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Marine Micropaleontology 33 (1998) 55–86

MARINE
MICROPALEONTOLOGY

Maastrichtian climate, productivity and faunal turnovers in planktic foraminifera in South Atlantic DSDP sites 525A and 21

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Received 26 July 1996; revised version received 21 February 1997; accepted 21 March 1997

Abstract

Stratigraphic, faunal and isotopic analyses of the Maastrichtian at DSDP sites 525A and 21 in the South Atlantic reveal a planktic foraminiferal fauna characterized by two major events, an early late Maastrichtian diversification and end-Maastrichtian mass extinction. Both events are accompanied by major changes in climate and productivity. The diversification event which occurred in two steps between 70.5 and 69.1 Ma increased species richness by a total of 43% and coincided with the onset of major cooling in surface and bottom waters and increased surface productivity. The onset of the terminal decline in Maastrichtian species richness began at 67.5 Ma and the first significant decline in surface productivity occurred at 66.2 Ma, coincident maximum cooling to 13°C in surface waters and the reduction of the surface-to-deep temperature gradient to less than 5°C. Major climatic and moderate productivity changes mark the mass extinction and the last 500 kyr of the Maastrichtian. Between 200 and 400 kyr before the K–T boundary surface and deep waters warmed rapidly by 3–4°C and cooled again during the last 100 kyr of the Maastrichtian. Surface productivity decreased only moderately across the K–T boundary. Species richness began to decline during the late Maastrichtian cooling and by K–T boundary time, the mass extinction had claimed 66% of the species. Viewed within the context of Maastrichtian climate and productivity changes, the K–T mass extinction could have resulted from extreme environmental stress even without the addition of an extraterrestrial impact. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Maastrichtian; climate; productivity; planktic foraminiferal biostratigraphy

1. Introduction

Stable isotope studies from southern high latitudes reveal that Maastrichtian climate was not as equably warm as generally assumed, but was marked by gradual cooling and low temperatures that suggest Antarctic ice formation (Barrera, 1994). Two major cool events at 71 and 68 Ma are accompanied by two third-order sea-level regressions (Haq et al., 1987).

The last 500 kyr of the Maastrichtian are marked by a short-term warm event followed by rapid cooling across the Cretaceous–Tertiary (K–T) boundary and major mass extinction (Stott and Kennett, 1990; Barrera, 1994). Little information exists on Maastrichtian faunal changes in planktic foraminifera. In southern high latitudes, species diversity increased slightly during the early–late Maastrichtian transition (Huber, 1990, 1992), whereas in the low and middle latitudes, species diversity increased significantly during the same interval (e.g., Boersma, 1981, 1984a; Caron, 1985). Increased species di-

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versity during the early–late Maastrichtian transition was also observed in ammonites and bivalves (Ward et al., 1991; Stinnesbeck, 1996), though inoceramids and rudists suffered a major decline followed by extinction (Ward, 1990; MacLeod and Ward, 1990; MacLeod, 1994; Johnson and Kauffman, 1996). The suspected cause for inoceramid and rudist extinctions, as well as the evolutionary diversification among other invertebrates and planktic foraminifera, is climate change. However, no studies to date have demonstrated a cause-and-effect relationship between these faunal turnovers and climate changes. The objective of this study is to examine Maastrichtian climatic and faunal changes in planktic foraminifera in an effort to determine the nature of each record and their possible relationship.

No quantitative studies of Maastrichtian planktic foraminifera together with isotope analysis have been published to date, though excellent isotope records exist from ODP Site 690C and 750 (Stott and Kennett, 1990; Barrera and Huber, 1990; Barrera, 1994). The present study was undertaken to fill this gap. DSDP Site 525A on Walvis Ridge was chosen because of its excellent paleomagnetic record, very good foraminiferal preservation and apparently continuous and high sediment accumulation rates. DSDP Site 21 on Rio Grande Rise was chosen as control site to evaluate whether faunal events observed at Site 525A are local artifacts or widespread oceanographic events. This study addresses the following major objectives: (1) Document the stratigraphic occurrences of planktic foraminifera and develop a high resolution planktic foraminiferal biozonation. (2) Document faunal turnovers based on first and last appearances and relative abundance changes of individual species. (3) Conduct stable isotopic measurements on monospecific benthic and planktic foraminifera in order to evaluate climatic and productivity changes through the Maastrichtian and relate these to faunal turnovers.

2. Material and methods

This study is based on sediment samples for the Maastrichtian interval from the South Atlantic DSDP Site 525A (Walvis Ridge, Fig. 1) and DSDP Site 21 (Rio Grande Rise). During the Maastrichtian, Site 525A was at 36°S paleolatitude and at lower to upper

bathyal paleodepth (Moore et al., 1984). From Site 525A, 57 samples were analyzed between cores 40 and 51 at 1.5 m intervals, providing an average of one sample every 140 kyr. From Site 21, 22 samples were analyzed between cores 3 and 6 with sample intervals ranging from 1.5 to 6 m. Sediment recovery during coring was good with 74% recovery for Site 525A and nearly 100% for Site 21.

Site 525A was located in an area where pelagic sediments are dominated by biogenic carbonate, with accumulation rates controlled by surface productivity and dissolution as well as detrital influx (Shackleton et al., 1984). Dissolution appears to have been relatively minor at Site 525A, where preservation of planktic foraminifera is generally good in cores 41 to 51 and moderate in core 40 (see Plates I and II). Significant carbonate dissolution was observed only in one sample in Core 47-1 (100–102 cm). At Site 21, preservation is very good and no significant dissolution was observed in the examined interval.

Samples were disaggregated in water and washed through a 63 μm sieve for Site 525A and a 106 μm sieve for Site 21. This process was repeated until a clean sample was obtained. Population counts for each sample are based on random splits (using an Otto micosplitter) of 300 or more specimens in the size fractions $>63 \mu\text{m}$ for Site 525A and $>106 \mu\text{m}$ for Site 21. The smaller size fraction was analyzed for Site 525A to evaluate relative abundances of very small species (e.g., globigerinellids, hedbergellids and small heterohelicids). The size difference resulted in relatively small changes in the overall species populations, although rare occurrences of small taxa were found to be more likely represented in the $>63 \mu\text{m}$ size fraction. This problem was generally circumvented by examining the coarser size fraction for rare species. All specimens were picked from each sample split, identified and mounted on microslides for a permanent record. The general taxonomy in this study follows Robaszynski et al. (1983, 1984) and Nederbragt (1989). Species identification was aided by publications by Smith and Pessagno (1973), Robaszynski et al. (1983, 1984), Caron (1985) and Nederbragt (1989, 1991). Relative percent abundances of picked specimens are listed in Table 1a and b for Site 525A and Table 2 for Site 21.

Stable isotope analysis was conducted on planktic

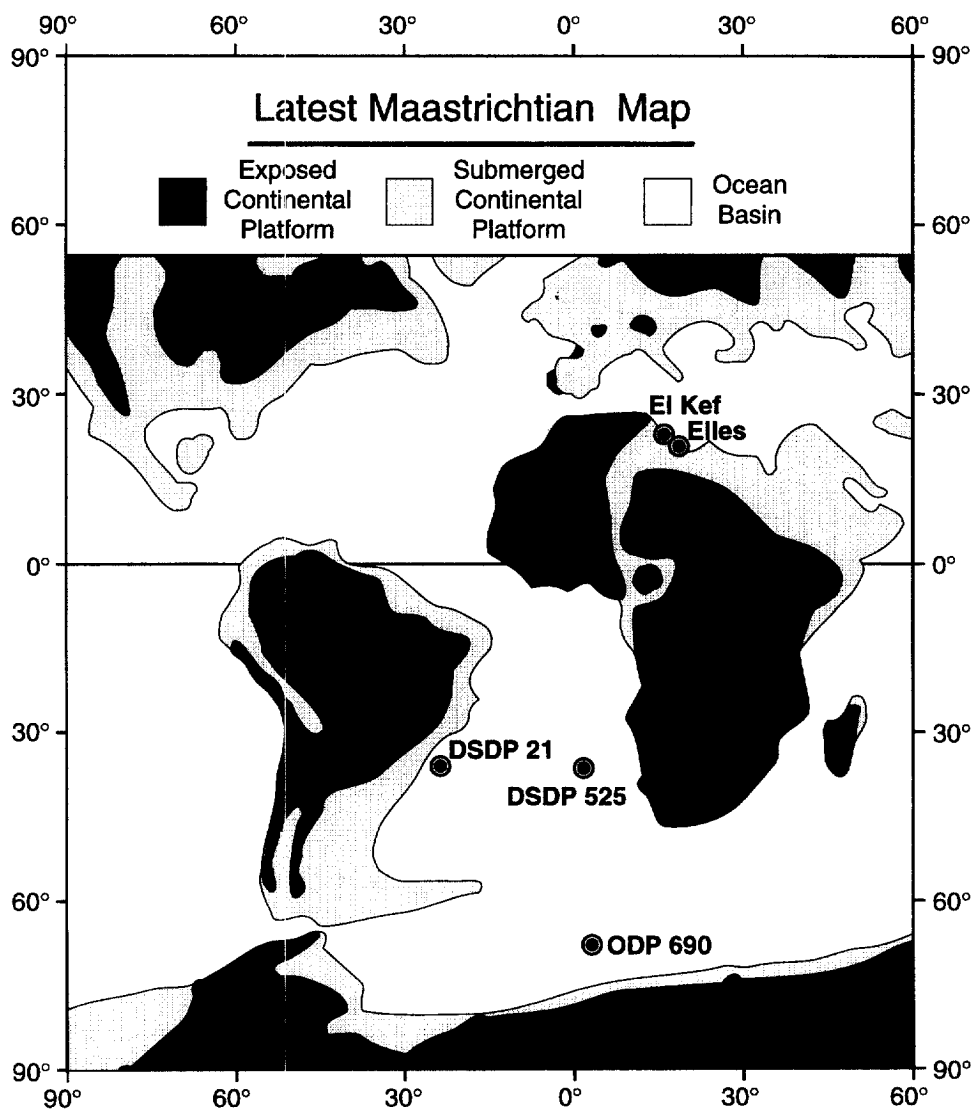
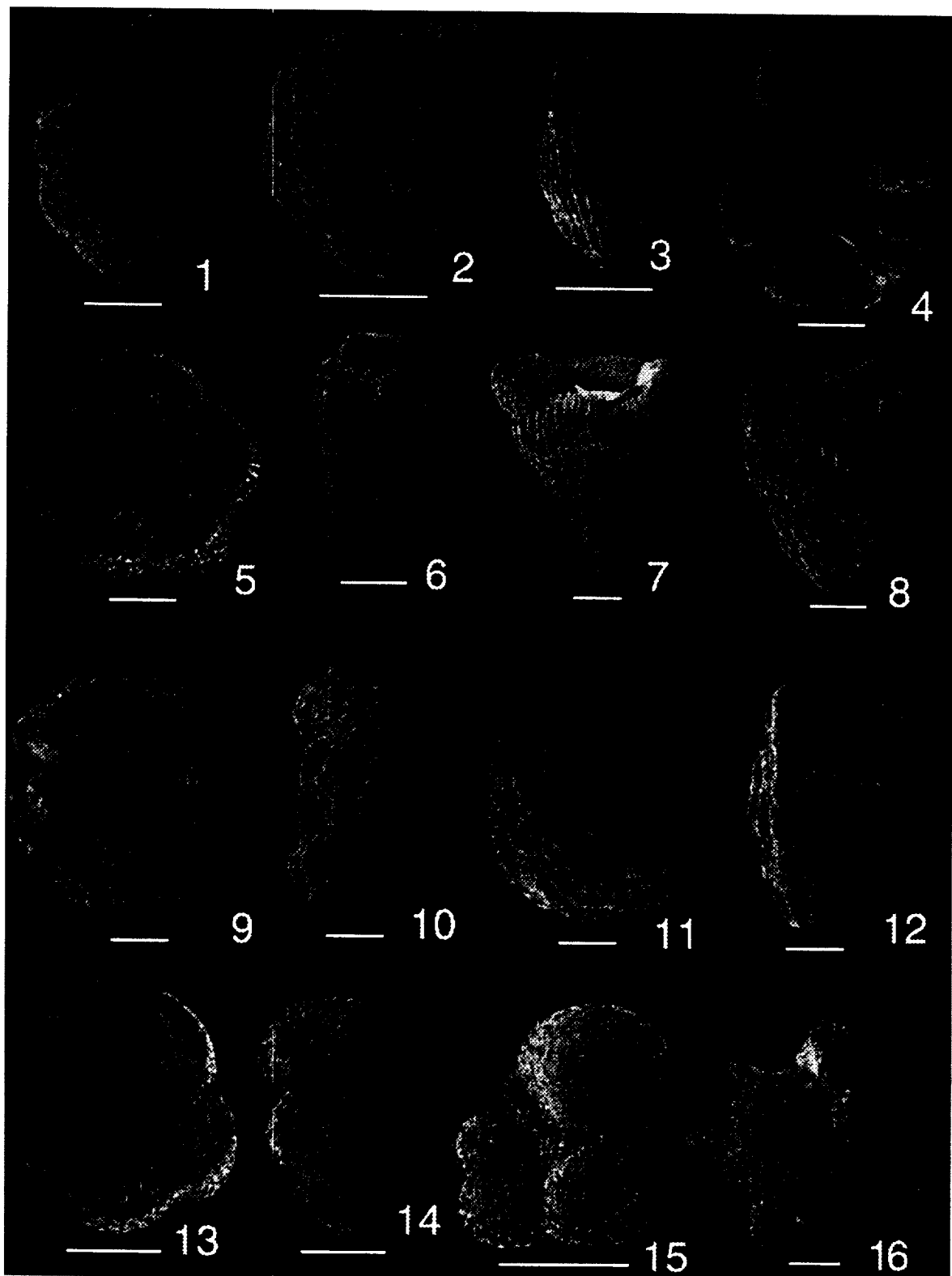


Fig. 1. Geographic location of DSDP sites 525A and 21 in the South Atlantic Ocean and other localities discussed.

and benthic foraminifera from Site 525A. For a surface water record, about 30 average-sized (150–250 μm) adult tests of the surface water dweller *Rugoglobigerina rugosa* were picked from each sample and analyzed for oxygen and carbon isotopes. For a bottom water record, about 20 adult tests (150–250 μm) of the benthic species *Anomalinoidea acuta* were analyzed from each sample. Stable isotopes were measured at the stable isotope laboratory of Princeton University using a VG Optima gas source mass spectrometer equipped with a common acid

bath. Isotopic results were calibrated to the PDB scale with a standard error of 0.07‰ for $\delta^{18}\text{O}$ and 0.03‰ for $\delta^{13}\text{C}$ (Table 3). Paleotemperature estimates follow the study of Erez and Luz (1983) with seawater $\delta^{18}\text{O} = -1.0‰$ (Shackleton and Kennett, 1975), assuming no major vital effects.

The preservation of foraminiferal species at Site 525A is generally good with only minor calcite overgrowth and without significant dissolution (Plates I and II). Thus, alteration of oxygen isotopic values may not have been significant in foraminifera at



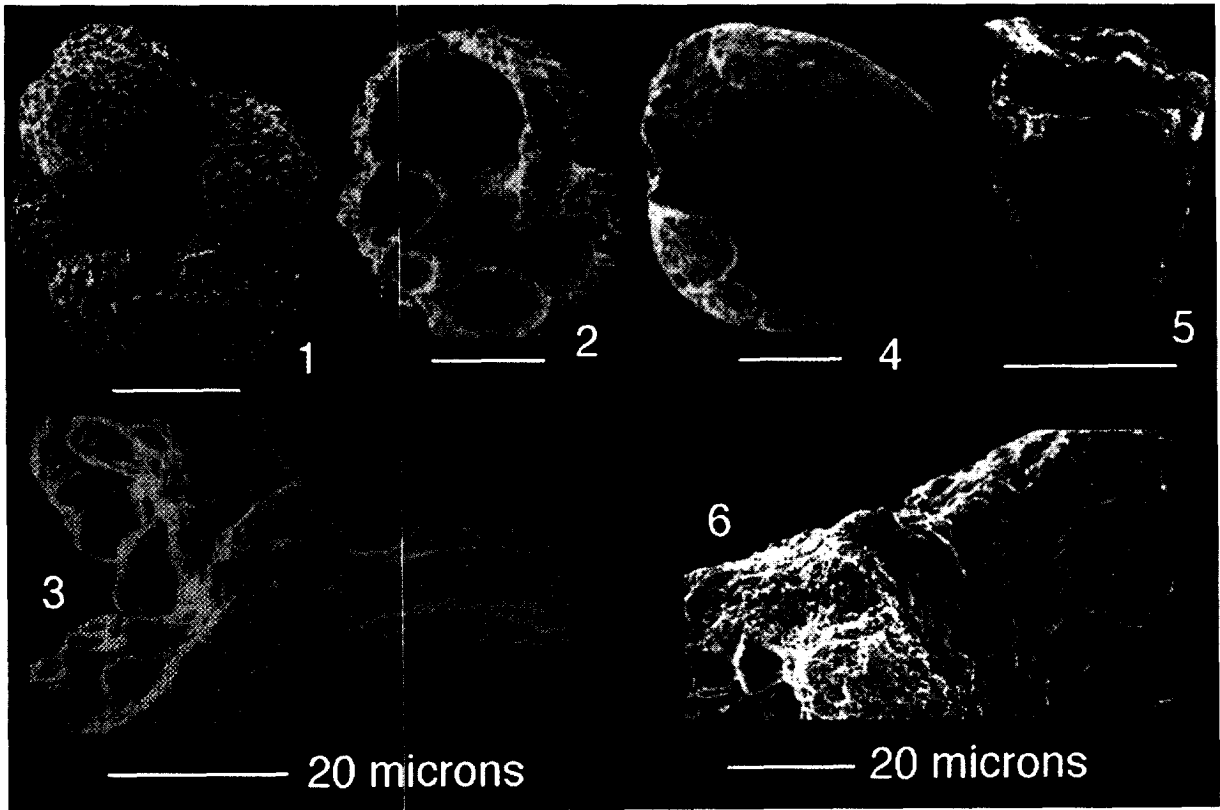


Plate II

All specimens from DSDP Site 525A. Scale bar = 100 μm .

1–2. *Rugoglobigerina rugosa* Bronnimann, Sample 45-4, 100–102 cm.

3. High magnification of broken surface of *R. rugosa* in 2. Note that there is little or no calcite encrustation on the inner parts of chambers and chamber walls are not recrystallized.

4. *Anomalinoidea acuta* (Plummer), Sample 45-4, 100–102 cm.

5. Broken chamber surface of *A. acuta*, Sample 45-4, 100–102 cm. Note that chamber walls are not recrystallized.

6. High magnification of broken chamber walls of *A. acuta* in 5. Note that the inner parts of chamber wall are encrusted with secondary calcite.

Plate I

All specimens from DSDP Site 525A, except for 16 which is from DSDP Site 21. Scale bar = 100 μm .

1. *Pseudoguembelina hariaensis* (Nederbragt), Sample 41-4, 100–102 cm.

2–3. *Pseudoguembelina palpebra* Bronnimann and Brown, Sample 42-4, 100–102 cm.

4, 8. *Racemiguembelina fruticosa* (Egger), Sample 42-4, 100–102 cm.

5–6. *Globotruncana linneiana* (d'Orbigny), Sample 45-4, 100–102 cm.

7. *Pseudotextularia intermedia* (De Klasz), Sample 42-4, 100–102 cm.

9–11. *Rosita contusa* (Cushman), Sample 43-4, 100–102 cm.

12. *Gansserina gansseri* (Bolli), Sample 45-4, 100–102 cm.

13–14. *Globotruncana aegyptiaca* Nakkady, Sample 45-4, 100–102 cm.

15. *Globotruncanella subcarinatus* (Bronnimann), Sample 45-4, 100–102 cm.

16. *Globotruncanella calcarata* (Cushman), Sample 6-4, 16 cm.

Table 1
Relative percent abundance of planktic foraminiferal species at DSDP Site 525A

Core Section Interval (cm)	40-1	40-2	40-3	40-4	40-5	41-1	41-2	41-3	41-4	41-5	42-1	42-2	42-3	42-4	42-5	42-6	43-1	43-2	43-3	43-4	43-5	43-6	44-1	44-2	44-3	44-4	44-5								
<i>Ammonia</i>	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX	XX							
<i>Ammobaculites</i>																																			
<i>Ammobaculites inflatum</i>																																			
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Table 2
Relative percent abundance of planktic foraminiferal species at DSDP Site 21

Core-Section Interval (cm)	Depth (mbsf)	3-1	3-2	3-5	3-6	4-1	4-2	4-3	4-4	4-5	4-6	5-1	5-2	5-3	5-4	5-5	5-6	6-1	6-2	6-3	6-4	6-5	6-6
		77.35	78.85	83.30	84.80	86.38	87.90	89.30	91.10	92.40	93.75	97.73	98.20	100.70	102.20	103.68	105.22	107.22	108.60	110.17	110.56	112.81	114.67
<i>Albainohyalus mayaroensis</i>		xx	X	3	xx	X																	
<i>Archeoheloberella blowi</i>																							
<i>A. cretacea</i>																							
<i>Gauesina ganseri</i>		X		xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>Globobulimina aspera</i>		X		2	12	18	18	17	24	20	6	18	13	7	23	21	11	3	12	20	17	10	18
<i>G. aff. roseobulimoides</i>		xx	4	4	2	3	3	2	3	3	6	6	X	5	5	3	9	6	5	5	2	3	2
<i>G. aff. ultramira</i>				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	xx	xx	xx	X
<i>G. multispirina</i>		4	3	X	2	X	X	X	X	X	X	X	2	7	X	xx	5	2	6	3	5	4	X
<i>G. botanica aegyptiaca</i>		2	2	3	6	2	3	9	4	6	2	4	8	9	6	7	3	5	4	3	X	4	X
<i>G. acuta</i>			X		X	2	15	6	xx	4	8	7	8	7	3	9	4	22	21	8	9	17	9
<i>G. bulimoides</i>																							
<i>G. insignis</i>																							
<i>G. lineolata</i>																							
<i>G. mairii</i>																							
<i>G. orientalis</i>		30	19	14	4	22	8	4	X	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>G. ventricosa</i>																							
<i>Globotruncanella livanensis</i>		4	1	X	X	X	X	xx	X	X	X	xx	xx	X	X								
<i>G. petaloides</i>		5	5	6	6	3	8	6	4	4	8	xx	3	2	X	3	3						
<i>G. subcarinata</i>		2	7	8	8	xx	X	xx															
<i>Globotruncanella argulata</i>																							
<i>G. calcarata</i>																							
<i>G. conica</i>		X	3	xx	X	X	3	xx	xx	xx	X	xx	X	xx	X	2	xx	3	xx	xx	xx	xx	xx
<i>G. stuarti</i>																							
<i>Gublerina acuta</i>																							
<i>G. multicamerata</i>		X	3	xx	xx	X	3	xx	xx	xx	X	xx	X	xx	X	2							
<i>Hebergella holmdelensis</i>		X	2																				
<i>H. monodentata</i>		xx																					
<i>H. simplex</i>		3	3	9	6	16	10	11	9	8	9	2	2	X	2	2	11	X	X	4	4	5	8
<i>Heterohelix globulans</i>		10	6	11	6	5	7	8	15	15	8	2	4	6	5	5	12	2	6	2	3	5	14
<i>H. globulosa</i>																							
<i>H. planata</i>		X	X	5	7	9	9	5	9	4	12	14	10	11	9	9	11	9	7	5	4	2	X
<i>H. pulchra</i>		xx	4	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>H. punctulata</i>		3	6	4	4	2	3	X	2	3	X		X										
<i>H. rajapalabani</i>		3	4	X	X	X	X	xx	xx	xx	xx	X	X	2	2	X	7	11	8	13	10	2	8
<i>Planoglobulina brazzoensis</i>		xx	X	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>P. carawayae</i>																							
<i>P. multicamerata</i>		X	X	2	xx	4	3	X	3	2	2	10	9	8	14	10	7	11	8	13	10	2	8
<i>Pseudogumbelina costulata</i>		23	9	12	17	9	4	X	X	X	X	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>P. palubra</i>		2	3	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>Pseudotulania deformis</i>		X	6	X	2	X	X	2	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>P. elegans</i>		3	X	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>P. inermis</i>		X	X	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>Racemigumbelina fructuosa</i>		X	X	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>R. powelli</i>		X	X	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>Rosta contusa</i>		X	X	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>R. fornicata</i>		X	X	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>R. plummerae</i>		X	X	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>Rugoglobigerina hexacamerata</i>		X	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>R. milanensis</i>		X	3	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>R. rotundata</i>		3	5	X	X	4	4	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
<i>R. rugosa</i>		2	X	3	X	9	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
<i>R. scotti</i>																							
Total Number counted		310	275	203	170	290	358	356	325	450	354	307	315	298	307	281	316	289	271	306	274	369	302

X = <2%; xx = rare species.

Site 525A. This is also suggested by $^{87}\text{Sr}/^{86}\text{Sr}$ values. Sugarman et al. (1995) determined Sr isotopic records for the Maastrichtian samples at Site 525A and concluded that these values are consistent with those of well-preserved foraminifera from other sites where diagenetic alteration was considered insignificant (Hess et al., 1986; Martin and MacDougall, 1991). Another source that may affect the original stable isotopic signals are foraminiferal vital effects, including different test sizes of a single species (Erez and Luz, 1983; Spero and Williams, 1988; Spero et al., 1991; Spero, 1992). In this study, we attempted to minimize such vital effects by analyzing narrowly constrained size fractions (150–250 μm) for both planktic and benthic foraminifera.

3. Biostratigraphy

The Maastrichtian stage is still poorly defined. Though everyone agrees that the Cretaceous–Tertiary boundary marks the top of the Maastrichtian, there is still no formal agreement as to the placement of the Campanian–Maastrichtian boundary. At a recent meeting in Brussels, the Maastrichtian Working Group of the Subcommittee of Cretaceous Stratigraphy reached the following conclusion: “the Campanian/Maastrichtian boundary will be proposed at a precise point in the disused quarry at Tercis (Landes, France) at the immediate proximity of the level where the oldest *Pachydiscus neubergicus* (Von Haner, 1858) have been found” (Odin, 1996, p. 111). The stratigraphic relationship of this ammonite datum event to the commonly used planktic foraminiferal datum of *Globotruncanella calcarata* (LA = last appearance) or *Gansserina gansseri* (FA = first appearance) is still unknown. Correlations suggest that the *G. gansseri* FA is significantly younger than the *P. neubergicus* FA and that the *G. calcarata* LA may be somewhat older (Stinnesbeck, pers. commun., 1996). However, ammonite and planktic foraminiferal datums have yet to be studied and calibrated within the same section. With these constraints, we have continued the practice of placing the Campanian–Maastrichtian boundary at the *G. calcarata* FA following Robaszynski et al. (1983, 1984) and Caron (1985).

At the same meeting in Brussels it was recommended that the Maastrichtian stage be formally di-

vided into two substages (lower and upper), though, “there was no agreement on the boundary-criterion for the base of the Upper Maastrichtian. Possible criteria mentioned included: the extinction of rudistid reefs, the extinction of the majority of inoceramids, the lowest occurrence of a calcareous nannofossils species or the ammonite *Pachydiscus freshvillensis*” (Odin, 1996, p. 115). It was suggested that the problem be further studied. Planktic foraminiferal workers have generally placed the lower–upper Maastrichtian boundary at the FA of *G. gansseri* (Robaszynski et al., 1983, 1984; Caron, 1985) or at the FA of *Abathomphalus mayaroensis*, which is diachronous and occurs earlier in high latitudes (Fig. 2; Boersma, 1984a; Huber, 1990). In this study we followed the practice of informally placing the lower–upper Maastrichtian boundary at the FA of *G. gansseri*, which is at Site 525A is close to the FA of *A. mayaroensis* (Fig. 2).

Fig. 2 shows commonly used Maastrichtian planktic foraminiferal zonations for low and high latitudes. In low latitudes, the zonation by Caron (1985) is generally employed. This zonal scheme divides the Maastrichtian into four zones: *Globotruncanella havanensis*, *Globotruncana aegyptiaca*, *Gansserina gansseri* and *Abathomphalus mayaroensis*. Little work has been done to date in high latitude Maastrichtian sequences except for Huber (1990) who divided the Maastrichtian into two zones: *Globotruncanella havanensis* and *Abathomphalus mayaroensis*. Earlier work at DSDP Site 525A by Boersma (1984a) also employed only two zones, *Globotruncana tricarinata* for the lower Maastrichtian and *Abathomphalus mayaroensis* for the upper Maastrichtian (Fig. 2). Based on our faunal and biostratigraphic analysis of DSDP sites 525A and 21. We propose to divide the Maastrichtian into eight biozones (labeled CF for Cretaceous Foraminiferal zones). This new biozonation provides a significantly higher biostratigraphic resolution than previous zonal schemes (Fig. 2).

An excellent Maastrichtian paleomagnetic record at Site 525A (Chave, 1984) provides the basis for estimating absolute ages for the new biozones. Our age estimates are based on magnetochron ages by Berggren et al. (1995), the assumption of constant sedimentation rates for each paleomagnetic period and extrapolation of ages for each datum event and

Table 3
Stable isotopic composition of planktic (*Rugoglobigerina rugosa*) and benthic foraminifera (*Anomalinoidea acuta*) at Site 525A

Core-section, cm	Depth (m b.s.f.)	<i>Rugoglobigerina rugosa</i>		<i>Anomalinoidea acuta</i>	
		$\delta^{31}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$
40-1, 100–102	451.11	1.89	-0.17	1.58	0.42
40-2, 48–50	452.09	2.62	-0.39	1.32	-0.10
40-2, 102–104	452.61	2.74	-0.41	1.79	0.30
40-3, 50–52	453.61	2.74	-0.52	1.62	-0.12
40-3, 100–102	454.11	2.51	-0.82	1.45	-0.34
40-4, 50–52	455.11	2.69	-0.68	1.44	-0.14
40-4, 100–102	455.61	2.64	-0.76	1.55	0.23
40-5, 100–102	457.11	2.66	-0.48	1.36	0.40
41-1, 100–102	460.61	2.62	-0.07	1.54	0.43
41-2, 100–102	462.11	2.80	-0.68	1.32	0.61
41-3, 98–100	463.59	2.96	-0.65	1.47	0.40
41-4, 100–102	465.11	2.98	-0.64	1.23	0.36
41-5, 100–102	466.61	2.96	-0.78	1.58	0.36
41-6, 100–102	468.11	2.94	-0.53	1.63	0.47
42-1, 100–102	470.11	2.79	-0.96	1.54	0.46
42-2, 100–102	471.61	2.90	-0.79	1.70	0.37
42-3, 100–102	473.11	3.07	-0.67	1.43	0.35
42-4, 100–102	474.61	3.04	-0.88	1.37	0.12
42-5, 100–102	476.11	3.46	-0.91	1.19	0.17
42-6, 100–102	477.61	3.12	-1.18	1.80	0.19
43-1, 100–102	479.61	2.91	-1.14	1.40	0.10
43-2, 96–98	481.07	2.92	-0.98	1.20	-0.15
43-3, 100–102	482.61	2.82	-0.83	1.55	0.04
43-4, 100–102	484.11	2.82	-0.45	1.64	0.13
43-5, 100–102	485.61	2.78	-1.21	1.46	0.29
43-6, 100–102	487.11	2.87	-0.99	1.36	-0.01
44-1, 100–102	489.11	2.87	-0.89	1.63	0.19
44-2, 98–100	490.59	2.90	-0.61	1.64	0.13
44-3, 95–97	492.06	2.83	-1.03	1.41	0.06
44-4, 100–102	493.61	2.75	-1.11	1.32	-0.17
44-5, 100–102	495.11	2.87	-1.02	1.22	-0.02
44-6, 100–102	496.61	2.71	-1.04	1.30	0.16
45-1, 100–102	498.61	2.67	-1.02	0.83	0.48
45-2, 103–105	500.14	3.27	-0.54	0.73	0.35
45-3, 100–102	501.61	2.74	-1.03	0.97	0.26
45-4, 100–102	503.11	2.60	-1.22	0.98	0.29
45-5, 100–102	504.61	2.73	-1.05	0.66	0.47
46-1, 100–102	508.11	2.59	-0.86	1.17	0.37
46-2, 100–102	509.61	2.47	-0.73	0.50	0.35
46-3, 90–92	511.01	2.20	-0.76	0.86	0.49
46-4, 100–102	512.61	2.12	-0.88	0.53	0.33
46-5, 100–102	514.11	2.19	-0.95	0.76	0.11
46-6, 100–102	515.61	1.80	-1.06	0.21	0.45
47-2, 98–100	519.09	1.80	-1.18	0.00	0.44
47-3, 90–92	520.51	2.13	-1.07	-0.20	0.40
47-4, 94–96	522.05	1.77	-1.35	0.14	-0.10
48-2, 103–105	528.63	1.68	-1.26	0.35	0.00
48-3, 100–102	530.11	2.27	-1.77	0.76	-0.20
49-1, 100–102	536.61	2.21	-1.30	0.65	-0.28
49-2, 100–102	538.11	1.85	-1.49	0.64	0.10
49-3, 100–102	539.61	2.07	-1.17	0.38	-0.17
50-1, 100–102	546.11	2.10	-1.56	0.66	-0.07

Table 3 (continued)

Core-section, cm	Depth (m b.s.f.)	<i>Rugoglobigerina rugosa</i>		<i>Anomalinooides acuta</i>	
		$\delta^{31}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$
50-2, 100–102	547.61	2.12	-1.49	0.66	0.17
50-3, 100–102	549.11	1.65	-1.96	0.27	-0.25
50-4, 100–102	550.61	1.96	-1.92	0.60	-0.30
51-1, 100–102	555.61	1.81	-1.58	0.43	-0.74
51-2, 90–92	557.01	1.96	-1.56	0.67	-0.70
51-3, 100–102	558.61	1.86	-1.78	0.84	-0.42
51-4, 100–102	560.11	1.93	-1.62	0.66	-0.47
51-5, 100–102	561.61	1.77	-2.02	-0.05	-0.79

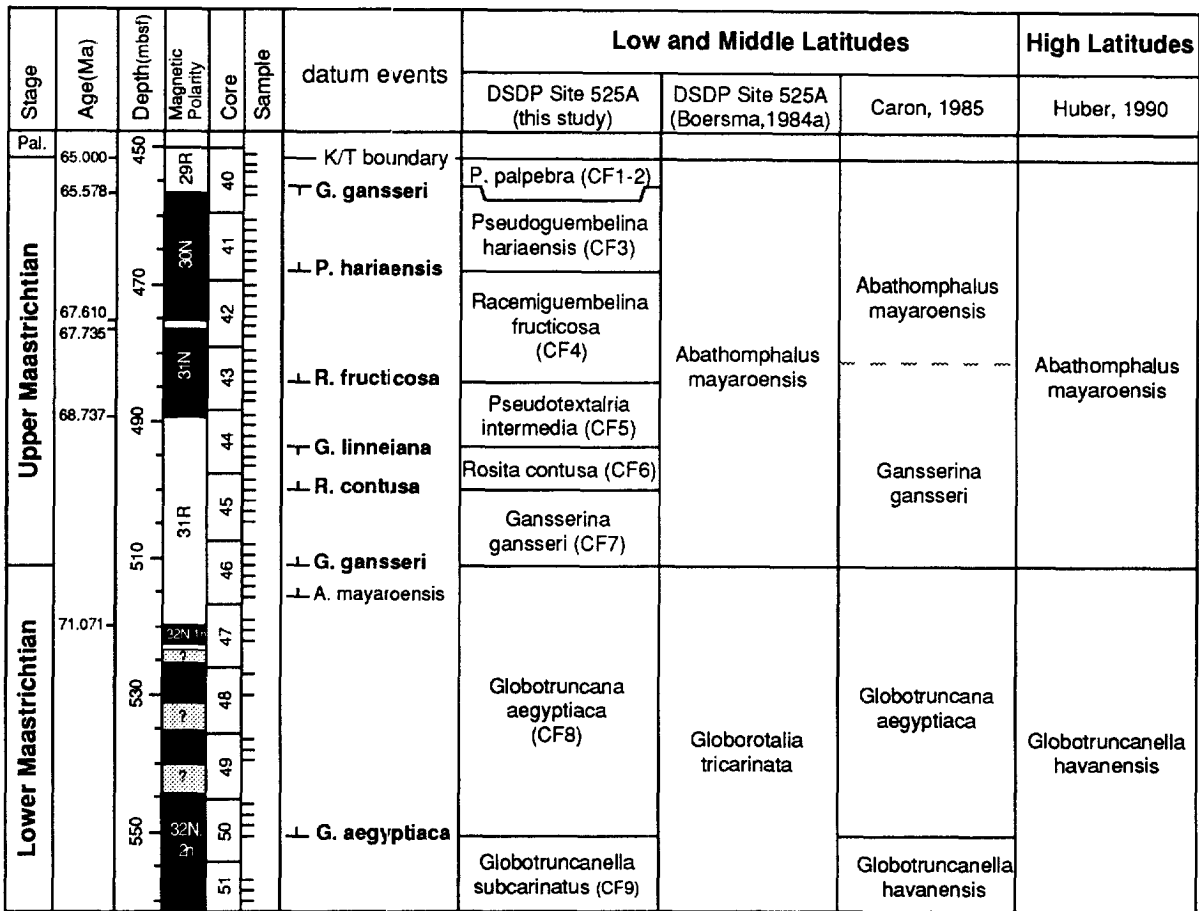


Fig. 2. Planktic foraminiferal zonation commonly used in low and high latitudes and new zonation proposed based on DSDP Site 525A. In the new zonal scheme, the late Maastrichtian is subdivided into eight biozones.

duration of each biozone (Fig. 3). Sediment accumulation rates average between 8.6 and 13.1 m/Myr between C29R and C32N.1n. Below this interval,

paleomagnetic control for C32N.2n is questionable (Chave, 1984). Table 4 lists depth of datum events in meters below sea floor (m b.s.f.), the age of datum

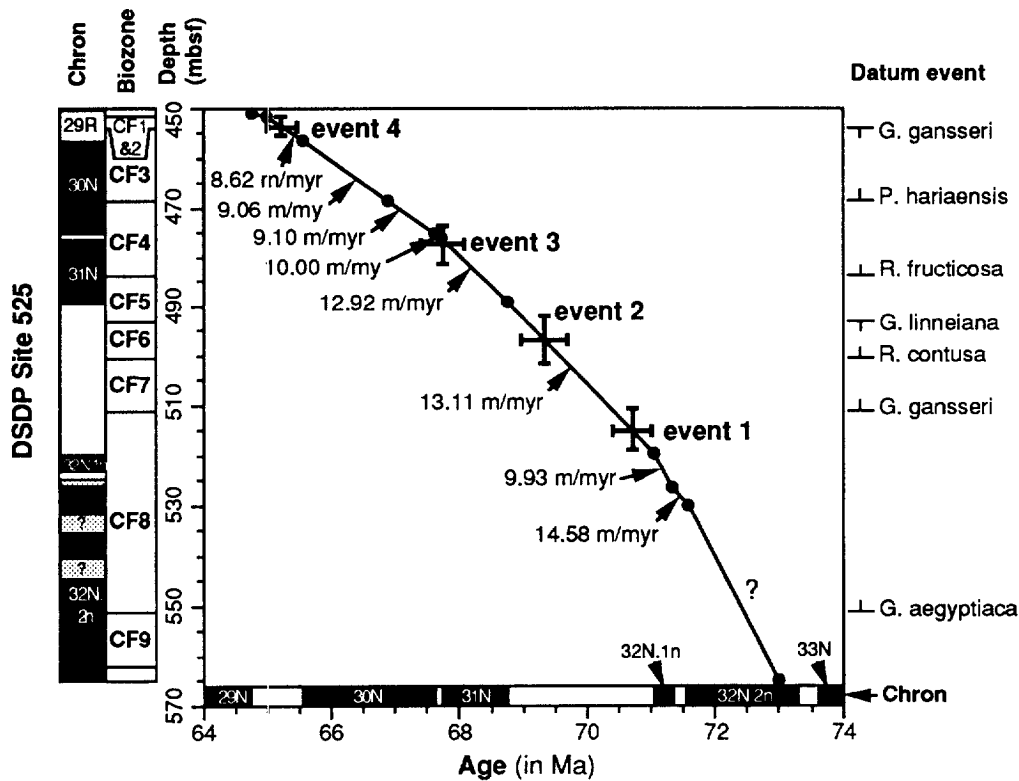


Fig. 3. Age/depth plot for DSDP Site 525A to evaluate average sediment accumulation rates for each paleomagnetic chron (see arrows), the age and duration of each faunal event and the age of datum events. Note that the sedimentation rates remain stable between 8.6 and 14.5 m/Myr during most of the Maastrichtian.

events and the average sedimentation rate for each paleomagnetic interval and for each biozone.

At Site 21, despite near 100% core recovery, the Maastrichtian spans only about 30 m as compared with nearly 100 m at Site 525A. This suggests a very condensed interval and possibly one or more hiatuses (discussed below). Nevertheless, the sequence of first and last appearances of species at the two sites is very similar and suggests regional assemblage changes.

3.1. The Cretaceous–Tertiary (K–T) boundary

The K–T boundary at Site 525A is marked by a thin (0.5–1 cm) blue-tinged and fine-grained sediment layer (core 40-2, 11–11.5 cm) located within C29R (Manivit, 1984). The lithological change coincides with the first appearance of the Tertiary species *Parvularugoglobigerina eugubina*, which

marks Zone Pl_a of Keller (1993). This suggests that the K–T boundary transition at Site 525A is very condensed and a short hiatus may be present as is generally observed in deep sea sections (MacLeod and Keller, 1991a,b; MacLeod, 1995). At Site 21, no lithological change is present and the K–T boundary is placed between cores 2 and 3, based on the abrupt change from an upper Maastrichtian (zones CF3–4) to an Upper Paleocene foraminiferal assemblage. This indicates the presence of a major hiatus spanning from the Upper Paleocene to the upper Maastrichtian.

3.2. *Pseudoguembelina palpebra* partial range zone (CF1–2)

The *Pseudoguembelina palpebra* or CF1–2 Zone is defined by the LA of *Gansserina gansseri* at the base and the LA of *P. palpebra* at the top (Plate 1, 2,

Table 4

DSDP Site 525A: Age of planktic foraminiferal datum events and average sedimentation rate calculated for each paleomagnetic period and each biozone

Core-section, cm	Depth (m b.s.f.)	Age (Ma)	Criteria	Average sed. rate by chron (m/myr)	Average sed. rate by zone (m/myr)
40-1, 100–102	450.99	64.75	base of C29N		
40-2, 48–50	451.71	65.00	K/T boundary		
				8.6 (lower C29R)	8.6 (CF1&2)
40-4, 100–102	455.61	65.45	LA of <i>G. gansseri</i>		
40-5, 100–102	456.69	65.58	C29R–C30N		9.1 (CF3)
				9.1 (C30N)	
41-6, 100–102	468.11	66.83	FA of <i>P. hariaensis</i>		
42-5, 100–102	475.15	67.61	Base C30N		9.1 (CF4)
				10 (C30R)	
42-5, 130–132	476.40	67.74	Top C31N		
43-4, 100–102	484.11	68.33	FA of <i>R. fructicosa</i>	12.9 (C31N)	
44-2, 98–100	489.35	68.74	Base C31N		13.0 (CF5)
444, 100–102	493.61	69.06	LA of <i>G. linneiana</i>		13.1 (CF6)
					13.1 (31R)
45-2, 103–105	500.14	69.56	FA of <i>R. contusa</i>		
					13.1 (31R)
46-4, 100–102	511.01	70.39	FA of <i>G. gansseri</i>		
46-6, 100–102	514.20	70.63	FA of <i>A. mayaroensis</i>		
47-3, 90–92	519.95	71.07	Top C32N.1n		
				9.9 (C32N.1n)	11.8 (CF7)
47-4, 144–146	522.61	71.34	Base C32N.1n		
48-1, 100–102	526.24	71.59	Top C32N.2n		
50-4, 100–102	550.61	72.48	FA of <i>G. aegyptiaca</i>	14.6 (C32N.1r)	
51-5, 100–102	561.61	72.88			
	565.00	73.00	still C32N		

3 and 12) which also coincides with the K–T boundary. At Site 525A this interval is estimated to span the last 450 kyr of the Maastrichtian (C29R below the K–T boundary) and the average sedimentation rate during this interval is 8.6 m/Myr (Table 4). At Site 21 this interval is missing as suggested by the presence of *G. gansseri* at the top of the recovered Maastrichtian interval.

In the Tethys region, the last 200 kyr of the Maastrichtian are marked by the total range of *Plummerita hantkeninoides*, or Zone CF1 (Masters, 1984, 1993; Pardo et al., 1996; Keller et al., 1996) and the *P. palpebra* Zone (CF2) spans the intervals from 450 to 200 kyr before the K–T boundary (Li, 1997). Because *Plummerita hantkeninoides* is a tropical species and absent in middle and high latitudes, the interval labeled *P. palpebra* Zone (CF1–2) at Site 525A spans both zones CF1 and CF2 of low latitudes. This zonal designation (CF1–CF2) will facilitate correlation with low latitude sequences.

3.3. *Pseudoguembelina hariaensis* partial range zone (CF3)

The *Pseudoguembelina hariaensis* or CF3 Zone is defined by the FA of *P. hariaensis* at the base and the LA of *G. gansseri* at the top. The marker species, *P. hariaensis* first appears in the middle of C30N. This biozone spans about 1.4 Myr (66.8–65.45 Ma), based on paleomagnetic data at Site 525A and has an average sedimentation rate of 9.1 m/Myr (Table 4). *Pseudoguembelina hariaensis* has a similar morphology as *Pseudoguembelina palpebra*, but differs in its last compressed chamber (Plate I, 1; Nederbragt, 1991).

3.4. *Racemiguembelina fructicosa* partial range zone (CF4)

The *Racemiguembelina fructicosa* or CF4 Zone is defined by the FAs of *R. fructicosa* at the base

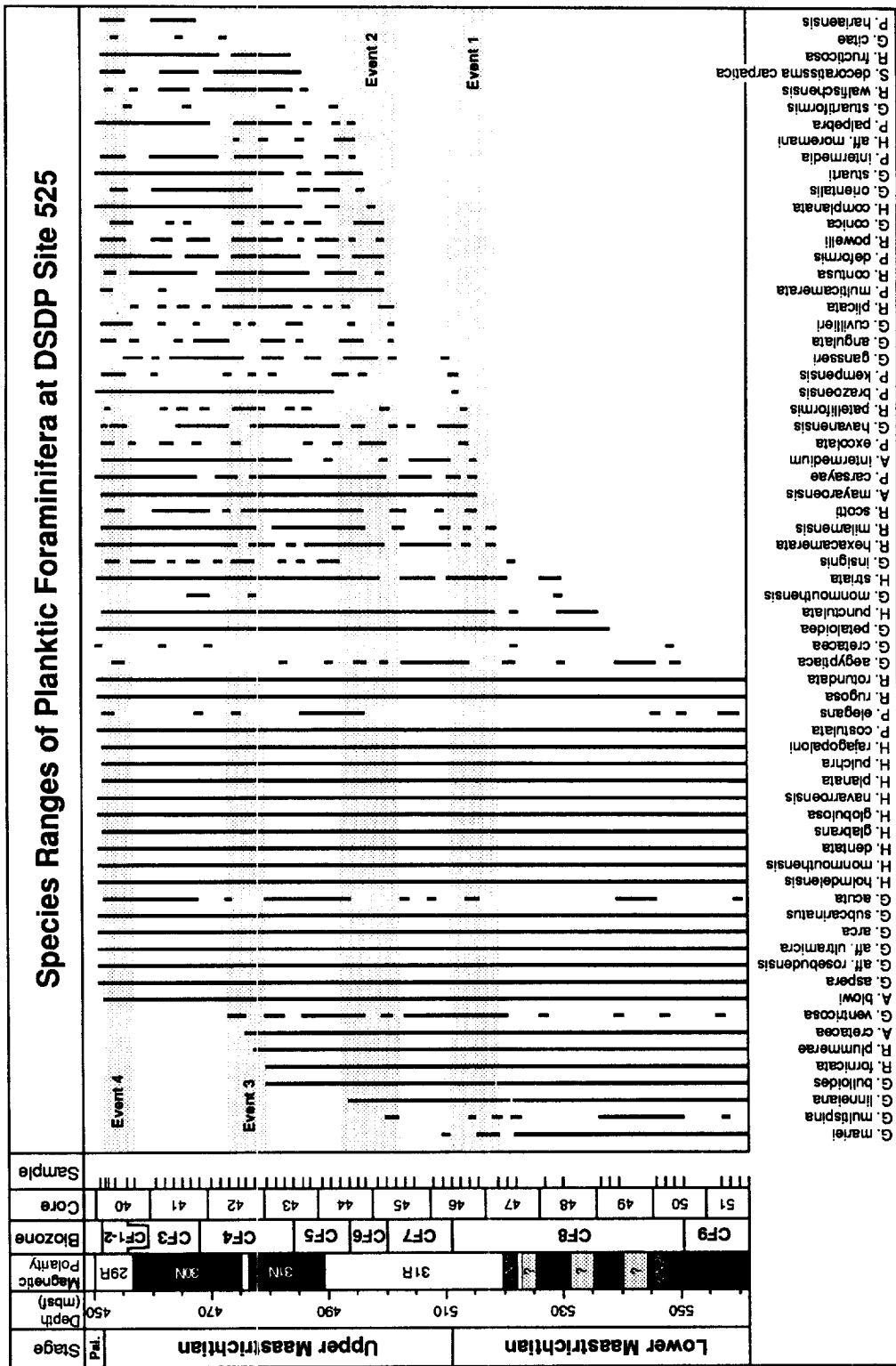


Fig. 4. Species ranges of planktic foraminifera at DSDP Site 525A. Four faunal turnover events can be recognized. Events 1 and 2 are origination events which increased species richness by a total of 43%. Event 3 is a mini-extinction event and event 4 is the K-T mass extinction which includes the pre-K-T and the K-T boundary extinctions.

and *P. hariaensis* at the top (Plate I, 4 and 8). At Site 525A, the first occurrence of *R. fructifera* was observed in the middle of C31N. Zone CF4 spans about 1.5 Myr (68.33–66.83 Ma) and has an average sedimentation rate of 9.1 m/Myr (Table 4). Several species disappear in the lower part of this biozone, including *Archaeoglobigerina cretacea*, *Globotruncana bulloides*, *G. ventricosa*, *Rosita fornicata* and *R. plummerae* (Figs. 4 and 8).

3.5. *Pseudotextularia intermedia* partial range zone (CF5)

The *Pseudotextularia intermedia* or CF5 Zone is defined by the LA of the *Globotruncana linneiana* at the base and the FA of *R. fructifera* at the top (Plate I, 5–7). *Globotruncana linneiana* was observed to range well into the upper Maastrichtian by several workers (e.g., Robaszynski et al., 1983, 1984; Caron, 1985). Because of its typical box-shape morphology, *G. linneiana* is easy to recognize and an excellent marker species. At Site 525A, the last *G. linneiana* was observed in the upper part of C31R. Zone CF5 is named for *P. intermedia*, which first appears in Zone CF6, but well-developed typical morphotypes of this species appear in CF5. Zone CF5 spans about 0.7 Myr (69.06–68.33 Ma) and has an average sedimentation rate of 13.0 m/Myr.

3.6. *Rosita contusa* partial range zone (CF6)

The *Rosita contusa* or CF6 Zone is defined by the FA of the nominate taxon at the base and the LA of *Globotruncana linneiana* at the top (Plate I, 9–11). At Site 525A, *R. contusa* first appears within the upper part of C31R at 69.56 Ma. Zone CF6 is estimated to span about 0.5 Myr (69.56–69.06 Ma) and has an average sedimentation rate of 13.1 m/Myr at Site 525A (Table 4). A major faunal turnover characterizes this zone with 16 species originations near the base at Site 525A (Figs. 4 and 5).

3.7. *Gansserina gansseri* partial range zone (CF7)

The *Gansserina gansseri* or CF7 Zone is defined by the FA of the nominate taxon at the base and the FA of *Rosita contusa* at the top (Plate I, 12). In most zonal schemes, including ours, the first appearance

of *G. gansseri* informally marks the lower–upper Maastrichtian boundary (Robaszynski et al., 1983, 1984; Caron, 1985; Nederbragt, 1991). At Site 525A, the first appearance of *G. gansseri* was observed in the lower part of C31R. We estimate that the *G. gansseri* Zone spans about 0.8 Myr (70.39–69.56 Ma) assuming constant sedimentation rates of 11.8 m/Myr through C31R (Table 4; Fig. 3).

Note that at Site 525A *Abathomphalus mayaroensis* first appears ~4 m below the *G. gansseri* FA (Figs. 2 and 4). We have not used *A. mayaroensis* as zonal marker because many studies have shown that both FA and LA of this species are diachronous. In addition, this taxon is rarely present in continental shelf sections due to its deeper dwelling habitat (e.g., Masters, 1984, 1993; Hultberg and Malmgren, 1987; Keller, 1988, 1989, 1993; Brinkhuis and Zachariasse, 1988; Huber, 1992; Nederbragt, 1991; Schmitz et al., 1992; Keller et al., 1996). *Abathomphalus mayaroensis* is therefore not a reliable zonal index species. At Site 525A, we observed the first occurrence of *A. mayaroensis* in Core 46-6, 100–102 cm (515.61 m b.s.f.), 14 m below the horizon in which Boersma (1984a) recorded it. However, in low latitudes the FA of *A. mayaroensis* is generally much later at approximately the first appearance of *R. fructifera* (Caron, 1985).

3.8. *Globotruncana aegyptiaca* partial range zone (CF8)

The *Globotruncana aegyptiaca* or CF8 Zone is defined by the FA of the index taxon at the base and the FA of *G. gansseri* at the top (Plate I, 13 and 14). The *G. aegyptiaca* Zone is commonly used to mark the lower Maastrichtian in low latitudes (Robaszynski et al., 1983, 1984; Caron, 1985). At Site 525A, the first appearance of *G. aegyptiaca* occurs in the lower C32N. Paleomagnetic control is poor in this interval (Chave, 1984) and therefore the duration of this biozone, estimated about 2.1 Myr (72.48–70.39 Ma), is probably unreliable. At Site 21, Zone CF8 spans only a 3 m interval and is probably incomplete. Within the lower two thirds of Zone CF8 at Site 525A, six species originate (e.g., *Globotruncana aegyptiaca*, *G. insignis*, *Globotruncanella petaloidea*, *Guembelitra cretacea*, *Heterohelix punctulata* and *H. striata*). In the upper part of Zone CF8, a rapid

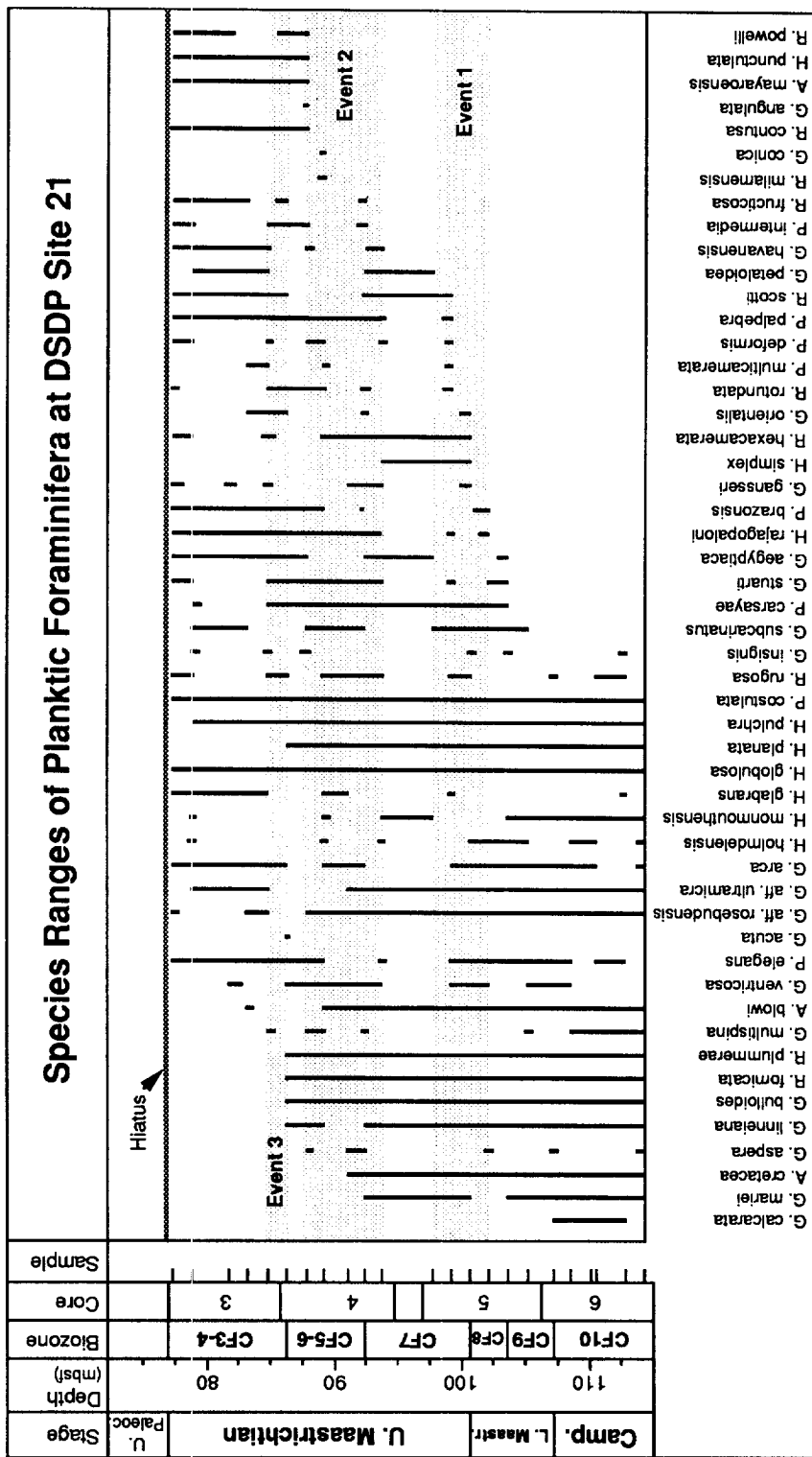


Fig. 5. Species ranges of planktic foraminifera at DSDP Site 21. Faunal turnover events 1 to 3 can be recognized with similar patterns as at Site 525A. The K–T boundary mass extinction is missing due to a hiatus.

diversification occurs with 12 species originations (Figs. 4 and 5).

3.9. *Globotruncanella subcarinatus* partial range zone (CF9)

The *Globotruncanita subcarinatus* or CF9 Zone is defined by the LA of *Globotruncanita calcarata* at the base and the FA of *G. aegyptiaca* at the top. The base of this zone informally marks the Campanian–Maastrichtian boundary in low latitudes (Robaszynski et al., 1983, 1984; Caron, 1985). Zone CF8 is equivalent to the *Globotruncanella havanensis* Zone of Caron (1985). However, we renamed this zone *G. subcarinatus* because *G. havanensis* was not found at this stratigraphic interval at sites 525A and 21. *Globotruncanita calcarata* is present at Site 21, but was not observed at Site 525A. Based on calcareous nannofossils, the basal sediments (Core 52-2) at Site 525A contain a characteristic *Quadrum trifidum* Zone flora which spans both the uppermost Campanian and the lower Maastrichtian (Manivit, 1984).

3.10. *Globotruncanita calcarata* total range zone (CF10)

This zone is defined by the total range of *Globotruncanita calcarata*. With its characteristic spines, *G. calcarata* is easily recognized and an excellent index species (Plate I, 16). The *G. calcarata* Zone was encountered only at Site 21 and therefore is not shown in Fig. 2 which shows the zonation based on Site 525A.

4. Faunal turnovers

4.1. Faunal event 1

Four major faunal assemblage changes are recognized in Maastrichtian sediments of sites 525A and 21 (Figs. 4 and 5). The first faunal assemblage change (event 1) occurs near the early–late Maastrichtian transition in the uppermost CF8 Zone (*G. aegyptiaca*) and in the lower part of C31R (Fig. 4). This faunal turnover is a major origination event where 12 species evolved rapidly over less than 600 kyr and species richness increased by 26% at

Site 525A (Fig. 4) and by 31% at Site 21 (Fig. 5). However, this origination event differs in sites 525A and 21. For instance, of the twelve species which originated at Site 525A, only four are at the same stratigraphic level as those at Site 21 (e.g., *Rugoglobigerina hexacamerata*, *R. scotti*, *Planoglobulina carseyae* and *P. brazoensis*), whereas five species appear earlier at Site 21 (e.g., *Globotruncana insignis*, *R. milamensis*, *Abathomphalus mayaroensis*, *A. intermedium* and *Globotruncanella havanensis*, Figs. 4 and 5). The remaining three species were not observed at Site 21 (e.g., *Pseudoguembelina excolata*, *P. kempensis* and *Rosita patelliformis*). We attribute these differences mainly to the different sampling resolutions between the two sites and possibly to diachronous species originations and extinctions. The latter has yet to be systematically examined in additional Maastrichtian sequences from low and middle latitudes. However, it is clear from the current data set that faunal event 1 is exclusively an origination event and did not result in significant species extinctions. In the following discussion, we will use Site 525A data to describe the faunal events because we consider Site 21 as stratigraphically condensed and our sampling resolution low.

At Site 525A, few species originated in the early Maastrichtian prior to faunal event 1. Prior to this faunal assemblage change and below C31R, a total of only six species originate during an interval of about 1.5 Myr (Fig. 4), as compared with 12 species during event 1 over an interval of only 600 kyr. This rapid increase in originations is apparent in Figs. 6 and 7 for sites 525A and 21 in the cumulative FA curves and the 26 and 31% increase in species richness, respectively. This major addition of new species seems not to have significantly increased the stress among the existing faunal assemblage. This is suggested by the fact that no species disappeared and relative abundances of most dominant species are not significantly affected (Figs. 8–10). At Site 525A, only three of the long ranging species (*Globigerinelloides* aff. *ultramicro*, *Heterohelix glabrans* and *Rugoglobigerina rugosa*) show a permanent major decrease in relative abundances at the time of the origination event. *Globigerinelloides* aff. *ultramicro* decreased across this interval from 20% in the upper CF8 Zone (*G. aegyptiaca*) to less than 3% in the lower CF7 Zone (*G. gansseri*), whereas

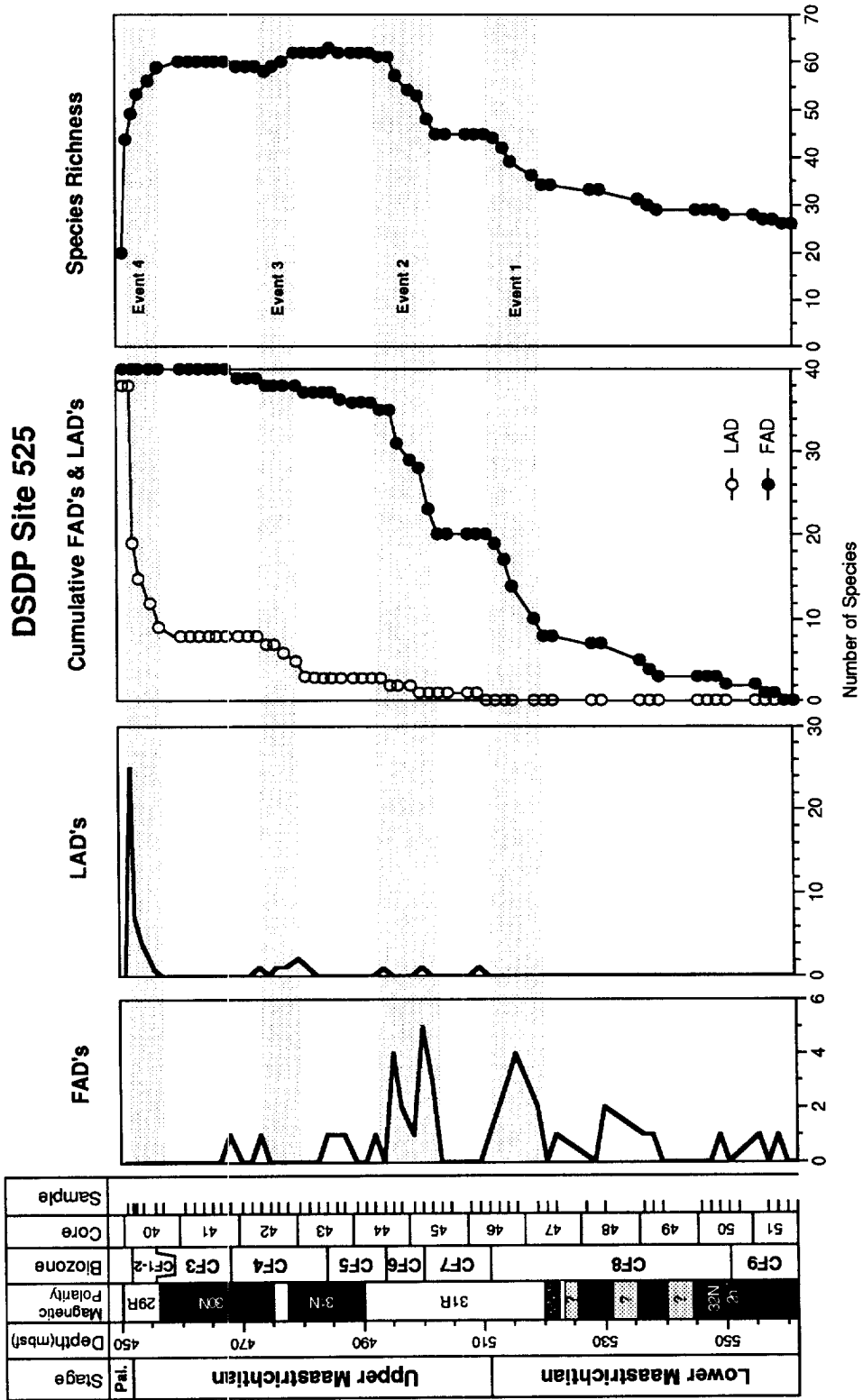


Fig. 6. Faunal turnover data based on first and last appearances and species richness at Site 525A. Note major peaks in FADs coincide with two origination events and peaks in LADs mark extinction event.

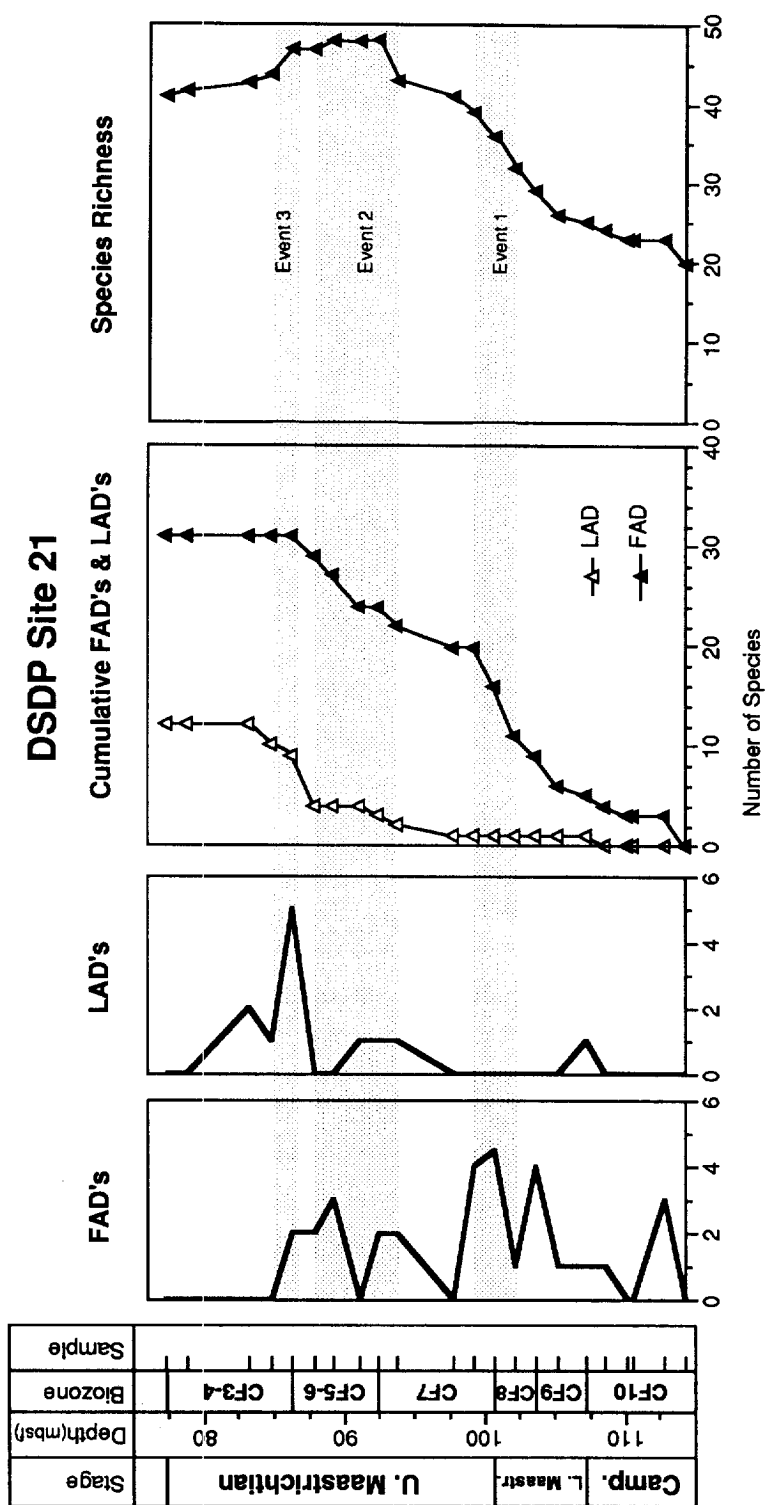


Fig. 7. Faunal turnover data based on first and last appearances and species richness at Site 21. Major FA peaks mark origination events and the L/A peak marks extinction event 3.

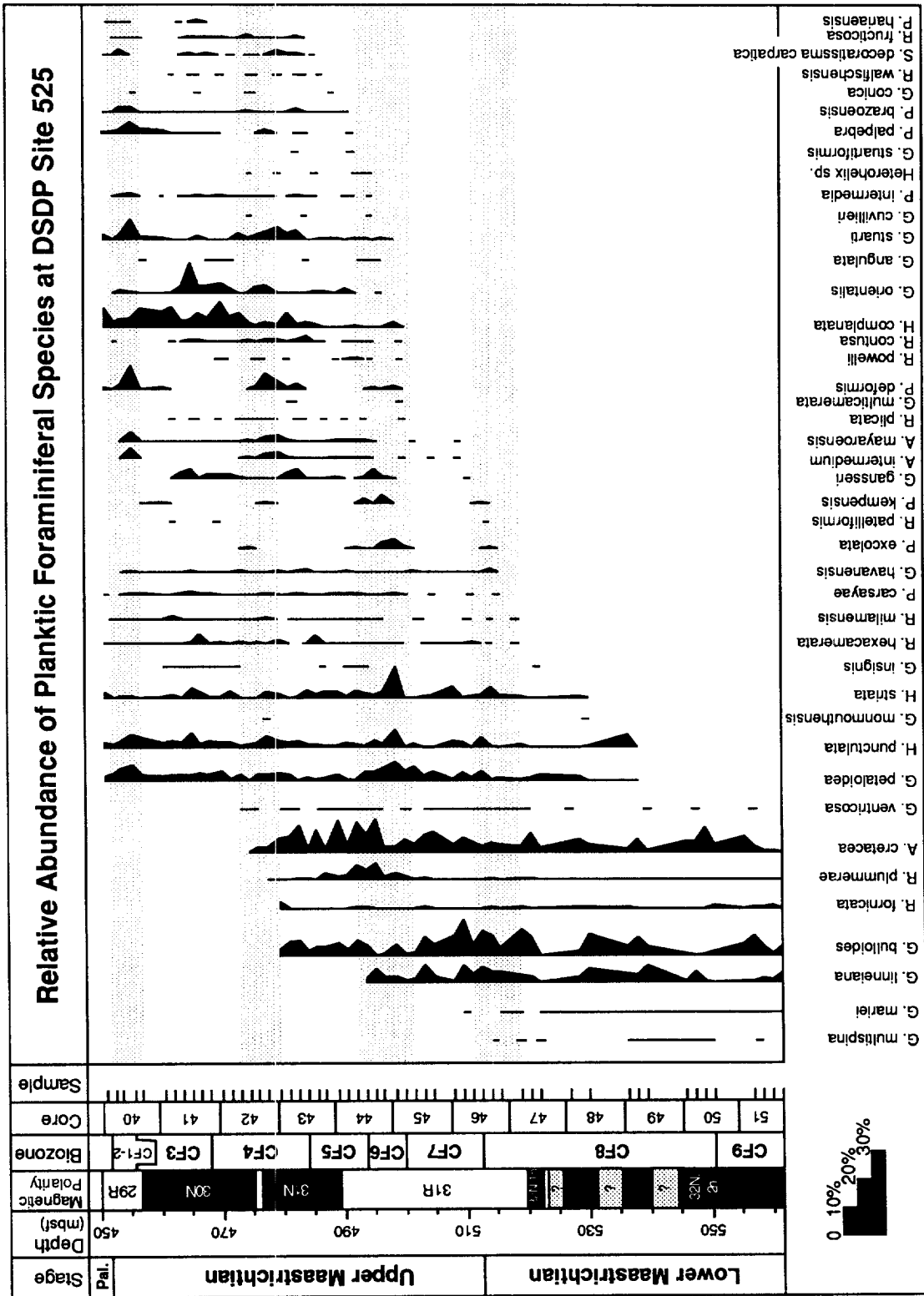


Fig. 8. Relative abundances of outgoing and incoming planktic foraminifera at Site 525A. Note that the relative abundance of the many originating species remains relatively low through the Maastrichtian, whereas extinct species during event 3 have relatively high abundances.

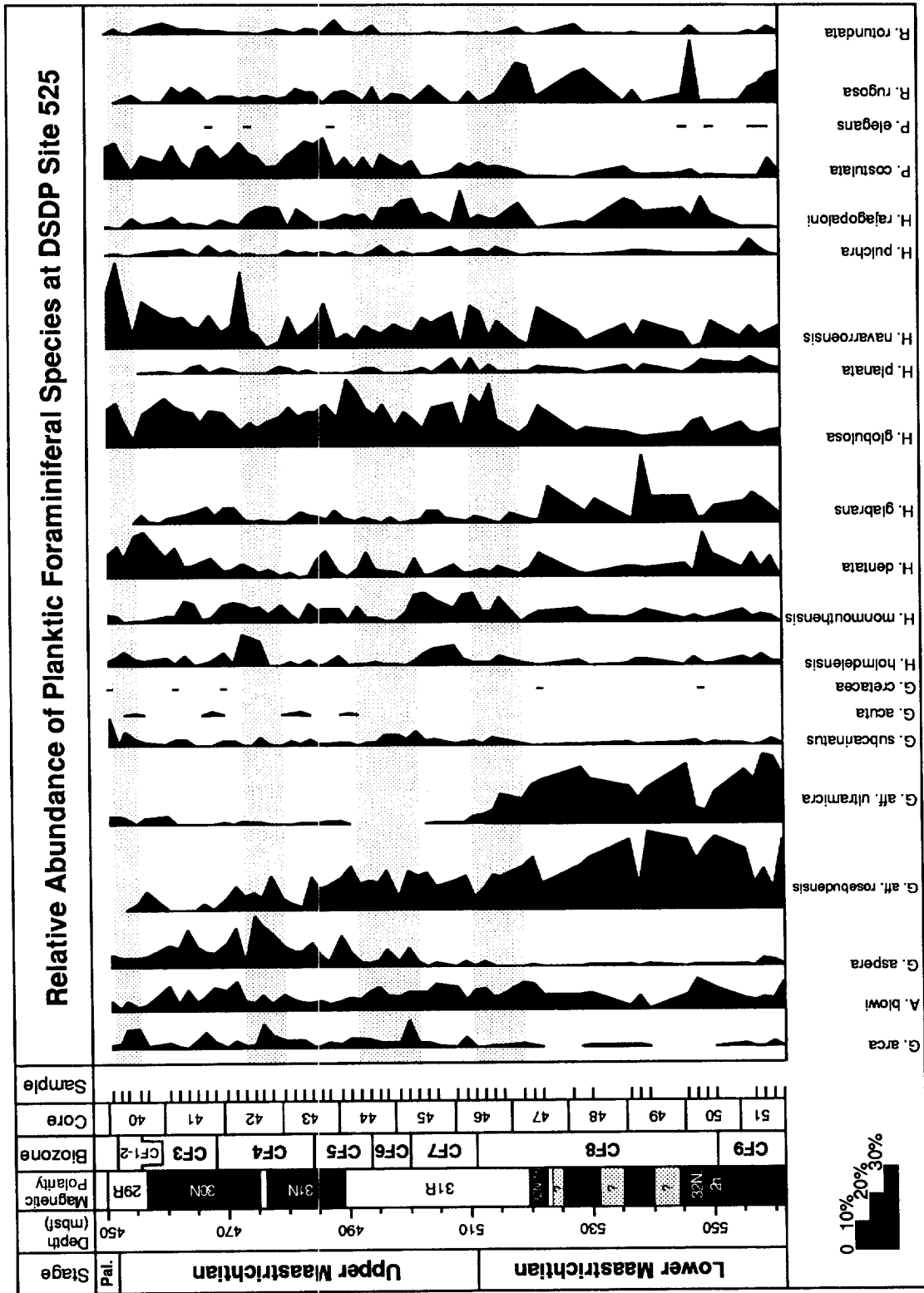


Fig. 9. Relative abundances of long-ranging planktic foraminifera at Site 525A. Note that *G. aff. ultramirca*, *G. aff. rosebudensis* and *H. glabrans* decreased in abundance during event 1 (upper CF7).

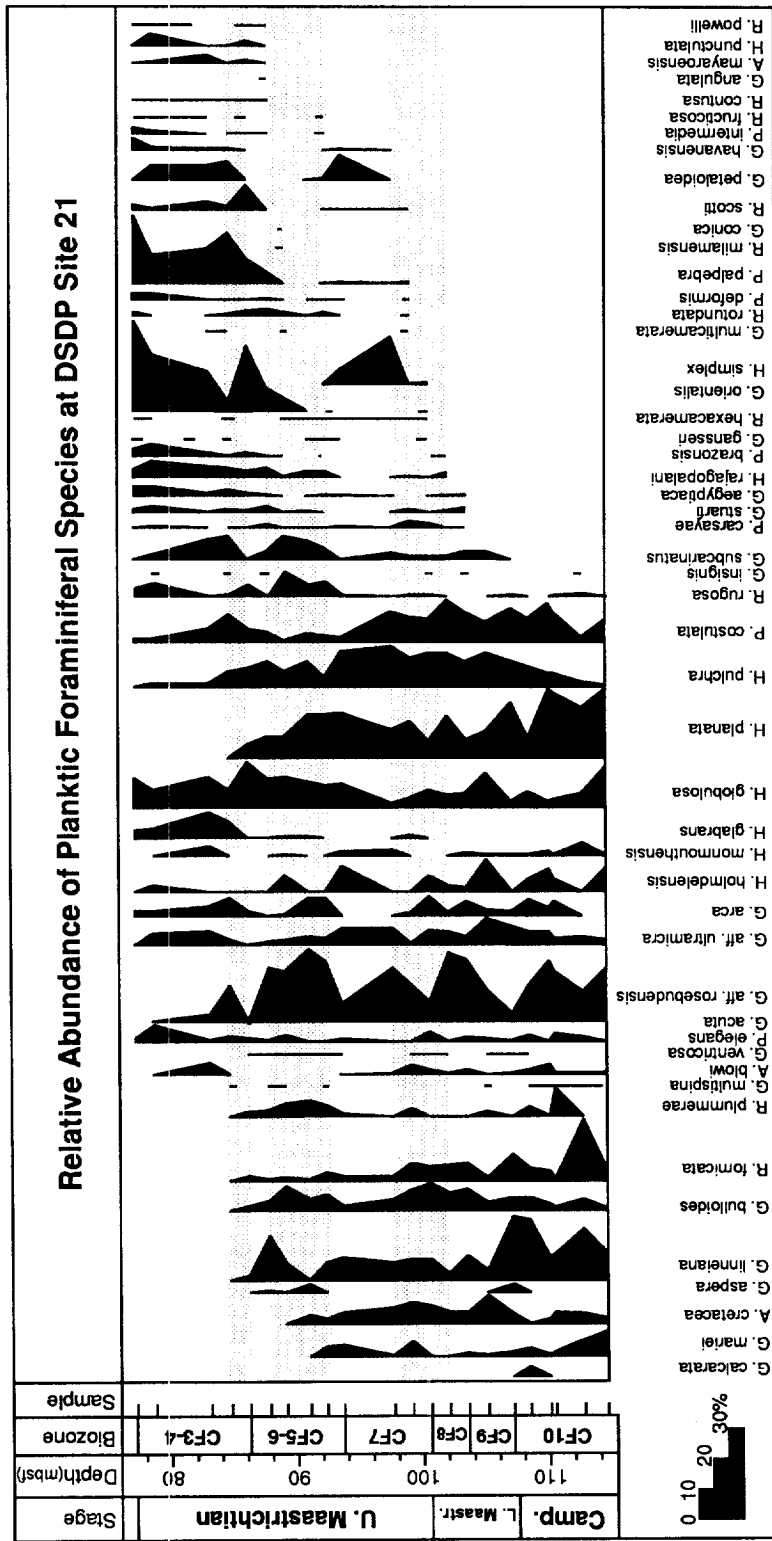


Fig. 10. Relative abundance of planktic foraminifera at Site 21. Note that Site 21 is more condensed than Site 525A and therefore faunal turnovers differ in detail, although the magnitude of change is comparable.

H. glabrans decreased from 5–10% to less than 3% (Fig. 9). Both of these taxa are deeper water dwellers living at or below thermocline depths (Boersma and Shackleton, 1981; D'Hondt and Arthur, 1995). *Rugoglobigerina rugosa*, a surface dweller, has a variable abundance during the early Maastrichtian, but permanently decreased during faunal event 1 to less than 2% (Fig. 9). Most long ranging species reacted favorably to the environmental change of event 1. Relative abundances remain mostly unchanged except for *H. globulosa* and *Pseudoguembelina costulata*, which significantly increased their relative abundances during and after event 1 at Site 525A (Fig. 9); *Heterohelix globulosa* is an intermediate dweller and *P. costulata* is a surface dweller (D'Hondt and Arthur, 1995). The fact that many species originate in surface (e.g., *R. hexacamerata*, *R. milamensis*, *R. scotti*, *P. kempensis* and *P. excolata*), intermediate (e.g., *G. gansseri*, *P. brazoensis* and *P. carseyae*) and deeper waters (*A. mayaroensis*, *A. intermedium*, *G. havanensis* and *R. patelliformis*), suggests high productivity and upwelling conditions.

4.2. Faunal event 2

Faunal event 2 is a second origination event in the early late Maastrichtian which begins near the base of Zone CF6 (*R. contusa*) in the upper C31R (Fig. 4). This origination event resulted in an even greater number of species originations than event 1 with a total of 16 new species at Site 525A. This led to a 26% increase in species richness at Site 525A and 20% at Site 21 over an interval spanning about 730 kyr (Figs. 6 and 7). Faunal event 2 led to a maximum of 63 species for the Maastrichtian for the mid-latitude South Atlantic and this high species richness remained stable up to faunal event 3.

As in event 1, originations differ in event 2 between sites 525A and 21. For instance, only eleven species originate at Site 21 and of these six have the same stratigraphic position at both sites (e.g., *G. angulata*, *G. conica*, *P. intermedia*, *R. contusa*, *R. fructifera* and *R. powelli*, Figs. 4 and 5). Five of the species in event 2 at Site 525A originate in event 1 at Site 21 (e.g., *P. multicamerata*, *P. deformis*, *G. orientalis*, *G. stuarti* and *P. palpebra*), whereas three species which originate in event 2 at Site 21 ap-

pear in event 1 at Site 525A (e.g., *A. mayaroensis*, *R. milamensis* and *G. havanensis*, Figs. 4 and 5). We attribute these differences in first appearances to lower sample resolution, a condensed section at Site 21 and/or diachronous originations. Moreover, at Site 21 species richness is generally lower with a maximum of 48 species as compared with 63 species at Site 525A. A possible reason for this difference is the larger (>106 μm) size fraction used for Site 21 as compared with that at Site 525A (>63 μm). However, because none of the Maastrichtian species have adult test sizes smaller than 106 μm and the smaller residue was routinely searched for rare species, the size fraction difference should not have affected overall species richness. Another factor controlling species richness and diachroneity may have been different local environments between Walvis Ridge and Rio Grande Rise during the mid-Maastrichtian.

As in turnover event 1, the major increase in species richness had no significant effect on relative abundances of long-ranging species and caused no significant extinctions (Figs. 8–10). All of the originating species are relatively rare and none evolved into dominant species in the late Maastrichtian. Only *H. complanata*, *G. stuarti* and *G. orientalis* became common in the late Maastrichtian, but never reached more than 15% of the total population (Fig. 8). In contrast to event 1, most of the originating species are deeper dwellers living at or below thermocline depths (e.g., *Globotruncanita angulata*, *G. conica*, *G. stuarti*, *G. stuartiformis*, *Globotruncana orientalis*, *Gublerina cuvillieri*, *Planoglobulina multicamerata*, *Racemiguembelina fructifera*, *R. powelli*, *Rosita plicata* and *R. walfischensis*). At Site 21, several species decreased in relative abundances (e.g., *Globigerinelloides* aff. *rosebudensis*, *Heterohelix planata* and *H. pulchra*) and two species increased (e.g., *Pseudoguembelina palpebra* and *Globotruncana orientalis*, Fig. 10).

The similarity in faunal events 1 and 2 suggests a similar cause and may signal continued cooling and increased upwelling. The stable isotopic record from the southern ocean ODP Site 690C suggests continued cooling into the late Maastrichtian (Barrera, 1994), whereas at Site 525A (this study) event 2 coincides with the transition to a short-term warming within the Maastrichtian cooling trend as discussed below.

4.3. Faunal event 3

Faunal event 3 marks the first, though relatively minor extinction event of planktic foraminifera in the Maastrichtian. It occurs within Zone CF4 in the C31N–C30N transition about 2.6 Myr prior to the K–T boundary and lasts about 600 kyr (Fig. 4). Five species disappear at this time at Site 525A (*Archaeoglobigerina cretacea*, *Globotruncana ventricosa*, *G. bulloides*, *Rosita fornicata* and *R. plummerae*, Fig. 4) and four species disappear at Site 21 (Fig. 5). The combined relative abundance of these extinct species is relatively high with 15–

20% at both sites 525A and 21 (Figs. 8 and 10). Several long ranging species increase their relative abundances at Site 525A (e.g., *Globigerinelloides aspera*, *Hederbergella holmdelensis*, *Heterohelix rajopaloni*, Fig. 8). The cause for this mini-extinction event may have been climatic cooling of 2–3°C at Site 525A (this study) and overall temperatures may have fallen below threshold levels for these taxa and caused their demise. Stable isotopic records from ODP Site 690C also reveal a temperature minimum in surface and deep waters in southern high latitudes at this time (Fig. 11; Barrera, 1994).

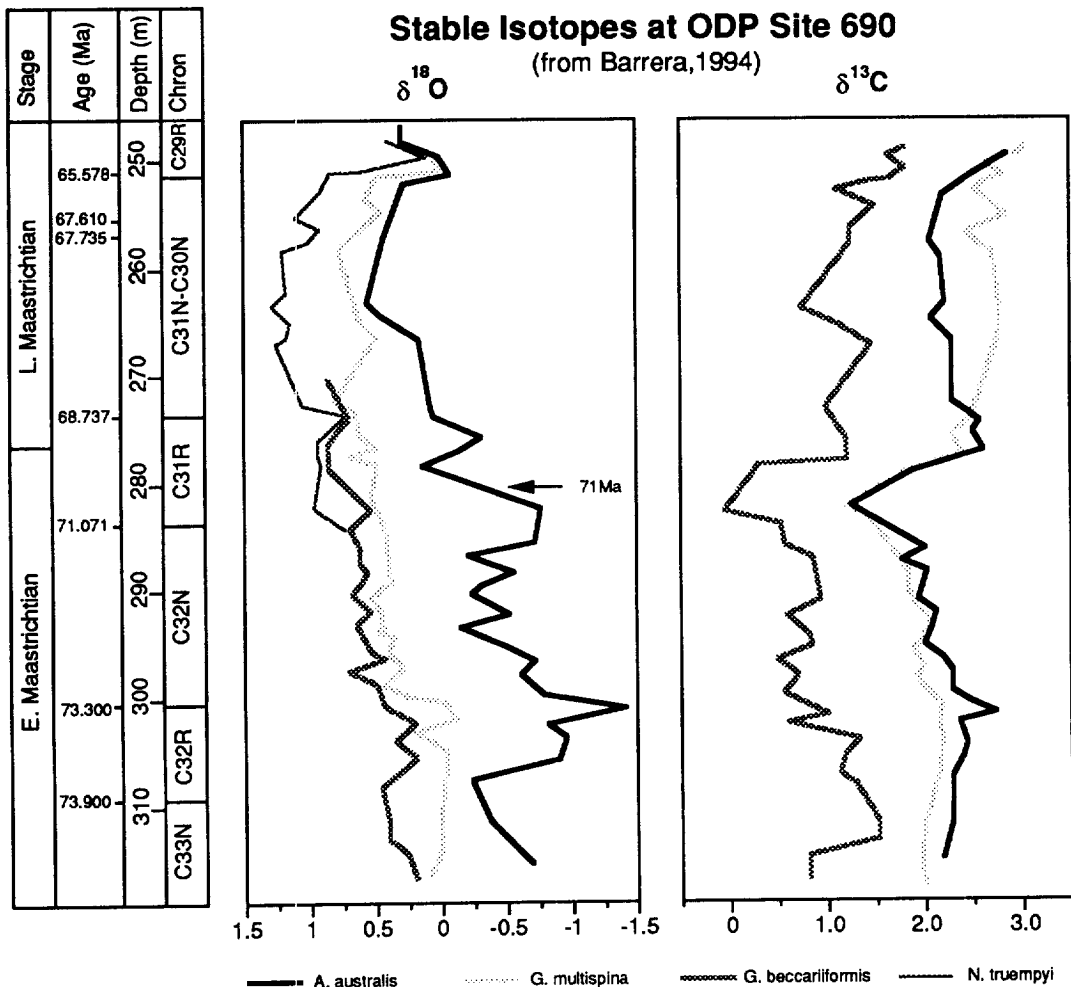


Fig. 11. Stable isotope record from ODP Site 690C (Barrera, 1994) reproduced for comparison with Site 525A. Note that the major cooling near the base of C31R (~71 Ma) correlates with a major coeval cool event at Site 525A.

4.4. Faunal event 4

Faunal event 4 includes the faunal changes that begins in the latest Maastrichtian CF2–CF1 interval and end at the K–T boundary and thus spans the last 450 kyr of the Maastrichtian (Fig. 4). During the last 400 kyr of the Maastrichtian at Site 525A, 11 species disappear (e.g., *G. gansseri*, *G. aegyptiaca*, *G. insignis*, *G. citae*, *G. conica*, *G. stuartiformis*, *G. aff. rosebudensis*, *R. patelliformis*, *R. plicata*, *R. walfischensis*, *R. scotti*, Fig. 4). Another twenty-four species disappear at the K–T boundary and 21 Cretaceous species remain present above the K–T boundary (Core 40-1, 100–102 cm, Fig. 4). Thus, a total of 35 species disappeared during event 4 at Site 525A (Fig. 6) and species richness declined by 65%. Relative species abundance changes indicate the decline of many species during event 4 (e.g., *P. palpebra*, *G. stuarti*, *P. deformis*, *H. punctulata*, *G. pateloidea*, *H. dentata*) and increased abundance of a few species (e.g., *P. costulata*, *H. complanata*, *H. navaroensis*, *G. subcarinatus*, Figs. 8 and 9). The latter are all environmentally tolerant cosmopolitan species which are generally observed to range into the Danian (Keller, 1988, 1989; MacLeod and Keller, 1994).

5. Stable isotopes

Maastrichtian global climate was significantly cooler than during the overall Late Cretaceous. Deep water temperatures from the Equatorial Pacific reached ~16–18°C during the Turonian–Coniacian, but only ~7°C during the late Maastrichtian (Barrera, 1994). This major decrease in deep water temperatures reflects polar cooling associated with the formation of high latitude cool deep waters and increased thermal gradients between equator and poles. The most complete Maastrichtian foraminiferal isotopic record is currently known from the southern high latitude ODP Site 690C (65°10'S, 1°12'E) as reproduced in Fig. 11 from Barrera (1994). This record shows an average increase of 1‰ in $\delta^{18}\text{O}$ of surface waters, or a 4.3°C temperature decline from the early Maastrichtian C32R (~73.5 Ma) to the early–late Maastrichtian boundary within C31R (~70.5 Ma). Coolest surface and deep water temperatures were reached in C31N–30N with deep water

temperatures of ~6–7°C between 69.7 and 66.5 Ma (Fig. 11; Barrera, 1994). In the lower part of C29R about 300 kyr prior to the K–T boundary isotopic values in surface and deep waters rapidly decreased by 0.5‰ indicating a warming of 2°C (Stott and Kennett, 1990). This short-term warming ended well prior to the K–T boundary in C29R. Northern high latitude sections also record this late Maastrichtian cooling followed by a pre-K–T short-term warming (e.g., Danian sections: Schmitz et al., 1992; Keller et al., 1993; Oberhansli and Keller, 1995). Our new surface and deep water isotopic records of Site 525A generally confirm the climatic cooling trend and pre-K–T warming observed at Site 690C, but significant differences are apparent.

5.1. Climate: $\delta^{18}\text{O}$ record

Isotopic $\delta^{18}\text{O}$ data at Site 525A appear to record largely original values and temperatures as suggested by the excellent preservation of planktic foraminifera without significant overgrowth or recalcification when examined with light and scanning electron microscopes, although benthic foraminifera appear to have some overgrowth (Plates I and II). Nevertheless, the consistent trends in measured $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values through the Maastrichtian and $^{87}\text{Sr}/^{86}\text{Sr}$ values consistent to be similar to deep-sea sites with unquestionable good preservation, suggests that the original record is largely preserved (Martin and MacDougall, 1991; Sugarman et al., 1995). Moreover, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ isotopic trends are similar to those at ODP Site 690C which are assumed to represent original signals (Stott and Kennett, 1990; Barrera and Huber, 1990; Barrera, 1994).

The Maastrichtian $\delta^{18}\text{O}$ temperature record at Site 525A is based on the surface dwelling planktic foraminifer *R. rugosa* and the benthic foraminifer *A. acuta* (Fig. 12). The deep water $\delta^{18}\text{O}$ record suggests that climatic change during the Maastrichtian occurred in broad steps of relatively stable intervals separated by rapid change. At the base of the section (Zone CF9 to CF8), a rapid increase of nearly 1‰ in benthic $\delta^{18}\text{O}$ values suggests a cooling of 4°C at about 72.5 Ma, followed by stable low temperatures between about 72.5 and 71.3 Ma (Fig. 12). This interval is followed by a rapid increase of 0.5‰, or 2°C cooling at 71.2 Ma. Beginning at the top of C32N

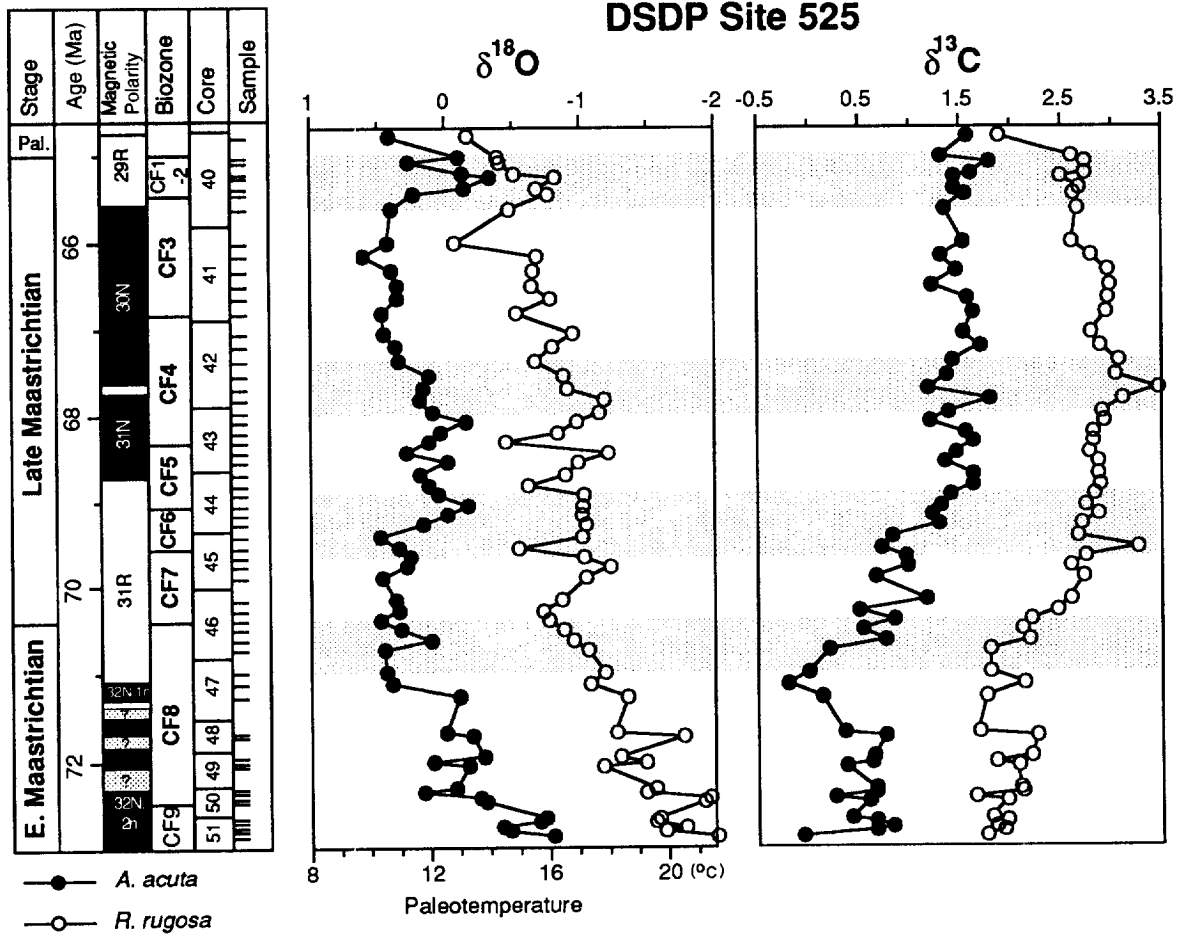


Fig. 12. Stable isotope records of surface (*R. rugosa*) and deep water (*A. acuta*) foraminifera at Site 525A. Note gradual, though fluctuating increase in surface water $\delta^{18}\text{O}$ values and more stepwise deepwater record with relatively stable phases separated by rapid change. $\delta^{13}\text{C}$ values show a major negative excursion coincident with the onset of maximum cooling, but gradually increase thereafter.

and continuing into the upper part of C31R, stable cool temperatures prevailed (from 71.2 to 69.2 Ma). At 69.2 Ma a decrease of 0.6‰ in benthic values marks a rapid warming of 2–3°C. These warmer but fluctuating temperatures continued until about 67.3 Ma at the base of C30N when $\delta^{18}\text{O}$ values increased by 0.4‰ and temperatures cooled again. Maximum cool temperatures, similar to the early–late Maastrichtian transition, prevailed from 67.2 to 65.5 Ma (C30N). This cool interval is terminated by a sudden decrease of 0.8‰ in benthic $\delta^{18}\text{O}$ values indicating a 3–4°C warming in the lower part of C29R, beginning about 400 kyr prior to the K–T boundary. During the last 100–200 kyr of the Maastrichtian a rapid

increase of 0.5‰ in benthic $\delta^{18}\text{O}$ values indicates a 2–3°C cooling prior to the K–T boundary event.

The stepwise pattern of relatively stable temperature intervals separated by rapid change is not observed in the surface water record. Instead, temperature change is more gradual, but with higher fluctuations (Fig. 12). Near the base of the studied interval (Zone CF9 to CF8) an increase of 0.8‰ in surface $\delta^{18}\text{O}$ values by 72.5 Ma mirrors the cooling observed in deep waters. However, this interval is followed by a more gradual increase of 0.6‰ which reached minimum temperatures at 70.2 Ma, about 1 Myr after the onset of deep water maximum cooling. Between 70 and 66 Ma surface $\delta^{18}\text{O}$ values remained

cool but fluctuating with 0.8‰ (~3°C) variations that seem to correlate with lower magnitude $\delta^{18}\text{O}$ variations in the deep water record (Fig. 12). Maximum cooling in surface waters occurred at the top of C30N (66.5–66 Ma) coincident with the end of a long cool interval in deep waters. However, the subsequent onset of rapid surface water warming preceded that in deep waters by about 100 kyr (Fig. 12). This short-term warming is followed by rapid cooling of 2–3°C during the last 100–200 kyr of the Maastrichtian in both surface and deep waters.

Both deep and surface water $\delta^{18}\text{O}$ records at Site 525A differ significantly from those at Site 690C. For instance, the deep water record at Site 690C indicates a more gradual cooling and no stepwise pattern is apparent. In contrast, the surface record shows greater temperature fluctuations with a rapid decline at Site 690C, whereas at Site 525A more gradual cooling is observed. The absolute timing of the temperature changes based on the respective paleomagnetic records at the two sites is also variable. These differences are likely due to the higher latitude location of Site 690C near the Antarctic continent and the middle latitude location of Site 525A on Walvis Ridge, as well as the higher sample resolution at Site 525A. However, the rapid warming in surface water and bottom waters near the base of C29R is present in middle and high latitudes deep-sea sites 690C, 528 and 525A (Stott and Kennett, 1990; Barrera, 1994; D'Hondt and Lindinger, 1994; this study).

5.2. Productivity: $\delta^{13}\text{C}$ record

Negative $\delta^{13}\text{C}$ excursions in both surface and deep waters during the upper part of the early Maastrichtian are generally interpreted as changes in surface productivity or organic matter input from continents during low sea-levels (Boersma, 1981,b; Barrera and Huber, 1990; Barrera, 1994). At Site 690C, a short-term negative excursion by 1‰ in $\delta^{13}\text{C}$ coincides with a rapid decrease in surface temperatures at ~71 Ma and correlates with a major sea-level regression (Haq et al., 1987). Thereafter, $\delta^{13}\text{C}$ values rapidly returned to pre-excursion values though with an increased surface-to-deep $\delta^{13}\text{C}$ gradient that reflects increased surface productivity (Fig. 11). A decrease of the surface-to-deep $\delta^{13}\text{C}$

($\Delta\delta^{13}\text{C}$) gradient beginning at the top of C30N and continuing to the K–T boundary reflects decreased surface productivity during the last 600 kyr of the Maastrichtian at Site 690C.

A similar $\delta^{13}\text{C}$ record is present at Site 525A. Beginning at ~72.8 Ma, the increasing trend in $\delta^{13}\text{C}$ values in surface and deep waters was punctuated by a negative excursion of 0.6‰ in surface and 0.8‰ in deep waters at ~71.5 Ma (Fig. 12). During this interval, the $\Delta\delta^{13}\text{C}$ gradient increased by 0.7‰ between 72.8 and 72.1 Ma and by 1.1‰ between 72 and 71.1 Ma (Fig. 13). These two $\Delta\delta^{13}\text{C}$ gradient changes indicate increased surface productivity. Thereafter, $\delta^{13}\text{C}$ values in both deep and surface waters increased gradually and reached maximum values by 69 Ma. Between 70.6 and 69.6 Ma, the overall $\Delta\delta^{13}\text{C}$ gradient increased by 1.1‰ (though fluctuated) and reflects a further increase in surface productivity (Fig. 13). Between 69 and 66.2 Ma, benthic $\delta^{13}\text{C}$ values remain relatively stable with the exception of a short-term fluctuation of 0.6‰ in faunal event 3 at 67.7 Ma and a 1‰ increase in the $\Delta\delta^{13}\text{C}$ gradient. Thus a short-term peak of high productivity similar to event 2 is indicated at this time (Fig. 13). At 66.2 Ma, surface $\delta^{13}\text{C}$ values decreased by 0.5‰ whereas benthic values remained relatively unchanged (Fig. 12). This decrease in the $\Delta\delta^{13}\text{C}$ gradient (Fig. 13) reflects reduced surface productivity. Between 66.5 and 65 Ma (K–T boundary) surface $\delta^{13}\text{C}$ values remained low, but relatively stable, whereas benthic values increased by 0.4‰ and hence further reduced the surface-to-deep $\delta^{13}\text{C}$ gradient (Fig. 13). At the K–T boundary, surface $\delta^{13}\text{C}$ values decreased by 0.8‰ and the $\Delta\delta^{13}\text{C}$ gradient decreased by 1‰ (Fig. 13). This reduction in the surface-to-deep gradient marks a severe decline in surface productivity, coincident with the K–T boundary mass extinction.

6. Discussion and conclusions

6.1. Climate

Oxygen isotopic data from Site 525A indicate major climatic cooling during the Maastrichtian. In the early Maastrichtian, surface and deep water temperatures register highs of 21 and 16°C, respectively. In contrast, at the K–T boundary surface and deep

D'Hondt and Lindinger, 1994; Barrera, 1994; Barrera and Keller, 1994).

The transition of each of these isotopic or temperature changes in deep waters is rapid, giving the appearance of prolonged stable climatic phases separated by rapid change. However, in surface waters these isotopic transitions are more gradual, except during the short-term latest Maastrichtian warming and subsequent cooling. This type of stepwise climatic change was also observed during the Eocene–Oligocene cooling and was interpreted by Berger et al. (1981) as a positive feedback system resulting from the phase transition from water to ice or vice versa. A similar mechanism may account for the Maastrichtian climate changes, although the presence of major Antarctic ice at this time remains to be demonstrated. However, Barrera (1994) suggested that the rapid cooling events at ~71 Ma at Site 690C may be related to Antarctic ice build-up. At sites 525A and 690C the prolonged cool phases from 71.2 to 69.2 Ma and 67.3 to 65.5 Ma coincide with major sea-level regressions (Haq et al., 1987) and probably Antarctic ice build-up (Barrera, 1994).

The short-term rapid warming near the end of the Maastrichtian appears to be a global event and was also observed in northern high latitude sections (Denmark: Keller et al., 1993). This warm event may be related to a greenhouse effect as a result of major global volcanism (Deccan Traps: Courtillot et al., 1988; Hansen et al., 1996). In southern high latitudes, major ash deposits are present in uppermost Maastrichtian sediments at sites 690C, 738, 750 and 752 (Peirce et al., 1989; Keller, 1993).

6.2. Productivity

The major climatic variations also reflected surface productivity as shown in the surface-to-deep gradient changes (Fig. 13). During the early–late Maastrichtian cooling (72–69 Ma), the $\Delta\delta^{13}\text{C}$ gradient increased by 1.1‰ from 72 to 71.1 Ma and again from 70.6 to 69.6 Ma at Site 525A. These two major increases in $\Delta\delta^{13}\text{C}$ gradient suggest increased surface productivity probably associated with global cooling and a sea-level lowstand (Haq et al., 1987). Surface productivity increased between 68.1 and 67.5 Ma, correlative with cooling in deep and surface waters (Fig. 12). At 66.2 Ma surface productivity de-

creased at both sites 525A and 690C (Barrera and Huber, 1990; Barrera, 1994), coincident with maximum surface cooling. Surface productivity remained low, but steady through the short-term warm event (65.4–65.2 Ma), but decreased during the subsequent pre-K–T boundary cooling.

Surface $\delta^{13}\text{C}$ values dropped by 0.8‰ and the surface-to-deep gradient decreased 1.0‰ at the K–T boundary, although this is a major gradient decrease in middle latitudes. In low latitude sections the surface-to-deep gradient decrease reaches 2–3‰ (Zachos et al., 1989; Keller and Lindinger, 1989; Barrera and Keller, 1990). High latitudes, however, show little or no $\delta^{13}\text{C}$ changes in either bottom or surface waters (e.g., sites 738C and 690C: Stott and Kennett, 1990; Barrera and Keller, 1994). Thus surface productivity changed dramatically between low, middle and high latitudes. Low latitudes suffered near total collapse in primary productivity, whereas middle and high latitudes were little affected. The fact that at Site 525A the K–T boundary decrease in $\Delta\delta^{13}\text{C}$ gradient is 1.0‰ indicates a relatively small reduction in surface productivity as compared with low latitudes.

6.3. Faunal turnovers

The Maastrichtian planktic foraminiferal record is characterized by two major faunal events: (1) species diversification during the early late Maastrichtian that results in highest species richness during the Cretaceous; and (2) a mass extinction at the end of the Maastrichtian that eventually leads to the extinction of the entire Cretaceous fauna in the Danian. This is a remarkable record over an interval of only 5 Myr. Species richness patterns across latitudes yield some clue to the nature of this upheaval in planktic foraminifera. During the early Maastrichtian species richness varied from a high of 45 species in the Tethys (Li, 1997) to 35 species in middle latitudes (Site 525A) and 21 species in the southern high latitudes (Huber, 1990). This represents a species gradient of 53% between high and low latitudes during the early Maastrichtian. The species gradient significantly increased during the late Maastrichtian from 70 species in the Tethys (Li, 1997) to 62 species in middle latitudes (Site 525A) and 23 species in the southern high latitudes (Huber, 1990; Keller, 1993).

The latitudinal species gradient thus increased from the early to the late Maastrichtian from 53 to 67%, whereas in the modern ocean the gradient is about 73%. The small difference (6%) in the latitudinal species gradient between the late Maastrichtian and modern ocean suggests that the temperature gradient during the late Maastrichtian was similar to that in the modern ocean. This observation does not support D'Hondt and Arthur's argument (D'Hondt and Arthur, 1996) very low ($\sim 5^{\circ}\text{C}$) latitudinal temperature gradients during the Maastrichtian.

The latitudinal species gradient at Site 525A changed during two rapid diversification events at 70.6–70 Ma and 69.8–69.1 Ma, which increased species richness by a total of 43%. The onset of both diversification events is associated with climatic cooling and relatively high surface-to-deep temperature gradients (δT , Fig. 13). The cooling appears to have resulted in a major increase in upwelling and nutrient supply which in turn lead to major evolutionary diversification in planktic foraminifera. Similar increases in species richness during the early late Maastrichtian have been observed in ammonites (Ward et al., 1991; Stinnesbeck, 1996), bivalves (Macellari, 1988) and palynofloras (Méon, 1990). Only inoceramids and rudistid reefs became extinct (MacLeod and Ward, 1990; MacLeod, 1994; Johnson and Kauffman, 1996). The disappearance of rudistid reefs is generally attributed to climatic cooling and lower sea-levels (Johnson et al., 1996).

The first permanent decline in species richness occurred between 68–67.3 Ma (Fig. 6), at a time of continued cooling and high surface productivity. The disappearance of five species (e.g., *G. bulloides*, *G. linneiana*, *R. plummerae*, *R. fornicata* and *A. cretacea*) which thrived up to this time is puzzling. The final decline in Maastrichtian species richness at Site 525A began about 300–400 kyr prior to the K–T boundary and coincided with the onset of a short-term warm event and decline in surface productivity. The surface-to-deep temperature gradient was reduced to 2–3°C during the short-term warm event when both surface and deep water temperatures increased by 3–4°C. Species extinctions accelerated during the subsequent 2–3°C cooling and reached maximum extinctions (66%) by K–T boundary time. This increased rate in species extinction coincided with a 0.8‰ negative shift in surface $\delta^{13}\text{C}$ and a

1.0‰ decline in surface-to-deep $\delta^{13}\text{C}$ gradient that reflects a drop in surface productivity. Viewed within the context of Maastrichtian climate and productivity changes, the K–T boundary mass extinction could have resulted from extreme climatic variations at the end of the Maastrichtian (rapid short-term warming of 3–4°C followed a rapid cooling of 2–3°C) even without the addition of an extraterrestrial impact.

Acknowledgements

This study benefited from discussions with Wolfgang Stinnesbeck, Thierry Adatte and Hedi Oberhansli. We thank Daniel Bryan for analysis of stable isotopes and two anonymous reviewers for their comments. Samples from DSDP Site 525A and Site 21 were provided by the Ocean Drilling Program. This study was supported by NFS grant OCE 9021338.A02.

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