Paleoenvironmental changes across the Cretaceous–Tertiary boundary at Koshak, Kazakhstan, based on planktic foraminifera and clay mineralogy

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Abstract

The Koshak section of the Mangyshlack Peninsula, Kazakhstan, is one of the most complete Cretaceous–Tertiary (K–T) transitions known from the boreal Paratethys. Cretaceous species richness is low (11 to 13 species), except for a peak of 20 species near the K/T boundary in the uppermost Maastrichtian (top 50 cm) that represents the temporary incursion of low-latitude taxa. This maximum species richness occurred during climatic warming associated with increased humidity, as suggested by clay mineral analyses. Biofacies analysis suggests external platform conditions at this time, followed by a more humid climate, a sea-level transgression, and deepening basinal facies in the lower Danian Subzone P1a. Shallower platform conditions resumed in Danian Subzones P1b and P1c, accompanied by a cooler and probably more arid climate. No abrupt mass extinction occurred at the Koshak K/T boundary which is marked by an Ir anomaly, a clay layer and the first appearance of Tertiary planktic foraminifera. The influx of lower-latitude species ends at or before the K/T boundary, whereas the majority of the indigenous Cretaceous assemblage survived into the Danian. These data suggest that long-term climatic changes may have been the principal factors in the progressive demise of the Cretaceous planktic foraminifera in the eastern boreal Paratethys. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Kazakhstan; K/T boundary; planktic foraminifera; clay minerals

1. Introduction

Planktic foraminifera suffered the most dramatic mass extinction of all marine organisms across the Cretaceous–Tertiary (K–T) transition; this mass extinction was associated with a 2–3‰ drop in surface $\delta^{13}C$ values that suggests a dramatic decline in surface water productivity (Zachos and Arthur, 1986; Zachos et al., 1989, 1992; Keller and Lindinger, 1989; Barrera and Keller, 1990). However, there is less consensus as to the nature and tempo of the mass extinction or the $\delta^{13}C$ shift, and whether these were geographically restricted or global. Some workers hypothesize the sudden extinction of nearly all planktic foraminifera species at the Cretaceous/Tertiary (K/T) boundary in a worldwide catastrophe as a result of a bolide impact (Alvarez et al., 1980; Smit, 1982, 1990; Smit et al., 1992; Liu and Olsson, 1992; Olsson and Liu,

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1993; Peryt et al., 1993; Arz et al., 1999). An alternative scenario suggests a more progressive and multi-causal mass extinction as a result of a confluence of environmental and climatic factors during the latest Maastrichtian including rapid climate warming followed by rapid cooling during the last 400 kyr of the Maastrichtian (Li and Keller, 1998a,b). This would have led to highly stressful conditions for marine biotas, particularly in low latitudes where specialized tropical–subtropical organisms are more vulnerable to environmental changes. A bolide impact superimposed over these already stressful environmental conditions could have been the proverbial 'straw that broke the camel's back' as suggested by a number of studies (e.g., Keller, 1988, 1989a,b, 1996; Canudo et al., 1991; Rohling et al., 1991; Schmitz et al., 1992; Keller et al., 1993, 1994, 1996; Pardo et al., 1995, 1996; Askin and Jacobson, 1996; Pardo, 1996; Lopez Oliva and Keller, 1996a,b; Stinnesbeck, 1996; Zinsmeister and Feldmann, 1996).

The current global database shows that both scenarios are associated with some degree of progressive and selective extinctions. For instance, planktic foraminifera in low to middle latitudes indicate that large, ornate, tropical to subtropical taxa disappeared first and that smaller, unornamented, cosmopolitan and opportunistic taxa survived into the Danian (Keller, 1988, 1989a,b, 1993, 1996; MacLeod and Keller, 1994; MacLeod, 1994, 1995; Keller et al., 1994, 1996; Pardo et al., 1996; Pardo, 1996). The pattern of the K/T mass extinction in low latitudes suggests that about 10% of the species disappeared below the K/T boundary, 50–60% disappeared at or near the K/T boundary, and about 30% ranged into the Paleocene (see also blind test results of Masters, 1997; Canudo, 1997; Orue-etxebarria, 1997). This species extinction pattern is restricted to low and middle latitudes where it is accompanied by a 2–3 permil shift in $\delta^{13}C$ values.

In higher latitudes, such as Nye Kløv (Denmark) and ODP Site 738 (Indian Antarctic Ocean) no sudden mass extinction is observed at the K/T boundary by Keller (1993) and Keller et al. (1993) and nearly all species survived well into the early Danian. Perhaps this is not surprising, because the tropical–subtropical taxa which disappeared in low latitudes are absent and only ecological generalists and cosmopolitan survivors are present. However, their exclusion in high latitudes is not the only reason for the diminished kill-effect. Environmental changes also appear significantly dampened. This is especially observed in the highly reduced or even absent $\delta^{13}C$ shift, which suggests that the productivity decrease was largely restricted to low latitudes (2–3‰ in low latitudes, but only 0.5–1‰ in high latitudes; Keller et al., 1993; Barrera and Keller, 1994; Oberhänsli et al., 1998).

Our database of the high-latitude faunal, climatic and oceanographic responses to the K–T transition is still very limited. Initial studies at Nye Kløv and ODP Site 738 strongly indicate that the low-latitude extinction and isotopic records have been erroneously assumed to reflect global conditions. In this study we examine the boreal Paratethys K/T section at Koshak, Kazakhstan (Fig. 1), to gain further insight into the climatic and environmental changes and their effects on planktic foraminifera. Specifically we examine: (1) biofacies to infer sea-level changes, (2) biotic turnover in planktic foraminifera to evaluate the nature and tempo of the mass extinction, (3) the biotic effects of shallow depth and latitude by comparing faunal assemblages at shallow neritic sections from Tunisia, Texas, Denmark, Kazakhstan and Site 738, (4) the Signor–Lipps effect and reworking on high-latitude assemblages, and (5) whole rock and clay mineral contents of the sediments in order to determine changes in terrigenous detrital influx and clay mineral ratios that may indicate changes in sea level and climate.

2. Location, lithology and biofacies

The Koshak section is located in the Aktau Mountains of the Mangyshlack Peninsula, Kazakhstan (44.5°N, 51°E; Fig. 1). The outcrop is located on the northern slope of the North Aktau Mountains and spans over 140 m of Maastrichtian marls and 60 m of Danian limestones (Sarkar et al., 1992). A 1-cm-thick finely laminated and bioturbated dark clay layer marks the K/T boundary (K/T b in Fig. 2). Lithologically, the section changes from a fine-grained friable chalk in the upper Maastrichtian, to a thin dark clay layer at the K/T boundary followed by a lithified chalk and micritic limestones in the lower Danian (Fig. 3). Danian sediments are characterized
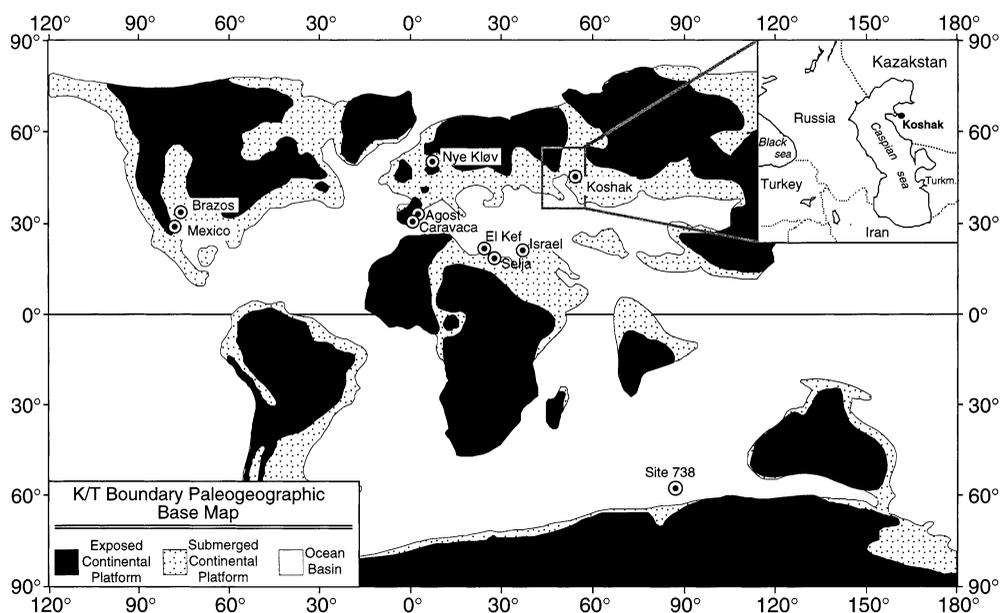
Fig. 1. Location of Koshak K/T section in Kazakhstan and the location of other K/T boundary sections discussed. The paleogeographic reconstruction at the K/T boundary time is based on MacLeod and Keller (1994).

by numerous hard-ground surfaces which indicate reduced sedimentation or hiatuses. Naidin (1987) has discussed the presence of two types of K/T boundary lithologies in the region, one characterized by clay and the other by a hardground surface (see also Naidin, 1996, 1997). Faunal and sedimentary characteristics suggest that deposition occurred in a shallow epicontinental sea relatively distant from terrigenous influx and at a water depth between 100 and 200 m. The outcrop is rich in echinoid fossils such as *Echinocorys* spp., *Phymosoma granulosum* and *Cyclaster danicus* (Sarkar et al., 1992; Jeffery, 1997).

Three biofacies have been recognized by thin section analysis. The uppermost Maastrichtian sediments consist of friable chalk with abundant echinoids, corals, bivalves, benthic foraminifera and some baculites (Fig. 3). This biofacies suggests external platform conditions and a depth of 100 m or less. Beginning about 40 cm below the K/T boundary, the clay content in chalks increases and suggests a wetter climate as indicated by the increased kaolinite, or deepening. This trend continues across the K/T boundary and reaches its maximum in the lower Danian (Subzone P1a) as indicated by deposition of a

muddy basinal biofacies with abundant calcispheres and planktic foraminifera. Moreover, this deepening tendency during the K/T transition is also reflected by a turnover in the echinoid fauna (Jeffery, 1997). In the upper part of Subzone P1a, the mud/clay content decreases. Upsection (Subzone P1c) the presence of limestones with abundant echinoids, bivalves, coccoliths and foraminifera indicates re-establishment of outer platform conditions (Fig. 3).

3. Methods

The section was trenched to remove surface contamination and to obtain fresh unweathered bedrock for a 5-m interval spanning the K/T boundary clay layer. Samples were collected at 5-cm intervals from 50 cm below to 50 cm above the clay layer, at 10-cm intervals from 50 cm to 200 cm and at 20-cm intervals from 200 cm to 300 cm above the clay layer. Few samples were taken in the upper Maastrichtian sediments below the −50-cm interval.

For foraminiferal analysis the samples were disaggregated in tap water overnight. Each sample was cleaned with ultrasonic agitation during repeated
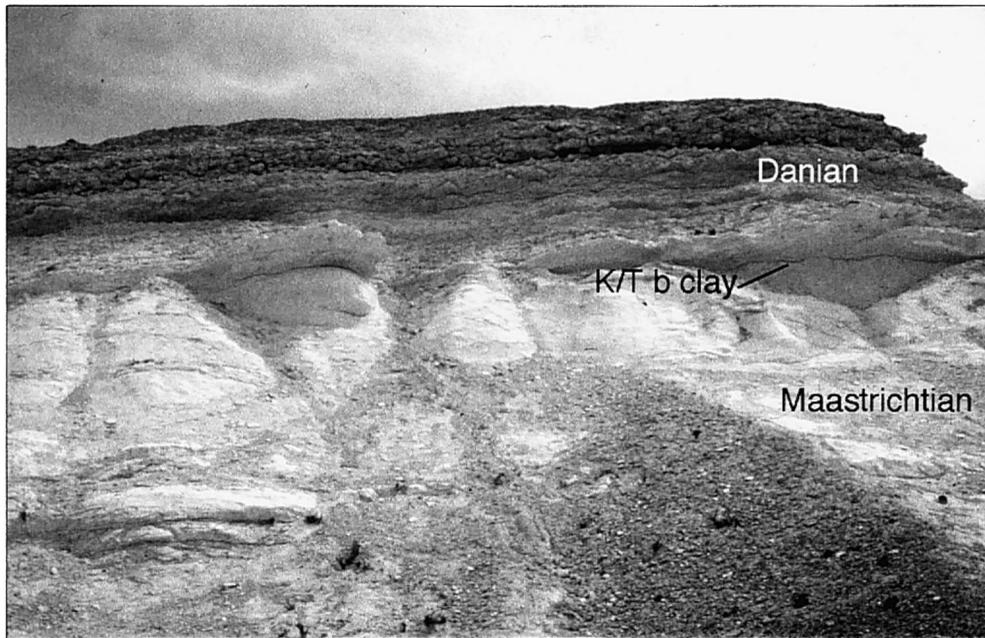
Fig. 2. Photo of the Cretaceous–Tertiary (K–T) transition at the Koshak section in the Aktau Montains, Kazakhstan. *K/Tb* = K/T boundary.
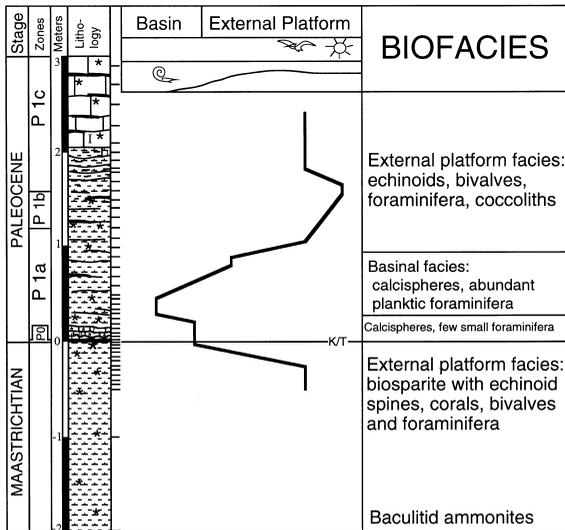

Fig. 3. Biofacies evolution across the K/T transition at Koshak, Kazakhstan. The key to lithological symbols is given in Fig. 6.

10- to 15-s intervals and washed through a 38-μm screen. The washed residue was dried in an oven at temperatures below 50ºC. Planktic and benthic fora-

miniferal shells are well preserved although original calcite shells are partly recrystallized. Above the K/T boundary, some sample intervals show strong dissolution with only few foraminifera preserved. Quantitative studies are based on population counts of 250–300 specimens, where possible, from the >38-μm size fraction picked from aliquots of representative random splits using an Otto microsplitter. Where foraminiferal abundance is low, population counts are based on a minimum of 100 specimens (note that 9 out of 32 samples above the K/T boundary have fewer than 100 specimens). However, because species richness is low, with only 7 to 15 species per sample, representative species abundance data can be obtained from 100 specimens (Buzas, 1990). For each sample, planktic foraminifera were picked from the aliquot and mounted on microslides for a permanent record and identified. The remaining sample was searched for rare species. Relative abundance data of planktic foraminifera are listed in Table 1. SEM photomicrographs of planktic foraminifera where taken in the Servicio de Microscopía Electrónica at the Universidad de Zaragoza, Spain, by means of a JEOL JSM 6400 SEM, and are shown

in Plates I–IV. Whole rock and clay mineral analyses were carried out at the Geological Institute of the University of Neuchâtel. Samples where prepared after the methods described in Adatte et al. (1996).

4. Biostratigraphy

Biostratigraphy of the Koshak section is based on the biozonation of Keller (1993) with the addition of the *Plummerita hantkeninoides* Zone to mark the last 170–200 kyr of the Maastrichtian (Pardo et al., 1996; Fig. 4). However, it was not possible to zone the uppermost Maastrichtian at Koshak based on *P. hantkeninoides*, which is a low-latitude index species and not present at Koshak. Nevertheless, there is no indication that the uppermost Maastrichtian is missing in this section.

The K/T boundary at the Koshak section can be identified by the same lithological, geochemical and planktic foraminiferal criteria as at the El Kef stratotype section (Keller et al., 1996; Fig. 5). The following boundary markers have been identified: (a) a 1-cm-thick laminated clay layer that represents a condensed Zone P0 interval, (b) an iridium anomaly occurring within the clay layer (Sarkar et al., 1992), and (c) the appearance of the first Tertiary planktic foraminifera 2.5 cm above the clay layer and marking the P0/P 1a boundary (i.e., *Eoglobigerina eobulloides*, *E. fringa*, *Parvularugoglobigerina longiapertura*, *P. eugubina*, *Woodringina claytonensis* and *W. hornerstownensis*; Plate IV).

Subzone P1a spans the total range interval of *P. longiapertura* and/or *P. eugubina* (Canudo et al., 1991; Keller, 1993; Pardo et al., 1996). At Koshak these species range from 2.5 cm to 120 cm above the K/T boundary. The first Danian evolutionary diversification occurs within this interval (e.g., *Chiloguembelina crinita*, *C. midwayensis*, *Eoglobigerina eobulloides*, *E. fringa*, *Globanomalina planocompressa*, *Globastica daubjergensis*, *Subbotina pseudobulloides*, *Woodringina claytonenis*, *W. hornerstownensis* and *Zeauvigerina teuria)*. Several Maastrichtian survivor species disappear in P1a (e.g., *H. holmdelensis, H. globulosa* and *H. complanata*, Fig. 6).

Subzone P1b spans the interval from the last appearance (LA) of *P. eugubina* and/or *P. longiapertura* to the first appearance (FA) of *Subbotina*

varianta. At Koshak, P1b spans 120 cm to 160 cm above the K/T boundary.

Subzone P1c spans the interval from the FA of *S. varianta* to the FA of *Morozovella trinidadensis*. At Koshak, several Maastrichtian species disappear in P1c (e.g., *G. cretacea, G. danica* and *H. dentata*; Fig. 6).

5. Faunal turnover

The Koshak section has late Maastrichtian and early Danian planktic foraminiferal assemblages characterized by very small specimen sizes (38–100 μm) and low Maastrichtian species diversity (11–13 species). The Maastrichtian assemblage between 50 cm and 2 m below the K/T boundary is poorly constrained, because few samples were available for this study. However, these samples contain primarily biserial and triserial morphotypes with *Chiloguembelina waiparaensis* the dominant taxon (∼50%, Fig. 6; Plate II, figs. 1–4). This suggests the presence of a typical boreal and oligotaxic surface assemblage with eleven species of small test size and cosmopolitan distribution dominated by chiloguembelinids, heterohelicids, guembelitrids and hedbergellids (Fig. 6; see Jackson, 1997, for the definition of the boreal climatic zone and its latitudinal span). Note that *Chiloguembelina waiparaensis* was originally considered a Danian species (Jenkins, 1971), but was later found to be common in latest Maastrichtian sediments at higher latitudes (Keller, 1993).

Higher sample resolution is available for the top 50 cm of the Maastrichtian. Faunal assemblages in this interval contain nine lower-latitude species (i.e., globotruncanids and globotruncanellids, Fig. 6). A similar temporary influx of lower-latitude species was observed in the Danish sections and related to climate warming and/or a sea-level transgression (Schmitz et al., 1992; Keller et al., 1993). Significant biotic variations are apparent in this interval at the Koshak section. For example, *Guembelitria irregularis*, *G. trifolia*, *Woodringina kelleri*, *Archaeoglobigerina mateola* and *Globotruncanella caravacaensis* may first appear in this interval (Fig. 6). Among these, the presence of *W. kelleri* below the K/T boundary is unusual because the genus *Woodring-*

Table 1
Relative percent of planktic foraminifera at Koshak, Kazakstan

Species	Sample (cm)																						
	−200	−100	−50	−45	−40	−35	−30	−25	−20	−15	−10	−5	−2.5	0	2.5	5	10	15	20	25	30	35	40
A. mateola										0.95													
C. crinita												0.61	1.01									7.14	
C. midwayensis																						7.14	
C. waiparaensis	58.66	60.26	58.25	40.88	16.22	50.16	41.25	30.00	33.44	31.23	46.56	34.25	37.71	43.42	47.16	71.00	89.32	74.23	75.95	54.55	81.25	85.71	66.67
E. edita																							
E. eobulloides																1.00							
E. fringa																	0.97		1.37				
E. trivialis																							
G. aspera	1.52	3.26	2.36	2.20	4.05		0.99	0.33	2.79	1.89	1.97		0.67										
G. multispina		0.33	0.34					0.33															
G. yaucoensis		1.95	1.95	1.26	1.01				0.31		1.31												
G. daubjergensis																							
G. arca			0.34	0.31	2.03			0.33		0.63													
G. petaloidea																							
G. caravacaensis					1.35			0.67		0.32													
G. cretacea	3.65	1.63	3.37	2.83	3.04	1.88	3.63	4.00	2.17	1.26	1.64	3.98	3.37	12.50	6.38	7.33	1.94	9.28	6.53				
G. danica	4.56	7.17	7.74	3.46	4.39	1.88	3.30	3.00	5.57	0.95	0.66	1.83	1.68	0.99	0.71	2.00	1.03		0.69				
G. irregularis				1.57				0.67			0.98	2.14	1.35	1.32	3.55	2.00	2.91	3.09	4.47	9.09			
G. trifolia						0.94		1.00	1.24							1.67		1.03	1.72				
H. complanata	0.30		0.67				2.97		2.84														
H. dentata	6.99	4.56	6.06	26.10	7.77	31.97	29.04	26.00	28.48	21.14	24.92	24.16	31.65	23.68	27.30	3.00		2.06					
H. glabrans					1.35																		
H. globulosa	14.29	10.75	9.76	11.32	44.26	7.21	8.58	22.33	13.31	29.02	16.39	24.16	11.45	11.51	8.51								
H. navarroensis	0.30	1.30	1.01		1.01		0.99		0.32	0.32	1.22		0.34	0.33					0.69				
H. pulchra					1.69			0.33	0.95			0.92											
H. punctulata					1.35			0.67	1.26														
H. holmdelensis	3.95	4.89	1.89	1.89	7.43	1.25	3.63	3.33	4.33	4.42	1.53	1.53	1.01	0.33	2.13			0.97					
H. monmouthensis	1.52	2.28	0.67	1.89	3.04			1.00	0.31	1.58	1.64	0.92	2.02	1.32									
P. eobulloides																							
P. eugubina																0.67							
P. longiapertura															0.33	0.33	0.97		4.81			3.57	
P. planocompressa																							
P. costulata																							
S. pseudobulloides																							
S. varianta															0.35								
W. claytonensis																	0.97						
W. hornerstowensis																							
W. kelleri												1.83	0.34	0.99	1.42	5.33		3.09	2.41		18.75	3.57	
Z. parri	4.26	1.63	3.37	6.29		4.70	5.61	6.00	6.50	1.26	3.93	2.45	7.41	2.63	0.71	5.67	1.94	6.19	1.03	36.36		3.57	
Z. teuria																			0.34				33.33
No identification														0.33									
Total No. count	329	307	297	318	296	319	303	300	323	317	305	327	297	304	282	300	103	97	291	11	16	28	3

Table 1 (continued)

Species	Sample (cm)																						
	45	50	60	70	80	90	100	110	120	130	140	150	160	170	180 (M)	180 (C)	190	200	210	230	250	270	290
A. mateola																							
C. crinita		0.37			0.81		0.32		2.20														
C. midwayensis										0.95			0.54		0.78		0.96						
C. waiparaensis		75.66	85.00	83.02	78.86	86.28	79.55	83.72	75.77	91.43		87.88	78.92	94.49	85.88	90.04	89.42	95.45	91.74	89.42	82.58		
E. edita																				2.88	1.52		
E. eobulloides		1.12																					
E. fringa		0.37																					
E. trivialis							0.32																
G. aspera																							
G. multispina																							
G. yaucoensis																					2.27	66.67	60.00
G. daubjergensis							0.64		2.64	1.90					3.14	1.48							
G. arca																							
G. petaloidea																							
G. caravacaensis	100																						
G. cretacea				2.26	2.44	1.81	3.51	2.33	2.64			2.02	2.70	0.79	1.96	1.11	2.88		2.75				
G. danica					0.81	0.36			0.88			1.01	1.08										
G. irregularis		1.50		0.75	0.81	0.36	0.96						0.54		0.39						1.52		
G. trifolia				0.38										0.79			0.96						
H. complanata		0.75																					
H. dentata		5.62	13.00	3.40	8.94	3.97	4.47						2.70										
H. glabrans																							
H. globulosa		1.12																					
H. navarroensis		0.75		0.75						1.90	33.33										0.76		
H. pulchra																							
H. punctulata																							
H. holmdelensis																							
H. monmouthensis																0.74							
P. eobulloides																							
P. eugubina		1.87		3.02	1.63		1.60																
P. longiapertura				3.02		1.81			2.20?														
P. planocompressa		2.62			1.63	0.36	0.32								0.78	0.37			0.92				
P. costulata		0.37r	100r																				20.00
S. pseudobulloides							0.88										0.96					33.33	20.00
S. varianta													1.62										
W. claytonensis		0.75			0.81							1.01			1.18	1.85							
W. hornerstowensis																				0.96			
W. kelleri		4.12	2.64	2.64	3.25	2.89	2.56		5.73	3.81	66.67	2.02	5.95	3.94	5.10	0.74	4.81	2.73	0.92	1.92	3.03		
Z. parri		3.00	1.00	0.75	2.17	2.17	5.43	13.95	8.37			6.06	5.95		0.78	3.69		1.82	3.67	4.81	8.33		
Z. teuria																							
No identification							0.32		0.88														
Total No. count	2	266	99	265	123	277	313	43	227	105	3	99	185	127	255	271	104	110	109	104	132	2	5

PLATE I
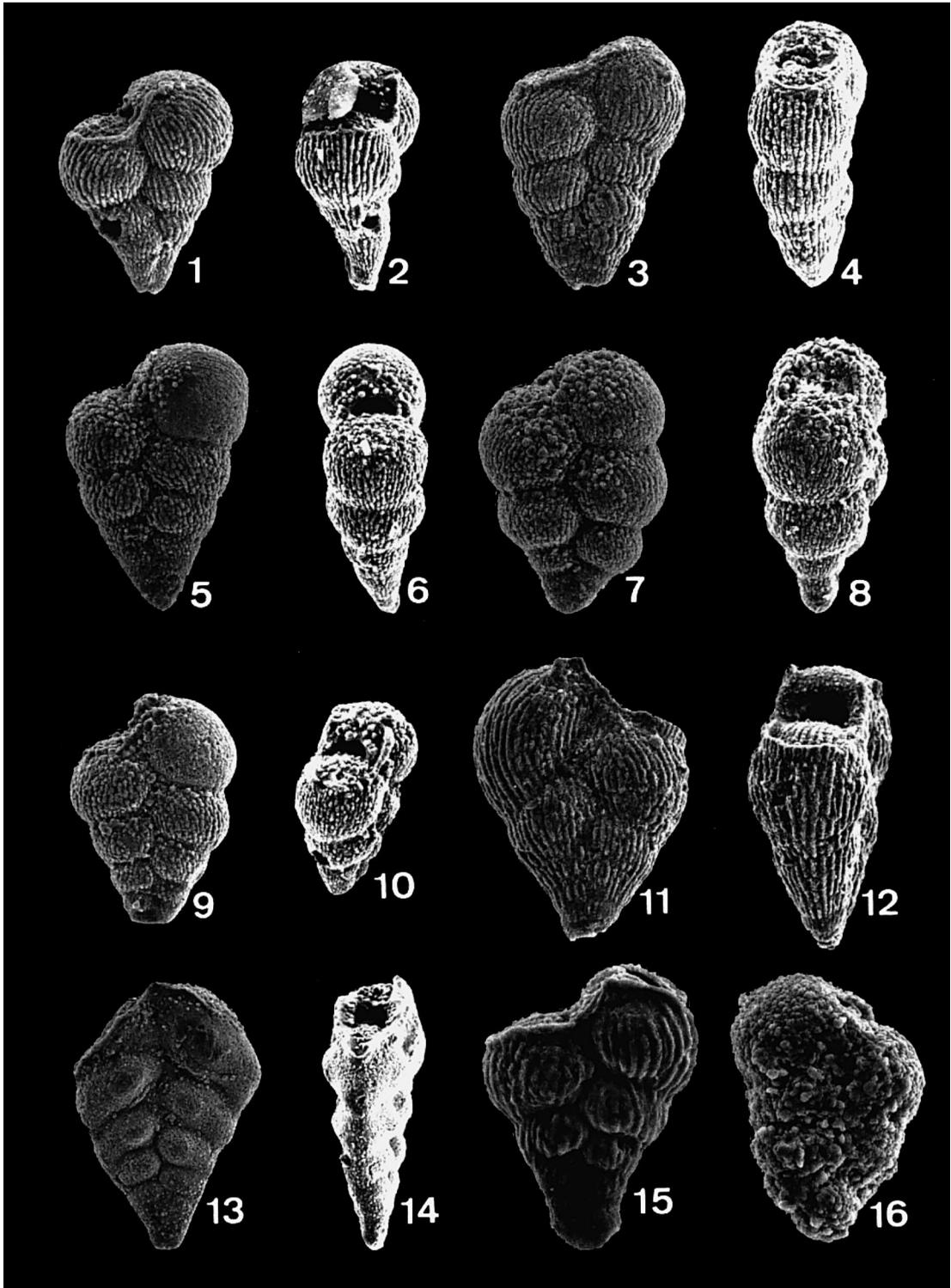
Stage	Datum events	This study	Keller, 1993 Pardo et al., 1996		Berggren et al., 1995
Early Paleocene (Danian)		P1c	P1c	P1c(1)	P1b
	S. varianta	P1b	P1b		
	P. eugubina / P. longiapertura			P1a(2)	
	S. pseudobulloides	P1 a	P1 a		P1 a
	P. eugubina / P. longiapertura			P1a(1)	
	P. hantkeninoides	P0	P0		Pα
Maastrichtian		UNZONED	P. hantkeninoides		A. mayaroensis
	P. hantkeninoides				

Fig. 4. Biostratigraphic zonal scheme used at Koshak, Kazakhstan, compared with the zonal schemes of Keller (1993), Berggren et al. (1995) and Pardo et al. (1996). Note that the uppermost Maastrichtian datum event *P. hantkenonoides* is absent at Koshak.

ina is considered a Tertiary development (MacLeod, 1993). Its presence below the K/T boundary at Koshak may be due to bioturbation in these echinoid-rich sediments.

The relative abundances of the dominant biserial taxa *Heterohelix globulosa* and *H. dentata* (Plate I, figs. 1–6) temporarily increased in the top 50 cm of the Maastrichtian at the Koshak section, whereas *C.*

waiparaensis declined from 50% to 25–30% (Fig. 6). However, the combined total of these three taxa is >75%. These biserial species are thought to have thrived in low-oxygen conditions and at thermoclinal depths (Boersma and Premoli Silva, 1988a,b; Keller, 1993; Keller et al., 1993; Barrera and Keller, 1994) and their increased abundance suggests an expanded O_2 minimum zone. Alternatively, it is also possible that these biserial taxa may be more tolerant of low-salinity conditions as suggested by Oberhänsli et al. (1998) based on stable isotopic data at Koshak.

The K/T boundary faunal turnover at Koshak shows no dramatic sudden extinctions. Just one species, *Archaeoglobigerina mateola*, disappeared at the K/T boundary. However, eight species disappeared within the 50 cm below the K/T boundary and three species disappeared within 15 cm above the K/T boundary (Figs. 6 and 7). The total planktic foraminiferal species turnover across the K–T transition is therefore ~50% (including the temporary incursion of lower-latitude species).

Eleven Cretaceous planktic foraminifera ranged into the Danian (Fig. 6). Five of these species disappeared within the early Danian zone P1a (*Hedbergella holmdelensis*, *H. monmouthensis* and *Globigerinelloides aspera*, *H. globulosa* and *H. complanata* d), and the remaining six species ranged into Subzone P1c or above (Figs. 6 and 7). Throughout the early Danian, the Maastrichtian survivor *C. waiparaensis* remained the dominant species (~80%).

The first six Danian species appeared simultane-
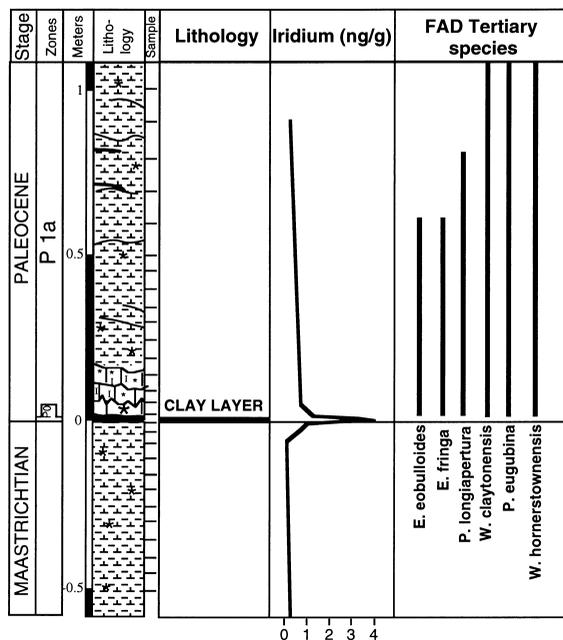
PLATE II

K/T Boundary Criteria at Koshak

Fig. 5. Illustration of the various criteria used to identify the K/T boundary at the Koshak section in Kazakhstan. Note that these criteria mark the K/T boundary worldwide.

ously 2.5 cm above the K/T clay layer at Koshak (Figs. 5 and 6). These six species, however, are known to evolve sequentially (Keller, 1988, 1996; Canudo et al., 1991; Keller et al., 1996), which suggests that a short hiatus or condensed interval is present at the P0/P1a zone boundary. A short hiatus at this inter-

val, as well as between P1a and P1b, has been documented worldwide (MacLeod and Keller, 1991a,b). At Koshak, there is no biostratigraphic evidence for a hiatus at the P1a/P1b boundary, although carbonate dissolution (evident in foraminiferal shells) in P1b, and near the base of P1a suggests the possibility of short hiatuses or condensed intervals (stippled intervals, Fig. 6).

The first generation of Danian species disappeared in P1a (e.g., *Eoglobigerina fringa*, *Parvularugoglobigerina eugubina*, *P. longiapertura*) and in the lower part of Subzone P1c (e.g., *Eoglobigerina eobulloides*, *Woodringina claytonensis*, *Chiloguembelina crinita*), coincident with the disappearance of several Cretaceous species (Fig. 6). The second generation of Danian species evolved between the upper P1a and lower P1c interval (e.g., *Planoglobulina planocompressa*, *Globastica daubjergensis*, *Eoglobigerina trivialis*, *Chiloguembelina midwayensis*, *Subbotina pseudobulloides*, *S. varianta*; Fig. 6). These Danian biotic changes are consistent with the evolution and extinctions of Danian species observed in sections from high to low latitudes.

6. Signor–Lipps effect

The Signor–Lipps effect addresses two problems: (1) sample size exerts a major control on the apparent diversity of the fossil assemblage, and (2) artificial range truncation occurs when the number of samples studied is low, though this error dimin-

PLATE II

1. *Chiloguebelina waiparaensis* Jenkins, 1966, ×700, side view, sample Ko −40 cm.
2. *Chiloguebelina waiparaensis* Jenkins, 1966, ×700, edge view, sample Ko −40 cm.
3. *Chiloguebelina waiparaensis* Jenkins, 1966, ×700, side view, sample Ko −40 cm.
4. *Chiloguebelina waiparaensis* Jenkins, 1966, ×700, side view, sample Ko −40 cm.
5. *Woodringina kelleri* MacLeod, 1993, ×1000, side view, sample Ko +5 cm.
6. *Woodringina kelleri* MacLeod, 1993, ×1000, edge view, sample Ko +5 cm.
7. *Zeauvigerina parri* Finlay, 1939, ×700, side view, sample Ko −2.5 cm.
8. *Zeauvigerina teuria* Finlay, 1947, ×700, side view, sample Ko +20 cm.
9. *Guembelitria trifolia* (Morozova, 1961), ×1500, side view, sample Ko +20 cm.
10. *Guembelitria cretacea* (Cushman, 1933), ×900, side view, sample Ko −40 cm.
11. *Guembelitria cretacea* (Cushman, 1933), ×900, side view, sample Ko −40 cm.
12. *Guembelitria danica* (Hofker, 1978), ×500, side view, sample Ko −40 cm.
13. *Guembelitria danica* (Hofker,1978), ×500, umbilical view, sample Ko −40 cm.
14. *Guembelitria irregularis* Morozova, 1961, ×1000, side view, sample Ko −40 cm.
15. *Guembelitria irregularis* Morozova, 1961, ×1000, side view, sample Ko −40 cm.

PLATE III
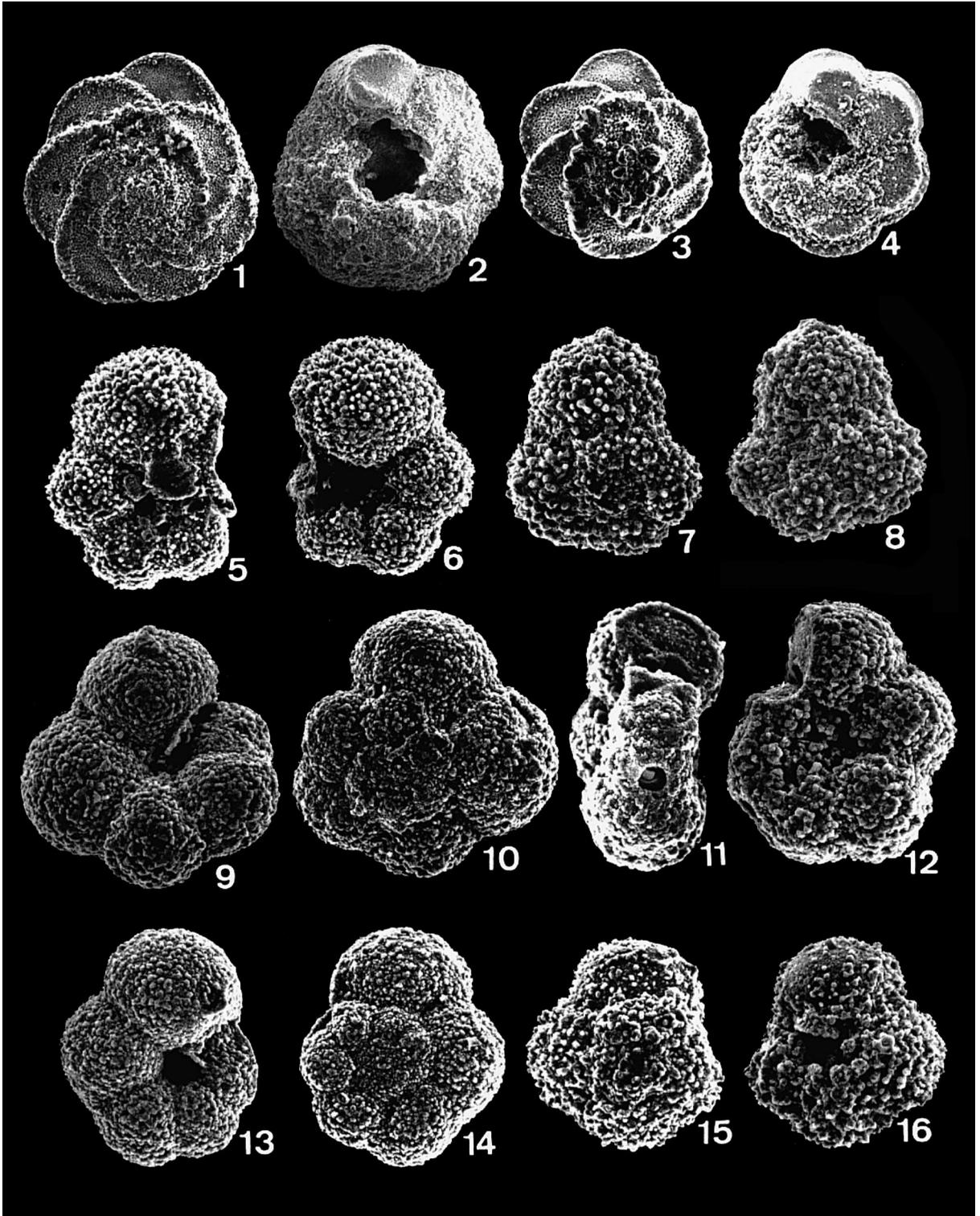
ishes with an increasing number of samples (Signor and Lipps, 1982). The first problem has been addressed by micropaleontologists by standardizing the quantitative analyses using 300 specimens to estimate foraminiferal assemblages (Buzas, 1990) and by searching the remaining sample residue for rare species. This allows representation of species that are present at ≤0.1% abundance. The second problem has been addressed at the Koshak section by the collection of samples near the K/T boundary at 2.5-cm intervals, though few samples were collected in the Maastrichtian below the uppermost 50 cm.

In K/T boundary transitions four planktic foraminiferal species groups can generally be distinguished: (1) species that disappeared below the K/T boundary, (2) species that disappeared at the K/T boundary, (3) Maastrichtian species that ranged into the Danian, and (4) new Tertiary species. The first three groups characterize Maastrichtian assemblages, and the number of species in each group is a measure of the severity of the K/T extinction event. When dealing with the K/T boundary mass extinction, species that disappeared above or below the K/T boundary are controversial because early disappearances are frequently ascribed to the Signor–Lipps effect, whereas species ranging into the Danian are interpreted as reworked. In reality, both of these phenomena affect species above and below the K/T boundary, but these interpretations are often arbitrarily applied to the K/T mass extinction based on the assumption that a bolide impact killed nearly all Cretaceous species (see MacLeod, 1996b, for a comprehensive discussion of this problem).

Regardless of the various interpretations of the K/T mass extinction, the Signor–Lipps effect points out the uncertainty in determining the actual timing of the demise of individual taxa. This is a particularly difficult problem for species that are rare in the assemblage and therefore may not be detected in the small samples that are used in faunal studies (Signor and Lipps, 1982). Any of the species that disappeared below the K/T boundary (39% at Koshak; Fig. 7) may have actually lived longer, either up to the K/T boundary or into the Danian. But, it is equally possible that any other species disappearances in the Danian (61% at Koshak) may have lived longer; hence the last appearances of taxa generally underestimate the true extinction datums. Similarly, reworking and bioturbation can extend the last appearances of species whether they are below or above the K/T boundary. Thus, there is no statistical or logical basis to assume that all Cretaceous species became extinct at the K/T boundary due to an impact event or that reworking only affected species in Danian sediment (MacLeod, 1996b).

The actual pattern of planktic foraminiferal taxa disappearing at or below the K/T boundary at Koshak (group 1 and 2 taxa) is difficult to determine because most of these species are rare or only intermittently present. Although they total 39% of the Maastrichtian assemblage, their combined relative abundance totals less than 20% at the Koshak

PLATE III

1. *Globotruncana arca* (Cushman, 1926), ×180, dorsal view, sample Ko −40 cm.
2. *Globotruncana arca* (Cushman, 1926), ×180, umbilical view, sample Ko −40 cm.
3. *Globotruncana arca* (Cushman, 1926), ×200, dorsal view, sample Ko −40 cm.
4. *Globotruncana arca* (Cushman, 1926), ×200, umbilical view, sample Ko −40 cm.
5. *Globigerinelloides aspera* Bolli, 1966, ×500, dorsal view, sample Ko −40 cm.
6. *Globigerinelloides aspera* Bolli, 1966, ×500, umbilical view, sample Ko −40 cm.
7. *Archaeoglobigerina mateola* Huber, 1990, ×600, dorsal view, sample Ko −2.5 cm.
8. *Archaeoglobigerina mateola* Huber, 1990, ×600, umbilical view, sample Ko −2.5 cm.
9. *Hedbergella monmouthensis* (Olsson, 1960), ×500, umbilical view, sample Ko −40 cm.
10. *Hedbergella monmouthensis* (Olsson, 1960), ×500, dorsal view, sample Ko −40 cm.
11. *Globigerinelloides yaucoensis* (Pessagno, 1967), ×700, side view, sample Ko −40 cm.
12. *Globigerinelloides yaucoensis* (Pessagno, 1967), ×700, umbilical view, sample Ko −40 cm.
13. *Hedbergella holmdelensis* Olsson, 1964, ×500, umbilical view, sample Ko −40 cm.
14. *Hedbergella holmdelensis* Olsson, 1964, ×500, dorsal view, sample Ko −40 cm.
15. *Globotruncanella caravacaensis* Smit, 1982, ×500, dorsal view, sample Ko −40 cm.
16. *Globotruncanella caravacaensis* Smit, 1982, ×500, umbilical view, sample Ko −40 cm.
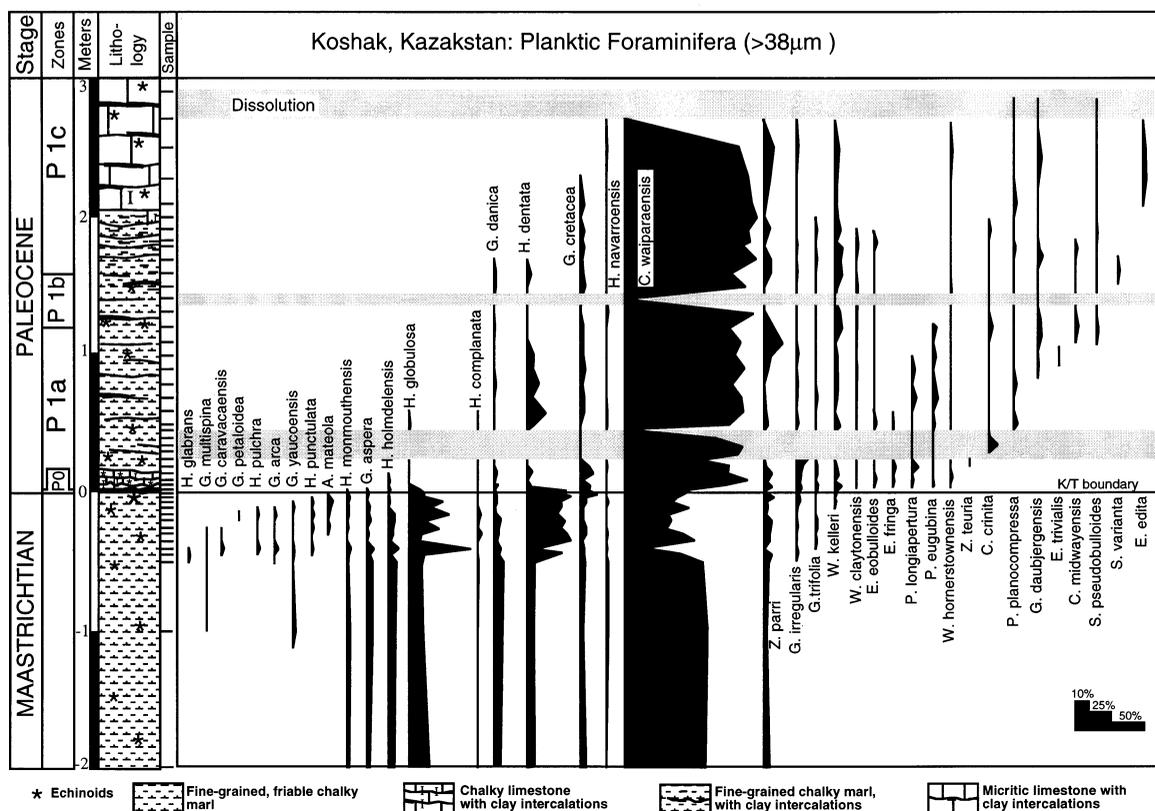
PLATE IV
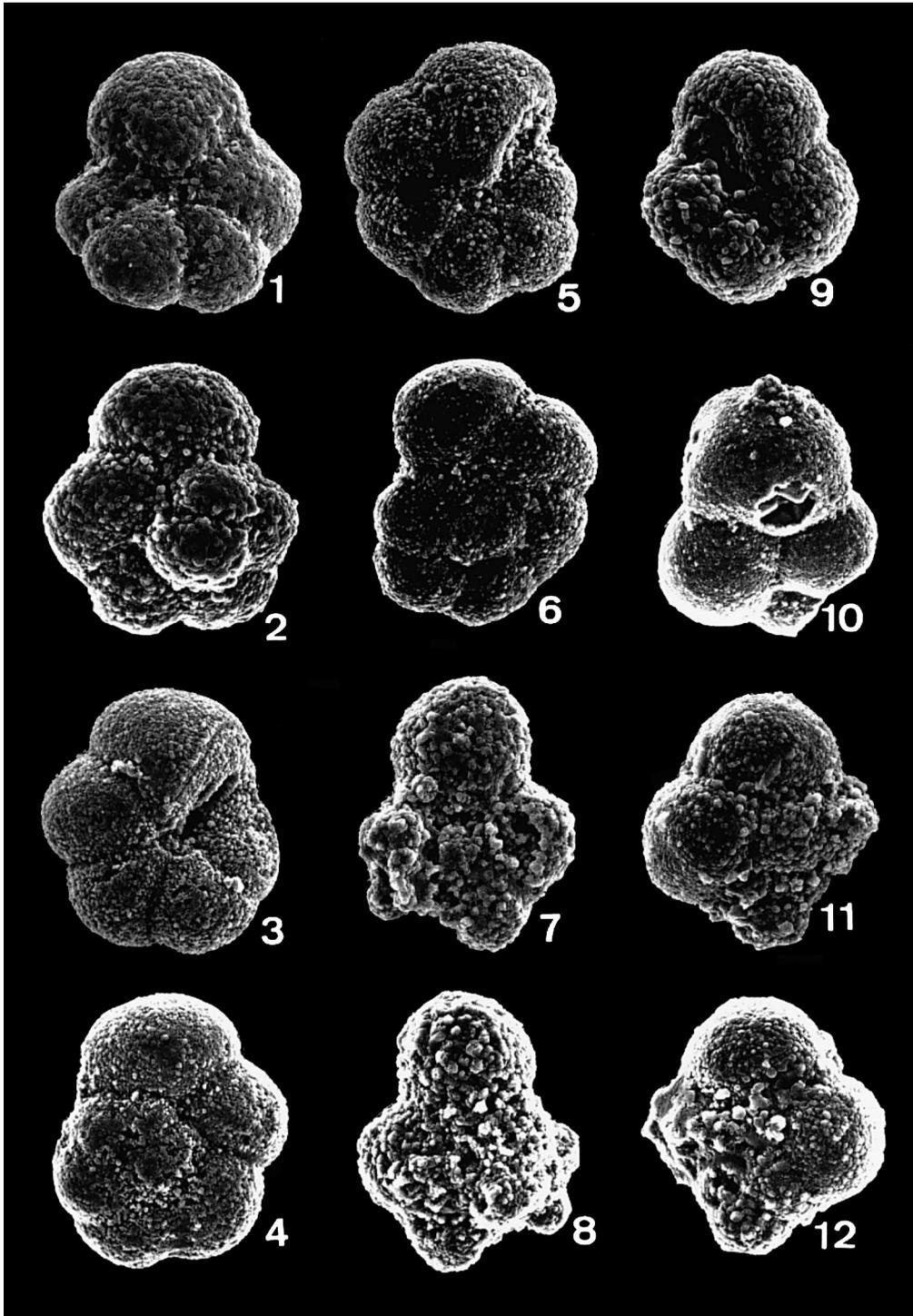
Fig. 6. Species ranges and relative abundances of planktic foraminifera across the K/T boundary at Koshak, Kazakhstan. Note that there is no sudden mass extinction at the K/T boundary and the extinction of Cretaceous species is progressive and coincident with the evolution of Tertiary species. Dissolution intervals in the Early Paleocene are marked with a stippled pattern.

section (Fig. 7). These species appear to have been rare and endangered as a result of climatic trends well before the K/T boundary and there seems to be no logical basis for arguing that their demise

was due to a bolide impact. Instead of the last appearance, the relative abundance of a species may be a more sensitive index of environmental change. Group 3 taxa which range into the early Danian total

PLATE IV

1. *Parvularugoglobigerina eugubina* (Luterbacher and Premoli Silva, 1964), ×1000, umbilical view, sample Ko +50 cm.
2. *Parvularugoglobigerina eugubina* (Luterbacher and Premoli Silva, 1964), ×1000, dorsal view, sample Ko +50 cm.
3. *Globanomalina planocompressa* (Shutskaya, 1965), ×700, umbilical view, sample Ko +50 cm.
4. *Globanomalina planocompressa* (Shutskaya, 1965), ×700, dorsal view, sample Ko +50 cm.
5. *Parvulorogoglobigerina longiapertura* (Blow, 1979), ×800, umbilical view, sample Ko +50 cm.
6. *Parvulorogoglobigerina longiapertura* (Blow, 1979), ×800, dorsal view, sample Ko +50 cm.
7. *Eoglobigerina eobulloides* (Morozova, 1959), ×1000, umbilical view, sample Ko +50 cm.
8. *Eoglobigerina eobulloides* (Morozova, 1959), ×1000, dorsal view, sample Ko +50 cm.
9. *Eoglobigerina fringa* (Subbotina, 1950), ×1300, umbilical view, sample Ko +50 cm.
10. *Globastica daubjergensis* (Brönnimann, 1953), ×700, side view, sample Ko +100 cm.
11. *Eoglobigerina trivialis* (Morozova, 1953), ×1000, dorsal viev, sample Ko +100 cm.
12. *Eoglobigerina trivialis* (Morozova, 1953), ×1000, umbilical viev, sample Ko +100 cm.
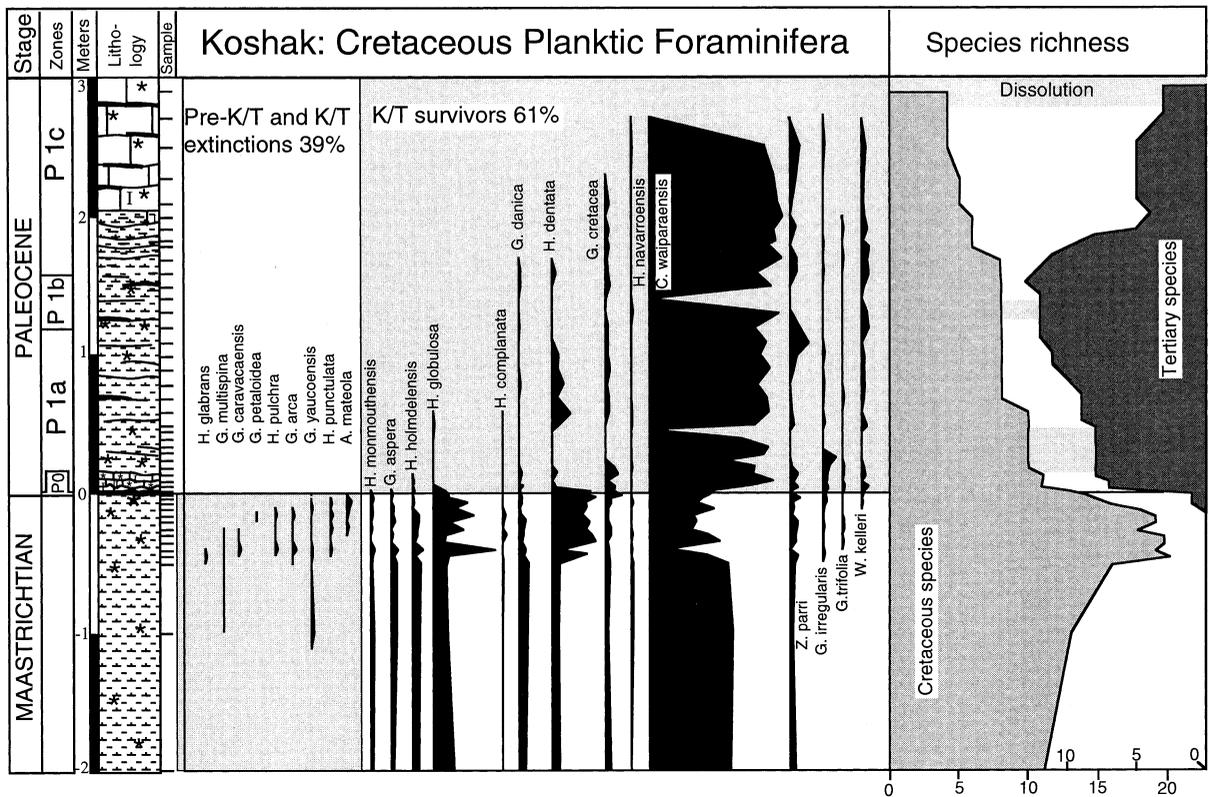
Fig. 7. Cretaceous planktic foraminifera at Koshak, Kazakhstan, grouped into pre-K/T and K/T extinctions (39%) and K/T survivors (61%). Species richness trends show temporary rapid increase due to the influx of low-latitude species below the K/T boundary and progressively decrease through the early Danian.

more than 80% of the assemblages (Figs. 6 and 7). But whether they are reworked or survivors is difficult to determine in the absence of preservational differences, and a significant carbon isotope shift at the K/T boundary (Oberhänsli et al., 1998). However, $\delta^{13}C$ values of the dominant Cretaceous species *Chiloguembelina waiparaensis* show a gradual decrease of 1 permil in the early Danian zones Pla and P1b which indicates that this species is a Cretaceous survivor (Oberhänsli et al., 1998).

7. Reworking of Cretaceous species

The observed progressive extinction pattern of Cretaceous species and particularly of Cretaceous species in Danian deposits is frequently interpreted to result from the Signor–Lipps effect or reworking.

A number of tests have been devised to assess reworking, including abundance patterns, preservational differences, geographic distribution and stable isotopes.

7.1. Abundance patterns

Faunal abundance patterns yield clues to reworking. Reworking processes tend to diminish the number of specimens, since chemical erosion and physical breakage of the fossils usually take place during bioturbation (Olsson and Liu, 1993; MacLeod, 1996b). Thus the predictable shape of the abundance plot of a reworked species would show a rapid decrease, as compared to the true survivors, and eventual disappearance within a few centimeters (MacLeod, 1996b). A consistent abundance pattern, as observed for *C. waiparaensis* at Koshak, is therefore unlikely to be related with any kind of reworking process.

However, abundances of the other Cretaceous species are too low in the early Danian sediments to apply this criterion.

7.2. Preservation

Reworked specimens are often easily recognized in planktic foraminiferal assemblages by their poorer test preservation due to erosion, transport and dissolution, and frequent discoloration due to different sediment source rocks, as compared with in-situ specimens. Such specimens are routinely isolated and omitted from quantitative counts in our studies. Planktic foraminiferal species vary in their abrasion and dissolution susceptibility depending on test size and thickness. It turns out that the survivor fauna is dominantly composed of delicate tests and abrasion/dissolution susceptible forms, whereas the fauna of ornate, heavy-walled globotruncanoids that are rarely seen above the boundary are abrasion/dissolution-resistant forms. If reworking were a serious and consistent problem, we should be finding more of the dissolution-resistant forms above the boundary than we do. Since we find the opposite pattern, the reworking model loses credibility as an overall explanation (MacLeod and Keller, 1994; MacLeod, 1996a,b, 1996c).

7.3. Geographic distribution

Another survivorship criterion is the similar distribution of cosmopolitan Cretaceous species in other high- and low-latitude sections which would not be expected from random reworking (MacLeod, 1993, 1996b; MacLeod and Keller, 1994). Based on this criterion, of fourteen group 3 species at Koshak, eight are considered survivors by most researchers: triserial *Guembelitria cretacea*, *G. danica*, *G. irregularis* and *G. trifolia* (often lumped together as '*G. cretacea*'; Smit, 1990; Liu and Olsson, 1992; Huber et al., 1994), and trochospiral *Hedbergella holmdelensis* and *H. monmouthensis*. Though the latter two disappeared just above the K/T boundary at Koshak they are generally considered survivors (Keller, 1988, 1996, 1993; Liu and Olsson, 1992; Olsson and Liu, 1993; Huber et al., 1994; Huber, 1996). Another four species (*Heterohelix dentata*, *H. navarroensis*, *Chiloguembelina waiparaensis*, *Zeauvigerina parri*) show consistent trends across the K/T boundary into the Danian and the abundance patterns are very similar, and in some cases even higher, than those exhibited in the Maastrichtian. These four taxa thus also show characteristics of being true survivors (Fig. 7; Huber, 1991, 1996; Keller, 1993; MacLeod, 1996b). Two species (*Heterohelix globulosa* and *H. complanata*) show the rapid decline and disappearance that may indicate reworking in the Koshak section. However, *Heterohelix globulosa* is a known survivor species from many sections including El Kef (Tunisia), Agost and Zumaya (Spain), Brazos (USA), Nye Kløv and Stevns Klint (Denmark) as indicated by their Danian isotopic signals (Barrera and Keller, 1990; Keller et al., 1993). The low abundance and early disappearance of *H. globulosa* at Koshak may be due to local environmental conditions.

Heterohelix complanata is a somewhat peculiar case. Defined by Marie (1941) as an intermediate morphotype between *H. planata* (Cushman) and *H. globulosa* (Ehremberg), '*Gümbelina' complanata* has had little success as a species and is usually lumped with other species (e.g., *H. planata* or *H. globulosa*; Huber et al., 1994; Arz, 1996). In low-latitude studies where a distinction is made between *H. complanata* and *H. planata*, the latter is considered to survive the K/T mass extinction whereas the former is thought to disappear below or at the K/T boundary (e.g., D'Hondt and Keller, 1991; Lopez Oliva and Keller, 1996a,b). In the higher-latitude sections at Nye Kløv and Site 738, *H. complanata* was lumped with *H. dentata* (Keller, 1993; Keller et al., 1993). At Koshak the ranges of *H. globulosa* and *H. complanata* coincide, which suggests that *H. complanata* may also be a survivor taxon. *Globigerinelloides aspera* disappeared 2.5 cm above the K/T clay layer, which suggests that this taxon is not a survivor (Olsson and Liu, 1993; MacLeod, 1996b). However, in many sections this species is frequently present in Danian sediments. Based on relative abundance patterns across latitudes, it thus appears that at Koshak thirteen out of fourteen Cretaceous species present in Danian sediments may be K/T survivor taxa.

7.4. $\delta^{13}C$ isotopes

An excellent criterion for determining K/T survivorship of Maastrichtian species is based on $\delta^{13}C$

isotope analysis of the individual species in question. This method works best in low-latitude sections because Danian surface waters were more enriched in ^{12}C than in the Maastrichtian and early Danian δ^{13}C values for planktic species are 2–3‰ lighter than their Maastrichtian ancestors. However, this method does not work well in high latitudes because K/T boundary δ^{13}C change is <1‰ and within the range of species vital effects (Barrera and Keller, 1990; Keller et al., 1993; Keller, 1996; Oberhänsli et al., 1998). This test has been successfully applied to a number of Cretaceous species in Danian sediments (e.g., *Hedbergella holmdelensis*, *Heterohelix monmouthensis*, *H. globulosa*, *H. navarroensis*, *Chiloguembelina waiparaensis*, *Zeuvigerina parri*, *Guembelitria cretacea*, *G. irregularis*, *G. trifolia* and *G. danica* , Barrera and Keller, 1990, 1994; Keller et al., 1993; MacLeod, 1993).

Although disagreements among workers about which species survived and which are reworked still continue, a consensus is building for survivorship. For example, Smit and Zachariasse (1996) which previously consistently denied the possibility of survivorship except for *Guembelitria*, recently concluded that there is a greater proportion of survivors than previously admitted, including *H. globulosa*, *G. messinae*, *R. circumnodifer* and *Globotruncana arca*. In contrast, Huber (1996) and MacLeod and Huber (1996) still argue that most Cretaceous planktic foraminifera in Danian sediments, especially in high latitudes, are reworked. They cite the presence of a single specimen of *Globigerinelloides impensus* and inoceramid prisms with Maastrichtian strontium isotope ratios in early Danian sediments of Site 738. Since *G. impensus* went extinct in the Campanian and inoceramids disappeared in the middle Maastrichtian, these taxa are obviously reworked. To support this argument further, Huber (1996) measured carbon isotope values of *Heterohelix globulosa* and *Globigerinelloides multispinus (G. aspera* in this study) at Sites 738 and 750 and found no significant change between specimens collected below and above the K/T boundary. However, as noted above there are problems in using the stable isotope test in high-latitude sections which show little change in δ^{13}C values.

We agree that Cretaceous reworking is common in these high-latitude sections as elsewhere and throughout the geological record. But the presence of reworked inoceramid prisms and one specimen of a Campanian species does not prove that any or all Cretaceous planktic foraminifera in these sediments are reworked. Moreover, carbon isotope values differ little (<1 permil) across the K–T boundary in high-latitude sections and are within variations related to different species size fractions (see Barrera and Keller, 1990, 1994; Keller, 1993; Keller et al., 1993). MacLeod et al. (1999) have shown that Cretaceous species in Danian sediments, including *C. waiparaensis* at Site 738, are always dwarfed with adult specimens up to 50% smaller than their Maastrichtian ancestors, which is likely to affect the isotopic values reported by Huber (1996).

Tests for survivorship must be carried out for the early Danian interval characterized by the *Parvularugoglobigerina eugubina* Zone (zone Pla in this study, APa in Huber, 1996) where these suspect species are most abundant (MacLeod and Keller, 1994). However, no analyses were carried out for this interval by Huber (1996). Instead, Cretaceous species were taken from intervals upsection (zones P1b and P1c) where they are generally very rare and likely reworked (Keller, 1993; Fig. 6). It is therefore not surprising that these specimens yielded Cretaceous δ^{13}C values. The reason for not analyzing this interval at Sites 750 and 690 is that they have major hiatuses with the early Danian zones P0 and Pla missing (Keller, 1993) as also noted by Huber (1996). Thus, while we independently agree with Huber's conclusion that there is significant reworking in the southern high-latitude sections, he seems to have tested reworked Cretaceous species to proof reworking.

7.5. Strontium isotopes

By measuring strontium isotope ratios of inoceramid prisms in late Maastrichtian and early Danian zone P1c sediments of Site 738, MacLeod and Huber (1996) argue that these prisms are reworked. They also measured *Globigerinelloides prariehillensis* and *G. subcarinatus* in Campanian and Maastrichtian sediments and one sample of *Eoglobigerina* spp. from the Danian zone P1c and found them in situ. From this data they conclude (MacLeod and Huber, 1996, pp. 463, 465) that there is "pervasive reworking throughout the Maastrichtian and lower

Danian strata in ODP Hole 738C. We estimate that up to 30% of the mass of foraminifers in any sample can be contributed by individuals that have been reworked."

This is a weighty conclusion based on a single inoceramid strontium isotope analysis from a Danian zone P1c sample which is above the range of most suspected survivor species (MacLeod and Keller, 1994). The estimated 30% of the foraminifera reworked is difficult to support on any basis. For example, *Chiloguembelina waiparaensis*, which is the most dominant species in the early Danian, totals over 60% of the foraminiferal mass at Site 738 (Keller, 1993) and an even higher abundance is observed at Koshak (Fig. 7). If the early Danian flood of *C. waiparaensis* is reworked, where did they come from? There are only an average of 20% of this species in the uppermost Maastrichtian at Site 738. Morphometric analysis of *C. waiparaensis* has shown that early Danian specimens differ from Maastrichtian specimens in both smaller size and other morphological characteristics, thus supporting the survivorship argument (Keller, 1993; MacLeod, 1993). Whether strontium isotope ratios can be used to differentiate reworked or in-situ Cretaceous species in early Danian sediments still remains to be tested.

8. Biotic effects of latitude and shallow depth

Planktic foraminiferal assemblages from the Koshak section may be strongly influenced by their northern boreal location as well as their shallow paleodepth which is estimated between 100 and 200 m based on macrofaunas (Sarkar et al., 1992). In an attempt to isolate latitudinal effects from paleodepth effects, we compare Koshak assemblages with planktic foraminferal assemblages from other shallow neritic sections, such as Nye Kløv in Denmark (middle neritic, Keller et al., 1993), Brazos, Texas (middle to inner neritic, Keller, 1989a, 1996), Selja, Tunisia (inner neritic, Keller et al., 1994) and Site 738 (bathyal ~1000 m, Keller, 1993). These studies are chosen because: (a) they use the same species concepts which is critical for direct comparisons, and (b) they provide quantitative data that include the small size fraction (38–63 μm). The small

size fraction is critical because planktic foraminifera tend to be dwarfed in high stress environments (Keller et al., 1994; MacLeod et al., 1999).

The uppermost Maastrichtian planktic foraminiferal assemblages at Koshak, Nye Kløv, Brazos, Selja and Site 738 are similar in that they are all characterized by a set of five to six dominant species which total 80–100% of the assemblages. However, these species may vary regionally and across latitudes. For example, all neritic sections share common to abundant *Heterohelix globulosa, H. dentata, Hedbergella* spp., *Guembelitria* spp. and few to common *Globigerinelloides* spp. (Fig. 8). All of these taxa are ecological generalists tolerant of varying environmental conditions, including low oxygen, salinity and temperature (Boersma and Premoli Silva, 1988a, Boersma and Premoli Silva, 1988b; Keller, 1993; Keller et al., 1994). These taxa are also present in the high-latitude Site 738, though their relative abundances are generally lower: *Guembelitria* spp. are rare, and *Chiloguembelina waiparaensis* and *Globotruncanella subcarinatus* common (Fig. 8). The lower-latitude sections at Brazos and Selja differ from Koshak and Nye Kløv in having common *H. navarroensis* and *Pseudotextularia costulata*, as well as a host of subtropical species which are generally rare or sporadically present. Nye Kløv and Koshak differ from the lower Tethys sections in the presence of *C. waiparaensis* which are abundant at Koshak, but rare at Nye Kløv (though common in the early Danian, Keller et al., 1993), and the presence of only few sporadically occurring subtropical taxa (also observed at Site 738, Keller, 1993).

Early Danian assemblages at all of the neritic sections, except Koshak, are dominated by abundant *Guembelitria* spp., opportunistic taxa that thrive in the shallow neritic Tethys region (Selja and Brazos, ~60–80%), but are less common at Nye Kløv, Koshak and Site 738 (Fig. 8). In addition, higher latitudes are dominated by *Chiloguembelina waiparaensis* which total about 80% at Site 738 and Koshak, but are less abundant at Nye Kløv (<40%). The sequence of evolving early Danian species is similar in all sections.

The similarities in the relative abundance patterns of dominant planktic foraminiferal taxa in shallow neritic environments across latitudes indicate that the Koshak assemblages do not reflect isolated regional
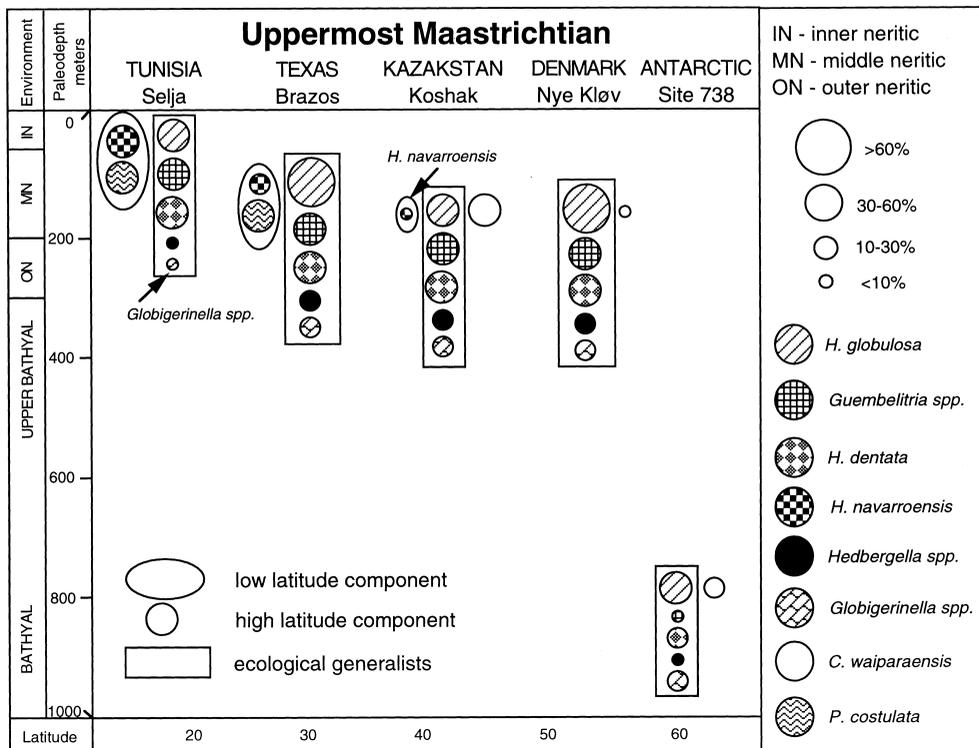
Fig. 8. Dominant uppermost Maastrichtian assemblages from shallow neritic sections in Tunisia, Texas, Denmark and Koshak and deep-sea Site 738 plotted against latitudes. Note that with minor variations, shallow neritic assemblages share the same dominant assemblages across latitudes. Variations include the addition of common *Hetrohelix navarroensis* and *P. costulata* in low latitudes and *Chiloguembelina waiparaensis* in high latitudes. High-latitude deep-water assemblages are most similar to higher-latitude shallow neritic assemblages and show more abundant *C. waiparaensis*. Data from Keller (1989b, 1993), Keller et al. (1993, 1996).

conditions. Comparison of these neritic assemblages with those of the bathyal Site 738 suggests that neither water depth nor high latitudes are the primary controlling factors in the dominant taxa of these assemblages. However, latitude and depth control species richness of assemblages by excluding tropical and subtropical taxa from higher-latitude cool water environments and by excluding deeper dwelling taxa from shallow neritic environments (see Li and Keller (1998c, for a recent discussion of depth ranking in Maastrichtian species).

Temperature appears to be a critical factor in these assemblages. Warm temperatures accompanied the presence of common *H. navarroensis* and *P. costulata*, and many rare subtropical species at Selja and Brazos. Likewise, warmer temperatures accompanied the incursion of subtropical taxa (rugoglobigerinids, globotruncanids) into higher latitudes at

Site 738, Koshak and Nye Kløv in the uppermost Maastrichtian. This incursion is well documented by a short-term climatic warming of 3–4°C in surface and deep waters between 200–400 kyr before the K/T boundary at Sites 690, 738 and 525 (Stott and Kennett, 1990; Barrera, 1994; Li and Keller, 1998a,b) and warm temperatures are also indicated at Stevns Klint and Nye Kløv (Schmitz et al., 1992; Keller et al., 1993).

Cool temperatures may be partly responsible for the presence and high abundance of *C. waiparaensis* at Site 738 and Koshak, but absence in lower-latitude sections. However, the near absence of this species in the uppermost Maastrichtian of Nye Kløv, but common presence in the early Danian (30–40%), suggests that other factors, such as salinity or oxygen, may also influence the distribution of this species. Barrera and Keller (1994) suggested that *C.*

waiparaensis is low-oxygen-tolerant. Oberhänsli et al. (1998) suggested that this species may also be tolerant of salinity variations as indicated by a significant fresh water admixture in the surface waters at Koshak. Further studies will be necessary to determine which geochemical factors control species variations.

9. Mineralogy

Relative changes in bulk rock composition and clay mineral content reflect variations in sediment sources related to weathering, erosion, climate and sea-level changes. For example, carbonate and detrital minerals on continental margins are sensitive indicators of eustatic sea-level and climatic changes because of the influence of nutrients on surface productivity, the effect of deep water circulation on the preservation of sediments, and the control of biogenic sediment production and terrigenous sediment distribution by sea-level fluctuations.

At Koshak, bulk sediments are primarily composed of biogenic calcite derived from planktic foraminifera and calcareous nannoplankton (Fig. 9). Carbonate content averages 90–95 weight%, except at the K/T boundary where it is reduced to about 80 weight%. Organic carbon and sulfur contents are extremely low (0.05% or less) though slightly increased at the K/T boundary (Oberhänsli et al., 1998). Detrital minerals (phyllosilicates, quartz and feldspar) are relatively minor components, but show peak values at the K/T boundary possibly due to carbonate dissolution, or enhanced influx of terrestrial sediments during a sea-level change. Gypsum present in the K/T clay layer is probably of late diagenetic origin, as observed in numerous sections in the Tethys region (e.g., Negev, Egypt, Tunisia, Spain, Austria; T. Adatte, unpubl. data). Though sample control is poor in the interval between 1 m and 2 m below the K/T boundary, the comparatively low calcite and high phyllosilicate and quartz contents suggest a lower sea level with increased continental erosion and transport of detritus to the marine basin. The increase in calcite to 99% beginning 40 cm below the K/T boundary, and the concomitant disappearance of phyllosilicates suggest a sea-level rise and the onset of warming as indicated
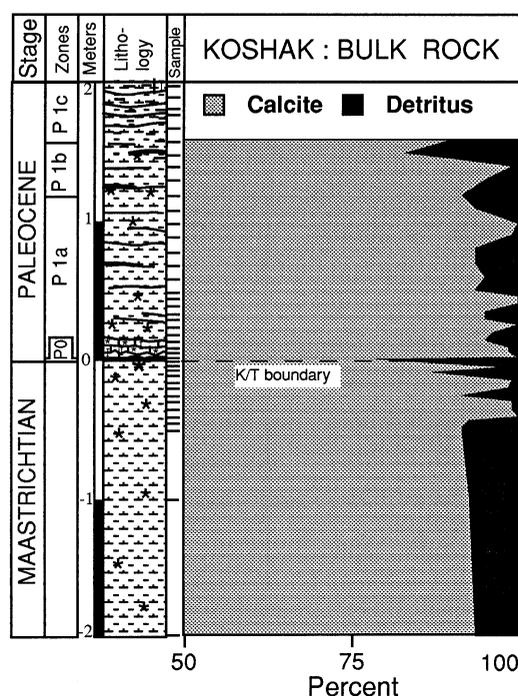

Fig. 9. Bulk rock analysis at Koshak, Kazakhstan. Biogenic calcite is the dominant mineral. The presence of detritus (quartz and feldspar) is a good indicator of increased terrestrial influx, particularly in the K/T boundary clay.

by the incursion of subtropical planktic foraminifera (Figs. 6, 9 and 10). In the uppermost 25 cm of the Maastrichtian, phyllosilicates, K-feldspars and quartz increased and reached maximum values at the K/T boundary (Fig. 9). Calcite is always high (>75%), even in the Ir-enriched clay layer, which suggests that there was no significant drop in carbonate productivity. In the basal Danian (lower part of Subzone P1a) the decrease in detrital minerals and the increase in calcite may indicate a rising sea level. Increased detrital influx in the upper Subzone P1a and into P1c suggests a lower sea level as also noted in biofacies analysis (Fig. 3).

Clay minerals are the result of chemical weathering of rocks associated with climate changes as well as continental morphology and tectonic activity linked to the structural evolution of margins (Chamley, 1989; Weaver, 1989). Mica and chlorite are the common byproducts of weathering reactions with low hydrolysis that is typical for cool to temperate and dry climates. Kaolinite is the byproduct
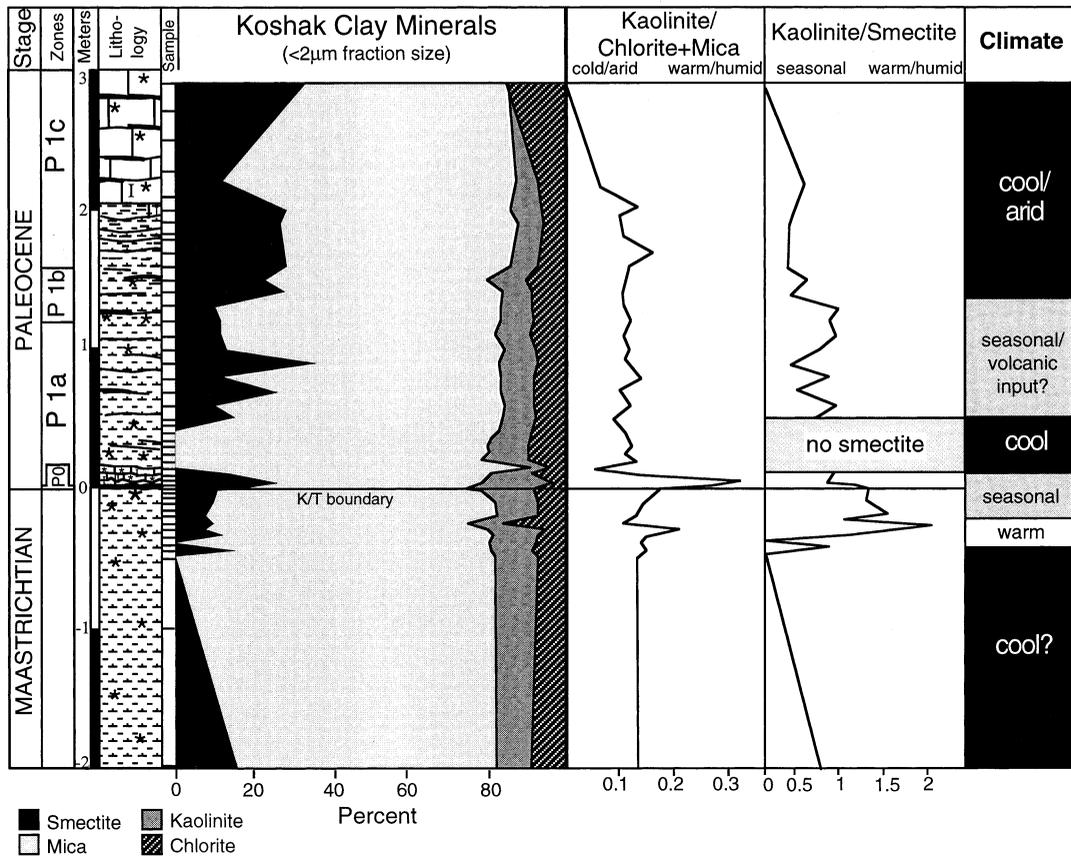
Fig. 10. Clay mineral analysis at Koshak, Kazakhstan, and inferred climatic evolution. Note that high abundance of mica (illite) suggests a cool and probably dry climate. Peak abundances in smectite suggest volcanic activity. The kaolinite/(chlorite + mica) ratio indicates a seasonal climate and/or volcanic influx.

of highly hydrolytic weathering reactions in warm humid climates and can also be associated with a sea-level transgression. The presence of abundant smectite is generally linked to transgressive seas and warm climate with alternating humid and arid seasons, but it can also be related to volcanic activity. Sharp increases in smectite content suggest increased volcanic activity in the adjacent areas (Chamley, 1989). Thus, the kaolinite/(chlorite + mica) (K/C + M) index provides an estimate of cold-dry and warm-humid climates. The kaolinite/smectite index reflects climate fluctuations from humid/warm to more seasonal conditions.

At K/T boundary time, the Koshak section was located on a relatively shallow open marine platform with little hydrodynamic activity. There was little detrital mineral segregation that could mask or exaggerate the climatic signal (Adatte and Rumbley, 1989; Chamley, 1989; Monaco et al., 1982). The most common clay mineral across the K/T transition is mica which varies between 50 and 85% (Fig. 9). Relatively low mica contents occurred in the 50 cm below the K/T boundary, in the upper part of Subzone P1a and in the lower part of Subzone P1c. Smectite shows an opposite trend, with low mica corresponding to high smectite. Kaolinite averaged 10% during the latest Maastrichtian and early Danian, but decreased in Subzone P1c. Two peaks of increased kaolinite to 15% and 18% are present 20 cm below and at the K/T boundary, respectively (Fig. 10). Chlorite also averages 10% through the section but increases where kaolinite decreases.

These data suggest the following climatic trends. The overall high mica content is consistent with a generally cool high-latitude climate for the Koshak region, with low humidity but strong physical erosion. The K/(C + M) (kaolinite/[chlorite plus mica]) ratio suggests short warm peaks at or just above the K/T boundary and 20 cm below it. The high values of the kaolinite/smectite (K/S) index between these two warm peaks suggest warm/humid but seasonal conditions. Note that this latest Maastrichtian warming is marked in planktic foraminiferal assemblages by the incursion of subtropical taxa and in the whole rock composition by an influx of carbonates and increased smectite, both of which suggest a rising sea level (Fig. 9). In the early Danian K/(C + M) values are relatively low but stable suggesting a cool climate in the lower part of Subzone P1c. However, the (K/S) (kaolinite/smectite) index suggests variable climatic conditions. For example, the absence of smectite in the earliest Danian suggests a cool and arid climate as also indicated by peak abundance in mica (Fig. 10). The high, though fluctuating, K/S values in Subzones P1a and P1b suggest a seasonal climate. In Subzone P1c, decreasing K/(C + M) values suggest generally cooler conditions.

10. Discussion

The mass extinction of planktic foraminifera and the coincident collapse in primary productivity at the K/T boundary have long been inferred on the basis of their extinction and $\delta^{13}C$ records in low-latitude sections. The interpretation of these coincidental events as the globally destructive effects of a bolide impact seemed natural and indisputable. The first hint that something was amiss in this scenario came with the investigation of high-latitude sections in Denmark (Nye Kløv and Stevns Klint; Schmitz et al., 1992; Keller et al., 1993) and the southern Indian Ocean (Site 738; Keller, 1993; Barrera and Keller, 1994). These studies concluded that no mass extinction occurred in high latitudes and that most Cretaceous species ranged well into the Danian (see also MacLeod and Keller, 1994). But equally important is the absence of a major change in $\delta^{13}C$ values, and hence the absence of a significant change in primary productivity. Our investigation of the Koshak

section supports these earlier studies and provides additional new information on pre- and post-K/T boundary climate changes.

The climate of the east boreal Paratethys of Kazakhstan, as inferred from clay mineral analysis, was relatively cool and seasonally variable during the late Maastrichtian followed by abrupt warming beginning about 40 cm below the K/T boundary. This warming is accompanied by the temporary incursion of lower-latitude species. A similar pre-K/T climatic warming based on the temporary incursion of lower-latitude taxa has been observed in K/T sections of Denmark (Nye Kløv and Stevns Klint) and the Antarctic Ocean (ODP Sites 690 and 738; Huber, 1991; Keller, 1993). In the Tethys region (e.g., Agost, Spain, and El Kef, Tunisia) benthic foraminiferal assemblages suggest a sea-level rise accompanied by increased abundance in low-oxygen-tolerant praebuliminid species (Pardo et al., 1996; Pardo, 1996; Li, 1997). These biotic changes coincided with warming of 2–3ºC in surface and intermediate waters of southern high latitudes (e.g., Sites 690, 528, 525; Barrera, 1994; D'Hondt and Lindinger, 1994; Li, 1997; Li and Keller, 1998a,b).

Mineralogical data suggest that seasonal climatic conditions prevailed across the K/T boundary accompanied by rapidly decreasing Cretaceous species richness (Fig. 7) and the evolution of Tertiary species. A cool climate in the earliest Danian (absence of smectite, Fig. 10) is marked by carbonate dissolution. There is no evidence of a sudden mass extinction of Cretaceous planktic foraminifera at the K/T boundary at Koshak. Foraminiferal extinctions appear progressive, beginning in the latest Maastrichtian and continuing into the Danian subzones P1a–P1c. This progressive disappearance of species appears to be related to climatic cooling and the lower sea level which may have increased competition with the newly evolving Tertiary fauna. The presence of similar progressive species extinction patterns in other high-latitude sections (e.g., Nye Kløv and ODP Site 738) and similar species ranges in sections worldwide (see MacLeod and Keller, 1994) indicates that these results are not likely due to the Signor–Lipps effect or reworking. Moreover, the Koshak data suggest that the biotic effects of the bolide impact were significantly reduced in higher latitudes as compared to low latitudes.

Mineralogical data suggest that cool, arid conditions prevailed during Danian Zones P1c, an interval accompanied by the extinctions of several Cretaceous survivor species (Fig. 6) as well as the first wave of Danian species. This suggests continued and probably increased stress upon both survivor and newly evolved Danian taxa at this time leading to very low species richness in the eastern Paratethys. This Danian cooling seems to mark the final phase of the stressful climatic and environmental conditions that led to the demise of Cretaceous planktic foraminifera.

11. Conclusions

Climatic and faunal changes inferred from clay mineralogy and planktic foraminifera from the Koshak section of Kazakhstan reveal a progressive mass extinction pattern related to climatic variations. Near the end of the Maastrichtian, a short-term climatic warming coincides with a temporary incursion of lower-latitude species which nearly doubled species richness. Although some of these species disappeared from the Koshak region during the seasonally cooler conditions that preceded the K/T event, no major species extinction coincided with the K/T boundary. The cooler early Danian climate saw a significant reduction in the abundance of some Cretaceous taxa and the disappearance of others along with the evolution of the first Danian taxa. Most of the early Danian species disappeared along with several Cretaceous survivor taxa during the subsequent climatic cooling in Danian Subzone P1c. This progressive pattern of species extinctions and climate changes indicates that in the eastern Paratethys region of Kazakhstan, the K/T mass extinction was strongly influenced by long-term climate changes. Though a bolide impact may have contributed to the adverse environmental conditions, its effects upon this boreal fauna cannot be determined.

Acknowledgements

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