phylloptychoceras* cf. *P. sipho*. Similarly, specimens of *Baculites* from this region are too incomplete and lack details of ornamentation and suture to permit species identification. On the Atlantic and Gulf Coastal plains, the poor state of preservation of some specimens of *Glyptoxoceras* and *Discoscaphites* also precludes their identification to species level. Even in sections that have been studied for decades, such as those in Denmark, some material is too crushed or incomplete to be assigned to a particular species with any certainty (e.g., *Saghalinites* n. sp. of Birkelund 1993).

19.3 Results

19.3.1 Atlantic Coastal Plain of North America

(Sites 1–3: New Jersey and Maryland). The *Discoscaphites iris* Zone, the highest ammonite zone in North America, is present in this area and has yielded nine species, four (sub)genera, and four families distributed among the Ammonitina (*Pachydiscus* (*Neodesmoceras*) and *Sphenodiscus*) and Ancyloceratina (*Eubaculites* and *Discoscaphites*) (Landman et al. 2004a, b, 2007; Figs. 19.2, 19.3; Tables 19.1, 19.2). This zone corresponds to Calcareous Nannofossil Zone CC26b, representing approximately the last 0.5 myr of the Maastrichtian. At offshore sites (~100 m deep) containing ammonites, the section is demonstrably incomplete with an unconformity at the K/Pg boundary. At more nearshore sites (~40 m deep) containing ammonites, the sequence is apparently more complete. The upper part of the section consists of a very fossiliferous unit (called the *Pinna* Layer) that yields numerous specimens of *Discoscaphites* and *Eubaculites*. The *Pinna* Layer is overlain by the Burrowed Unit, which bears many fewer ammonites, almost all of which are *Eubaculites*. However, the *Pinna* Layer occurs above a horizon with a weak iridium anomaly (520 pg/g). The crucial question is whether this iridium anomaly represents the record of the bolide impact and, if so, whether it is in place or has migrated downward (Landman et al. 2007, 2012b; Miller et al. 2010; for additional discussion about the remobilization of iridium, see Racki et al. 2011). For example, if the iridium anomaly is in place, then the ammonites in the *Pinna* Layer and the Burrowed Unit may have been short-term survivors of the bolide impact, possibly persisting into the earliest Danian. However, even if the iridium anomaly has migrated downward from the top of the *Pinna* Layer, a more conservative interpretation favored here and elsewhere (Landman et al. 2014), the species of *Eubaculites* in the Burrowed Unit are still Danian survivors (see 19.4.1).

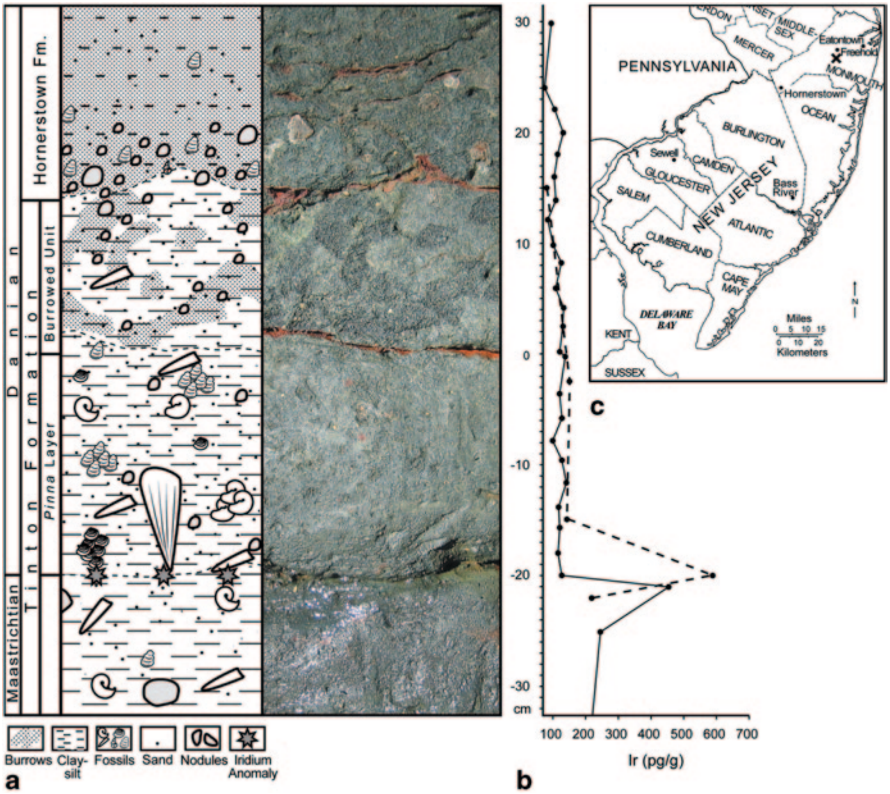


Fig. 19.2 Stratigraphic section of the upper Maastrichtian and lower Danian in Monmouth County, New Jersey, Atlantic Coastal Plain, USA. **a** The top of the Tinton Formation consists of the *Pinna* Layer overlain by the Burrowed Unit, which is overlain, in turn, by the Hornerstown Formation. An enriched concentration of iridium occurs at the base of the *Pinna* Layer (indicated by the stars). The position of the K/Pg boundary is based upon the assumption that the enriched concentration of iridium has been remobilized. **b** Iridium profile from two sites (represented by the solid and dashed lines) (Landman et al. 2007). **c** Map of part of New Jersey with the locality marked by an X

19.3.2 Gulf Coastal Plain of North America

(Sites 4–7: Missouri, Mississippi, and Texas). The *Discoscaphites iris* Zone is present on the Gulf Coastal Plain in Missouri (Stephenson 1955), Mississippi (Cobban and Kennedy 1995; Kennedy and Cobban 2000), and Texas (Kennedy et al. 2001) and contains as many as 15 species, although not all of them are present at every site (Fig. 19.4; Tables 19.1, 19.2). In Stoddard and Scott Counties, southeastern Missouri, the Owl Creek Formation consists of clayey sands, which were probably deposited at depths of less than 100 m, and is unconformably overlain by the Clayton Formation (Campbell et al. 2008). In Tippah County, northeastern Mississippi, the Owl Creek Formation consists of micaceous clays, which were probably deposited at similar depths. The Owl Creek Formation at this site is also unconformably

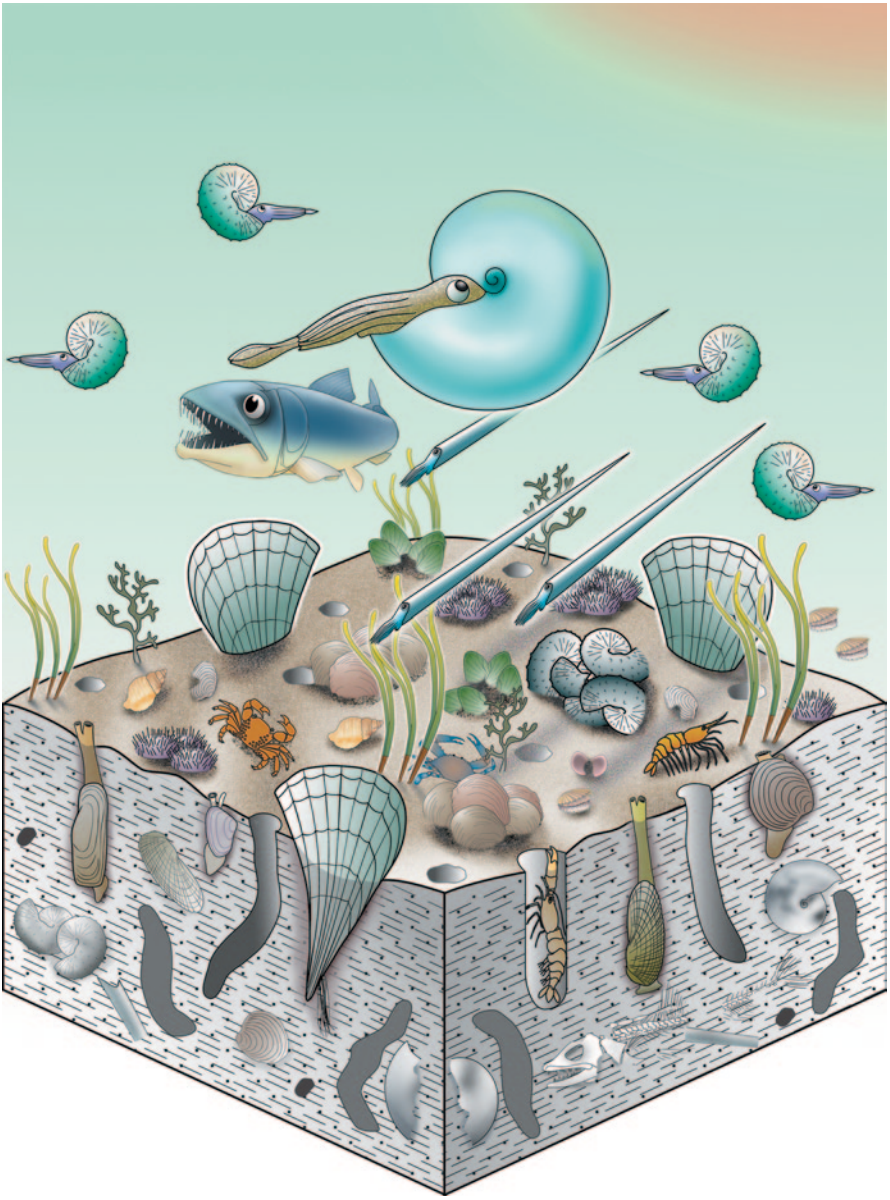


Fig. 19.3 Hypothetical reconstruction of the sea bottom on the Atlantic Coast at the end of the Maastrichtian just before the meteor impact, as inferred from sections in Monmouth County, New Jersey. The ammonites include *Sphenodiscus lobatus*, *Discoscaphites iris*, and *Eubaculites latecarinatus* (from Landman et al 2007)

Table 19.2 Geographic distribution of 31 ammonite genera at 29 sites in the last 0.5 my of the Cretaceous

		ATLANTIC COAST			GULF COAST					DENMARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMERICA		AN	
	Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	N occurrences
1	*H.* (*Neophylloceras*)									1		1							1	1	1		1				1				7
2	*Phyllopachyceras*																		1	1	1		1								4
3	*Gaudryceras*																		1								1				2
4	*Anagaudryceras*																		1	1	1	1	1				1			1	7
5	*Vertebrites*																					1									1
6	*Zelandites*																		1				1	1			1			1	5
7	*Tetragonites*																						1	1							2
8	*Saghalinites*									1		1									1		1								4
9	*Pseudophyllites*																				1	1	1	1	1					1	6
10	*Desmophyllites*																		1												1
11	*Hauericeras*																						1	1	1						3
12	*Pseudokossmaticeras*																				1										1
13	*B.* (*Brahmaites*)												1							1			1	1	1						5
14	*Grossouvreites*																													1	1

Table 19.2 (continued)

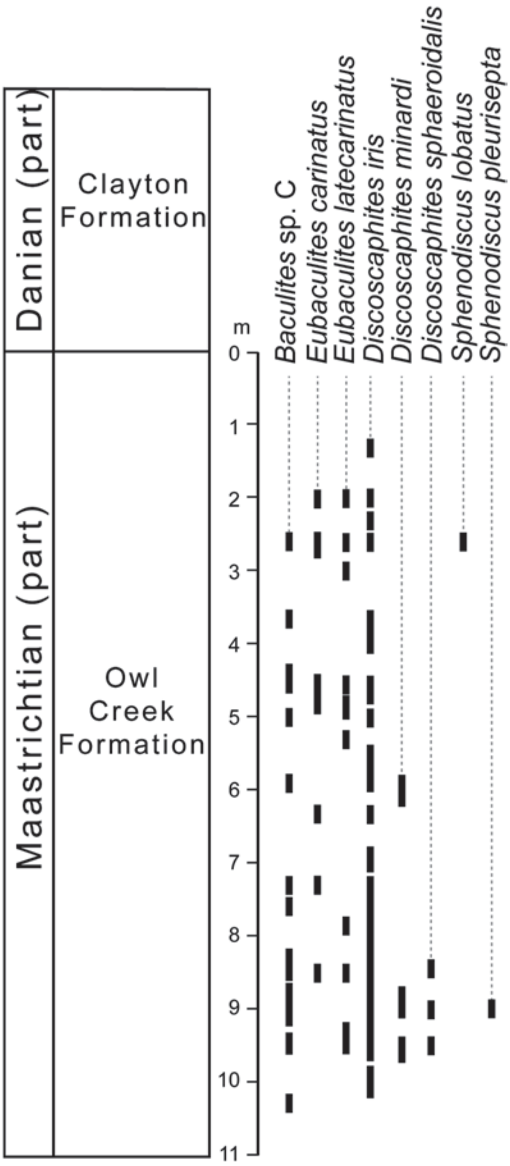
		ATLANTIC COAST			GULF COAST					DEN-MARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMER-ICA		AN	
	Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	N occur-rences
15	*Maorites*																													1	1
16	*Kitchinites*																													1	1
17	*P.* (*Pachydiscus*)							1					1	1					1	1	1	1	1	1	1		1	1		1	13
18	*P.* (*Neodesmoceras*)	1			1																		1	1	1		1				6
19	*Menuites*									1		1	1	1					1	1	1	1	1	1	1						11
20	*Sphenodiscus*	1	1		1	1	1		1				1	1																	8
21	*Nostoceras*												1																		1
22	*Glyptoxoceras*							1					1																		2
23	*Diplomoceras*									1		1	1							1	1		1	1	1		1	1		1	11
24	*Phylloptychoceras*									1			1										1	1	1						5
25	*Baculites*				1	1	1		1	1	1	1	1	1	1	1	1	1					1	1	1	1					16
26	*Eubaculites*	1	1	1	1	1	1	1					1																1		9
27	*Fresvillia*																						1	1	1						3
28	*Indoscaphites*																						1	1	1	1					4
29	*Hoploscaphites*									1	1	1	1	1	1	1	1	1													8

Table 19.2 (continued)

		ATLANTIC COAST			GULF COAST					DENMARK			MA	POLAND			KA	TR	BISCAY REGION			BU	TUNISIA			EG	FER	SOUTH AMERICA		AN	
	Taxon/Site number:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	N occurrences
30	*Acanthoscaphites*												1																		1
31	*Discoscaphites*	1	1	1	1	1	1	1																							7

The genera represent all four orders of Cretaceous Ammonoid: Phylloceratina (1-2), Lytoceratina (3-9), Ammonitina (10-20), and Ancyloceratina (21-31). For a description of localities, see Appendix. Abbreviations: *AT*: Atlantic Coast; *MA*: Maastrichtian type area, The Netherlands and Belgium; *KA*: Kazakhstan; *TR*: Turkmenistan; *BU*: Bulgaria; *EG*: Egypt; *FER*: Far East Russia; *S.Am*: South America; AN: Antarctica; N.occ: Number of occurrences.

Fig. 19.4 Stratigraphic range chart of the ammonites in the Owl Creek Formation in Tippah County, northeastern Mississippi, Gulf Coastal Plain, USA (Larina et al. 2012). The Owl Creek Formation is unconformably overlain by the Clayton Formation, with no evidence of impact debris. Ammonites extend to approximately 1 m below the unconformity, which presumably contains the K/Pg boundary



overlain by the Clayton Formation, without any evidence of impact debris. Ammonites extend to approximately 1 m below the unconformity, which presumably contains the K/Pg boundary, and the absence of ammonites above this level may be due to dissolution (Larina et al. 2012). Towards the southeast in Chickasaw County, Mississippi, the Owl Creek Formation passes into the Prairie Bluff Chalk, which contains the same assemblage of ammonites. However, the base of the Clayton Formation in this area consists of a 30-cm-thick unit filled with impact spherules and reworked Maastrichtian fossils (Boas et al. 2013a, b).

On the other side of the Mississippi Embayment, ammonites are present in the upper Corsicana Formation along the Brazos River, Falls County, Texas. The erosional surface at the top of this formation has been interpreted as the K/Pg boundary (Hansen et al. 1987; for further discussion of this interpretation see Hart et al. 2012). The ammonites are the same as those in Mississippi with the addition of *Pachydiscus* (*P.*) *j. jacquoti* and *Glyptoxoceras* cf. *G. rugatum*. Two ammonite species (*Eubaculites carinatus* and *Discoscaphites* cf. *D. gulosus*) extend into the uppermost 1 m of the formation (Kennedy et al. 2001). In addition, Keller et al. (2009, p. 54) reported a single specimen of *D. iris* at the base of the *Pseudoguembelina palpebra* CF2 Zone in the Brazos River Mullinax-1 Core.

19.3.3 La Popa Basin, Northeastern Mexico

(Site 8). In northeastern Mexico, Stinnesbeck et al. (2012: table 1) reported *Sphenodiscus pleurisepta* and *Baculites ovatus* from Planktic Foraminifera Zone CF3. The highest occurrence of *S. pleurisepta* is 3 m below an erosional unconformity marking the K/Pg boundary.

19.3.4 Denmark

(Sites 9–11: Stevns Klint, Kjølby Gård, and the "*Dania*" Quarry). The ammonite record in Denmark has been extensively studied because these sections exhibit nearly continuous deposition across the K/Pg boundary (Birkelund 1979, 1993; Schiøler et al. 1997; Machalski 2005a, b; Machalski and Heinberg 2005; Rasmussen et al. 2005; Surlyk et al. 2006; Hart et al. 2011; Damholt and Surlyk 2012; Gravesen and Jakobsen 2013). The environment is interpreted as a shelf sea ranging from the euphotic zone to several hundred meters deep (Surlyk 1997; Surlyk et al. 2006; Schulte et al. 2010). The stratigraphy along the 14.5 km long classic section at Stevns Klint is complex, with the upper, but not uppermost, Maastrichtian Sigerslev Member separated by one or two closely spaced hardgrounds from the uppermost Maastrichtian Højerup Member (Fig. 19.5). These hardgrounds were probably produced by early diagenetic cementation during shallowing events (Hansen 1990; Surlyk 1997; Surlyk et al. 2006). Correlation of these events with those in the upper part of the Nekum and Meerssen members in the Maastricht area (Hart et al. 2011) suggests that the hardgrounds developed in the last 240 kyr of the Maastrichtian (Schiøler et al. 1997). The Højerup Member corresponds to the uppermost Maastrichtian *Stensioeina esnehensis* Foraminifera Zone.

The Højerup Member is internally organized into a series of low asymmetrical bryozoan bioherms alternating with basins, producing a relief of as much as 4 m. The K/Pg transition is continuous in the basins with the Højerup Member conformably overlain by the basalmost Danian Fiskeler Member (Fish Clay), which is overlain, in turn, by the Cerithium Limestone Member (Rødvig Formation; Surlyk et al. 2006). The uppermost Højerup Member is rich in ammonites, especially on

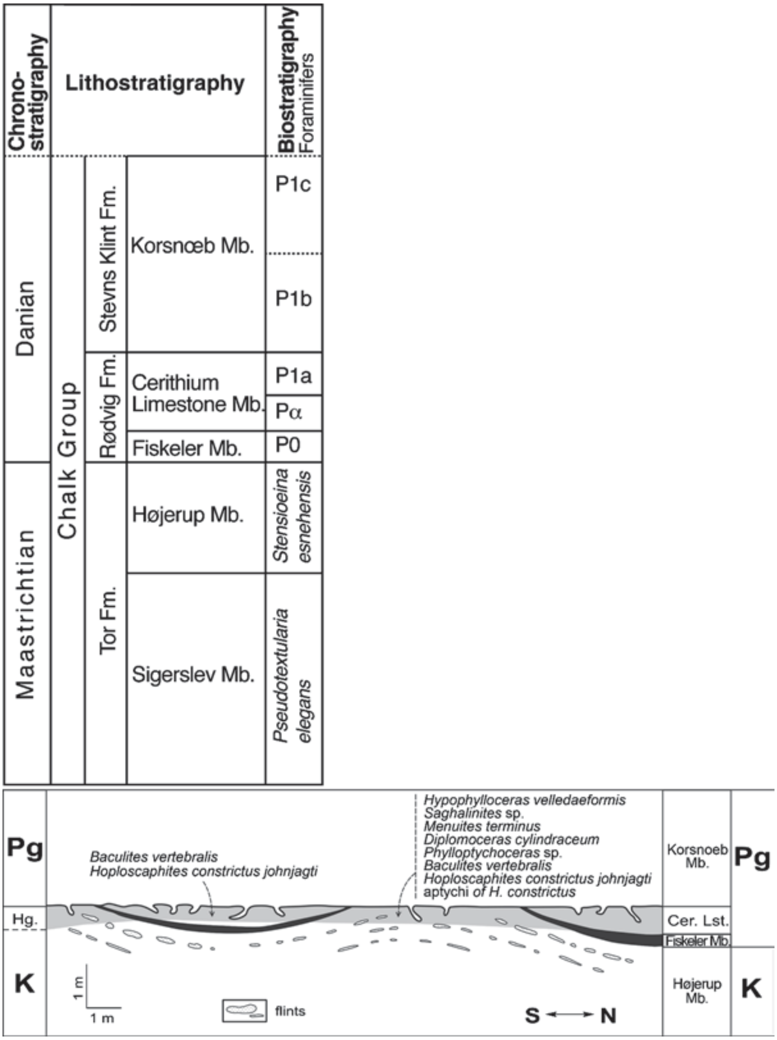


Fig. 19.5 *Top*. Stratigraphic chart of the K/Pg section at Stevns Klint, Denmark (modified from Surlyk et al. 2006). *Bottom*. Diagram of the boundary interval. Hg = Hardground (modified from Machalski and Heinberg 2005)

the crests of the bioherms, which are incorporated into a Danian hardground that truncates both the Højerup Member and Cerithium Limestone (Birkelund 1993; Machalski 2005a). In total, the fauna consists of eight species, seven genera, and six families distributed among the Phylloceratina (*Hypophylloceras* (*Neophylloceras*)), Lytoceratina (*Saghalinites*), Ammonitina (*Menuites*), and Ancyloceratina (*Phylloptychoceras*, *Diplomoceras*, *Baculites*, *Hoploscaphites*) (Tables 19.1, 19.2). Specimens of *B. vertebralis* and *H. constrictus johnjagti* also occasionally occur in the basal Danian Cerithium Limestone Member (Birkelund 1979, 1993; Surlyk and Nielsen 1999; Machalski 2002). These specimens have generally been interpreted

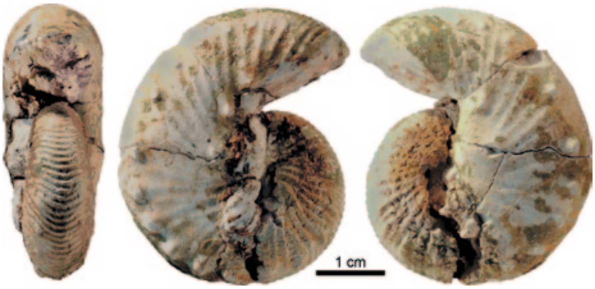


Fig. 19.6 *Hoploscaphites constrictus johnjagti* from the Cerithium Limestone Member at Stevns Klint, Denmark (modified from Machalski and Heinberg 2005)

as reworked material, but Machalski and Heinberg (2005) argued that they may represent early Danian survivors (Fig. 19.6).

At Kjølby Gård, ammonites occur up to 20 cm below the K/Pg boundary (Birkelund 1993). The "*Dania*" Quarry, northern Denmark, has also been thoroughly studied and represents the *stevensis-chitoniformis* brachiopod Zone, which correlates with the *Palynodinium grallator* dinoflagellate Zone (Hansen 1977; Håkanssan and Hansen 1979; Birkelund 1993; Machalski 2005a, b; Gravesen and Jakobsen 2013). The sequence at "*Dania*" is unique among Danish boundary sequences in containing the uppermost Maastrichtian zonal species *Micula prinsii*. This nannofossil is present in one of the marl layers low in the sequence (Håkansson and Hansen 1979), which implies that the "*Dania*" succession occurs within Calcareous Nannofossil Zone CC26b of Perch-Nielsen (1985).

19.3.5 Maastrichtian Type Area

(Site 12: the Netherlands and northeast Belgium). Several outcrops and quarries near Maastricht on both sides of the border between the Netherlands and Belgium that expose the uppermost Maastrichtian are treated together. This area has been extensively studied because of its importance for biostratigraphy (Zijlstra 1994; Smit and Brinkhuis 1996; Schiøler et al. 1997; Jagt 1996, 2002; Jagt et al. 2003, 2006; Jagt and Jagt-Yazykova 2012; Mai 1998). The clay beds just above the Berg en Terblijt Horizon at the base of the IVf-7 interval (Meerssen Member) are assigned to Planktic Foraminifera Zone P0. Our targeted interval of 0.5 myr was bracketed by reference to this horizon and by using the cyclostratigraphic interpretation of Zijlstra (1994) and Schiøler et al. (1997) to define the lower part of our interval. According to them, the Nekum and Meerssen members (upper part of the Maastricht Formation) represent the last 300 kyr of the Maastrichtian. This part of the formation is interpreted as having been deposited on a shallow carbonate platform (Kennedy and Jagt 1998; Jagt 1996, 2002, 2005, 2012; Jagt et al. 2006).

We examined the record of ammonites from the Meerssen and Nekum members. In terms of dinoflagellate zonation, this interval (upper Nekum and Meerssen members) corresponds to the *Palynodinium grallator* dinoflagellate Zone, and the Meerssen Member to the *Thalassiphora pelagica* dinoflagellate Subzone (e.g., Mai 1998). A total of 19 species, 12 genera, and seven families of ammonites are present near or at the K/Pg boundary distributed among the Ammonitina (*Brahmaites*, *Pachydiscus*, *Menuites*, and *Sphenodiscus*) and Ancyloceratina (*Nostoceras*, *Glyptoxoceras*, *Diplomoceras*, *Phylloptychoceras*, *Baculites*, *Eubaculites, Hoploscaphites,* and *Acanthoscaphites*?) (Fig. 19.7; Tables 19.1, 19.2). The most common ammonites are *Baculites* and *Hoploscaphites*.

Several scaphitids and baculitids have also been recorded from Unit IVf-7 of the Meerssen Member above the Berg en Terblijt Horizon in the section exposed at the former Curfs quarry near Geulhem, southern Limburg, southeast Netherlands (Jagt et al. 2003; Machalski et al. 2009; Jagt 2012; Fig. 19.8). As stated above, this horizon is generally interpreted as marking the K/Pg boundary (although there is no evidence of impact debris) and these specimens are assigned to Planktic Foraminifera Zone P0. Because the species of *Baculites* are different from those below this

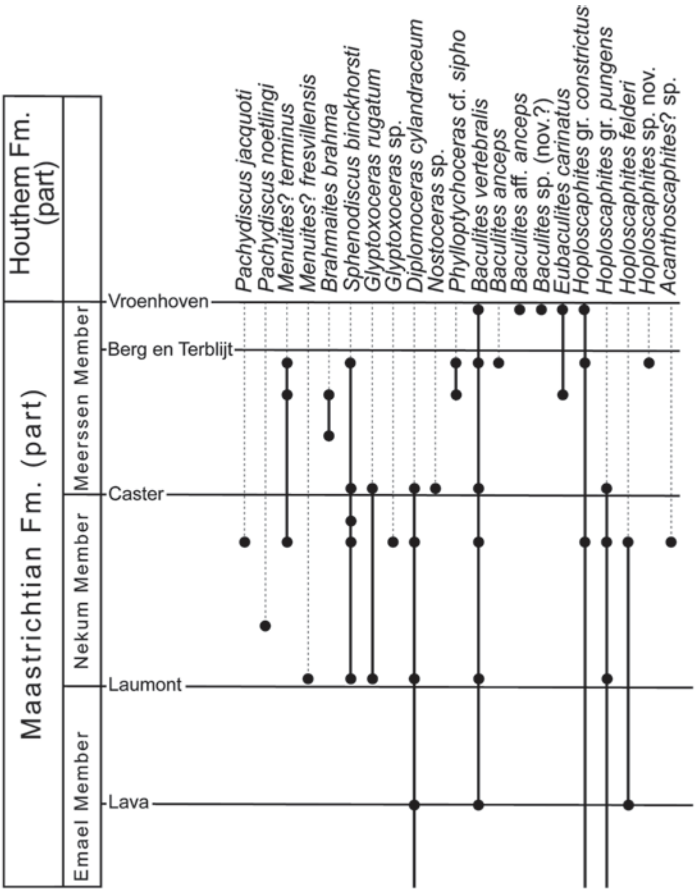


Fig. 19.7 Stratigraphic range chart of the ammonites at the K/Pg section in the Maastrichtian region, the Netherlands and northeast Belgium (modified from Jagt et al. 2006). The Berg en Terblijt Horizon, which forms the base of section IVf-7, is interpreted as the K/Pg boundary. The dots indicate isolated occurrences and the lines indicate "more or less" complete ranges

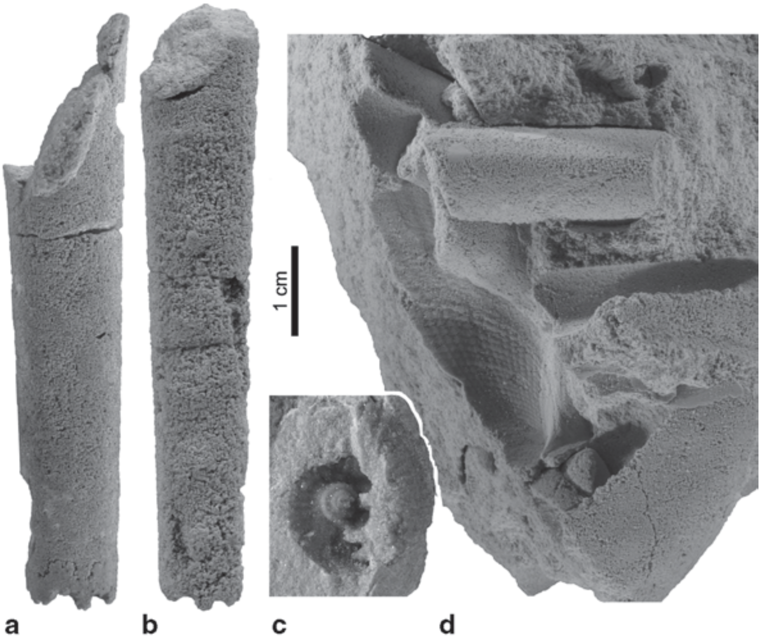


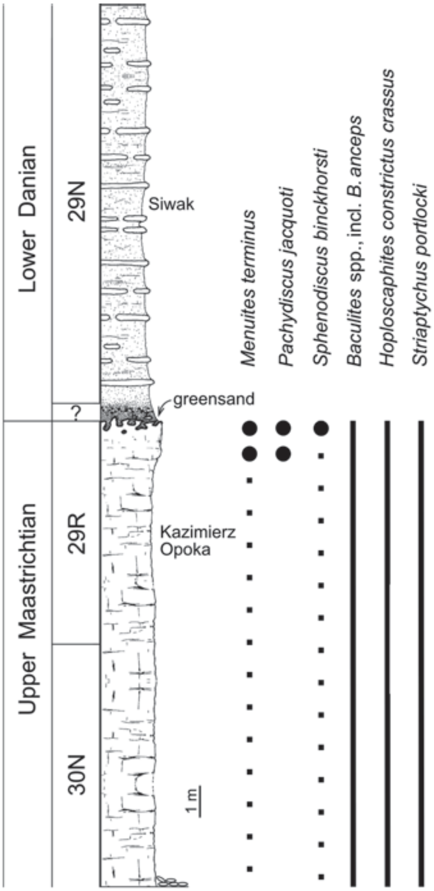
Fig. 19.8 Ammonites from the top of Unit IVf-7 of the Meerssen Member above the Berg en Terblijt Horizon in the section exposed at the former Curfs quarry near Geulhem, southern Limburg, southeast Netherlands (Jagt et al. 2003; Jagt 2012; Machalski et al. 2009). **a**, **b**, **d** *Baculites* aff. *anceps* (Jagt Collection, NHMM). The mature apertures are preserved in **a** and **b**. The empty spaces in **d** are voids left by dissolution of the original aragonite. **c** *Hoploscaphites constrictus*, with incomplete filling of the phragmocone (Jagt Collection, NHMM). All of these features indicate that the ammonites in this unit were buried with their shells intact without significant reworking or transport, which would have otherwise destroyed the delicate apertural features. In addition, the shells must have been buried rapidly enough to prevent complete infilling of the phragmocones

horizon and because many of them are preserved with their apertures intact, they may represent early Danian survivors (Smit and Brinkhuis 1996; Jagt et al. 2003).

19.3.6 Poland

(Sites 13–15: Nasiłów, Mełgiew, and Lechówka). The K/Pg boundary is exposed in Nasiłów in the Kaziemerz Dolny area, Poland (Hansen et al. 1989; Machalski 2005a). According to Abdel-Gawad (1986), the upper part of the section represents deposition in an inner shelf environment. However, the section is incomplete with a hiatus that spans the topmost Maastrichtian and the lowermost Paleocene encompassing as much as 500 kyr, but possibly much less. This inference is based in part on the absence of *H. constrictus johnjagti*, the terminal Maastrichtian chrono-subspecies of the *H. constrictus* lineage, which characterizes the uppermost Maastrichtian of Denmark (Højerup Member) and the Netherlands and northeast

Fig. 19.9 Stratigraphic range chart of the ammonites at the K/Pg section in Nasiłów, Poland (Machalski and Walaszczyk 1987, 1988; Machalski 2005a). Reworked specimens are present in the greensand



Belgium (top Nekum-Meerssen members) (Machalski and Walaszczyk 1987, 1988; Machalski 2005a).

Ammonites occur in the *Belemnella kazimiroviensis* belemnite Zone, Magnetic Chron 29r, and lower part of the *Palynodinium grallator* dinoflagellate Zone. They are preserved in a hard limestone layer at the top of the Kazimierz Opoka (silicious chalk) (Figs. 19.9, 19.10). This unit passes into a thin layer of soft opoka, with both layers penetrated by crustacean burrows filled with sediment derived from the overlying Danian glauconitic sandstone. A total of six species, five genera, and four families are present (Tables 19.1, 19.2). The fauna is dominated by *Baculites* spp., including *Baculites anceps*, followed by *Hoploscaphites constrictus crassus*. The rest of the ammonite fauna consists of *Menuites terminus*, *Pachydiscus* (*P.*) *j. jacquoti*, and *Sphenodiscus binckhorsti.*

A K/Pg boundary interval similar to that of Nasiłów is exposed nearby, on the opposite side of the Wisła River at Bochotnica. The section at Mełgiew, Poland, is more complete than that at Nasiłów with a hiatus of only a few thousand years at the K/Pg boundary (Machalski 2005a), as indicated by the presence of the chrono-subspecies *Hoploscaphites constrictus johnjagti*. The only additional ammonites include *Baculites* spp., but this section has not been as thoroughly studied

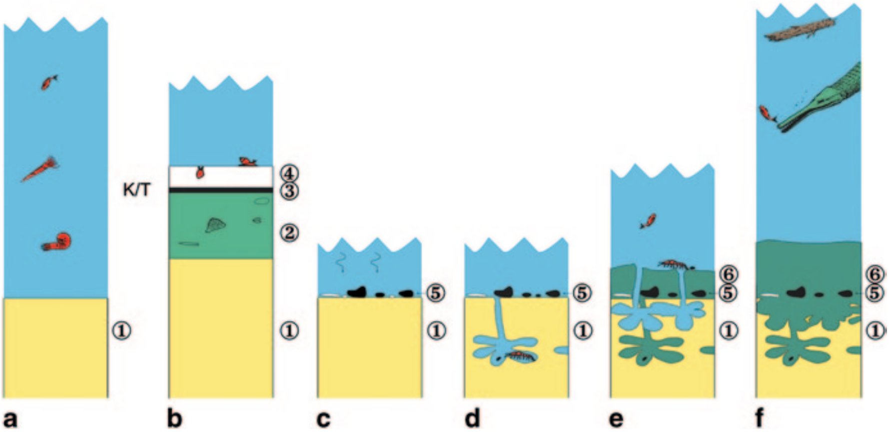


Fig. 19.10 Depositional and erosional history at the K/Pg boundary in the Kazimierz Dolny region, Poland (from Machalski 1998). Stage **a**: Sedimentation of the siliceous chalk (Kazimierz Opoka) of late Maastrichtian age (*1*). Stage **b**: Sedimentation of a slightly glauconitic carbonate mud unit (*2*) of late Maastrichtian age, followed by a clay layer (*3*) and a carbonate unit (*4*), both of Danian age. Stage **c**: Erosion or dissolution (?) episode in early Danian leading to the destruction of the top of unit 1 and total destruction of units 2–4, and to the formation of a residual lag (*5*) composed of reworked nodules, early diagenetic molds, and other fossils of Maastrichtian and Danian age. Stage **d**: Omission conditions on the sea floor and the development of burrowing leading to the formation of the first generation of visible burrows during the Danian. Stage **e**: Start of sandy-glauconitic sedimentation (*6*) of Danian age, filling of earlier burrows and formation of the next generation, origin of pseudobreccia at the top of the Kazimierz Opoka, and additional reworking of the residual lag. Stage **f**: Continuation of Danian sedimentation

as the Nasiłów section. At Lechówka, Poland, ammonites occur just below the iridium spike in the top of the *Guembelitria cretacea* planktic foraminifera Zone *sensu* Peryt (1980) (Racki et al. 2011).

19.3.7 Kyzylsay, Kazakhstan

(Site 16). The uppermost Maastrichtian of the Mangyshlak Peninsula contains rare and poorly preserved specimens of *Baculites* sp. and *Hoploscaphites constrictus* (see Naidin 1987; Herman et al. 1988; Jeffrey 1997; Tables 19.1, 19.2). They occur in white chalks that were deposited at depths of less than 100 m. The specimens of *H. constrictus* occur in the *Belemnella kazimiroviensis* belemnite Zone immediately below the boundary clay, which is marked by an anomalous concentration of iridium, with no signs of any sedimentary breaks.

19.3.8 Sumbar River, Turkmenistan

(Site 17). An apparently complete boundary section occurs in the Sumbar River area, western Kopet Dagh, southwest Turkmenistan (Machalski et al. 2012). The boundary is marked by a clay layer with an anomalous iridium concentration. The area is interpreted as a relatively deep-water environment on the outer shelf, based on the high percentage of planktic species in the foraminiferal assemblages. Two ammonite species, *Hoploscaphites constrictus johnjagti* and *Baculites* cf. *B. vertebralis*, have been recovered from the *Pseudotextularia elegans* Planktic Foraminiferal Zone as high up as 5 cm below the boundary clay (Moskvin 1959; Alekseev et al. 1988; Machalski et al. 2012; Tables 19.1, 19.2). These records represent the southeasternmost extent of these two (sub)species, which are otherwise known from northwest and central Europe. In addition, a single specimen of what appears to be *H. constrictus* is present in the Danian part of the section in an interval 22–24 cm above the base of the boundary clay. However, it is currently unclear if this specimen is reworked from the Maastrichtian or dates from the Danian.

19.3.9 Bay of Biscay

(Sites 18–20: Zumaya, Hendaye, and Bidart). This region of southwestern France and northeastern Spain encompasses many K/Pg sections that are apparently continuous and complete (Wiedmann 1987, 1988a, b; Kennedy 1993; Ward and Kennedy 1993; Ten Kate and Sprenger 1993; Rocchia et al. 2002). The strata consist of massive marls with rare turbidites deposited in an outer-shelf setting with water depths of 100–500 m (Mathey 1982; Schulte et al. 2010). In Zumaya, using the cyclostratigraphic studies of Batenburg et al. (2012) and Dinarès-Turell et al. (2013), our targeted interval (last 0.5 myr of the Maastrichtian) appears to correspond to the top few meters of Member IV and the entire Member V of Ward and Kennedy (1993). This is a conservative estimate as due to small differences in measured thicknesses between Ward and Kennedy (1993), Dinarès-Turell et al. (2013), and Batenburg et al. (2012), the exact position of the base of our 0.5 myr interval cannot be situated more precisely than 1 m. The base of Member V is approximately 15 m below the K/Pg boundary in Ward and Kennedy (1993), 12 m below the K/Pg boundary in Batenburg et al. (2012), and 10.2 m below the K/Pg boundary in Dinarès-Turell et al. (2013). The base of our 0.5 myr interval thus equates to approximately 20 and 18 m below the K/Pg boundary on the Batenburg et al. (2012) and the Dinarès-Turell et al. (2013) logs, respectively. Thus, being conservative, only ammonite records from Member V and the top few meters of Member IV were included in our tally. Unit V of Ward and Kennedy (1993) falls within the *Micula prinsii* Zone (= Calcareous Nannofossil Zone CC26b of Perch-Nielsen 1985).

Ammonites are rare throughout most of the section in the Bay of Biscay (Fig. 19.11). They are present in the uppermost few meters of Member IV and the entire Member V of Ward and Kennedy (1993). In total, they consist of 13 species, representing 11 genera belonging to the Phylloceratina (*Phylloceras*, *Phyllopachyceras*), Lytoceratina (*Anagaudryceras*, *Zelandites*, *Pseudophyllites*), Ammonitina (*Desmophyllites*, *Brahmaites*, *Pachydiscus*, *Pseudokossmaticeras*, *Menuites*), and Ancyloceratina (*Diplomoceras*). The top 1.5 m in the combined sections at Zumaya, Hendaye, and Bidart contain approximately 40 specimens representing ten species, although only one of these specimens is present in the highest 10–15 cm of the section (Ward

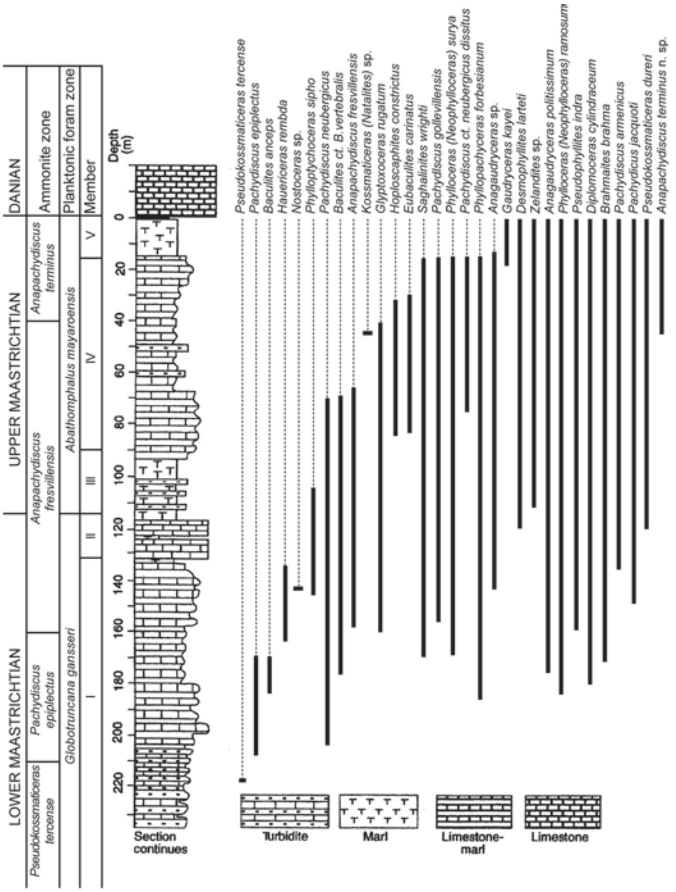


Fig. 19.11 Composite stratigraphic range chart of the ammonites at the K/Pg section in the Bay of Biscay plotted on the measured section at Zumaya, Spain (modified from Marshall and Ward 1996)

and Kennedy 1993). In addition, Rocchia et al. (2002) reported the occurrence of a poorly preserved specimen from 5 cm below the boundary clay at Bidart, which contains Ni-rich spinel crystals and an anomalously high concentration of iridium.

Marshall and Ward (1996) also used statistical methods (confidence intervals) to examine the ranges of ammonite species in the top 1.5 m of the composite section in the Bay of Biscay to determine the likelihood that the actual ranges extended above the observed ranges. Using a 50 % confidence range interval, they concluded that at least two of these species could have persisted to the K/Pg boundary, even though they are not actually preserved at this level.

19.3.10 Bjala (= Byala), Bulgaria

(Site 21). In the area of Bjala (= Byala), eastern Bulgaria, along the shores of the Black Sea, several sections of the Bjala Formation contain a complete K/Pg boundary succession (Preisinger et al. 1993; Ivanov and Stoykova 1994; Ivanov 1995; Stoykova and Ivanov 2004, 2005). The formation consists of marls in the lower part of the section and marls alternating with marly limestones in the upper part, which were deposited on the outer shelf and inner slope. The section is capped by a 1–3-cm thick clay bed marked by an anomalous concentration of iridium. Five species occur in Calcareous Nannofossil Zone CC26b (Preisinger et al. 1993; Ivanov and Stoykova 1994; Ivanov 1995; Stoykova and Ivanov 2004, 2005): *Pseudophyllites indra*, *Anagaudryceras politissimum*, *Vertebrites kayei*, *Menuites terminus,* and *Pachydiscus* sp. indet. (Tables 19.1, 19.2). Two of these species (*P. indra* and *A. politissimum*) occur 40 cm below the iridium enriched layer of clay.

19.3.11 Tunisia and Egypt

Tunisia (Sites 22–24: El Kef, Kalaat Senan, and Garn Halfaya); Egypt (Site 25: Dababiya Quarry Corehole). Several of the most complete K/Pg boundary sections are located in the Tunisian Trough Basin (Goolaerts et al. 2004; Goolaerts 2010a). Indeed, the reddish layer at the base of the Boundary Clay near El Kef (the KS locality) is the Global Stratotype Section and Point (GSSP) for the K/Pg boundary (Molina et al. 2006). Ammonites occur as high as 1–2 m below the boundary at El Kef (GSSP section), Kalaat Senan (Aïn Settara, Tabet Zaara, and Oued Raïne sections), and Garn Halfaya (Garn section), although almost all of the specimens occur as surface float and may have moved slightly downslope. The highest ammonite occurs 1 m below the boundary at Garn Halfaya, which is approximately equivalent to 50 kyr prior to the end of the Cretaceous based on the cyclostratigraphic data of Hennebert and Dupuis (2003). All of the reported ammonites occur in the highest ammonite zone, the *Indoscaphites pavana* Assemblage Zone, which represents approximately the last 420 kyr of the Maastrichtian based on the cyclostratigraphy of Hennebert and Dupuis (2003) and Hennebert (2012). In the Dababiya Quarry Corehole, specimens occur within Calcareous Nannofossil Zone CC26b (Goolaerts and Dupuis 2012; Berggren and Ouda 2013; Berggren et al. 2012).

The ammonite assemblage in the ultimate 0.5 myr of the Maastrichtian in the Tunisian Trough Basin consists of 22 species, 17 genera, and 10 families (Fig. 19.12; Tables 19.1, 19.2). This assemblage is the taxonomically most diverse terminal Maastrichtian fauna discovered to date. However, because the specimens consist of small septate inner whorls less than 20 mm in diameter, they are sometimes difficult to identify to species or even genus level. They are distributed among the Phylloceratina (*Neophylloceras* and *Phyllopachyceras*), Lytoceratina (*Anagaudryceras*, *Zelandites*, *Tetragonites*, *Pseudophyllites*, and *Saghalinites*), Ammonitina (*Hauericeras*, *Brahmaites*, *Menuites*, *Pachydiscus*, *Neodesmoceras*, and Desmoceratoidea gen. indet.), and Ancyloceratina (*Diplomoceras*, *Phylloptychoceras*, *Fresvillia*, *Baculites*, and *Indoscaphites*) (Tables 19.1, 19.2).

The ammonite fauna is dominated by scaphitids (*Indoscaphites*), baculitids (*Baculites*), and pachydiscids. The environment is interpreted as outer neritic to bathyal (Schulte et al. 2010), but the variation in the abundance of *Indoscaphites* suggests a depth gradient. The abundance increases from a minimum of 48 % at El

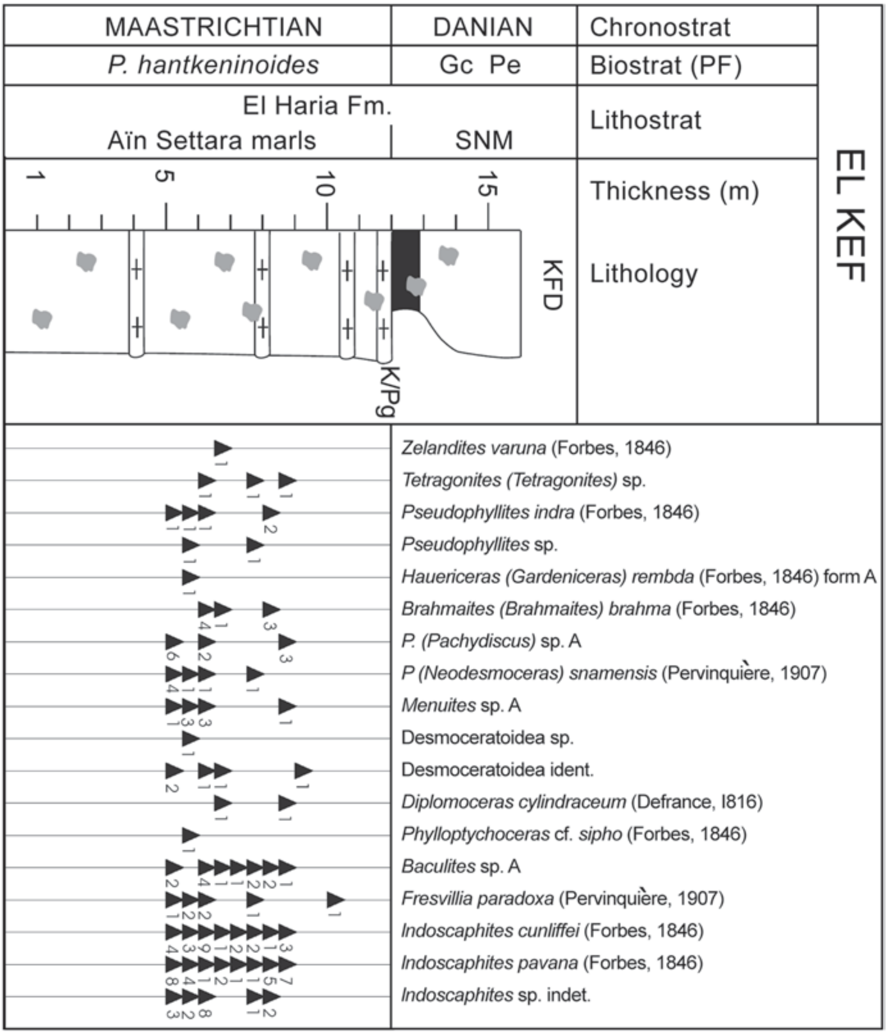


Fig. 19.12 Stratigraphic distribution of ammonite species by number of specimens in the upper part of the El Haria Formation at the El Kef GSSP section for the base of the Paleogene Period (modified from Goolaerts 2010a)

Kef to 60 % at Garn Halfaya to a maximum of 76 % at Kalaat Senan. Correlatively, the abundance of Lytoceratina decreases along this same transect. Phylloceratina are extremely rare, and have only been found at Kalaat Senan, which is probably due to the greater number of specimens collected at this site (643) compared to that at El Kef (145) and Garn Halfaya (108). The dominant elements of the fauna, the scaphitids and baculitids, are also reported from the uppermost Maastrichtian of Egypt (Dababiya Core; Berggren et al. 2012; Goolaerts and Dupuis 2012). The absence of other species in this region is probably due to the paucity of specimens collected from this site (10).

19.3.12 Naiba River Valley, Sakhalin, Far East Russia

(Site 26). The latest Maastrichtian ammonites at this site are not very well constrained in terms of biostratigraphy. Numerous well-preserved specimens of *Zelandites*, and a few specimens of *Gaudryceras* and *Hypophylloceras* (*Neophylloceras*) have been recovered from a concretionary horizon approximately 2 m below a 20-cm-thick green clay marking the K/Pg boundary (Yazykova in Zonova et al. 1993; Yazikova 1994; Yazykova 1991, 2004; Jagt-Yazykova 2011, 2012; *contra* Kodama et al. 2000; Kodama 2003; Hasegawa et al. 2003). The next lower concretionary horizon is 4–5 m below the K/Pg boundary and contains seven ammonite (sub)genera: *Hypophylloceras* (*Neophylloceras*), *Zelandites*, *Gaudryceras*, *Anagaudryceras*, *P*. (*Pachydiscus*), *P*. (*Neodesmoceras*), and *Diplomoceras*.

19.3.13 South America

(Site 27: Poty Quarry, Brazil; Site 28: Lomas Colorados, Bajada de Jagüel, Neuquén Basin, Argentina). In the Poty quarry in northeastern Brazil, ammonites are rare but *Pachydiscus* (*P*.) *neubergicus* and *Diplomoceras* sp. have been collected in the *Plummerita hantkeninoides* CF1 Zone at 100 and 80 cm, respectively, below the erosional unconformity containing the K/Pg boundary (Stinnesbeck and Keller 1996; Stinnesbeck et al. 2012; Tables 19.1, 19.2). In the Neuquén Basin, near Bajada de Jagüel (Argentina), a single specimen of *Eubaculites* sp. (ex gr. *E. simplex*) is present in the *Pseudoguembelina palpebra* CF2 Zone (Stinnesbeck et al. 2012).

19.3.14 Seymour Island, Antarctica

(Site 29). The section at Seymour Island has been extensively studied (Macellari 1986, 1988; Elliot et al. 1994; Zinsmeister and Feldmann 1996; Zinsmeister 1998; Zinsmeister et al. 1989; Tobin et al. 2012). The sequence consists of mid-shelf clastic to inner-shelf concretionary siltstones and silty sandstones of the López de Bertodano Formation. The K/Pg boundary is defined as the first occurrence of Paleogene dinocyst fossils, which coincide with the presence of an enhanced concentration of iridium. The *Pachydiscus* (*P*.) *ultimus* Zone is the highest ammonite zone and contains the lower part of Magnetic Chron 29r. It contains nine species, eight genera, and six families distributed among the Lytoceratina (*Zelandites*, *Anagaudryceras*, *Pseudophyllites*), Ammonitina (*Maorites*, Grossouvrites, *Kitchinites*, and *Pachydiscus*), and Ancyloceratina (*Diplomoceras*) (Fig. 19.13; Tables 19.1, 19.2). According to Zinsmeister (1998), five ammonite species are present at 50 cm below the K/Pg boundary: *Zelandites varuna*, *Pseudophyllites loryi*, *Maorites densicostatus*, *Kitchinites* (*K*.) *laurae*, and *Diplomoceras maximum* (for a discussion of the taxonomy of *Diplomoceras lambi, D*. *maximum*, and *D*. *cylindraceum*, see Machalski 2012).

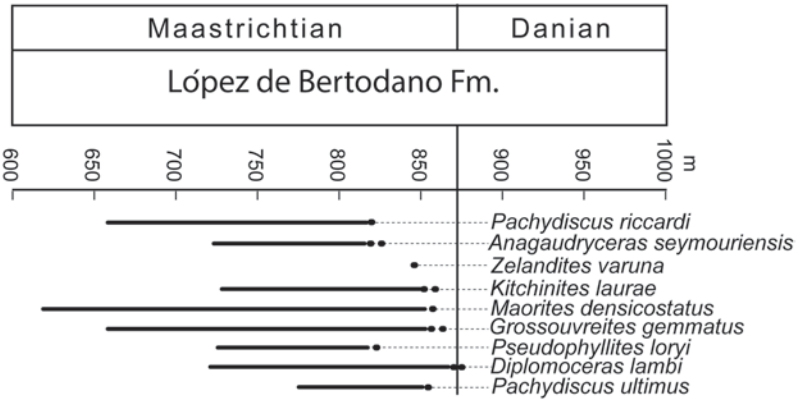


Fig. 19.13 Stratigraphic range chart of the ammonites at the K/Pg section in Antarctica (modified from Tobin et al. 2012). The solid bars indicate actual ranges (Zinsmeister et al. 1989). The dots indicate 20 % range extensions based on a statistical analysis of confidence intervals. (Wang and Marshall 2004)

Wang and Marshall (2004) used statistical methods to examine the stratigraphic ranges of the highest ammonite species on Seymour Island. Using 50 % range extensions, they estimated that the fossil record is consistent with the possibility that all of the species actually extended to the K/Pg boundary. More recently, Tobin et al. (2012) analyzed additional occurrence data using the same techniques as those of Wang and Marshall (2004) and reached a similar conclusion.

19.4 Discussion

19.4.1 Ammonite Diversity at the K/Pg Boundary

Based on the above compilation, ammonites are abundant and diverse in the last 0.5 million years of the Maastrichtian. They are distributed across all four Cretaceous suborders, the Phylloceratina, Lytoceratina, Ammonitina, and Ancyloceratina, comprising six superfamilies (Phylloceratoidea, Tetragonitoidea, Desmoceratoidea, Acanthoceratoidea, Turrilitoidea, and Scaphitoidea) and 31 (sub)genera (*Hypophylloceras* (*Neophylloceras*), *Phyllopachyceras*, *Gaudryceras*, *Anagaudryceras*, *Zelandites*, *Vertebrites*, *Tetragonites, Saghalinites*, *Pseudophyllites*, *Desmophyllites*, *Hauericeras*, *Kitchinites*, *Pseudokossmaticeras*, *Brahmaites* (*Brahmaites*), Grossouvreites, *Maorites*, *P.* (*Pachydiscus*), *P.*(*Neodesmoceras*), *Menuite*s, *Sphenodiscus*, *Nostoceras*, *Glyptoxoceras*, *Diplomoceras*, *Phylloptychoceras*, *Baculites*, *Eubaculites*, *Fresvillia*, *Indoscaphites*, *Hoploscaphites*, *Acanthoscaphites*, and *Discoscaphites*) (Table 19.2). They comprise 57 species (Figs. 19.14, 19.15, 19.16, 19.17; Table 19.1). If the specimens in open nomenclature are also included in the count, the tally increases to 93 species.

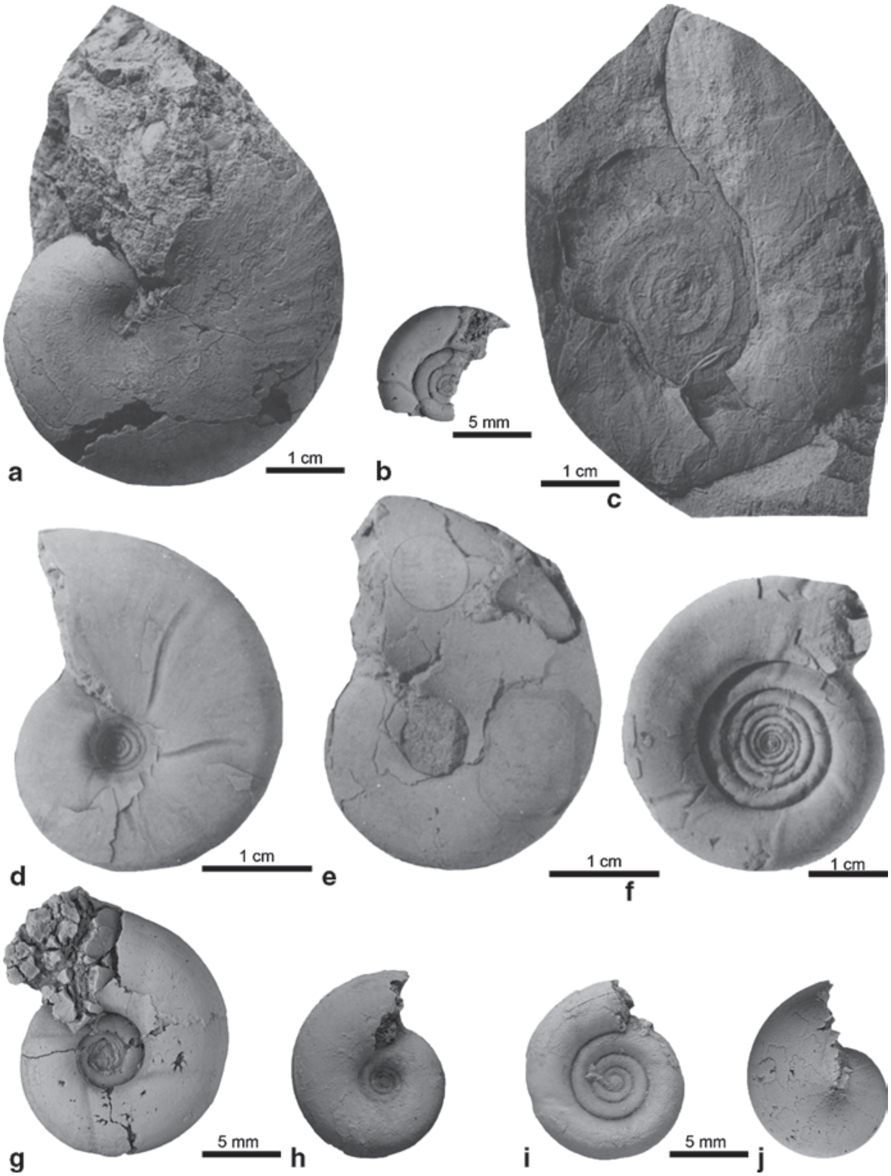


Fig. 19.14 Illustration of some of the youngest ammonites belonging to the Phylloceratina and Lytoceratina at the close of the Maastrichtian. **a** *Phyllopachyceras forbesianum,* Bay of Biscay (Ward and Kennedy 1993, Fig. 18.6). **b** *Saghalinites cala,* Tunisia (Goolaerts 2010b, pl. 1, Fig. 24). **c** *Anagaudryceras politissimum,* Bay of Biscay (Ward and Kennedy 1993, Fig. 17.12). **d** *Zelandites varuna,* Antarctica (Macellari 1986, Fig. 11.11). **e** *Pseudophyllites loryi,* Antarctica (Macellari 1986, Fig. 11.1). **f** *Anagaudryceras seymouriense,* Antarctica (Macellari 1986, Fig. 9.3). **g** *Tetragonites sp.,* Tunisia (Goolaerts 2010b, pl. 2, Fig. 4). **h** *Pseudophyllites indra,* Tunisia (Goolaerts 2010b, pl. 2, Fig. 18). **i** *Anagaudryceras* cf. *A. politissimum,* Tunisia (Goolaerts 2010b, pl. 1, Fig. 20). **j** *Phyllopachyceras forbesianum,* Tunisia. (Goolaerts 2010b, pl. 1, Fig. 9)

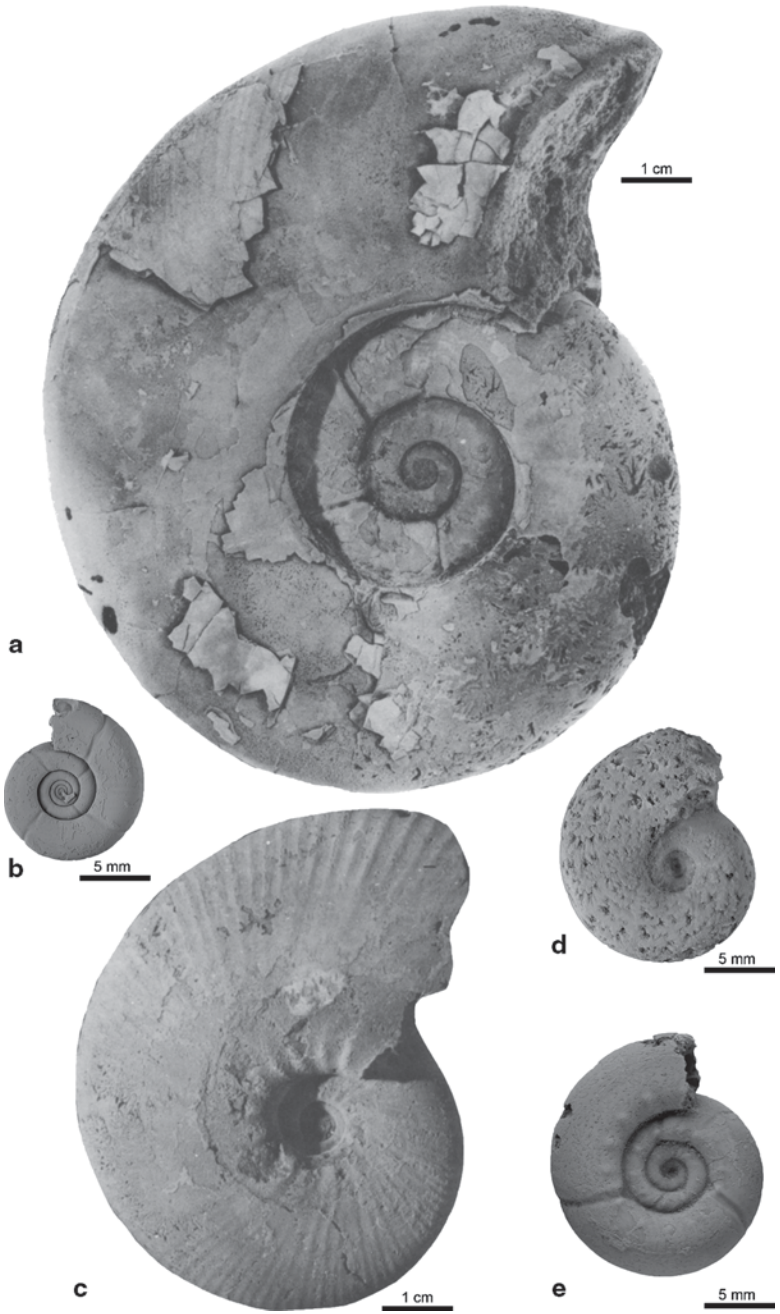


Fig. 19.15 Illustration of some of the youngest ammonites belonging to the Ammonitina at the close of the Maastrichtian. **a** *Kitchinites laurae,* Antarctica (Macellari 1986, Fig. 20.3). **b** *Hauericeras rembda,* Tunisia (Goolaerts 2010b, pl. 3, Fig. 19). **c** *Pachydiscus (P.) riccardi,* Antarctica (Macellari 1986, Fig. 37.4). **d** *Pachydiscus (Neodesmoceras) snamensis,* Tunisia (Goolaerts 2010b, pl. 7, Fig. 16). **e** *Brahmaites brahma,* Tunisia. (Goolaerts 2010b, pl. 4, Fig. 14)

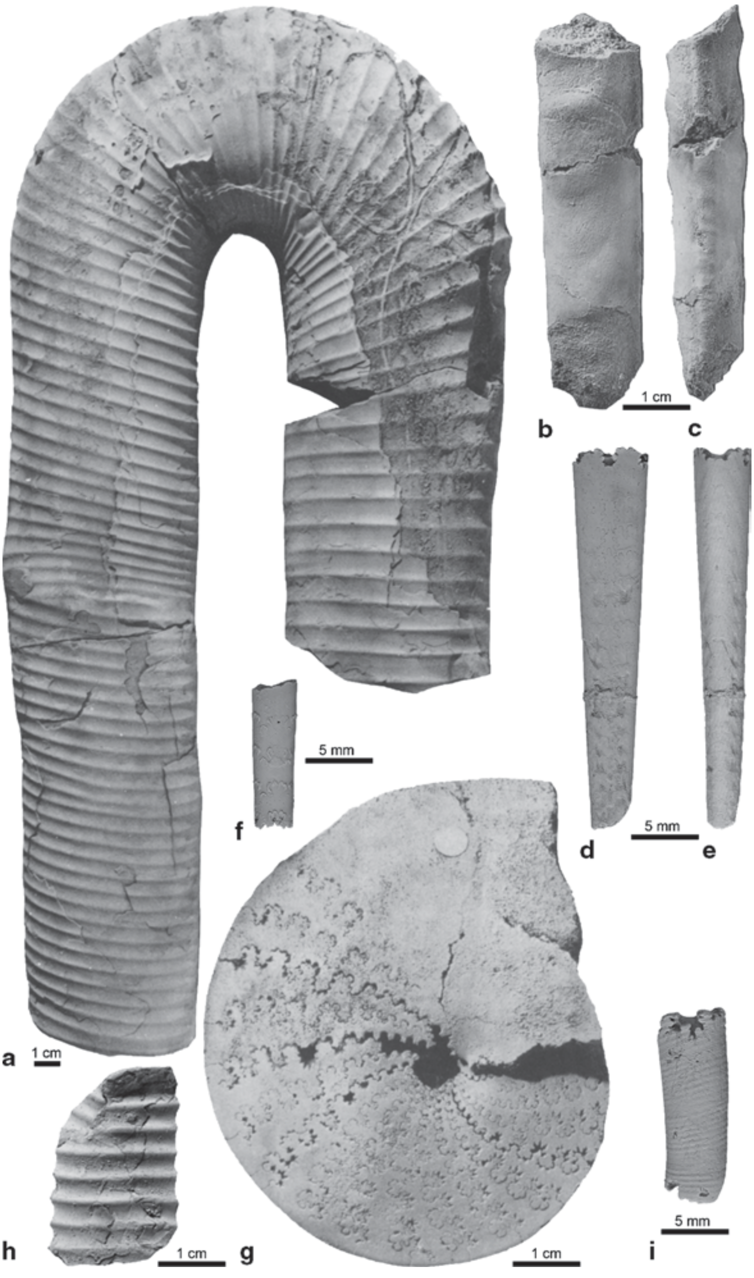


Fig. 19.16 Illustration of some of the youngest ammonites belonging to the Ammonitina and Ancyloceratina at the close of the Maastrichtian. **a** *Diplomoceras lambi,* Antarctica (Macellari 1986, Fig. 14.1). **b**, **c** *Eubaculites carinatus,* lateral and dorsal views, New Jersey (Landman et al. 2007, Figs. 32O, Q). **d**, **e** *Baculites* sp. A, lateral and dorsal views, Tunisia (Goolaerts 2010b, pl. 9, Figs. 2, 3). **f** *Fresvillia paradoxa,* Tunisia (Goolaerts 2010b, pl. 8, Fig. 22). **g** *Sphenodiscus binckhorsti,* the Netherlands (Kennedy 1986, Fig. 9C). **h** *Glyptoxoceras* cf. *G. rugatum,* Texas (Kennedy et al. 2001, Fig. 4d). **i** *Diplomoceras cylindraceum,* Tunisia (Goolaerts 2010b, pl. 8, Fig. 11)

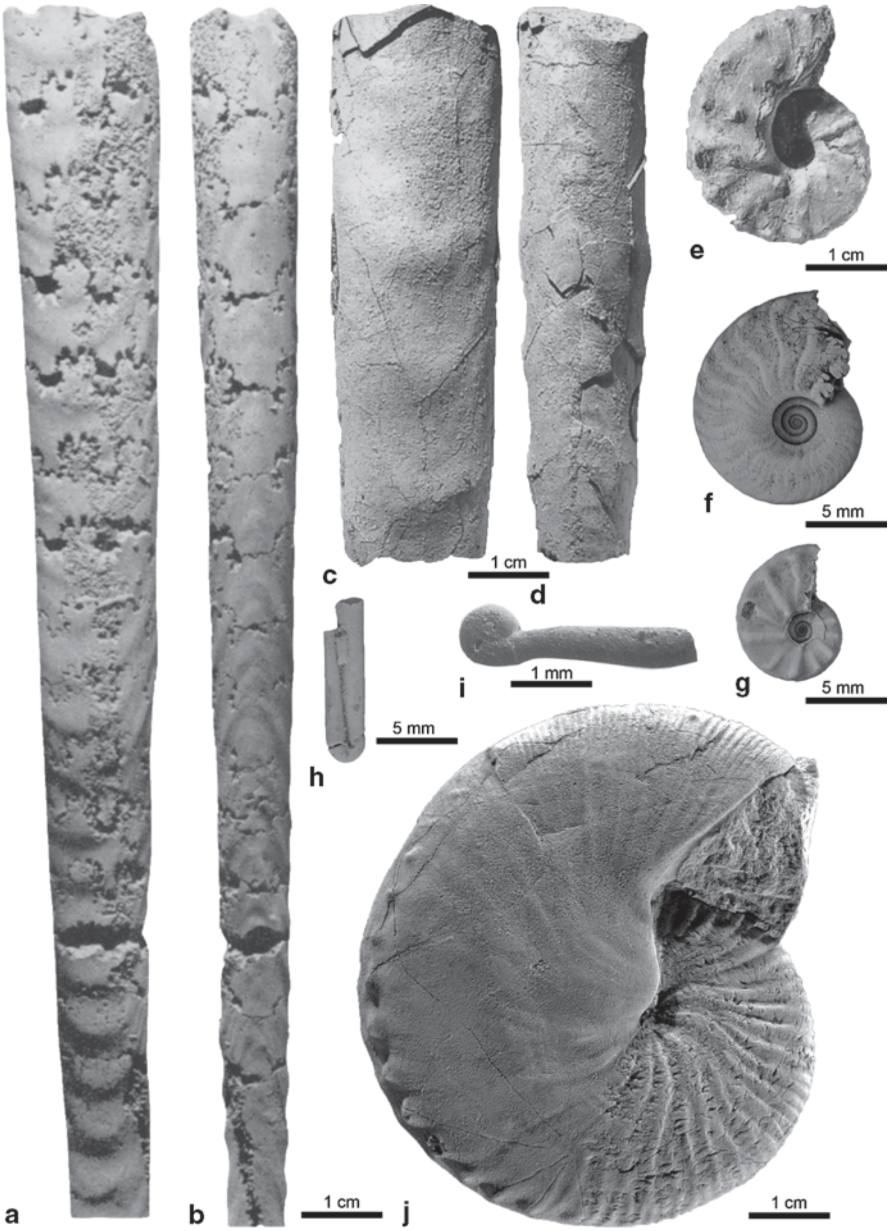


Fig. 19.17 Illustration of some of the youngest ammonites belonging to the Ancyloceratina at the close of the Maastrichtian. **a**, **b** *Baculites anceps,* lateral and dorsal views, the Netherlands (Kennedy 1986, Figs. 10N, O). **c**, **d** *Baculites* cf. *B. undatus,* lateral and dorsal views, Mississippi (Kennedy and Cobban 2000, pl. 2, Figs. 29, 30). **e** *Discoscaphites iris,* microconch, Mississippi (Kennedy and Cobban 2000, pl. 3, Fig. 14). **f** *Indoscaphites pavana*, Tunisia (Goolaerts 2010b, pl. 15, Fig. 10). **g** *Indoscaphites cunliffei,* Tunisia (Goolaerts 2010b, pl. 14, Fig. 19). **h** *Phylloptychoceras* cf. *P. sipho,* Tunisia (Goolaerts 2010b, pl. 8, Fig. 15). **i** *Baculites vertebralis,* early ontogenetic stage, Denmark (Birkelund 1993, Fig. 6A). **j** *Hoploscaphites constrictus crassus,* Poland (Machalski 2005a, Fig. 8D)

The stratigraphic distribution of these species demonstrates that ammonites are present in the uppermost part of the Maastrichtian just below or at the K/Pg boundary. For example, in northeastern Mississippi, eight species extend to approximately 1 m below an unconformity, which presumably encompasses the K/Pg boundary. The absence of ammonites above this level may be due to dissolution (Larina et al. 2012). In Denmark, eight species occur in the upper part of the Maastrichtian Højerup Member (Birkelund 1979, 1993; Surlyk and Nielsen 1999), and two of *them* extend into the overlying Danian Cerithium Limestone Member (Machalski and Heinberg 2005). In Turkmenistan, two species have been recovered from as high up as 5 cm below the boundary clay and a single specimen is present in the Danian part of the section (Machalski et al. 2012). In Bulgaria, Ivanov and Stoykova (1994) and Ivanov (1995) recorded five specimens comprising at least two species at 40 cm below the boundary clay, which is marked by an anomalous concentration of iridium. In northeastern Brazil, two species have been collected in the uppermost 1 m of the section below an erosional unconformity encompassing the K/Pg boundary (Stinnesbeck et al. 2012). In Antarctica, five species are present in the López de Bertodano Formation at 50 cm below the K/Pg boundary, as indicated by an enriched concentration of iridium (Zinsmeister 1998). In addition, based on a statistical analysis of the range data of these five species, they may even have persisted into the early Danian (Wang and Marshall 2004). In Sakhalin, Jagt-Yazykova (Yazikova 1994; Jagt-Yazykova 2011, 2012) reported three species from a concretionary horizon approximately 1.5 m below a 20-cm-thick green clay marking the K/Pg boundary.

How does stratigraphic distance below the K/Pg boundary translate into years before the asteroid impact? In stratigraphically complete K/Pg sections, the time can be estimated by taking into account the thickness between the impact layer (time zero) and the base of the highest biostratigraphic zone (estimated, for example, at 300 kyr before impact), assuming a constant rate of sedimentation. A better approach is to use cyclostratigraphy, which permits the construction of a high-resolution time scale that takes into account variation in the rate of sedimentation and the degree of completeness of the section. For example, in the Tunisian Trough Basin, the highest ammonites occur 1 m below the boundary (Goolaerts 2010a). Based on a cyclostratigraphic study of the alternation of limestones and marls at this site (Hennebert and Dupuis 2003), these ammonites were probably deposited at approximately 50 kyr prior to the K/Pg boundary. In the Bay of Biscay, ten species are present in the top 1.5 m of the section, and one species is present in the top 10–15 cm of the section (Ward and Kennedy 1993). Rocchia et al. (2002) also noted the occurrence of a poorly preserved specimen filled with iridium debris at 5 cm below the boundary clay. Based on the temporal interpretation of the alternation of limestone and marl beds in this area, the two highest specimens were buried at less than 500–800 years prior to the boundary (Rocchia et al. 2002). Near Maastricht, in the Netherlands and northeast Belgium, 19 species are present near or at the K/Pg boundary in the upper part of the Nekum Member and overlying Meerssen Member. According to interpretations of the short-term cyclicity (centimeter-meter scale) of the beds in this area, the highest Maastrichtian ammonites were deposited at less than 20 kyr before the K/Pg boundary (Zijlstra 1994; Schiøler et al. 1997).

The stratigraphic distribution of ammonites at or near the K/Pg boundary has been examined using statistical methods (confidence intervals) to estimate the degree to which their observed ranges underestimate their actual ranges. In Antarctica, the highest ammonite zone contains nine species, five of which extend to 50 cm below the K/Pg boundary. Using 50 % range extensions, Wang and Marshall (2004) estimated that five of these species actually persisted to the K/Pg boundary. Using a more conservative approach (20 % range extensions), they estimated that only one of these species persisted to the boundary. In the Bay of Biscay, ten species are present in the top 1.5 m of the section. Using a statistical method employing 50 % confidence intervals, Marshall and Ward (1996) argued that at least two of these species persisted to the boundary. Indeed, in both areas, recent, intense collecting has yielded additional specimens in the uppermost Maastrichtian, consistent with the previously noted statistical predictions (Rocchia et al. 2002; Olivero 2012; Tobin et al. 2012).

The paucity of specimens in the uppermost Maastrichtian in some sections, and their absence altogether in the uppermost Maastrichtian of other sections, is probably due to taphonomic bias, collection failure, or local environmental changes rather than to their actual disappearance. For example, in the Tunisian Trough Basin, the species that occur in the highest levels are the most common species, suggesting that the likelihood of fossilization correlates with species abundance. The best explanation for the observed decrease in species richness in the uppermost Maastrichtian in this area is either collection failure or local environmental change rather than extinction (Goolaerts 2010a). In addition, as noted for the Bay of Biscay, Antarctica, and the classic area of Maastricht, ongoing research has yielded additional specimens in the uppermost part of the section, emphasizing the importance of renewed collecting efforts even in well-studied areas (Machalski et al. 2009; Jagt 2012). Thus, it is likely that the commonly cited decline in ammonite diversity at the end of the Maastrichtian (Stinnesbeck et al. 2012) is related more to local environmental changes or collection failure rather than to global extinction.

It is possible that ammonites not only persisted to the K/Pg boundary, but survived for days to tens of thousands of years later, according to various estimates. Most of this evidence comes from shallow-water settings. In New Jersey, nine ammonite species are present in a 20-cm-thick unit (the *Pinna* Layer) above a horizon with a weak iridium anomaly (Landman et al. 2012b; Figs. 19.2, 19.3). The mode of occurrence of the fossils in this layer indicates an autochthonous accumulation with little or no time-averaging. Fewer ammonites are present above this layer in the so-called Burrowed Unit and consist of broken specimens of *Eubaculites carinatus* associated with isolated jaws (aptychi) of this species. Because such jaws are absent in the underlying *Pinna* Layer, it suggests that these fossils were not reworked from below but were fossilized during the deposition of the Burrowed Unit. If the horizon with iridium marks the K/Pg boundary, it implies that ammonites persisted and perhaps even initially thrived in the early Danian (as shown by the ammonites in the *Pinna* Layer), followed by a brief appearance of a more impoverished fauna (as shown by the ammonites in the Burrowed Unit). Even if the iridium anomaly was displaced downward from the top of the Pinna Layer, as previously noted, it still implies that the ammonites in the Burrowed Unit would have survived. In the

Maastrichtian type region, Jagt et al. (2003) reported several dozen specimens of *Baculites* and *Hoploscaphites* in Unit IVf-7 of the Meerssen Member above the Berg en Terblijt Horizon, which is generally interpreted as marking the K/Pg boundary, rather than the overlying Vroenhoven Horizon. The fact that many of the baculitids are preserved with their apertures intact suggests that they may have survived into the early Danian (Planktic Foraminiferal Zone P0) (Fig. 19.8). In Denmark, Machalski and Heinberg (2005) reported *B. vertebralis* and *H. constrictus johnjagti* in the lower Danian Cerithium Limestone Member (Fig. 19.6). These specimens have generally been interpreted as reworked material. However, the mode of occurrence of these specimens suggests that they were fossilized at the same time as the deposition of the Cerithium Limestone Member. In addition, the most common fossils in the underlying Maastrichtian chalk are virtually absent in the Cerithium Limestone, which is inconsistent with a hypothesis of reworking. Thus, both these lines of evidence suggest that the ammonites in the Cerithium Limestone Member represent early Danian survivors (Machalski and Heinberg 2005).

19.4.2 Depth Distribution of Ammonites at the K/Pg Boundary

At the end of the Maastrichtian, shallower water settings (< 100 m) are represented by deposits in northern and central Europe and North America. In northern and central Europe, the most abundant ammonites are *Baculites* followed by *Hoploscaphites* (Figs. 19.16, 19.17) In addition, the fauna contains a few species of desmoceratoids, including *Menuites terminus*, and a few species of diplomoceratids including *Glyptoxoceras rugatum* and *Diplomoceras cylindraceum*. In North America, the most abundant ammonites are also baculitids, represented by *Eubaculites* and *Baculites,* followed by scaphitids, represented by *Discoscaphites*. Sphenodiscids are relatively common but desmoceratoids and diplomoceratids (e.g., *Glyptoxoceras*) are rare, and phylloceratids and lytoceratids are absent.

Deeper-water settings (> 100 m) at the end of the Maastrichtian are represented by deposits in the Bay of Biscay, the Tunisian Trough, Antarctica, and Sakhalin. In the Bay of Biscay, the fauna is characterized by several species of phylloceratids and lytoceratids, many of which are endemic to the area (Fig. 19.14). In addition, the fauna contains a high diversity of desmoceratoids. In contrast, only one species of *Diplomoceras* is present and *Eubaculites* and *Hoploscaphites* are absent in the upper part of the section. Several of the same species of phylloceratids and lytoceratids (*Hypophylloceras* (*Neophylloceras*) *ramosum* and *Anagaudryceras politissimum*) are present in Bulgaria. The fauna in the Bay of Biscay also has several species in common with the fauna in Tunisia, including phylloceratids and lytoceratids (e.g., *Phyllopachyceras forbesianum* and *Pseudophyllites indra*) and desmoceratoids (e.g., *B.* (*Brahmaites*) *brahma*). The most distinctive elements of the Tunisian fauna, however, are species of *Indoscaphites*, suggesting a strong connection with southern India. In Antarctica, phylloceratids are absent but lytoceratids are present, including *A. seymouriense* and *Pseudophyllites loryi*, both of which are endemic to the area. The fauna is also characterized by five endemic species of desmoceratoids including *Maorites densecostatus*, *Kitchinites laurae*, and *Pachydiscus* (*P.*) *riccardii*. Surprisingly, few species are shared with South America, especially with the slightly older Quiriquina Formation in central Chile (Salazar et al. 2010), which contains two species of phylloceratids but no lytoceratids. In Sakhalin, the fauna is dominated by phylloceratids and lytoceratids, with a few genera and species in common with Tunisia, Bulgaria, and the Bay of Biscay. It is also characterized by two species of pachydiscids that are endemic to the area.

19.4.3 Ecology of Ammonites at the K/Pg Boundary

The phylloceratids and lytoceratids, although never abundant in terms of individuals, are well represented in deeper-water settings (>100 m deep) at the end of the Maastrichtian (Fig. 19.14). A total of seven genera are each present in Tunisia and the Bay of Biscay, and three each in Bulgaria and Antarctica. They are characterized by relatively compressed shells without much ornament, and comprise the traditional Leiostraca, and are restricted to the distal shelf and upper continental slope based on paleoenvironmental data. This habitat is consistent with depth estimates based on studies of the strength of the siphuncular tube and septa (Hewitt 1996). The buccal apparatus of these forms is different from other ammonites at the end of the Cretaceous in featuring a calcareous deposit at the apical end of the lower jaw, possibly permitting them to feed on hard material, like crustacean carapaces (Tanabe and Landman 2002; Tanabe et al. 2013). Depending on the genus, Westermann (1996) interpreted the mode of life of these forms as demersal swimmers, planktic vertical migrants, or nektic swimmers. However, an analysis of the isotopic composition of the outer shell of several species of Late Cretaceous *Hypophylloceras*, *Phyllopachyceras*, and *Gaudryceras* from Japan suggests that these forms lived close to the sea floor (Moriya et al. 2003).

The desmoceratoids at the end of the Maastrichtian also favored deeper-water settings, with five genera each in Tunisia and the Bay of Biscay, and four in Antarctica (Fig. 19.15). With their relatively thick septa, narrow but thick-walled siphuncular tubes, and long septal necks, desmoceratoids are well adapted to deeper-water settings. They possess moderately compressed, involute shells with a rounded venter and relatively smooth surface. The hydrodynamic properties of desmoceratoids are, thus, similar to those of other Mesozoic ammonites with low shell-thickness ratios (Seki et al. 2000). These forms are considered to have been demersal swimmers, which lived on the distal shelf and upper continental slope (Westermann 1996). This interpretation is consistent with isotopic analyses of the outer shell, which suggest a mode of life near the bottom (Moriya et al. 2003). It is notable that desmoceratoids appear to have modified their aptychus-type jaw, reducing the aptychus to only a thin covering (Tanabe and Landman 2002; Tanabe et al. 2013). This may have permitted them to broaden their diet to include carrion from the sea floor.

Scaphitids at the close of the Cretaceous occur in shallow-water settings such as the Gulf and Atlantic Coastal Plains of North America and northern and central Europe, although they occasionally occur in deeper-water settings such as

Turkmenistan (Fig. 19.17). In terms of numbers of individuals, they are probably the most abundant ammonites after baculitids. The mode of life and habitat of Late Cretaceous scaphitids has been investigated by Landman et al. (2012a) based on analyses of the functional morphology of the shell and buccal apparatus, light stable isotopes, facies distributions, faunal associations, and the mechanical strength of the septa, shell, and siphuncle. Based on this evidence, scaphitids were probably sluggish swimmers that preferred well-oxygenated water just above the bottom. They may have exploited a low-energy lifestyle, remaining at a single site for an extended period of time. As members of the Aptychophora Engeser and Keupp 2002, scaphitids possessed an aptychus-type lower jaw and may have preyed upon small organisms in the water column, such as decapod crustaceans, copepods, and newly hatched ammonites.

Sphenodiscids were also relatively common in the same facies as scaphitids in North America and northern and central Europe at the end of the Maastrichtian (Fig. 19.16). Based on their streamlined, oxyconic shells and distribution in nearshore facies, sphenodiscids have been interpreted as inhabitants of shallow-water environments ranging from around wave base to slightly below (Ifrim and Stinnesbeck 2010). They may have been capable of brief spurts of relatively rapid swimming permitting ambush predation (Westermann 1996). However, they are equipped with aptychus-type lower jaws without sharp cutting edges, precluding the likelihood of a diet of hard-shelled prey.

The diplomoceratids (*Glyptoxoceras*, *Diplomoceras*, and *Phylloptychoceras*) and baculitids are nearly cosmopolitan at the end of the Cretaceous, suggesting that they were facies-independent. The diplomoceratids occur at eight regions ranging from deeper-water (Bay of Biscay) to shallower-water settings (the Netherlands and northeast Belgium) (Fig. 19.16). The baculitids (*Baculites*, *Eubaculites*, and *Fresvillia*) are even more widespread than the diplomoceratids and occur in ten regions (Figs. 19.16, 19.17). Indeed, baculitids are probably the most abundant ammonites at the end of the Cretaceous in terms of number of individuals. The wide distribution of these forms with respect to environmental settings suggests that they may have lived high in the water column, well above the bottom. This is consistent with the fact that they are occasionally preserved even in areas with dysoxic bottom water that excluded benthic fauna. Baculitids have generally been interpreted as sluggish swimmers (Klinger 1981) hovering in the water column at an inclined angle to the vertical (Fig. 19.3), but this requires a counterbalance at the adapical end. Based on studies of the morphology of the radula and the presence of prey remains in the buccal apparatus, it is possible that baculitids preyed on small micro-organisms in the water column, such as tiny crustaceans (Kruta et al. 2011). This interpretation may also have applied to the diplomoceratids with their upturned aperture at maturity, which is also consistent with a microphagous mode of life.

19.4.4 Causes of Ammonite Extinction

Following the Alvarez hypothesis, it is now generally accepted that the disappearance of ammonites in the latest Maastrichtian/earliest Danian was due to the asteroid impact. However, the exact killing mechanism is still unknown. The most plausible explanation is perhaps a transient episode of surface water acidification on the heels of the asteroid impact (Alegret et al. 2012; Arkhipkin and Laptikhovsky 2012; Hönisch et al. 2012). According to these arguments, the gypsum-rich deposits at the impact site would have vaporized, producing sulfuric acid. In addition, the heating of the atmosphere would have generated nitric acid due to the oxidation of N_2, resulting in acid rain. The alternative hypothesis of a global collapse in primary productivity (called the Strangelove Ocean) or export productivity (called the Living Ocean) lacks support because the benthic foraminifera in the deep sea did not suffer a severe extinction at the time, unlike the planktic foraminifera (Alegret et al. 2012). Darkness due to the fine dust in the atmosphere following the collision may also have been a contributing factor, blocking solar radiation and leading to a short-lived cold spell (Vellekoop et al. 2014).

Surface ocean acidification would have had disastrous consequences for planktic calcifiers, including calcareous nannofossils, planktic foraminifera, and ammonites. All the ammonites at the end of the Cretaceous, irrespective of their mode of life at maturity, probably followed a planktic mode of life immediately after hatching (Landman et al. 1996; Westermann 1996; Arkhipkin and Laptikhovsky 2012). This hypothesis is based on two functional arguments: the small size of the embryonic shell (ammonitella), which ranges from 0.5 to 1.5 mm in diameter, and its near-spherical shape, both of which are presumably adaptations to life in the plankton (Fig. 19.18). The newly hatched ammonites may have been passive vertical migrators, drifting with surface currents. This interpretation is consistent with a number of observations on the mode of occurrence of ammonites preserved at this stage of development. For example, the Late Cretaceous Sharon Springs Member of the Pierre Shale in Wyoming contains small specimens of newly hatched ammonites. These sediments are interpreted to have been deposited on an anaerobic bottom with oxygenated water above, implying that the newly hatched ammonites were planktic or at least nektic (Landman 1988). This mode of life may have been very ‘effective’ during background times, but it may have proved to be an Achilles Heel for ammonites during stressful times (Arkhipkin and Laptikhovsky 2012).

Variation in the degree of surface ocean acidification can help explain the fact that all of the evidence for the short-term survival of ammonites in the early Danian is from relatively shallow-water settings (the Atlantic Coastal Plain, the Netherlands and northeast Belgium, and Denmark). The ammonites in these areas may have survived for days to tens of thousands of years after the impact. It is possible that these coastal areas may have been buffered from transient surface water acidification due to the burning of plants on the land, and the resultant increase in riverine run-off. As a consequence, some planktic organisms that secreted calcium carbonate, including ammonites, may have persisted for a brief interval of time in these regions. Ironically, this kill mechanism apparently favored scaphitids and baculitids, which are characterized by short-term species longevities, rather than phylloceratids and lytoceratids, which are characterized by long-term species longevities (for a discussion of the evolutionary mode and tempo of Cretaceous ammonites, see Ward and Signor 1983). Thus, this kill mechanism was independent of the evolutionary success of particular ammonites, as least as measured by their species longevity.

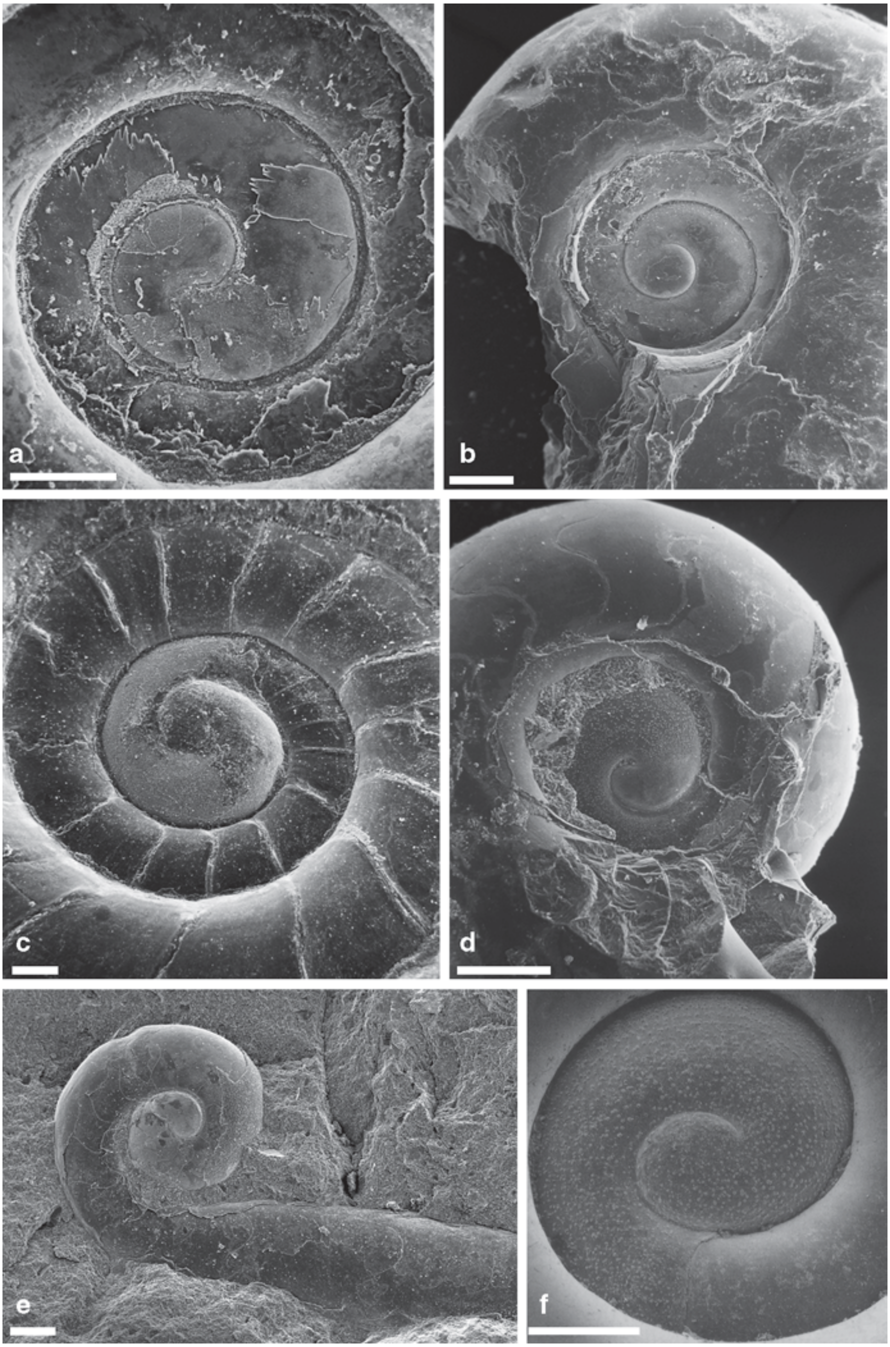


Fig. 19.18 Illustration of the embryonic shells of six species of Late Cretaceous ammonites (**a**–**e**, with kind permission of K. Tanabe, University of Tokyo). The embryonic shell consists of the protoconch and approximately one whorl ending in the primary constriction, and is ornamented

The geographic distribution of ammonite genera may also have played a role in their pattern of extinction. Landman et al. (2014) compiled a database of all ammonite genera in the last 0.5 myr of the Maastrichtian. They also incorporated data on ammonite genera that appear to have briefly survived into the Paleocene (Jagt et al. 2003; Jagt 2012; Machalski and Heinberg 2005; Machalski et al. 2009; Landman et al. 2012b). Using two metrics to evaluate the geographic range of each genus (first, a convex hull encompassing all of the occurrences of each genus and, second, the maximum distance between occurrences for each genus), they documented that most ammonite genera at the end of the Maastrichtian were restricted in their geographic distribution, possibly making them vulnerable to extinction. However, the geographic distribution of those genera that may have briefly survived into the Paleocene is significantly greater than that of 'non-surviving' genera, implying that more broadly distributed genera were more resistant to extinction. Similar geographic patterns of survivorship have been observed in other molluscs at the K/Pg boundary. For example, Jablonski (2008) noted that it terms of marine bivalve genera, survivors were significantly more broadly distributed than victims. However, even the most widely distributed ammonites eventually succumbed to extinction. Evidently, a broad geographic distribution may have initially protected some ammonites against extinction, but it did not guarantee their survival.

19.5 Conclusions

Ammonites are abundant and diverse in the last 0.5 million years of the Maastrichtian. They are distributed across all four Cretaceous suborders, the Phylloceratina, Lytoceratina, Ammonitina, and Ancyloceratina, comprising six superfamilies, 31 (sub)genera, and 57 species. The distribution of ammonites is dependent on the environmental setting. In shallow-water environments (< 100 m deep), almost all of the ammonites are ancyloceratines, including scaphitids, baculitids, and diplomoceratids. In fact, baculitids and diplomoceratids are the most widespread ammonites at the end of the Cretaceous. In deeper-water settings (> 100 m deep), almost all taxa comprise phylloceratids, lytoceratids, and ammonitids (especially desmoceratoids). The commonly cited decline in ammonite diversity at the end of the Maastrichtian is related more to local environmental changes or collection failure rather than to global extinction. Indeed, ongoing research has yielded additional specimens even in well-studied areas. In addition, recent data from shallow water settings (Atlantic Coastal Plain, the Netherlands and northeast Belgium, and Denmark) suggest

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with a microtuberculate ornamentation. **a** *Hypophylloceras subramosum* (Phylloceratina), middle Campanian, Hokkaido, Japan (refigured from Tanabe 1989, Fig. 2D). **b** *Phyllopachyceras ezoense* (Phylloceratina), middle Campanian, Hokkaido, Japan (refigured from Tanabe 1989, Fig. 2C). **c** *Gaudryceras denseplicatum* (Lytoceratina), Coniacian, Hokkaido, Japan (refigured from Tanabe 1989, Fig. 2A, B). **d** *Menuites* sp. (Ammonitina), middle Campanian, Hokkaido, Japan (refigured as *Anapachydiscus* sp. in Tanabe 1989, Fig. 1A, B). **e** *Baculites compressus* (Ancyloceratina), late Campanian, South Dakota, USA. **f** *Hoploscaphites* sp. (Ancyloceratina), upper Maastrichtian, South Dakota (Refigured from Landman and Waage 1993, Fig. 13D). Scale bar = 200 um that not only did ammonites persist to the boundary, but some species may even have survived for as much as tens of thousands of years afterward. The most likely explanation for ammonite extinction is a brief episode of surface water acidification immediately following the Chixculub impact, which caused the decimation of the calcareous plankton including, possibly, the planktic post-hatching stages of ammonites. However, the geographic distribution of ammonites may also have played a role in the events at the end of the Cretaceous, with more broadly distributed genera more resistant to extinction.

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Appendix of Localities

1: Manasquan River Basin, Monmouth County, New Jersey, U.S.A., 40°12′30″N, 74°17′30″W
2: Northeastern Monmouth County, New Jersey, U.S.A., 40°17′30″N, 74°7′14″W
3: Round Bay, Anne Arundel County, Maryland, U.S.A., 39°2′13″N, 76°33′28″W
4: Stoddard and Scott counties, Missouri, U.S.A., 37°00′17″N, 89°51′02″W
5: Tippah County, Mississippi, U.S.A., 34°44′55″N, 88°54′47″W
6: Chickasaw County, Mississippi, U.S.A., 33°58′04″N, 89°00′05″W
7: Brazos River, Falls County, Texas, U.S.A.,31°8′11″N, 96°49′40″W
8: La Popa Basin, Northeastern Mexico, 26°12′44″N, 101°4′25″W
9: Stevns Klint, Denmark, 55°16′45″N, 12°26′47″E
10: Kjølby Gård, Denmark, 57°3′15″N, 8°44′55″E
11: “Dania” Quarry, northern Denmark, 56°39′42″N, 10°1′56″E
12: Maastrichtian Type Area, The Netherlands and Belgium, 50°49′18.41″N, 5°41′39.54″E
13: Nasiłów, Poland, 51°20′39″N, 21°57′35″E
14: Mełgiew, Poland, 51°13′30″N, 22°47′8″E
15: Lechówka, Poland, 51°10′17″N, 23°14′43″E
16: Kyzylsay, Kazakhstan, 44°20′1″N, 52°26′10″E
17: Sumbar River, Turkmenistan, 38°27′18″N, 56°12′41″E
18: Zumaya, Bay of Biscay Area, 43°17′54″N, 2°16′16″W
19: Hendaye, Bay of Biscay Area, 43°23′1″N, 1°49′26″W
20: Bidart, Bay of Biscay Area, 43°26′25″N, 1°35′41″W
21: Bjala (=Byala), Bulgaria, 42°52′44″N, 27°53′57″E
22: Kalaat Senan, Tunisia, 35°47′15″N, 8°27′21″E
23: El Kef, Tunisia, 36°9′15″N, 8°38′55″E
24: Garn Halfaya, Tunisia, 36°0′40″N, 8°33′23″E

25: Dababiya Quarry Corehole, Egypt, 25°30′10″N, 32°31′27″E
26: Naiba River Valley, Sakhalin, Far East Russia, 47°28′34″N, 142°24′10″E
27: Poty Quarry, Brazil, 7°53′95″S, 34°51′14″W
28: Lomas Colorados, Bajada de Jagüel, Neuquen Basin, Argentina, 37°59′24″S, 68°47′38″W
29: Seymour Island, Antarctica, 64°16′50″S, 56°43′23″W

References

Abdel-Gawad GI (1986) Maastrichtian non-cephalopod mollusks (Scaphopoda, Gastropoda and Bivalvia) of the Middle Vistula Valley, Central Poland. Acta Geol Pol 36:69–224

Alegret L, Thomas E, Lohmann KC (2012) End-Cretaceous marine mass extinction not caused by productivity collapse. Proc Natl Acad Sci U S A 109:728–732

Alekseev AS, Nasarovm MA, Barsukova LD, Kolesov GM, Nuzhegorodova IV, Amanniâzov KN (1988) The Cretaceous-Paleogene boundary in southern Turkmenia and its geochemical characteristics. Bûelleten Moskovskgo Obŝestva Prirody, Otdel Geologiĉeskij 63:55–69 (in Russian)

Alvarez LW, Alvarez W, Asaro F, Michel HV (1980) Extraterrestrial cause for the Cretaceous-Tertiary extinction. Science 208:1095–1108

Arkhipkin A, Laptikhivsky VV (2012) Impact of ocean acidification on plankton larvae as a cause of mass extinctions in ammonites and belemnites. N Jb Geol Paläont Abh 266:39–50

Atabekian AA, Akopian VT (1969) Late Cretaceous ammonites of the Armenian SSR (Pachydiscidae). Izvestiya AN Armyanskoj SSR, Nauki o Zemle 6:3–20 (in Russian)

Batenburg SJ, Sprovieri M, Gale AS, Hilgen FJ, Hüsing S, Laskar J, Liebrand D, Lirer F, Orue-Etxebarria X, Pelosi N, Smit J (2012) Cyclostratigraphy and astronomical tuning of the Late Maastrichtian at Zumaia (Basque country, Northern Spain). Earth Planet Sci Lett 359/360:264–278

Berggren WA, Ouda K (2013) Early Paleogene geohistory of Egypt: the Dababiya Quarry corehole. Stratigraphy 9(2012):183–188

Berggren WA, Alegret L, Aubry M-P, Cramer BS, Dupuis C, Goolaerts S, Kent DV, King C, O'Knox RW, Obaidalla Nh, Ortiz S, Ouda AK, Sabour AA, Salem R, Senosy MM, Soliman MF, Soliman A (2012) The Dababiya corehole: upper Nile Valley, Egypt: preliminary results. Austrian J Earth Sci 105:161–168

Binkhorst van den Binkhorst JT (1861–1862) Monographie des gastéropodes et des céphalopodes de la Craie supérieure du Limbourg, suivie d'une description de quelques espèces de crustacés du même dépôt crétacé, avec dix-huit planches dessinées et lithographiées par C. Hohe, de Bonn. A. Muquardt/Muller Frères, Bruxelles/Maastricht

Birkelund T (1965) Ammonites from the Upper Cretaceous of West Greenland. Meddr om Grønland, vol 179., pp 1–192

Birkelund T (1979) The last Maastrichtian ammonites. In: Birkelund T, Bromley RG (eds) Cretaceous-Tertiary boundary events symposium 1, The Maastrichtian and Danian of Denmark. University of Copenhagen, Copenhagen

Birkelund T (1993) Ammonites from the Maastrichtian White Chalk of Denmark. Bull Geol Soc Denmark 40:33–81

Blakey R (2011) Mollewide plate tectonic maps. http://cpgeosystems.com/mollglobe/html. Accessed April 2014

Boas C, Garb MP, Rovelli R, Larina E, Myers CE, Naujokaityte J, Landman NH, Phillips GE (2013a) New K/Pg localities along the eastern Gulf Coastal Plain: More evidence of impact and tsunamis: GSA Abst with Prog 45:133

Boas C, Garb MP, Landman NH, Rovelli R, Larina E (2013b) The significance of a fossiliferous spherule bed at the K/Pg boundary in northern Mississippi. GSA Abst with Prog 45:61

Böhm J (1898) Ueber *Ammonites pedernalis* v. Buch, Zeitschr Deut Geol Ges. pp 183–201 (50)

Brunnschweiler RO (1966) Upper Cretaceous ammonites from the Carnarvon Basin of Western Australia. 1. The heteromorph Lytoceratina, Bulletin Bureau of Mineral Resources Geology and Geophysics no 58. Bureau of Mineral Resources Geology and Geophysics, Capital of Australia, 58:1–158

Burnett JA (= Lees JA) (1998) Upper Cretaceous. In: Bown PR (ed) Calcareous nannofossil biostratigraphy. Chapman & Hall, Kluwer Academic, London

Campbell CE, Oboh-Ikuenobe FE, Eifert TL (2008) Megatsunami deposit in Cretaceous-Paleogene boundary interval of southeastern Missouri. In: Evans KR, Horton JR Jr, King DT Jr, Morrow JR (eds) The sedimentary record of meteorite impacts. The Geological Society of America Special Paper 437, pp 189–198

Cobban WA, Kennedy WJ (1995) Maastrichtian ammonites chiefly from the Prairie Bluff Chalk in Alabama and Mississippi. Paleontol Soc Mem 44:1–40

Collignon M (1952) Ammonites néocrétacés du Menabe (Madagascar). II.–Les Pachydiscidae. Travaux du Bureau géologique de Madagascar 41:1–114

Conrad TA (1857) Descriptions of Cretaceous and Tertiary fossils. In: Emory WH (ed) Report on the United States and Mexican boundary survey. US 34th Congress, 1st Session, Senate Ex Documents 108 and House Ex Document 135, 1(2)

Conrad TA (1858) Observations on a group of Cretaceous fossil shells found in Tippah County, Mississippi, with descriptions of fifty-six new species. J Acad Natl Sci Phila 3:323–336

Damholt T, Surlyk F (2012) Nomination of Stevns Klint for inclusion in the World Heritage List. Østsjaellands Museum, St. Heddinge

Defrance MJL (1816) In: Dictionnaire des Sciences naturelles, dans lequel on traite méthodiquement des differents Etres de la Nature 3. Levrault, Paris

Dinarès-Turell J, Pujalte V, Stoykova K, Elorza J (2013) Detailed correlation and astronomical forcing within the Upper Maastrichtian succession in the Basque Basin. Boletín Geológico Minero 124:253–282

Elliot DH, Askin RA, Kyte FT, Zinsmeister WJ (1994) Iridium and dinocysts at the Cretaceous-Tertiary boundary on Seymour Island, Antarctica: implications for the K-T event. Geology 22:675–678

Engeser T, Keupp H (2002) Phylogeny of aptychi-possessing Neoammonoidea (Aptychophora nov., Cephalopoda). Lethaia 24:79–96

Fatmi A, Kennedy WJ (1999) Maastrichtian ammonites from Balochistan, Pakistan. J Paleontol 73:641–662

Forbes E (1846) Report on the fossil Invertebrata from southern India, collected by Mr. Kaye and Mr. Cunliffe. Trans Geol Soc Lond 7:97–174

Gardin S, Galbrun B, Thibault N, Coccioni R, Premoli Silva I (2012) Bio-magnetostratigraphy for the upper Campanian-Maastrichtian from the Gubbio area, Italy: new results from the Contessa Highway and Bottaccione sections. Newsl Stratigr 45:75–103

Goolaerts S (2010a) Late Cretaceous ammonites from Tunisia: chronology and causes of their extinction and extrapolation to other areas. Aardkundige Mededelingen 21:1–220

Goolaerts S (2010b) Late Cretaceous ammonites from Tunisia: chronology and causes of their extinction and extrapolation to other areas. PhD manuscript. Arenberg Doctoral School Katholieke Universiteit Leuven, Part 1: xii + 220 pp; Part 2: 317 pp (PhD thesis, in english)

Goolaerts S, Dupuis C (2012) Ammonites from the Dababiya corehole: taxonomic notes and age assessment. In: Berggren WA, Ouda K, Aubry MP (eds) The Paleocene-Eocene succession of the upper Nile Valley and southwestern Desert (southern Egypt): Part 2: Biostratigraphy and paleoecology, A. Dababiya Core. Stratigraphy 9:261–266

Goolaerts S, Kennedy WJ, Dupuis C, Steurbaut E (2004) Terminal Maastrichtian ammonites from the Cretaceous-Paleogene Global Stratotype Section and Point, El Kef, Tunisia. Cretaceous Research, vol 25. Academic press ltd elsevier science ltd, pp 313–328

Gould SJ (1995) Dinosaur in a haystack: reflections in natural history. Harmony Books, New York

Gravesen P, Jakobsen SL (2013) Skrivekridtets Fossiler. Gyldendal Fakta, Kobenhavn

Håkansson E, Hansen JM (1979) Guide to Maastrichtian and Danian boundary strata in Jylland. In: Birkelund T, Bromley RG (eds) Cretaceous-Tertiary Boundary Events Symposium I, Copenhagen

Hansen JM (1977) Dinoflagellate stratigraphy and echinoid distribution in upper Maastrichtian and Danian deposits from Denmark. Bull Geol Soc Denmark 26:1–26

Hansen HJ (1990) Diachronous extinctions at the Cretaceous-Tertiary boundary: a scenario. In: Sharpton VL, Ward PD (eds) Global catastrophes in Earth history; an interdisciplinary conference on impacts, volcanism, and mass mortality. Geological Society of America Special Paper 247: 417–423

Hansen T, Farrand RB, Montgomery HA, Billman HG, Blechschmidt G (1987) Sedimentology and extinction patterns across the Cretaceous-Tertiary boundary interval in east Texas. Cretac Res 8:229–252

Hansen HJ, Rasmussen KL, Gwozdz R, Hansen JM, Radwański A (1989) The Cretaceous/Tertiary boundary in Central Poland. Acta Geol Pol 39:1–12

Hart MB, Searle SR, Feist SE, Leighton AD, Price GD, Smart CW, Twitchett RJ (2011) The distribution of benthic foraminifera across the Cretaceous-Paleogene boundary in Texas (Brazos River) and Denmark (Stevns Klint). In: Keller G, Adatte T (eds) End-Cretaceous mass extinction and the Chixculub impact in Texas: SEPM Special Publication no 100:179–196

Hart MB, Yancey TE, Leighton AD, Miller B, Liu C, Smart CW, Twitchett RJ (2012) The Cretaceous-Paleogene Boundary on the Brazos River, Texas: new stratigraphic sections and revised interpretations. Gulf Coast Assoc Geol Sci J 1:69–80

Hasegawa T, Pratt LM, Maeda H, Shigeta Y, Okamoto T, Kae T, Uemura K (2003) Upper Cretaceous stable carbon isotope stratigraphy of terrestrial organic matter from Sakhalin, Russian Far East: a proxy for the isotopic composition of paleoatmospheric CO_2. Palaeogeogr Palaeoclimatol Palaeoecol 189:97–115

Hauer F von (1858) Über die Cephalopoden der Gosauschichten. Beitr Paläont Österr 1:7–14

Henderson RA, McNamara KA (1985) Maastrichtian non-heteromorph ammonites from the Miria Formation. Palaeontology 28:35–88

Hennebert M (2012) Hunting for the 405-kyr eccentricity cycle phase at the Cretaceous-Paleogene boundary in the Aïn Settara section (Kalaat Senan, central Tunisia). Carnets de Géol 2012/5:93–116

Hennebert M, Dupuis C (2003) Proposition d'une échelle chronométrique autour de la limite Crétacé-Paléogène par cyclostratigraphie: coupe de l'Aïn Settara (Kalaat Senan, Tunisie centrale). Geobios 36:707–718

Herman Y, Bhattacharya SK, Perch-Nielsen K, Kopaevitch LF, Naidin DP, Frolov VT, Jeffers JD, Sarkar A (1988) Cretaceous-Tertiary boundary marine extinctions: the Russian platform record. Rev Española Paleont, n° Extraord "Palaeontology and Evolution: Extinction Events": 31–40

Hewitt RA (1996) Architecture and strength of the ammonoid shell. In: Landman NH, Tanabe K, Davis RA (eds) Ammonoid paleobiology. Plenum, New York

Hönisch B, Ridgwell A, Schmidt D, Thomas E, Gibbs SJ, Sluijs A, Zeebe R, Kump L, Martindale RC, Greene SE, Kiessling W, Ries J, Zachos JC, Royer DL, Barker S, Marchitto TM Jr, Moyer R, Pelejero C, Ziveri P, Foster GL, Williams B (2012) The geological record of ocean acidification. Science 335:1058–1063

Hupé P (1854) Malacología y conquiliología. In: Gay C (ed) Historia fisica y politica de Chile. Zoología 8:5–385

Husson D, Galbrun B, Laskar J, Hinnov LA, Thibault N, Gardin S, Locklair RE (2011) Astronomical calibration of the Maastrichtian (Late Cretaceous). Earth Planet Sci Lett 305:328–340

Ifrim C, Stinnesbeck W (2010) Migration pathways of the late Campanian and Maastrichtian shallow facies ammonite *Sphenodiscus* in North America. Palaeogeogr Palaeoclimatol Palaeoecol 292:96–102

Ivanov M (1995) Upper Maastrichtian ammonites from the sections around the town of Bjala (eastern Bulgaria). Rev Bulg Geol Soc 56:57–73 (in Bulgarian)

Ivanov MI, Stoykova KH (1994) Cretaceous/Tertiary boundary in the area of Bjala, eastern Bulgaria—biostratigraphical results. Geol Balc 24(6):3–22

Jablonski D (2008) Extinction and the spatial dynamics of biodiversity. Proc Natl Acad of Sci U S A 105:11528–11535

Jagt JWM (1995) A Late Maastrichtian ammonite faunule in flint preservation from northeastern Belgium. Meded Rijks Geol Dienst 53:21–47

Jagt JWM (1996) Late Maastrichtian and early Palaeocene index macrofossils in the Maastrichtian type area (SE Netherlands, NE Belgium). In: Brinkhuis H, Smit J (eds) The Geulhemmerberg Cretaceous/Tertiary boundary section (Maastrichtian type area, SE Netherlands). Geol Mijnbouw 75:153–162

Jagt JWM (2002) Late Cretaceous ammonite faunas of the Maastrichtian type area. In: Summesberger H, Histon K, Dauer A (eds) Cephalopods—Present and past. Abh Geol B-A Wien 57:509–522

Jagt JWM (2005) Stratigraphic ranges of mosasaurs in Belgium and the Netherlands (Late Cretaceous) and cephalopod-based correlations with North America. In: Schulp AS, Jagt JWM (eds) Proceedings of the First Mosasaur Meeting. Netherlands J Geosci 84:283–301

Jagt JWM (2012) Ammonieten uit het Laat-Krijt en Vroeg-Paleogeen van Limburg. Staringia 13:154–183

Jagt JWM, Jagt-Yazykova EA (2012) Stratigraphy of the type Maastrichtian—a synthesis. In: Jagt JWM, Donovan SK, Jagt-Yazykova EA (eds) Fossils of the type Maastrichtian (Part 1). Ser Geol Spec issue 8:5–32

Jagt JWM, Smit J, Schulp A (2003) Early Paleocene ammonites and other molluscan taxa from the Ankerpoort-Curfs quarry (Geulhem, southern Limburg, the Netherlands). In: Lamolda MA (ed) Bioevents: their stratigraphical records, patterns and causes. Caravaca, 3rd–8th June 2003, Ayuntamiento de Caravaca de la Cruz

Jagt JWM, Goolaerts S, Jagt-Yazykova EA, Cremers G, Verhesen W (2006) First record of *Phylloptychoceras* (Ammonoidea) from the Maastrichtian type area, The Netherlands. Bull Inst Roy Sci nat Belg, Sci Terre 76:97–103

Jagt-Yazykova EA (2011) Palaeobiogeographical and palaeobiological aspects of mid- and Late Cretaceous ammonite evolution and bio-events in the Russian Pacific. Scr Geol 143:15–122

Jagt-Yazykova EA (2012) Ammonite faunal dynamics across bio-events during the mid- and Late Cretaceous along the Russian Pacific coast. Acta Palaeontol Pol 57:737–748

Jeffrey CH (1997) All change at the Cretaceous-Tertiary boundary? Echinoids from the Maastrichtian and Danian of the Mangyshlak Peninsula, Kazakhstan. Palaeontology 40:659–712

Keller G, Abramovich S, Berner Z, Adatte T (2009) Biotic effects of the Chicxulub impact, K-T catastrophe and sea level change in Texas. Palaeogeogr Palaeoclimatol Palaeoecol 271:52–68

Kennedy WJ (1986) The Campanian-Maastrichtian ammonite sequence in the environs of Maastricht (Limburg, the Netherlands), Limburg and Liège provinces (Belgium). Newsl Stratigr 16:149–168

Kennedy WJ (1987) The ammonite faunas of the type Maastrichtian, with a revision of *Ammonites colligatus* Binkhorst, 1861. Bull de l'Inst Roy des Sci Nat de Belgique 56:151–267

Kennedy WJ (1993) Ammonite faunas of the European Maastrichtian; diversity and extinction. In: House MR (ed) The ammonoidea: environment ecology evolutionary change, Systematics Association Spec. vol 47. Clarendon Press, Oxford, pp 285–326

Kennedy WJ, Cobban WA (2000) Maastrichtian (Late Cretaceous) ammonites from the Owl Creek Formation in northeastern Mississippi, U.S.A. Acta Geol Pol 50:175–190

Kennedy WJ, Jagt JWM (1998) Additional Late Cretaceous ammonite records from the Maastrichtian type area. Bull Inst Roy des Sci de Belgique 68:155–174

Kennedy WJ, Gale AS, Hansen TA (2001) The last Maastrichtian ammonites from the Brazos River sections in Falls County, Texas. Cretac Res 22:163–171

Kiessling W, Claeys P (2002) A geographic database approach to the KT Boundary. In: Buffetaut E, Koeberl C (eds) Geological and biological effects of impact events. Springer, Berlin

Kilian W, Reboul P (1909) Les céphalopodes néocrétacés des îles Seymour et Snow Hill. Wissenschaftliche Ergebnisse der Schwedischen Südpolar-Expedition 3:1–75

Klinger HC (1981) Speculations on buoyancy control and ecology in some heteromorph ammonites. In: House MR, Senior JR (eds) The Ammonoidea. Systematics Association Special vol 18. Academic , New York

Kodama K (2003) Magnetostratigraphic correlation of the Upper Cretaceous System in the North Pacific. J Asian Earth Sci 21:949–956

Kodama K, Maeda H, Shigeta Y, Kase T, Takeuchi T (2000) Magetostratigraphy of Upper Cretaceous strata in South Sakhalin, Russian Far East. Cretac Res 21:469–478

Kossmat F (1895–1898) Untersuchungen über die Südindische Kreideformation. Beitr Paläont Österr. Ungarns Orients 9(1895):97–203; 11(1897):1–46; 11(1898):89–152

Kruta I, Landman NH, Rouget I, Cecca F, Tafforeau P (2011) The role of ammonites in the marine Mesozoic food web revealed by jaw preservation. Science 311:70–72

Lamarck JP (1801) Système des animaux sans vertèbres. Verdière, Paris

Lamarck JP (1822) Histoire naturelle des animaux sans vertèbres. Verdière, Paris

Landman NH (1988) Early ontogeny of Mesozoic ammonites and nautilids. In: Wiedmann J, Kullmann J (eds) Cephalopods—present and past. Schweizerbart, Stuttgart

Landman NH, Waage KM (1993) Scaphitid ammonites of the Upper Cretaceous (Maastrichtian) Fox Hills Formation in South Dakota and Wyoming. Am Mus Natl Hist Bull 215:1–257

Landman NH, Tanabe K, Shigeta Y (1996) Ammonoid embryonic development. In: Landman NH, Tanabe K, Davis RA (eds) Ammonoid paleobiology. Plenum, New York

Landman NH, Johnson RO, Edwards LE (2004a) Cephalopods from the Cretaceous/Tertiary boundary interval on the Atlantic Coastal Plain, with a description of the highest ammonite zones in North America. Part 1. Maryland and North Carolina. Amer Mus Novatites 3454:1–66

Landman NH, Johnson RO, Edwards LE (2004b) Cephalopods from the Cretaceous/Tertiary Boundary interval on the Atlantic Coastal Plain, with a description of the highest ammonite zones in North America. Part 2. Northeastern Monmouth County, New Jersey. Bull Amer Mus Natl Hist 287:1–107

Landman NH, Johnson RO, Garb MP, Edwards LE, Kyte FT (2007) Cephalopods from the Cretaceous/Tertiary boundary interval on the Atlantic Coastal Plain, with a description of the highest ammonite zones in North America. Part III. Manasquan River Basin, Monmouth County, New New Jersey. Bull Amer Mus Natl Hist 303:1–122

Landman NH, Cobban WA, Larson NL (2012a) Mode of life and habitat of scaphitid ammonites. Geobios 45:87–98

Landman NH, Garb MP, Rovelli R, Ebel DS, Edwards LE (2012b) Short-term survival of ammonites in New Jersey after the end-Cretaceous bolide impact. Acta Palaeontol Pol 57:703–715

Landman NH, Goolaerts S, Jagt JWM, Jagt-Yazykova EA, Machalski M, Yacobucci MM (2014) Ammonite extinction and nautilid survival at the end of the Cretaceous. Geology 42:707–710

Larina E, Landman NH, Cochran K, Thibault N, Garb MP, Edwards LE (2012) Insights into climatic and faunal changes at the end of the Maastrictian at the type locality of the Owl Creek Formation, Mississippi. GSA Abstracts with Programs, 44:398

Macellari CE (1986) Late Campanian-Maastrichtian ammonite fauna from Seymour Island (Antarctic Peninsula). Paleontol Soc Mem 18:1–55

Macellari CE (1988) Stratigraphy, sedimentology, and paleontology of Upper Cretaceous/Paleocene shelf sediments of Seymour Island. In: Feldmann RM, Woodburne MO (eds) Geology and paleontology of Seymour Island, Antarctic Peninsula. GSA Mem. 169, pp 25–53

Machalski M (1998) Granica kreda-trzeciorzęd w przełomie Wisy. Prz Geologiczny 46:1153–1161 (in Polish)

Machalski M (2002) Danian ammonites: a discussion. Bull Geol Soc Den 49:49–52

Machalski M (2005a) The youngest Maastrichtian ammonite faunas from Poland and their dating by scaphitids. Cretac Res 26:813–836

Machalski M (2005b) Late Maastrichtian and earliest Danian scaphitid ammonites from central Europe: taxonomy, evolution, and extinction. Acta Palaeontol Pol 50:653–696

Machalski M (2012) Stratigraphically important ammonites from the Campanian-Maastrichtian boundary interval of the Middle Vistula River section, central Poland. Acta Geol Pol 61:91–116

Machalski M, Walaszczyk I (1987) Faunal condensation and mixing in the uppermost Maastrichtian/Danian greensand (Middle Vistula Valley, central Poland). Acta Geol Pol 37:75–91

Machalski M, Walaszczyk I (1988) The youngest (uppermost Maastrichtian) ammonites in the Middle Vistula Valley, central Poland. Bull Polish Acad Sci Earth Sci 36:67–70

Machalski M, Heinberg C (2005) Evidence for ammonite survival into the Danian (Paleogene) from the Cerithium Limestone at Stevns Klint, Denmark. Bull Geol Soc Den 52:97–111

Machalski M, Jagt JWM, Heinberg C, Landman NH, Håkansson E (2009) Dańskie amonity—obecny stan wiedzy i perspektywy badań. Prz Geol 57:486–493 [in Polish]

Machalski M, Jagt JWM, Alekseev AS, Jagt-Yazykova EA (2012) Terminal Maastrichtian ammonites from Turkmenistan, Central Asia. Acta Palaeontol Pol 57:729–735

Mai H (1998) Paleocene coccoliths and coccospheres in deposits of the Maastrichtian stage and the "type locality" and type area in SE Limburg, The Netherlands. Mar Micropaleontol 36:1–12

Marshall CR, Ward PD (1996) Sudden and gradual molluscan extinctions in the latest Cretaceous in western European Tethys. Science 274:1360–1363

Mathey B (1982) El Cretácico superior de Arco Vasco. In: El Cretácico de España. Universidad Complutense de Madrid, Madrid

Matsumoto T (1938) *Zelandites*, a genus of Cretaceous ammonite. Jpn J Geogr Geol 15:137–148

Matsumoto T (1942) A short note on the Japanese Cretaceous Phylloceratidae. Proc Imp Acad Jpn 18:674–676

Matsumoto T (1979a) Some new species of *Pachydiscus* from the Tobetsu and the Hobetsu valleys. In: Matsumoto T, Kanie Y, Yoshida S (eds) Notes on *Pachydiscus* from Hokkaido, vol 24. Mem Fac Sci Kyushu Univ, Series D, Geology. pp 47–73, 50–64

Matsumoto T (1984) Some gaudryceratid ammonites from the Campanian and Maastrichtian of Hokkaido, Part 1. Sci Rep Yokosuka City Mus 32:1–10

Matsumoto T Yoshida S (1979b) A new gaudryceratid ammonite from the Cretaceous of Hokkaido and Saghalien (Studies of the Cretaceous ammonites from Hokkaido and Saghalien XXXVII). Trans Proc Palaeontol Soc Jpn 114:65–76

Meek FB (1858) Descriptions of new organic remains from the Cretaceous rocks of Vancouver's Island. Transactions of Albany Institute 4, pp 37–49

Miller KG, Sherrell RM, Browning JV, Field MP, Gallagher W, Olsson RK, Sugarman PJ, Tuorto S, Wahyudi H (2010) Relationship between mass extinction and iridium across the Cretaceous-Paleogene boundary in New Jersey. Geology 38:867–870

Molina E, Alegret L, Arenilas I, Arz JA, Gallala N, Hardenbol J von, Salis K, Steurbaut E, Vandenberghe N, Zaghbib-Turki D (2006) The global boundary stratotype section and point for the base of the Danian stage (Paleocene, Paleogene, "Tertiary", Cenozoic) at El Kef, Tunisia—original definition and revision. Episodes 29:263–273

Moriya K, Nishi H, Kawahata H, Tanabe K, Takayanagi Y (2003) Demersal habitat of Late Cretaceous ammonoids: evidence from oxygen isotopes for the Campanian (Late Cretaceous) northwestern Pacific thermal structure. Geology 31:167–170

Morozumi Y (1985) Late Cretaceous (Campanian and Maastrichtian) ammonites from Awaji Island, southwest Japan, vol 39. Osaka Mus Nat Hist 39:1–58

Morton SG (1834) Synopsis of the organic remains of the Cretaceous groups of the United States. Illustrated by nineteen plates, to which is added an appendix containing a tabular view of the Tertiary fossils discovered in America. Key and Biddle, Philadelphia

Moskvin MM (ed) (1959) Atlas of Upper Cretaceous fauna from northern Caucasus and Crimea. Trudy VNIIGAZ, Gostoptechizdat, Moscow (in Russian)

Naidin DP (1987) The Cretaceous-Tertiary boundary in Mangyshlak, U.S.S.R. Geol Mag 124:13–19

Olivero EB (2012) Sedimentary cycles, ammonite diversity and palaeoenvironmental changes in the Upper Cretaceous Marambio Group, Antarctica. Cretac Res 34:348–366

Orbigny AD d' (1850) Prodrome de paléontologie stratigraphique universelle des animaux mollusques et rayonnés 2. Masson, Paris

Perch-Nielsen K (1985) Mesozoic calcareous nannofossils. In: Bolli HM, Saunders JB, Perch-Nielsen K (eds) Plankton stratigraphy. Cambridge University, Cambridge

Peryt D (1980) Planktic foraminifera zonation of the Upper Cretaceous in the Middle Vistula Valley, Poland. Palaeontol Pol 41:3–101

Pervinquière L (1907) Études de paléontologie tunisienne. 1. Céphalopodes des terrains secondaires. Carte Géologique de la Tunisie, Direction Générale des Travaux Publics, De Rudeval, Paris

Preisinger A, Aslanian S, Stoykova K, Grass F, Mauritsch HJ, Scholger R (1993) Cretaceous/Tertiary boundary sections on the coast of the Black Sea near Bjala (Bulgaria). Palaeogeogr Palaeoclimatol Palaeoecol 104:219–228

Racki G, Machalski M, Koeberl C, Harasimiuk M (2011) The weathering-modified iridium record of a new Cretaceous-Paleogene site at Lechówka near Chelm, SE Poland, and its palaeobiologic implications. Acta Palaeontol Pol 56:205–215

Rasmussen JA, Heinberg C, Håkansson E (2005) Planktonic foraminifers, biostratigraphy and the diachronous deposition of the lowermost Danian Cerithium Limestone at Stevns Klint, Denmark. Bull Geol Soc Den 52:113–131

Redtenbacher A (1873) Die Cephalopodenfauna der Gosauschichten in den nordöstlichen Alpen. Abh der KK Geol Reichsanst 5:91–114

Rocchia R, Robin E, Smit J, Pierrard O, Lefevre I (2002) K/T impact remains in an ammonite from the uppermost Maastrichtian of Bidart section (French Basque Country). In: Buffetaut E, Koeberl C (eds) Geological and biological effects of impact events. Springer, Berlin

Salazar C, Stinnesbeck W, Quinzio-Sinn LA (2010) Ammonites from the Maastrichtian (Upper Cretaceous) Quiriquina Formation in central Chile. N Jb Geol Paläontol Abh 257:181–236

Say T (1821) Observations on some species of zoophytes, shells, & etc. principally fossil. Am J Sci 2:34–45

Schiøler P, Brinkhuis H, Roncaglia L, Wilson GJ (1997) Dinoflagellate biostratigraphy and sequence stratigraphy of the Type Maastrichtian (Upper Cretaceous), ENCI Quarry, The Netherlands. Mar Micropaleontol 31:65–95

Schlüter C (1871–1876) Cephalopoden der oberen deutschen Kreide. Palaeontographica 21:1–120; 24:1–144

Schulte P, Alegret L, Arenillas I, Arz JA, Barton PJ, Bown PR, Bralower TJ, Christeson GL, Claeys P, Cockell CS, Collins GS, Deutsch A, Goldin TJ, Goto K, Grajales-Nishimura JM, Grieve RAF, Gulick SPS, Johnson KR, Kiessling W, Koeberl C, Kring DA, MacLeod KG, Matsui T, Melosh J, Montanari A, Morgan JV, Neal CR, Nichols DJ, Norris RD, Pierazzo E, Ravizza G, Rebolledo-Vieyra M, Reimold WU, Robin E, Salge T, Speijer RP, Sweet AR, Urrutia-Fucugauchi J, Vajda V, Whalen MT, Willumsen PS (2010) The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary. Science 327:1214–1218

Seki K, Tanabe K, Landman NH, Jacobs DK (2000) Hydrodynamic analysis of late Cretaceous desmoceratine ammonites. Rev Paléobiol Vol spéc 8:141–155

Seunes J (1890) Contributions à l'étude des cephalopods du Crétacé supérieur de France, 1. Ammonites du Calcaire à Baculites du Cotentin. Mém Soc géol de France. Paléont 1:1–7

Seunes J (1891) Contributions à l'étude des cephalopods du Crétacé supérieur de France, 1. Ammonites du Calcaire à Baculites du Cotentin (Suite). II. Ammonites du Campanien de la region sous-pyrénéenne, Département de Landes. Mém Soc géol de France. Paléont 2:8–22

Smit J, Brinkhuis H (1996) The Geulhemmerberg Cretaceous/Tertiary boundary section (Maastrichtian type area, SE Netherlands); summary of results and a scenario of events. In: Brinkhuis H, Smit J (eds) The Geulhemmerberg Cretaceous/Tertiary boundary section (Maastrichtian type area, SE Netherlands). Geol Mijnbouw 75(2–3):293–307

Smit J, Keller G, Zargouni F, Razgallah S, Shimi M, Ben Abdelkader O, Ben Haj Ali N, Ben Salem H (1997) The El Kef sections and sampling procedures. Mar Micropaleontol 29:65–103

Sowerby J (1812–1822) The mineral conchology of Great Britain. The author, London

Spath LF (1953) The Upper Cretaceous cephalopod fauna of Grahamland. Scientific Reports of the British Antarctic Survey 3:1–60

Stephenson LW (1941) The larger invertebrates of the Navarro Group of Texas (exclusive of corals and crustaceans and exclusive of the fauna of the Escondido Formation). Univ Texas Bull 4101:1–641

Stephenson LW (1955) Owl Creek (Upper Cretaceous) fossils from Crowley's Ridge, southeastern Missouri. USGS Professional Paper 274, 97–140

Stinnesbeck W, Keller G (1996) Environmental changes across the Cretaceous-Tertiary boundary in northeastern Brazil. In: McLeod N, Keller G (eds) Cretaceous-Tertiary mass extinctions: biotic and environmental changes. WW Norton & Co, New York

Stinnesbeck W, Ifrim C, Salazar C (2012) The last Cretaceous ammonites in Latin America. Acta Palaeontol Pol 57:717–728

Stoykova K, Ivanov M (2004) Calcareous nannofossils and sequence stratigraphy of the Cretaceous/Tertiary transition in Bulgaria. J Nannoplankton Res 26:47–61

Stoykova K, Ivanov M (2005) Calcareous nannofossils and sequence stratigraphy of the Cretaceous/Tertiary transition in Bulgaria (Errata). J Nannoplankton Res 27:99–106

Surlyk F (1997) A cool-water carbonate ramp with bryozoan mounds: Late Cretaceous-Danian of the Danish Basin. In: James NP, Clarke JDA (eds) Cool-water carbonates, vol 56. SEPM Special Publications, pp 293–307

Surlyk F, Nielsen JM (1999) The last ammonite? Bull Geol Soc Den 46:115–119

Surlyk F, Damholt T, Bjerager M (2006) Stevns Klint, Denmark: uppermost Maastrichtian chalk, Cretaceous-Tertiary boundary, and lower Danian bryozoan mound complex. Bull Geol Soc Den 54:1–48

Tanabe K (1989) Endocochliate embryo model in the Mesozoic Ammonitida. Hist Biol 2:183–196

Tanabe K, Landman NH (2002) Morphological diversity of the jaws of Cretaceous Ammonoidea. In: Summesberger H, Histon K, Daurer A (eds) Cephalopods-present and past. Abh Geol B-A 57:157–165

Tanabe K, Misaki A, Landman NH, Kato T (2013) The jaw apparatuses of Cretaceous Phylloceratina (Ammonoidea). Lethaia 46:399–408

Ten Kate WGHZ, Sprenger A (1993) Orbital cyclicities above and below the Cretaceous/Paleogene boundary at Zumaya (N Spain), Agost and Relleu (SE Spain). Sediment Geol 87:69–101

Tobin TS, Ward PD, Steig EJ, Olivero EB, Hilburn IA, Mitchell RN, Diamond MR, Raub TD, Kirschvink JL (2012) Extinction patterns, $\delta^{18}O$ trends, and magnetostratigraphy from a southern high-latitude Cretaceous-Paleogene section: links with Deccan volcanism. Palaeogeogr Palaeoclimatol Palaeoecol 350–352:180–188

Tuomey M (1856) Description of some new fossils from the Cretaceous rocks of the southern States. Proc Acad of Natl Sci Phila 7(1854):167–172

Van der Tuuk LA, Zijlstra JJP (1979) Eerste vondst van een *Nostoceras* [sic] (orde Ammonoidea) in Nederland. Grondboor Hamer 33:116–120

Vellekoop J, Sluijs A, Smit J, Schouten S, Weijers JWH, Sinninghe Damste JS, Brinkhuis H (2014) Rapid short-term cooling following the Chicxulub impact at the Cretaceous-Paleogene boundary. Proc Natl Acad of Sci U S A 111:7531–7541

Wang SC, Marshall CR (2004) Improved confidence intervals for estimating the position of a mass extinction boundary. Paleobiology 30:5–18

Ward PD (1996) Ammonoid extinction. In: Landman NH, Tanabe K, Davis RA (eds) Ammonoid paleobiology. Plenum, New York

Ward PD, Kennedy WJ (1993) Maastrichtian ammonites from the Biscay region (France, Spain). Paleontol Soc Mem 34:1–58

Ward PD, Signor PW III (1983) Evolutionary tempo in Jurassic and Cretaceous ammonites. Paleobiology 9:183–198

Westermann GEG (1996) Ammonoid life and habitat. In: Landman NH, Tanabe K, Davis RA (eds) Ammonoid paleobiology. Plenum, New York

Wiedmann J (1987) The K/T Boundary section of Zumaya, Guipuzcoa. In: Lamolda MA (ed) Field excursion to the K/T boundary at Zumaya and Biarritz. Paleontología et Evolutío: exstinctionis phaenomina III. Journados de Paleontología. Keia (Vizcaya), Octobre de 1987, Univ de Païs Vasco, Bilbao

Wiedmann J (1988a) Ammonite extinction and the "Cretaceous-Tertiary Boundary Event". In: Wiedmann J, Kullmann J (eds) Cephalopods—present and past. Schweizerbart, Stuttgart

Wiedmann J (1988b) The Basque coastal sections of the K/T Boundary—a key for understanding "mass extinction" in the fossil record. Rev Esp Paleont, no. extraord 1988:127–140

Yazykova EA (1991) Maastrichtian ammonoids of the eastern USSR and their stratigraphical significance. Bull MOIP Geol 66:68–73 [In Russian]

Yazikova EA (1994) Maastrichtian ammonites and biostratigraphy of the Sakhalin and Shikotan islands, Far Eastern Russia. Acta Geol Pol 44:277–303

Yazykova EA (2004) Ammonite biozonation and litho-chronostratigraphy of the Cretaceous in Sakhalin and adjacent territories of Far East Russia. Acta Geol Pol 54:273–312

Zijlstra JJP (1994) Sedimentology of the Late Cretaceous and Early Tertiary (tuffaceous) chalk of northwest Europe. Geol Ultraiect 119:1–192

Zinsmeister WJ (1998) Discovery of fish mortality horizon at the K-T boundary on Seymour Island: re-evaluation of events at the end of the Cretaceous. J Paleontol 72:556–571

Zinsmeister WJ, Feldmann RM (1996) Late Cretaceous faunal changes in the high southern latitudes: a harbinger of global biotic catastrophe? In: MacLeod N, Keller G (eds) Cretaceous-Tertiary mass extinctions: biotic and environmental changes. WW Norton, New York

Zinsmeister WJ, Woodburne O, Elliot DH (1989) Latest Cretaceous/earliest Tertiary transition on Seymour Island, Antarctica. J Paleontol 63:731–738

Zonova TD, Kazintsova LT, Yazykova EA (1993) Atlas of the main groups of the Cretaceous fauna from Sakhalin. Nedra, Sankt Peterburg (In Russian)