GSA DATA REPOSITORY 2014264

Ammonite Extinction and Nautilid Survival at the End of the Cretaceous

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DESCRIPTION OF SITES

We recognize 29 sites (Fig. 1; Table DR1) in which ammonites (and, occasionally, *Eutrephoceras*) occur in the last 0.5 my of the Maastrichtian. Below, we list the localities and the data we relied upon to demarcate our target interval–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 Zumaya, Kalaat Senan, and, in part, in the Maastrichtian type area, cyclostratigraphy allowed direct placement of the lower limit of our targeted interval. 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 k.y. (Hennebert, 2012) to 530 k.y. (Dinarès-Turell et al., 2013) before the end of the Cretaceous (see also Gardin et al., 2012). This zone 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 palpebra* CF2 Zone, and possibly also the upper part of the *Pseudoguembelina fructicosa* CF3 Zone. The base of CF1 is ~0.23 myr prior to the K/Pg boundary, according to Hennebert and Dupuis (2003).

Site 1: Manasquan River Basin, Monmouth County, New Jersey, U.S.A

References: Landman et al., 2007; Landman et al., 2012
Biotratigraphy: *Discoscaphites iris* Ammonite Assemblage Zone, which correlates with Calcareous Nannofossil Zone CC26b.
Location: 40°12′30’’N, 74°17′30’’W

Site 2: Northeastern Monmouth County, New Jersey, U.S.A

References: Landman et al., 2004b
Biotratigraphy: *Discoscaphites iris* Ammonite Assemblage Zone, which correlates with Calcareous Nannofossil Zone CC26b.
Location: 40°17′30’N, 74°7′14’’W

Site 3: Round Bay, Anne Arundel County, Maryland, U.S.A

References: Landman et al., 2004a
Biotratigraphy: *Discoscaphites iris* Ammonite Assemblage Zone, which correlates with Calcareous Nannofossil Zone CC26b.
Location: 39°2′13’’N, 76°33′28’’W

Site 4: Stoddard and Scott Counties, Missourri, U.S.A

References: Stephenson, 1955; Landman et al., 2007
Biotratigraphy: *Discoscaphites iris* Ammonite Assemblage Zone, which correlates with Calcareous Nannofossil Zone CC26b.
Location: 37°00′17’’N, 89°51′02’’W

Site 5: Tippah County, Mississippi, U.S.A

References: Kennedy and Cobban, 2000: Landman et al., 2007
Biotratigraphy: *Discoscaphites iris* Ammonite Assemblage Zone, which correlates with Calcareous Nannofossil Zone CC26b.
Location: 34°44′55’’N, 88°54′47’’W

Site 6: Chickasaw County, Mississippi, U.S.A

References: Landman et al., 2007; Boas et al., 2013
Biotratigraphy: *Discoscaphites iris* Ammonite Assemblage Zone, which correlates with Calcareous Nannofossil Zone CC26b.
Location: 33°58′04”N, 89°00′05”W

Site 7: Brazos River, Texas, U.S.A.

References: Hansen et al., 1987; Kennedy et al., 2001; Keller et al., 2009; Hart et al., 2012
Biotratigraphy: *Discoscaphites iris* Ammonite Assemblage Zone, which correlates with Calcareous Nannofossil Zone CC26b.
Location: 31°8′11’’N, 96°49′40’’W

Site 8: La Popa Basin, Northeastern Mexico

References: Ifrim and Stinnesbeck, 2010; Stinnesbeck et al., 2012
Biotratigraphy: According to Stinnesbeck et al. (2012: Table 1), the ammonites occur in Planktic Foraminiferal Zone CF3. The record of *Baculites* is from the Middle Siltstone Member of the PotrerillosFormation.
Location: 26°12′44’’N, 101°4′25’’W

Site 9: Stevns Klint, Denmark

References: Birkelund, 1993; Schiøler et al., 1997; Machalski, 2005a, b; Machalski and Heinberg, 2005; Surlyk et al., 2006, Hart et al., 2011; Rasmussen et al., 2005; Damholt and Surlyk, 2012; Gravesen and Jakobsen, 2012
Biotratigraphy: Specimens are from the Højerup Member, which corresponds to the uppermost Maastrichtian *Stensioeina esnehensis* Foraminiferal Zone. They are derived from levels directly below the K/Pg boundary clay with no visible breaks between them and the boundary clay. One may safely assume that they correspond to the *Micula prinsii* zone.
Location: 55°16′45′′N, 12°26′47′′E

Site 10: Kjølby Gård, Denmark

References: Birkelund, 1993
Biotratigraphy: The ammonites occur up to 20 cm below the base of the Danian.
Location: 57°3′15′′N, 8°44′55′′E

Site 11: "Dania" Quarry, northern Denmark

References: Hansen, 1977; Haakanssan and Hansen, 1979; Birkelund, 1993; Machalski, 2005a, b; Gravesen and Jakobsen, 2012
Biostratigraphy: Specimens are from the *stevensis-chitoniformis* Brachiopod Zone, which correlates with the *Palynodinium grallator* Dinoflagellate Zone. The sequence at "Dania" is unique among Danish boundary sequences by containing the topmost Maastrichtian zonal species *Micula prinsii*. It was recorded from 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)
Location: 56°39′42′′N, 10°1′56′′E

Site 12: Maastrichtian Type Area, The Netherlands and Belgium

References: Zijlstra, 1994; Smit and Brinkhuis, 1996; Schiøler et al., 1997; Mai, 1998; Jagt, 1996, 2002; Jagt et al., 2003, 2006; Jagt and Jagt-Yazykova, 2012
Biotratigraphy: 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. The clay beds just above the Berg en Terblijt Horizon at the base of the IVf-7 interval (Meerssen Member) are assigned to Planktic Foraminiferal Zone P0. The targeted interval was bracketed by using the Berg en Terblijt Horizon as the K/Pg boundary level and by using the cyclostratigraphic interpretation of Zijlstra (1994) and Schiøler et al. (1997) to define the lower part of the interval. Zijlstra (1994) stated that the Meerssen and Nekum members were deposited in a time frame of 300 k.y., and the lower part of the Maastricht Formation in another 400 k.y. We used occurrences from only the Meerssen and Nekum members. In terms of dinoflagellate zonation, this interval (upper Nekum and Meerssen members) corresponds to the Donoflagellate *Palynodinium*

grallator Zone, and the Meerssen Member to the Dinoflagellate *Thalassipora pelagica* Subzone (e.g., Mai, 1998).
Location: 50°49′18.41′′N, 5°41′39.54′′E

Site 13: Nasiłów, Poland

References: Łopuski, 1912; Kongiel and Matwiejówna, 1937; Hansen et al., 1989; Machalski, 2005a
Biotratigraphy: Specimens are derived from a K/Pg boundary section with a "large" hiatus, *Belemnella kazimiroviensis* Belemnite Zone, Magnetic Chron C29r, and lower part of the Dinoflagellate *Palynodinium grallator* Zone. A K/Pg boundary interval similar to that of Nasiłów is exposed nearby, on the opposite side of the Wisła River at Bochotnica.
Location: 51°20′39′′N, 21°57′35′′E

Site 14: Mełgiew, Poland

References: Machalski, 2005a
Biotratigraphy: The hiatus in this section is smaller than that at Nasiłów, as indicated by the presence of chrono-subspecies *Hoploscaphites constrictus johnjagti*.
Location: 51°13′30′′N, 22°47′8′′E

Site 15: Lechówka, Poland
References: Łopuski, 1912; Kongiel and Matwiejówna, 1937; Peryt, 1980; Racki et al., 2011
Biostratigraphy: Ammonites occur just below the iridium spike in the top of the Planktic Toraminiferal *Guembelitria cretacea* Zone *sensu* Peryt (1980). This zone encompasses almost the entire upper Maastrichtian.
Location: 51°10′17′′N, 23°14′43′′E

Site 16: Kyzylsay, Kazakhstan

References: Naidin, 1987; Herman et al., 1988; Jeffrey, 1997
Biostratigraphy: *Belemnella kazimiroviensis* Belemnite Zone. The ammonites occur directly below the iridium-bearing boundary clay, with no signs of any breaks.
Location: 44°20′1′′N, 52°26′10′′E

Site 17: Sumbar River, Turkmenistan

References: Moskvin, 1959; Alekseev et al., 1988; Machalski et al., 2012
Biostratigraphy: All specimens except one ammonite occurs in the topmost part of the Maastrichtian. An iridium anomaly is present at the K/Pg boundary. The Maastrichtian ammonites are from the Planktic Foraminiferal *Pseudotextularia elegans* Zone.
Location: 38°27′18′′N, 56°12′41′′E

Site 18: Zumaya, Bay of Biscay Area

References: Wiedmann, 1988; Ward and Kennedy, 1993; Batenburg et al., 2012; Dinarès-Turell et al., 2013
Biostratigraphy: Using the cyclostratigraphic studies of Batenburg et al. (2012) and Dinarès-Turell et al. (2013), our targeted interval (uppermost 0.5 myr of the Maastrichtian) seems to correspond to the top 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 on Ward and Kennedy (1993: fig. 5) cannot be situated more precisely than 1 m. The base of Member V is ~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 equates to ~20 m 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 topmost 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).
Location: 43°17′54′′N, 2°16′16′′W

Site 19: Hendaye, Bay of Biscay Area

References: Ward and Kennedy, 1993
Biostratigraphy: Ammonites occur in the uppermost 1 m of Member IV and entire Member V of Ward and Kennedy (1993). See explanation for Zumaya.
Location: 43°23′1′′N, 1°49′′26′′W

Site 20: Bidart, Bay of Biscay Area

References: Ward and Kennedy, 1993; Rocchia et al., 2002
Biostratigraphy: Ammonites occur in the uppermost 1 m of Member IV and the entire Member V of Ward and Kennedy (1993). See explanation for Zumaya.
Location: 43°26′25′′N, 1°35′41′′W

Site 21: Bjala (= Byala), Bulgaria

References: Preisinger et al., 1993; Ivanov and Stoykova, 1994; Ivanov, 1995; Stoykova and Ivanov, 2004, 2005
Biostratigraphy: The ammonites occur in Calcareous Nannofossil Zone CC26b.
Location: 42°5244′′N, 27°53′57′′E

Site 22: Kalaat Senan, Tunisia

References: Hennebert and Dupuis, 2003; Goolaerts, 2010; Hennebert, 2012
Biostratigraphy: Specimens occur in the *Indoscaphites pavana* Ammonite Assemblage Zone of Goolaerts (2010), which represents approximately the last 420 k.y. of the Maastrichtian, based on the cyclostratigraphy of Hennebert and Dupuis (2003) and Hennebert (2012).
Location: 35°47′15′′N, 8°27′21′′E

Site 23: El Kef, Tunisia

References: Goolaerts et al., 2004; Goolaerts, 2010
Biostratigraphy: Ammonites occur in the uppermost 12 m of the Maastrichtian of the GSSP for the K/Pg boundary, *Indoscaphites pavana* Ammonite Assemblage Zone.
Location: 36°9′15′′N, 8°38′55′′E

Site 24: Garn Halfaya, Tunisia

References: Goolaerts, 2010
Biostratigraphy: Ammonites occur in the uppermost 8 m of the Maastrichtian of the Garn Halfaya K/Pg boundary section, *Indoscaphites pavana* Ammonite Assemblage Zone.
Location: 36°0′40′′N, 8°33′23′′E

Site 25: Dababiya Quarry Corehole, Egypt

References: Goolaerts and Dupuis, 2012; Berggren and Ouda, 2012; Berggren et al., 2012
Biostratigraphy: Specimens occur within Calcareous Nannofossil Zone CC26b.
Location: 25°30′10′′N, 32°31′27′′E

Site 26: Naiba River Valley, Sakhalin, Far East Russia

References: Yazykova in Zonova et al., 1993; Yazikova, 1994; Yazykova, 1991, 2004; Jagt-Yazykova, 2011, 2012
Biostratigraphy: 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 ~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*.
Location: 47°28′34′′N, 142°24′10′′E

Site 27: Poty quarry, Brazil

References: Stinnesbeck et al., 2012
Biostratigraphy: Ammonites occur 100 and 80 cm below the K/Pg boundary, Planktic Foraminiferal *Plummerita hantkeninoides* CF1 Zone.
Location: 7°53′95′′S, 34°51′14′′W

Site 28: Lomas Colorados, Bajada de Jagüel, Neuquen Basin, Argentina

References: Stinnesbeck et al., 2012
Biostratigraphy: Ammonites occur in Planktic Foraminiferal *Pseudoguembelina palpebra* CF2 Zone.
Location: 37°59′24′′S, 68°47′38′′W

Site 29: Seymour Island, Antarctica

References: Macellari 1986, 1988; Elliot et al., 1994; Zinsmeister, 1998; Zinsmeister et al., 1989; Zinsmeister and Feldmann, 1996; Tobin et al., 2012; pers. comm., J.D. Witts, 2014
Biostratigraphy: K/Pg boundary interval with iridium anomaly (Elliot et al., 1994). All taxa occur in the *Pachydiscus ultimus* Ammonite Zone of Macellari (1986) and within Magnetic Chron C29r (Tobin et al., 2012).
Location: 64°16′50′′S, 56°43′23′′W

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Table DR1. Geographic distribution of 31 ammonite genera and 1 nautilid genus *Eutrephoceras* at 29 sites in the last 0.5 my of the Cretaceous.

		ATLANTIC COAST			GULF COAST					DENMARK			MA	POLAND				KA	TR	BISCAYE REGION			BU	TUNISIA			EG	FER	SOUTH AMERICA		AN	
	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	*Grossouvrites*																													1	1
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
30	*Acanthoscaphites*												1																		1
31	*Discoscaphites*	1	1	1	1	1	1	1																							7
32	*Eutrephoceras*	1	1	0	1	1	0	0	0	1	0	1	1	1	0	1	0	1	0	0	0	0	1	0	0	0	0	0	0	1	12

The genera represent all four orders of Cretaceous ammonoids: Phylloceratina (1-2), Lytoceratina (3-9), Ammonitina (10-20), and Ancyloceratina (21-31). For a description of localities, see the text of the Data Repository.
Abbreviations: MA: Maastrichtian type area, The Netherlands and Belgium; KA: Kazakhstan; TR: Turkmenistan; BU: Bulgaria; EG: Egypt; FER: Far East Russia; AN: Antarctica.

Table DR2. As described in the main text, the locality data were rotated to 70 Ma paleopositions and projected onto a Molleweide equal area projection. Two methods of quantifying geographic ranges were used. Geographic area was measured as the area of a convex hull that encompassed the localities for each genus. Maximum distances spanning localities for each genus were also computed. These values were then $\log_{10}$-transformed.

Genus	Geogr. Area (km^2)	Max. Distance (km)	$\log_{10}$(Geogr. Area)	$\log_{10}$(Max. Distance)
NON-SURVIVORS				
Vertebrites	10	1	1.00	0.00
Desmophyllites	10	1	1.00	0.00
Pseudokossmaticeras	10	1	1.00	0.00
Grossouvrites	10	1	1.00	0.00
Maorites	10	1	1.00	0.00
Kitchinites	10	1	1.00	0.00
Nostoceras	10	1	1.00	0.00
Acanthoscaphites	10	1	1.00	0.00
Hauericeras	31	45	1.49	1.65
Fresvillia	31	45	1.49	1.65
Tetragonites	45	45	1.65	1.65
Glyptoxoceras	6954	6954	3.84	3.84
Gaudryceras	9971	9971	4.00	4.00
Phyllopachyceras	37539	1489	4.57	3.17
Indoscaphites	63444	2866	4.80	3.46
Discoscaphites	398247	2438	5.60	3.39
Phylloptychoceras	569500	2597	5.76	3.41
B. (*Brahmaites*)	687988	2142	5.84	3.33
Saghalinites	1281441	2742	6.11	3.44
Sphenodiscus	3065897	8867	6.49	3.95
Menuites	3804168	2742	6.58	3.44
H. (*Neophylloceras*)	13435258	9971	7.13	4.00
P. (*Neodesmoceras*)	17801251	15225	7.25	4.18
Anagaudryceras	52103728	19076	7.72	4.28
Zelandites	52103728	19076	7.72	4.28
SURVIVORS				
Hoploscaphites	2238229	4390	6.35	3.64
Pseudophyllites	14852118	12420	7.17	4.09
Baculites	29827374	11779	7.47	4.07
Eubaculites	33776401	11211	7.53	4.05
Diplomoceras	58481713	19076	7.77	4.28
Eutrephoceras	67927054	14004	7.83	4.15
P. (*Pachydiscus*)	95264874	19076	7.98	4.28