

The Late Campanian and Maastrichtian in northwestern Tunisia: palaeoenvironmental inferences from lithology, macrofauna and benthic foraminifera



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Late Campanian through Maastrichtian sea-level changes are examined based on lithology, macrofossils and benthic foraminifera at the Elles and El Kef sections in Tunisia. Six major sea-level regressions are identified during the late Campanian (74.4–74.2 Ma, 74.0–72.5 Ma), the Campanian-Maastrichtian transition (72.2–70.3 Ma), early Maastrichtian (69.6–69.3 Ma, 68.9–68.3 Ma), and late Maastrichtian (~65.5 Ma). Correlation of the Maastrichtian sea-level regressions with the oxygen isotope record of DSDP Site 525 in the middle latitude South Atlantic reveals that they coincide with episodes of high latitude cooling and appear to be of eustatic origin.

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1. Introduction

Lithological variations are generally indicative of environmental changes, with faunas providing more specific information on the nature and tempo of these changes. One of the most commonly used faunal indicators for sea-level changes are benthic foraminifera and invertebrate faunas which live abundantly on the ocean floor of shelf (0–200 m) and upper slope (200–600 m) regions. Benthic foraminifera are generally used to infer palaeodepths (shelf, slope or bathyal depths) and consequently to infer relative sea-level changes (Sliter & Baker, 1972; Aubert & Berggren, 1976; Haig, 1979; Ingle, 1980; Van Morkhoven *et al.*, 1986; Keller, 1988, 1992; Widmark & Malmgren, 1988; Koutsoukos & Hart, 1990; Corliss & Emerson, 1990; Corliss, 1991; Kaiho, 1994; Speijer, 1994; Widmark, 1995; Speijer & Van Der Zwaan, 1996; Pardo *et al.*, 1996). Such palaeodepth inferences, based on upper depth limits of benthic foraminiferal species, are generally based on the assumption that foraminifera are only transported downslope and do not migrate upslope. However, it is also well known that benthic foraminiferal species change their upper and/or lower depth ranges, as well as their depths of maximum abundances, with changing bottom water conditions, including organic matter influx, that

accompany a rise or drop in sea-level (Douglas, 1979; Ingle, 1980; Douglas & Woodruff, 1981; Tjalsma & Lohmann, 1983; Miller & Katz, 1987; Kurihara & Kennett, 1988; Thomas, 1990; Hermelin & Shimmield, 1990; Corliss & Emerson, 1990; Corliss, 1991; Gooday, 1993; Kaiho, 1994; Speijer, 1994). Consequently, benthic foraminiferal faunas provide important clues to relative changes in sea-level, oxygen, salinity and nutrient conditions.

A number of studies have examined benthic foraminiferal turnovers in the Tethys region, including Tunisia, during the Cretaceous-Tertiary (K-T) boundary transition and into the Paleocene (e.g., Aubert & Berggren, 1976; Luger, 1985; Keller, 1988, 1992; Speijer, 1994; Coccioni & Galeotti, 1994, 1998; Pardo *et al.*, 1996). Most of these studies have attributed the K-T faunal turnover to a combination of sea-level and climatic changes, oxygen depletion, and possibly the effects of a bolide impact. Few studies have examined palaeoenvironmental conditions preceding the K-T boundary event during the late Campanian and Maastrichtian in the Tethys region, though published studies on pollen, ostracods and planktic foraminifera for this interval at El Kef all indicate major faunal and floral turnovers well before the K-T boundary event. For instance, Méon's (1990)

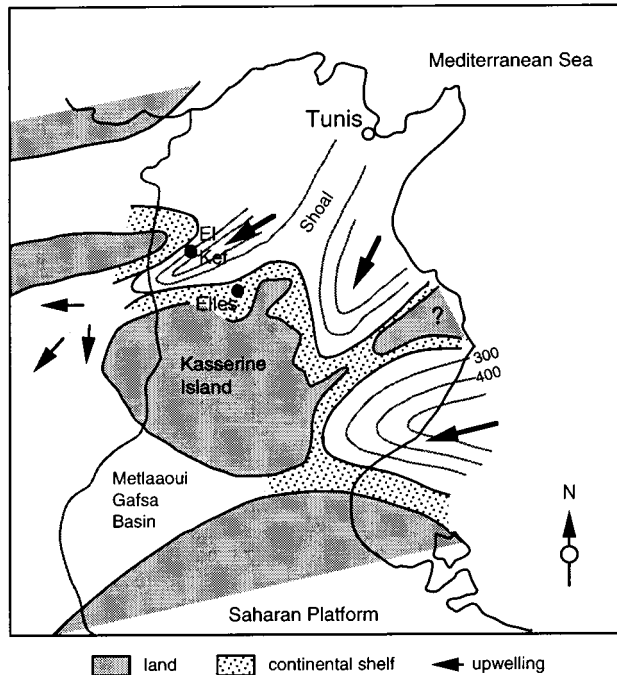


Figure 1. Late Cretaceous palaeogeography of Tunisia and locations of the El Kef and Elles sections (modified after Burolet, 1967, and Peypouquet *et al.*, 1986).

study of pollen at El Kef revealed a major floral turnover through the middle and late Maastrichtian with gradually decreasing diversity indicating climatic cooling. Studies on ostracods for the same interval at El Kef by Donze *et al.* (1985) and Peypouquet *et al.* (1986) revealed a major faunal turnover in the *Gansserina gansseri* Zone. A recent study on planktic foraminifera parallels this pattern, suggesting that major environmental changes occurred through the Maastrichtian in the southwestern Tethys (Li & Keller, 1998b).

In this study, we examine the late Campanian and Maastrichtian sea-level fluctuations at Elles and El Kef in northwestern Tunisia based on lithological variations, macrofossils and benthic foraminiferal assemblages. We then correlate the observed sea-level changes with the $\delta^{18}\text{O}$ record of DSDP Site 525 in the middle latitude South Atlantic in order to determine the relationship, if any, between global cooling and sea-level regressions in the southwestern Tethys.

2. Material and methods

Samples

The El Kef section is located about 7 km west of the town of El Kef in northwestern Tunisia (Figure 1). Maastrichtian and Campanian sediments crop out

along valleys about 1 km from the road to Hamman Mellégué. The Elles section is located about 75 km southeast of El Kef near the hamlet of Elles, where a continuous sequence of Campanian, Maastrichtian and Palaeogene sediments is exposed along a valley. During the late Campanian to Maastrichtian sediment deposition at El Kef occurred in outer shelf to upper slope environments, and at Elles in somewhat shallower middle-outer shelf to outer slope environments (Peypouquet *et al.*, 1986; Figure 1). Sedimentary sequences spanning the upper Campanian through the Maastrichtian were sampled at both El Kef and Elles. At El Kef, the Maastrichtian interval consists of grey marly shales that are cut by two local faults at 10 m and 22 m below the K-T boundary where an unknown interval is missing (Figure 2). The upper Campanian consists of thick limestone beds followed by marls interlayered with limestone layers. In one interval, grey marly shales partly covered by vegetation and a slump covers about five metres of the section (53.4–48.5 m, Figure 2). A total of 47 samples were collected from the upper Campanian-Maastrichtian interval.

The discontinuous exposure at El Kef necessitated collecting this interval at Elles. At this location the sedimentary sequence is similar to that at El Kef and continuously exposed. The upper Campanian interval consists of thick limestone beds interlayered with thin marls. This interval is overlain by 10 m of marly shales followed by marls interlayered with limestones (Figure 2). A total of 21 samples were analyzed from this interval.

Methods

In the field, the limestone and marl layers were examined for macrofaunas and bioturbation and their stratigraphic position noted. Limestone/marl contacts were carefully examined for evidence of hardground, bioturbation and erosion. In the laboratory, thin sections were made of all limestone and hard resistant marl layers to search for further evidence of invertebrate fossils, and the sedimentological composition was examined. For benthic and planktic foraminiferal analyses, sediment samples were disaggregated by soaking in water for several days and then washed through a 63 μm sieve with tap water. Sediment infilling of foraminiferal tests was removed by repeated sonic agitation of the residues for about 15 seconds.

Benthic foraminifera were quantitatively analyzed for El Kef and qualitatively for Elles. Benthic foraminiferal species at El Kef were picked from representative sample splits of 300–500 specimens,

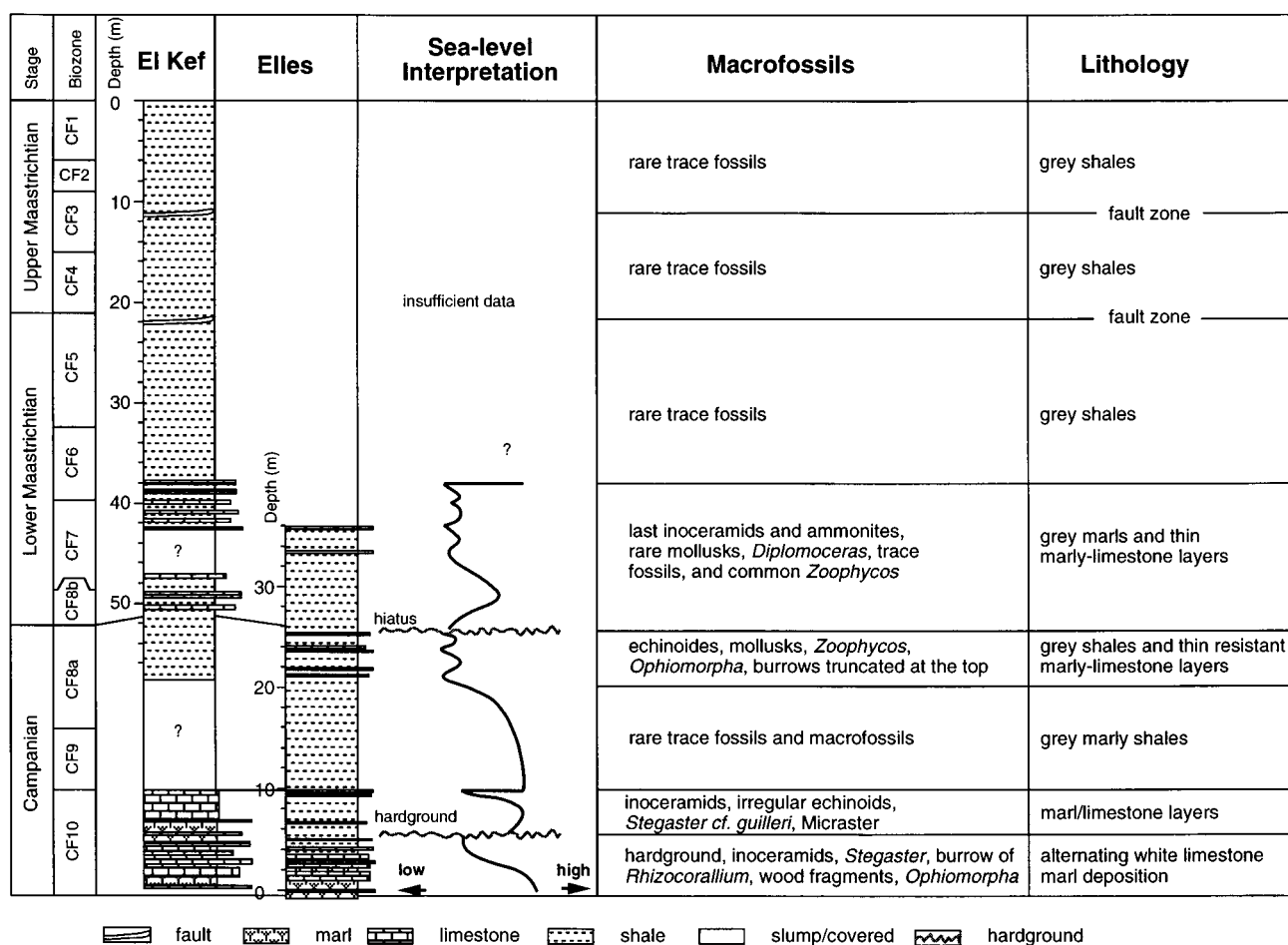


Figure 2. Lithological variations, macrofaunas and inferred sea-level changes at El Kef and Elles during the late Campanian through Maastrichtian. Planktic foraminiferal zonation from Li & Keller (1998a, b) with subdivision of Zone CF8 into CF8a and CF8b.

identified and mounted on microslides for a permanent record. For Elles, a representative split of 300–500 specimens was examined and a census taken of species present which were mounted on microslides for identification and permanent record. The qualitative abundance of species was noted as abundant, >10%; common, 5–10%; few, 2–5%; and rare, <2%. For both Elles and El Kef samples, the remaining residue from each sample was searched for rare species and these were added to the picked slides. Species identifications were primarily based on the studies of Sliter (1968), Aubert & Berggren (1976), Van Morkhoven *et al.* (1986), Keller (1988, 1992), Bolli *et al.* (1994), and Speijer (1994). Over 128 benthic foraminiferal species were identified at Elles and El Kef. The relative abundances and occurrences of all species which are present in more than two samples are listed in Table 1 for El Kef. However, all species from the sample splits and the

rare species subsequently added from the residue searches were included in calculating the species richness.

3. Biostratigraphy

The biostratigraphy and correlation of the Elles and El Kef sections is based on a refined high resolution planktic foraminiferal zonation which was developed based on DSDP Site 525 and its palaeomagnetic timescale and applied to the Tunisian sections (Li & Keller, 1998a, b) as shown in Figure 3. This biozonation is similar to the zonations by Caron (1985) and Nederbragt (1991), except that the interval encompassed by the two late Maastrichtian zones, *Abathomphalus mayaroensis*, or *Racemiguembelina fructifera* of Nederbragt (1991), and *Gansserina gansseri* is subdivided into seven biozones (CF1–7), and the *Globotruncana aegyptiaca* Zone is subdivided into

Table 1. Continued.

Depth (m) below KTB	12	12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18	18.5	19	19.5	20	21	22.5	23.5	24.5	25.5	26.5	29.5			
<i>Neoflabellina rogusa</i>					X											X	X	X						X	X		
<i>Nodosaria limbata</i>					X																				X	X	
<i>Nuttallides truempyi</i>	2	X	3	2	X																		2		X	X	
<i>Nuttallides apera</i>	X			X																						X	
<i>Oolina apiculata</i>																										X	
<i>Oolina delicata</i>																										X	
<i>Oolina globulosa</i>																										X	
<i>Oridorsalis umbonatus</i>																										X	
<i>Osangularia cordieriana</i>	9	5	2	4	3	4	2	2	2	2	3	5	3	2	2	2	5	4							2	5	
<i>Palmula primitiva</i>		X			X																					X	X
<i>Praebulimina aspera</i>	2	6	4	4	4	5	8	2	3	4	4	X	14	4	9	2	3	3							2	X	X
<i>Praebulimina carseyae</i>	18	15	17	2	14	19	21	20	13	21	16	X	X	X	X		3	X							X	3	
<i>Praebulimina cushmani</i>																										X	X
<i>Praebulimina kickapoensis</i>					2							2	X													2	
<i>Praebulimina lajollaensis</i>																										X	X
<i>Praebulimina quadrata</i>	X	X	X				2	X	X	X	X	X	3	5	3		5	X								3	4
<i>Praebulimina reussi</i>	2	2	4	X	2	X	X	X	5	4	3	4	3	X	X	6	5	X								3	X
<i>Praebulimina trochoides</i>	2			X	X		X	X			2			X												2	X
<i>Praebulimina midwayensis</i>	X		X		X	X	X	X	X	X	X	X	X	X	X											X	3
<i>Pseudonodosaria manifesta</i>																										7	2
<i>Pseudonodosaria obesa</i>	X	3	X	X	X		X	X	3	X	X		X	X	2	4	X	X								X	2
<i>Pullenia eretacea</i>	X	2	3	2	X	2	X	3	X	3				2	2	X	2	X								2	2
<i>Pullenia jareisi</i>																										4	X
<i>Pullenia sp.</i>																											
<i>Pyramidina triangularis</i>	X																										
<i>Pyralina sp.</i>	X																										
<i>Quadrinorphina camerata</i>																											
<i>Saracenaria naevicula</i>	X	X	X	X	2	X	X	X	X	X	X	2	2	X		2	2	X								2	X
<i>Saracenaria triangularis</i>	X	X			X						3	X	X	X	X	3	2	X								2	X
<i>Spiroplectammima knebeli</i>																										X	X
<i>Spiroplectammima spectabilis</i>		X	X	3	3	6	X	4	2	X	3	4	2	2	3	X	X	X								2	X
<i>Stensioina beccomiformis</i>																										X	X
<i>Stensioina excolata</i>	X	X	X	2		2	X		X		X															X	X
<i>Tritaxia esnaensis</i>	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X								X	X
<i>Tritaxia midwayensis</i>	X	2	X	X	X	X	X	X	X	X	X	2	X	X	3	X	X	X								X	2
<i>Vauliana aegyptiaca</i>																										6	3
<i>Vaginulinopsis directa</i>																											2
Total counted	207	313	242	277	264	226	222	224	246	263	239	201	225	205	239	239	242	219	225	239	244	276	233	236	236		

Table 1. Continued.

	32.5	32.8	33.5	34.2	35	35.7	36.5	37	37.8	38.2	38.5	39	39.8	40.2	40.6	41.2	41.6	42	47.9	48.8	49.5	50.2	50.7	51	57	
<i>Margulinina bullata</i>					X			X													X					
<i>Neoflabellina jarvisi</i>	X		X		X			X																X		X
<i>Nodosaria limbata</i>				X		X				X												X				X
<i>Nodosaria distans</i>						X																				
<i>Nonionella austriana</i>																										
<i>Nonionella cretacea</i>		X																								
<i>Nuttallides truempyi</i>																										
<i>Oolina delicata</i>																										
<i>Oridorsalis umbonatus</i>	3	X	X				X	2		X																
<i>Oxangularia cordieriana</i>	5	X	X	X	X		2	X		3																
<i>Palmula primitiva</i>	X	X	X	X																						
<i>Praebulimina carseyae</i>	4	3	2	X	X		4	8		5																
<i>Praebulimina cushmani</i>	X																									
<i>Praebulimina lajollaensis</i>																										
<i>Praebulimina quadrata</i>	X			5			X	8																		
<i>Praebulimina reussi</i>	X	X		X	X		8	2		9																
<i>Praebulimina trochoides</i>							2	X																		
<i>Praebulimina midceayensis</i>																										
<i>Pseudonodosaria manifesta</i>	X	2	X	X	3		3	X		X																
<i>Pseudonodosaria obesa</i>	X	X		X			X	X																		
<i>Pseudonodosaria</i> sp.	X																									
<i>Pullenia cretacea</i>	2	X		X	X		X	3		X																
<i>Pullenia jarvisi</i>	X	X	X	X	X		X	X		X																
<i>Pullenia</i> sp.	X	X	X		2		X	X		X																
<i>Pyrulina apiculata</i>							3	X																		
<i>Pyrulina</i> sp.	2																									
<i>Saracenaria navicula</i>		X		X	X		X	X																		
<i>Saracenaria triangularis</i>	X	X	X	X	X		2	X		2																
<i>Spiroplectammima knebeli</i>	X																									
<i>Spiroplectammima spectabilis</i>	2	X	X	X	X		2			2																
<i>Stensioina beccortiformis</i>	X			X	X																					
<i>Stensioina excolata</i>					X																					
<i>Tritaxia esnaensis</i>		X		X	X			X		2																
<i>Tritaxia midceayensis</i>																										
<i>Valvulana aegyptiaca</i>	4	7	5	7	3	2	2	2		2																
<i>Valvulana</i> sp.																										
Total counted	226	222	237	224	220	213	230	237	221	254	244	236	215	216	200	223	212	252	215	216	216	202	222	210	230	

Stage	Age(Ma)	DSDP Site 525				Sample	datum events	Planktic Foraminiferal Zonations			Stage	Nannofossils		Ammonites		Stage
		Depth (mbsf)	Magnetic Polarity	Core				this study	DSDP Site 525A, El Kef and Elles, Tunisia (Li & Keller, 1998a, b)	age (Ma)		Caron, 1985	Bralower <i>et al.</i> , 1995	Stage	Gradstein <i>et al.</i> , 1995	
Late Maastrichtian	65.000	450	29R	40		K/T boundary	<i>P. hantkeninoides</i> (CF1)	<i>P. hantkeninoides</i> (CF1)	65.0				N. America	Europe		
	65.578		30N	41		↑ <i>G. gansseri</i>	<i>P. palpebra</i> (CF2)	<i>P. palpebra</i> (CF2)	65.3 65.5		<i>M. murus</i> (NC23)					
Late Maastrichtian	67.610	470				↓ <i>P. hariaensis</i>	<i>Pseudoguembelina hariaensis</i> (CF3)	<i>Pseudoguembelina hariaensis</i> (CF3)	66.8		<i>L. quadratus</i> (NC22)		No data	<i>Golevillensis</i>	Late Maastrichtian	
	67.735					↓ <i>R. fructicosa</i>	<i>Racemiguembelina fructicosa</i> (CF4)	<i>Racemiguembelina fructicosa</i> (CF4)								
Early Maastrichtian	68.737	490	31N	42		↑ <i>G. gansseri</i>	<i>Pseudotextalria intermedia</i> (CF5)	<i>Pseudotextalria intermedia</i> (CF5)	68.3		<i>L. praequadratus</i> (NC21)		<i>Nebrascensis</i>			
						↑ <i>G. linneiana</i>	<i>Rosita contusa</i> (CF6)	<i>Rosita contusa</i> (CF6)	69.1					<i>Nicoletti</i>		
Early Maastrichtian	71.071	510	31R	43		↓ <i>R. contusa</i>	<i>Gansserina gansseri</i> (CF7)	<i>Gansserina gansseri</i> (CF7)	69.6				<i>aff. Nicoletti</i>			
						↑ <i>G. gansseri</i>	<i>Rugoglobigerina hexacamerata</i> (CF8b)		70.4				<i>Clinobatus</i>	<i>Neubergicus tridens</i>	E. Maastrichtian	
Late Campanian	74.0	550	32N	44		↑ <i>A. mayaroensis</i>	<i>Globotruncana aegyptiaca</i> (CF8a)	<i>Globotruncana aegyptiaca</i> (CF8)	71.0				<i>Grandis</i>			
						↑ <i>P. carseyae</i>							<i>Baculus</i>			
Late Campanian			32N	45		↑ <i>R. hexacamerata</i>							<i>Eliasi</i>			
						↓ <i>G. aegyptiaca</i>	<i>Globotruncanella subcarinatus</i> (CF9)	<i>Globotruncanella subcarinatus</i> (CF9)	72.5				<i>Jenseni</i>			
Late Campanian			2n	46		↑ <i>G. calcarata</i>	<i>Globotruncanella calcarata</i> (CF10)	<i>Globotruncanella calcarata</i> (CF10)	74.0				<i>Reesidei</i>			
						↓ <i>G. calcarata</i>							<i>Guneatus</i>	<i>Hyatti</i>	Campanian	
Late Campanian						↑ <i>G. calcarata</i>							<i>Compressus</i>			
						↓ <i>G. calcarata</i>							<i>Cheyennense</i>			

Figure 3. Integrated microfossil and ammonite zonation for the late Campanian and Maastrichtian intervals. The Tunisian El Kef and Elles sections are correlated with DSDP Site 525 and its geomagnetic polarity time scale based on planktic foraminiferal biostratigraphy (see Li & Keller, 1998a, b). Note the differences in the position of the Campanian-Maastrichtian and early-late Maastrichtian boundaries in the various zonal schemes. In this study, we follow Gradstein *et al.* (1995) in the placement of the Campanian-Maastrichtian boundary.

two subzones (CF8a and CF8b) to yield a higher resolution time control.

Numeric ages are generally estimated based on the geomagnetic time scale, or where this information is not available, such as at El Kef and Elles, on biostratigraphic correlation. In this study, numeric ages of Zones CF2 to CF10 for the Tunisian sections were extrapolated based on correlation of planktic foraminiferal datum events with DSDP Site 525 in the South Atlantic which contains an excellent palaeomagnetic record (Li & Keller, 1998a) and the revised time scale of Cande & Kent (1995). However, Zone CF1 was not recognized at Site 525 because of the absence of the low latitude index species *Plummerita hantkeninoides*. For this reason, the age for Zone CF1 was determined from magnetostratigraphy at Agost, Spain (Groot *et al.*, 1989; Pardo *et al.*, 1996).

Note that these biozone age estimates are for the duration of each biozone. We were unable to estimate the missing intervals at two fault zones within CF3 and near the CF5–CF4 transition, and at two hiatuses at the CF8a/b boundary and within Zone CF10

(Figure 2). In addition, extrapolating ages based on biostratigraphic correlation may result in age uncertainties because of potentially diachronous datum events in different ecosystems. Thus, our age assignments for the Tunisian sections are best estimates which need to be further evaluated for potential diachroneity of the datum events in different geographic regions. However, despite these uncertainties, the extrapolated age estimates provide a reasonable time control for the Maastrichtian to late Campanian interval in this region until palaeomagnetic studies are forthcoming.

The Campanian-Maastrichtian boundary

The Campanian-Maastrichtian boundary has not been formally defined, though various proposals have been made. For example, at the IGCP meeting on this Cretaceous Stage Boundary in Brussels (August, 1995), a section at Tercis near Dax in Aquitaine, southwestern France, was proposed as a possible new boundary stratotype (Odin, 1996) with the first

appearance (FA) of the ammonite *Pachydiscus neubergicus* as the boundary marker. However, Gradstein *et al.* (1995) proposed that the Campanian-Maastrichtian boundary be placed at the top of the *Baculites jenseni* ammonite Zone, or possibly the overlying *B. eliasi* Zone based on macrofossil and strontium isotope correlations between the Kronsmoor section of Germany, the English Chalk and the United States Western Interior (see Kennedy *et al.*, 1992; MacArthur *et al.*, 1993). Based on linear interpolation between K/Ar ages of two bentonites at 70.1 ± 0.7 Ma and 73.2 ± 0.7 Ma, Gradstein *et al.* (1995, p. 102) estimated an age of 71.6 ± 0.7 Ma for the Campanian-Maastrichtian Stage boundary.

No studies are known to us that correlate either the *P. neubergicus* FA or the *B. jenseni* Zone to the planktic foraminiferal datum events and biozonation within the same section, though informal reports suggest that the FA of *P. neubergicus* and the *B. jenseni* Zone predate the FA of *Gansserina gansseri* and postdate the LA of *Globotruncanita calcarata*. Microfossil workers, however, have generally placed the Campanian-Maastrichtian boundary at the top of the *G. calcarata* Zone (e.g., Robaszynski *et al.*, 1983–1984; Bralower *et al.*, 1995; Li & Keller, 1998a, b). However, an informal correlation can be made between the age for the Campanian-Maastrichtian boundary estimated at 71.6 ± 0.7 Ma and at the base of C32N.1n (71.3 ± 0.7 Ma) by Gradstein *et al.* (1995, pp. 102, 110). This interval corresponds to within the upper *G. aegyptiaca* Zone and near the first appearance of the planktic foraminifera *Rugoglobigerina hexacamerata* and *Planoglobulina carseyae* which subdivide this zone into two Subzones CF8a and CF8b. In this study we informally use the planktic foraminiferal datum of *R. hexacamerata* at 71 Ma for the Campanian-Maastrichtian boundary based on biostratigraphic correlation with the geomagnetic time scale at DSDP Site 525. This datum event is within the range of Gradstein *et al.*'s estimate of 71.6 ± 0.7 Ma for this boundary (Figure 3).

The Early-Late Maastrichtian boundary

At the Brussels meeting it was recommended that the Maastrichtian stage be formally divided into two substages (early and late), although there was no agreement on the boundary-criterion for the base of the late Maastrichtian (Odin, 1996, p. 115). Planktic foraminiferal workers have generally placed the early-late Maastrichtian boundary at the FA of *G. gansseri* (Robaszynski *et al.*, 1983–84; Caron, 1985; Li & Keller, 1998a, b), or at the FA of *A. mayaroensis* or *R. fructifera* (Boersma, 1984; Nederbragt, 1991).

However, *A. mayaroensis* is a poor biostratigraphic marker because this species, which is known to be diachronous (Keller, 1989; Huber, 1990; Pardo *et al.*, 1996), appears much earlier in high latitudes and is rare or absent in neritic environments. Gradstein *et al.* (1995, p. 110) proposed that the early-late Maastrichtian boundary be placed at 69.5 Ma within the upper part of C31R. This interval corresponds to the first appearance of *Rosita contusa* at DSDP Site 525 which marks the base of Zone CF6 (Figure 3; Li & Keller, 1998a). In contrast, Bralower *et al.* (1995) proposed that this boundary be placed at the base of C30N, which corresponds to within the middle of Zone CF4 (*R. fructifera* Zone) at about 67.6 Ma (Figure 3). In this study we informally use the first appearance of *R. fructifera* to approximate the early-late Maastrichtian boundary at 68.3 Ma based on biostratigraphic correlation with the geomagnetic time scale at DSDP Site 525.

4. Lithology, macrofauna and inferred sea-level changes

During the late Campanian and early Maastrichtian, sediment deposition at Elles and El Kef varied between upper slope (>250 m) and middle to outer shelf depths (~100–250 m), as indicated by limestone/marl deposition with limestones rich in macrofaunas and marls rich in benthic foraminifera (Figure 4A). In the upper Campanian interval (0–5 m), sediments consist of alternating 20–60-cm-thick layers of white marls and white marly limestones which are fissile near the base. At El Kef a thick limestone bed marks the top of this interval, and the overlying marl is covered by vegetation. Macrofossils are common, particularly in the limestone layers. Inoceramids were commonly observed in the field, as well as two species of irregular echinoids (*Stegaster altus* and *S. chalmesi*) and a fragment of *Diplomoceras*, an ammonite known worldwide to range from the Campanian to Maastrichtian. Trace fossils, such as large *Cancellophycos* (up to 1 m), are abundant.

The surface of the limestone layer at 5 m at Elles is a hardground (foreground surface in Figure 4A) as suggested by the presence of abundant inoceramids, *Stegaster* and wood fragments as well as an ichnofauna that consists of horizontal *Ophiomorpha* with large (~3 cm diameter) branching tubes, some *Rhizocorallium*, and unspecified small vertical tubes filled with dark marl from the overlying sediments. Although *Ophiomorpha* is most commonly observed in inner shelf environments, these taxa are also present in middle shelf to slope and deep basin environments (Ekdale, 1988; Bottjer & Droser, 1992). *Ophiomorpha*



hardground



the Campanian-Maastrichtian boundary

are common in late Cretaceous shelf and slope environments of northeastern Mexico and Tunisia (Stinnesbeck *et al.*, 1996; Keller *et al.*, 1997).

In the Tunisian sections, the hardground, wood fragments, invertebrate abundance and trace fossils (including *Ophiomorpha*) all suggest that the sea floor was consolidated, or even semi-lithified, prior to deposition of the overlying sediments and hence indicates a period of non-deposition and/or erosion during a sea-level lowstand (Figures 3, 4A). Based on planktic foraminifera, this hardground surface occurs within the *G. calcarata* Zone.

The hardground surface marks a major sedimentological change from the white marls and marly limestones below to the blue-grey fissile marly shale above which contains several resistant layers of yellow marly limestones, which suggests a higher, though fluctuating sea-level (Figure 4A). Macrofaunas are scarce in the marly shales, except for irregular echinoids. We collected several well preserved specimens of *Stegaster* cf. *guilleri*, *Micraster*, spatangoids and holectypoids, and noted impressions of *Inoceramus* near the base of the unit. The last inoceramids were observed in a couplet of marly limestone layers at 9.7 m. These resistant limestone layers suggest a sea-level lowstand near the top of Zone CF10.

Up-section (between 10 and 20 m in biozone CF9-CF8, Figure 4B), sediments grade into grey marly shales which are increasingly fissile towards the top and suggest deeper waters, as also indicated by the presence of rare macrofossils. Trace fossils are also rare, possibly because the shales do not allow good preservation. Between 21 and 25.5 m in Zone CF8a (*G. aegyptiaca*), five individual limestone layers are present, each about 20 cm thick (Figure 4B). Microfacies studies of these limestone layers indicate that they are wackestones, similar to those in the lower part of the section, with abundant planktic and rare benthic foraminifers, echinoids and fragments of molluscs (e.g., small gastropods). We observed several specimens of *Zoophycos* in the marls, and *Zoophycos* and *Ophiomorpha* in the uppermost marly limestone layer (25.5 m). Truncation of *Ophiomorpha* burrows suggests the presence of a hiatus between the last marly limestone and overlying marly shales. We interpret this interval as a sea-level lowstand accompanied by erosion.

Between 25.5 and 36 m at Elles, sediments consist of grey shales and two resistant marly limestones near the top. Trace fossils are rare and no macrofossils were observed other than rare echinoids. Planktic foraminiferal correlations between Elles and El Kef indicate that the upper part of this interval corresponds to the base of Zone CF8a (*R. hexacamerata*).

At El Kef, the base of Zone CF8a (*R. hexacamerata*) is in a grey marl layer at 50.7 m immediately below a thin marly limestone layer. Above this interval are three limestone layers separated by thin grey marls. Note that the absence of these marly limestone layers in CF8a at Elles suggests erosion, whereas the absence of the marly limestone layers in CF8b at El Kef may be due to erosion and/or lack of sediment exposure (interval covered by slump, Figure 2). Alternatively, the first appearance of *R. hexacamerata* may be diachronous. We interpret the marly limestone layers within CF8a at El Kef to correlate to a sea-level lowstand and the hiatus surface at Elles (Figure 2).

A slump covers the interval between 43 and 47 m and the exposed sediments overlying the slump (38–43 m) consist of alternating grey marls and marly limestones. Macrofossils are generally rare and restricted to the limestone layers, which contain rare inoceramids, very rare *Diplomoceras*, mollusks and common trace fossils (e.g., *Zoophycos*). The last ammonite (*Diplomoceras*) and inoceramids were observed in this interval at El Kef (Figure 2). The earlier disappearance of inoceramids and ammonites at Elles (at 9.7 m Zone CF9/10), as compared with El Kef (CF7), is probably owing to preservation, rarity of fossils, or the shallower depth of the Elles section. Above the last limestone layer at El Kef, five new planktic foraminiferal species suddenly appear (*Abathomphalus intermedius*, *Globigerinelloides volutus*, *G. yaucoensis*, *Rosita plicata* and *R. walfischensis*; Li & Keller, 1998b) and suggest the presence of a condensed interval or short hiatus. Based on the presence of the macrofossils and microfossils, we interpret this sequence of limestone/marl layers as representing a lower sea-level followed by a hiatus at the top of the last limestone layer (first appearance of five species).

Up-section, El Kef consists of monotonous grey shales with rare trace fossils. Two local faults are present at 22 m and 11 m, and several metres may be missing at these fault zones. Though these shales

Figure 4. A, Late Campanian at Elles. Note the flat surface in foreground is a hardground with abundant inoceramids, *Stegaster*, wood fragments, *Ophiomorpha* with large (3 cm diameter) branching tubes and *Rhizocorallium*. This hardground surface marks a period of non-deposition and/or erosion during a sea-level low. B, Campanian-Maastrichtian transition at Elles. This boundary is placed at the top of a series of five thin limestone layers. It is marked by a hiatus, as indicated by the truncation of *Ophiomorpha* burrows.

suggest a higher sea-level than in the underlying marl/limestone layers, the near absence of macrofossil, prevents a more detailed interpretation.

5. Benthic foraminifera and inferred sea-level changes

Benthic foraminifera are commonly used as palaeo-depth indicators though there is little agreement among workers as to the depth ranges of many species. The disagreement is partly due to the fact that species are not limited by depth *per se*, but probably by characteristics of particular water masses. In addition, downslope transport artificially extends the range of shell species into bathyal depths. Despite these problems, various species and species associations can be reliably used to infer the relative palaeodepth of deposition, especially within shelf-slope depositional environments where sedimentological parameters and macrofossils provide additional palaeodepth indicators for erosion and sea-level fluctuations.

In this study we have used the upper depth limits of benthic foraminiferal species as employed by many workers (e.g., Sliter, 1968; Sliter & Baker, 1972; Aubert & Berggren, 1976; Douglas, 1979; Ingle, 1980; Van Morkhoven *et al.*, 1986; Berggren & Miller, 1989; Bolli *et al.*, 1994) including application to sequence stratigraphy (Armentrout *et al.*, 1991, 1993, 1997). Based on these studies, we have grouped the species into middle neritic, outer neritic and outer neritic-bathyal depths (Figures 5, 6). Most species interpreted as middle and outer neritic dwellers are common to abundant and mostly continuously present in the studied sections. In contrast, species grouped as outer neritic-bathyal have low abundances and decrease in species richness up-section (Figures 5, 6), which indicates a strong environmental signal. We therefore use this subset of the benthic assemblage to infer sea-level changes.

Although by using this small and relatively well constrained subset of the benthic assemblage we decrease the uncertainties introduced by erroneous depth limit assignments, this problem is by no means eliminated. For example, species known from upper bathyal depths are frequently present in deeper bathyal as well as shallower outer neritic depths. For this reason, we have labeled this group “outer neritic-bathyal”. Among this group are *Angulogavelinella avnimelechi*, *Coryphostorma incrassata* (*C. incrassata gigantea?*), and *Stensioina excolata* which Van Morkhoven *et al.* (1986) list as “primarily bathyal, but ranges into outer neritic depths”. Predominantly bathyal species include *Nuttallides truempyi*, *Berthelinella delicatulus*, *Gyroldina cretacea*, *Praebulimina*

cushmani, *P. lajollaensis*, *Pullenia sp.*, *Spiroplectammina spectabilis*, and *Stensioina beccariiformis* (e.g., Van Morkhoven *et al.* 1986). In order to use this predominantly bathyal species group as palaeodepth indicator, we assume that they are either absent or rare during periods of low sea-levels and common or present during periods of high sea-levels. These assumptions are supported by the Maastrichtian and Campanian data from El Kef and Elles.

Maastrichtian at El Kef

Benthic foraminifera from the Maastrichtian at El Kef were quantitatively analyzed with common and abundant species shown in Figure 5 and the relative abundances of all species tabulated in Table 1. The outer neritic species group dominates through the entire Maastrichtian, both in species richness (17–20 species) and relative abundances, whereas common middle neritic taxa are relatively few (4–6 species). Most middle and outer neritic taxa range through the Maastrichtian. In contrast, the species group labeled “outer neritic-bathyal” has relatively low species abundances (generally <10%) and few species range through the Maastrichtian (Figure 5).

The most diverse assemblages in the outer neritic-bathyal species group are present in the late Campanian-early Maastrichtian (maximum of 20 species in Zones CF8-CF6, Figure 5). Up-section, species richness decreases to 11 species near the Cretaceous-Tertiary boundary. This overall decrease in the number of species from 20 to 11 suggests increasingly less favourable environmental conditions for this group or generally upward shallowing, as also suggested by the increased abundance of outer neritic species. However, this decrease in the outer neritic-bathyal species group is not linear, but shows alternating intervals of high and low species richness (Figure 6). Moreover, the combined relative percent abundance of these species consistently covaries with intervals of low species richness (Figure 6).

Since the preservation of foraminiferal species is generally very good and these variations are restricted to the deeper water assemblages, they are not artifacts of preservation, but reflect environmental changes. We interpret these variations in the outer neritic-bathyal species group as reflecting sea-level fluctuations. During periods of lower sea levels, we assume that the predominantly bathyal species disappear or temporarily disappear, thus reducing the number of outer neritic-bathyal species (low species richness and the combined percent abundance of these species). During subsequent rises in sea level, these species may reappear. However, if the long-term trend is that of a

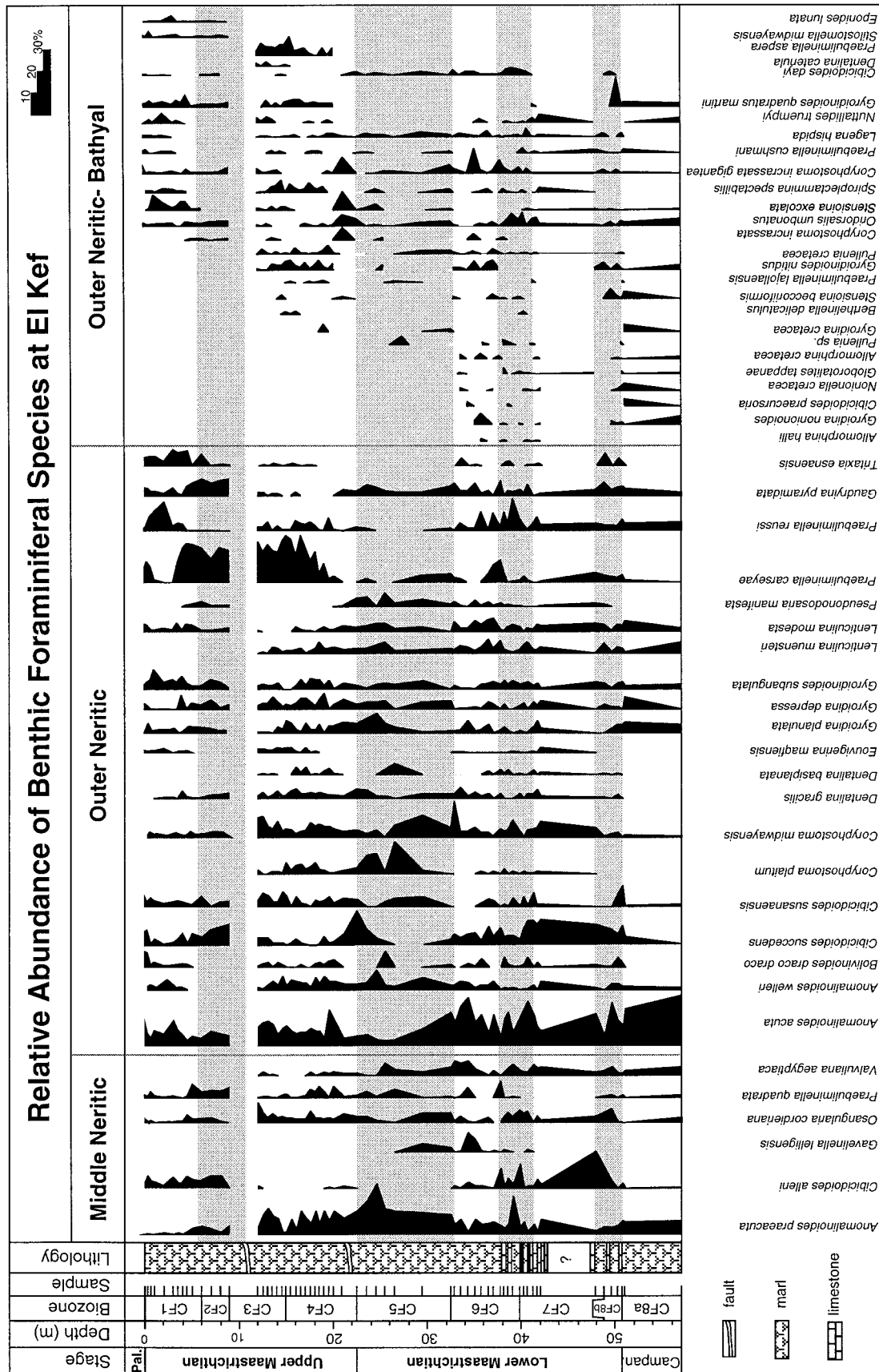


Figure 5. Relative percent abundances of common benthic foraminifera at El Kef grouped into middle and outer neritic, and outer neritic-bathyal assemblages based on upper depth limits of species and environmental associations (see text for discussion). Stippled intervals indicate sea-level lowstands as suggested by changes in benthic foraminifera.

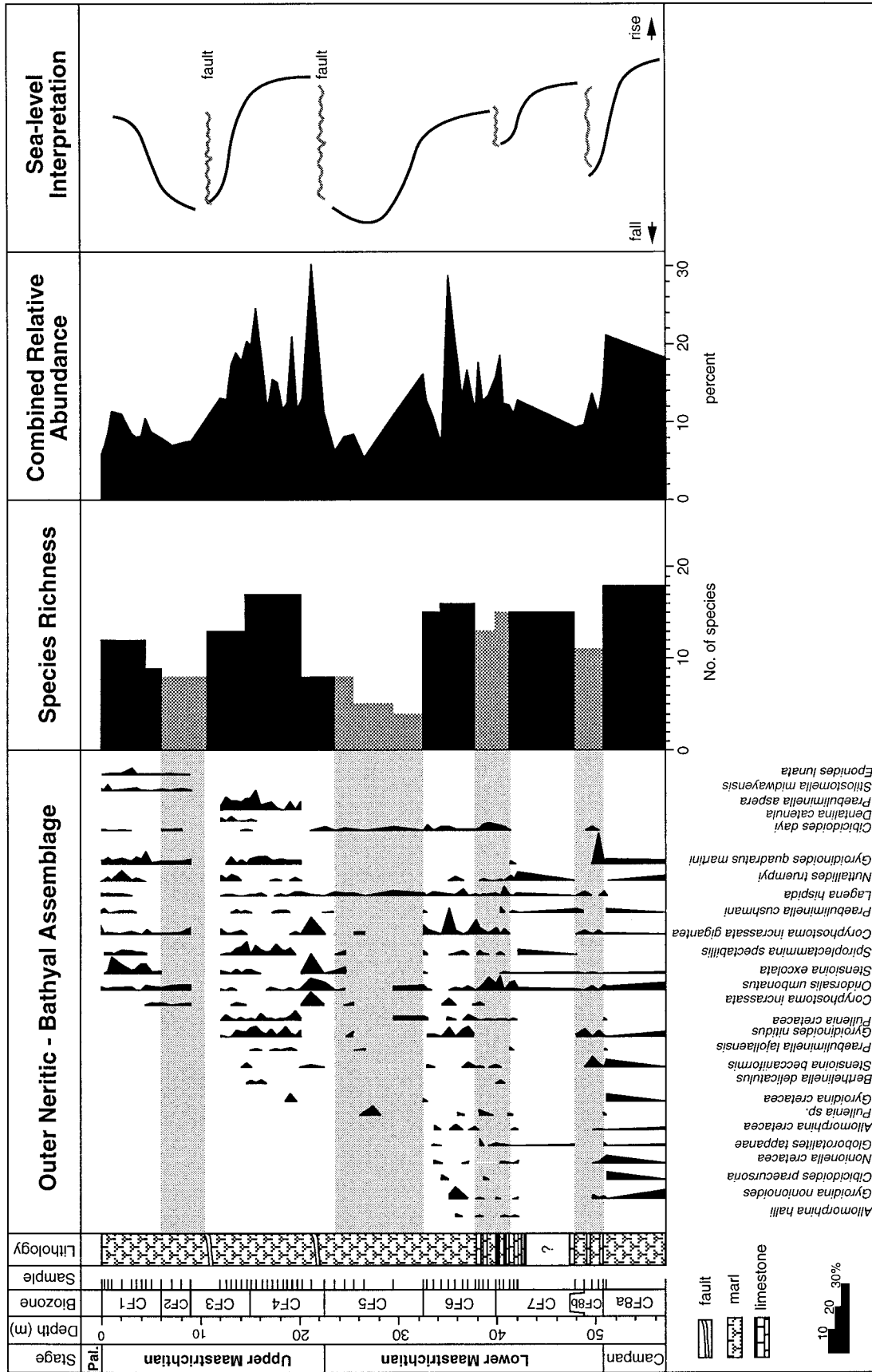


Figure 6. Variations in the distribution of outer neritic-bathyal species, species richness and the combined relative abundance of this assemblage through the Maastrichtian at El Kef. Sea level interpretations are based on relative abundances and species richness; reduced presence of deeper dwelling benthic foraminifera indicate lower sea-levels (stippled intervals).

generally decreasing (though fluctuating) sea-level, the deeper dwelling taxa will continue to decrease. Figure 6 (shaded intervals) illustrates a consistent pattern of periods of low species richness and low combined relative percent abundance marked by the absence of predominantly bathyal species that suggest lower sea-levels. These periods alternate with high species richness and high combined percent relative abundances marked by the presence of predominantly bathyal species that suggest higher sea-levels.

Thus, the first Maastrichtian sea-level lowstand coincides with the change from marl to alternating marl/limestone deposition at the base of the Maastrichtian. At this lithological change predominantly bathyal species (*N. truempyi*, *P. cushmani*, *G. cretacea*, *P. cretacea*, and *S. spectabilis*) temporarily disappeared. Species richness decreased from 17 to a low of 7 species and the combined relative abundance decreased from 20% to 9% (CF8b/CF7, Figure 6). Planktic foraminifera in this interval also show a major faunal turnover and probably a hiatus at El Kef, as indicated by the simultaneous appearance of several species (*Globotruncanita angulata*, *G. gansseri*, *P. carseyae*, *R. hexacamerata* and *R. pennyi*; Li & Keller, 1998b). This sea-level lowstand is well documented globally and correlates with a major global cooling (e.g., Barrera *et al.*, 1997; Li & Keller, 1998a).

The second Maastrichtian sea-level lowstand also coincides with an interval of limestone/marl deposition that spans the CF7/CF6 transition (69.6–69.3 Ma). Benthic foraminifera in this interval are marked by intermittent and sporadic occurrences of outer neritic-bathyal species as well as variably fluctuating abundances between 12% and 18% (Figure 6). A low sea-level and hiatus are also indicated by the simultaneous appearances of seven planktic foraminiferal species (*Gansserina wiedenmayeri*, *Globigerinelloides volutus*, *G. yaucoensis*, *Heterohelix globocarinata*, *Pseudotextularia deformis*, *Rugoglobigerina rotundata*, and *R. scotti*; Li & Keller, 1998b). In Zone CF6, a relatively high sea-level is indicated by the more diverse benthic foraminiferal assemblage, sporadic high abundance (18–28%) and abundance of predominantly bathyal species (*G. nitidus*, *P. cretacea*, *C. incrassata*, and *N. truempyi*; Figure 6).

The third Maastrichtian sea-level lowstand is indicated in Zone CF5 between 68.9–68.3 Ma. Outer neritic-bathyal benthic foraminifera in this interval drop from 15 to a low of 4–5 species (all predominantly bathyal taxa are absent) and from 16% to 4% of the total foraminiferal assemblage. Planktic foraminiferal assemblages within this interval show little change. The presence of a local fault above this

interval at El Kef prevents determination of the transition to a higher sea-level up-section (Figure 6).

A relatively high sea-level marks Zones CF4–CF3 up to a second fault zone. Benthic species richness in this interval ranges from 7 to 13 species and the combined relative abundance is high, reaching a maximum of 30% of the total benthic assemblage (Figure 6). Predominantly bathyal species are common in this interval (*G. cretacea*, *B. delicatulus*, *G. nitidus*, *P. cretacea*, *C. incrassata*, *N. truempyi*, *P. cushmani*, and *S. spectabilis*).

The fourth Maastrichtian sea-level lowstand occurs at or above the local fault zone in Zones CF3–CF2. At this interval, the outer neritic-bathyal species are reduced to 7 species and their combined relative abundance is less than 10% (Figure 6). All predominantly bathyal species are absent in this interval. This sea-level lowstand is well documented in marine sequences worldwide (Keller & Stinnesbeck, 1996) and corresponds to the 67 Ma sea-level low of Haq *et al.* (1987). No major planktic foraminiferal species changes are associated with this sea-level lowstand. During the last 300 Kyr of the Maastrichtian in Zone CF1, a rising sea-level is indicated by the increasing number of deeper dwelling benthic species (from 7 to 11) including five predominantly bathyal species and their increasing combined relative abundance (Figure 6).

Late Campanian at Elles

Benthic foraminifera from the late Campanian to early Maastrichtian indicate similarly strong environmental changes at Elles. Compared with El Kef, sediment deposition at Elles occurred in a shallower outer neritic to upper bathyal environment, as suggested by the lower species richness in the outer neritic-bathyal group (2–12 species, Figures 7, 8) and the absence of the predominantly bathyal species (e.g., *N. truempyi*, *C. incrassata*, and *G. cretacea*). Although benthic foraminiferal abundances for the Elles section were only qualitatively analyzed, the alternating low-high species richness patterns for the outer neritic-bathyal group is pronounced and identifies the sea-level fluctuations.

A hardground and low sea-level mark the top of the last thick late Campanian limestone (CF10, *G. calcarata* Zone) at Elles as noted on the basis of macrofossils and trace fossils (Figure 2). In this interval, the outer neritic-bathyal benthic foraminifera decreases from 9 to 5 species. Species richness is higher in the marly interval above this hardground (upper CF10) and decreases again to 3 species in the limestone layer at 9.7–10 m (Figure 8). Another interval with low

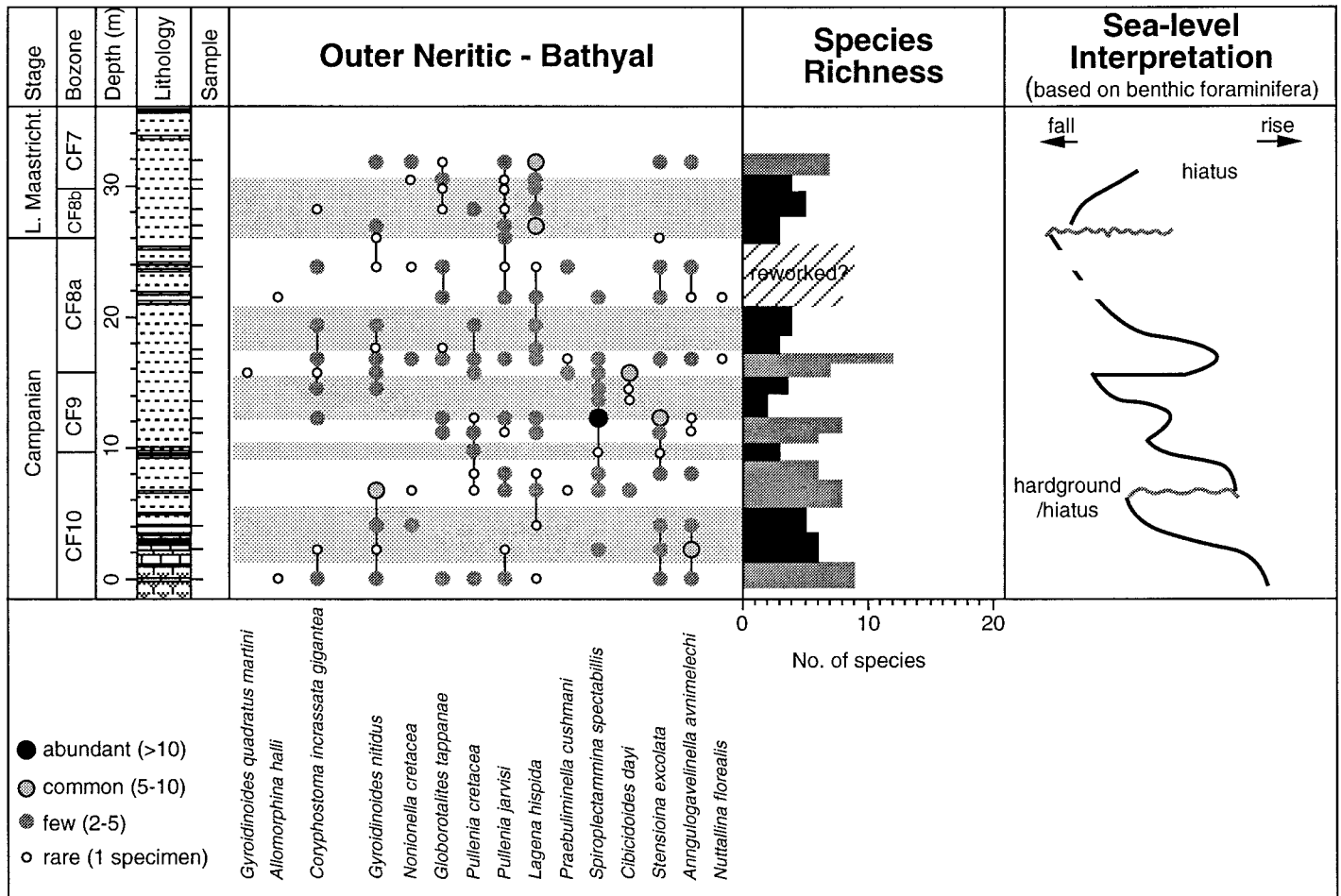


Figure 8. Variations in the distribution of outer neritic-bathyal species and species richness during the late Campanian through the early Maastrichtian at Elles. Sea-level interpretations are based on variations in species richness with reduced presence of deeper dwelling benthic foraminifera indicating lower sea levels (stippled intervals).

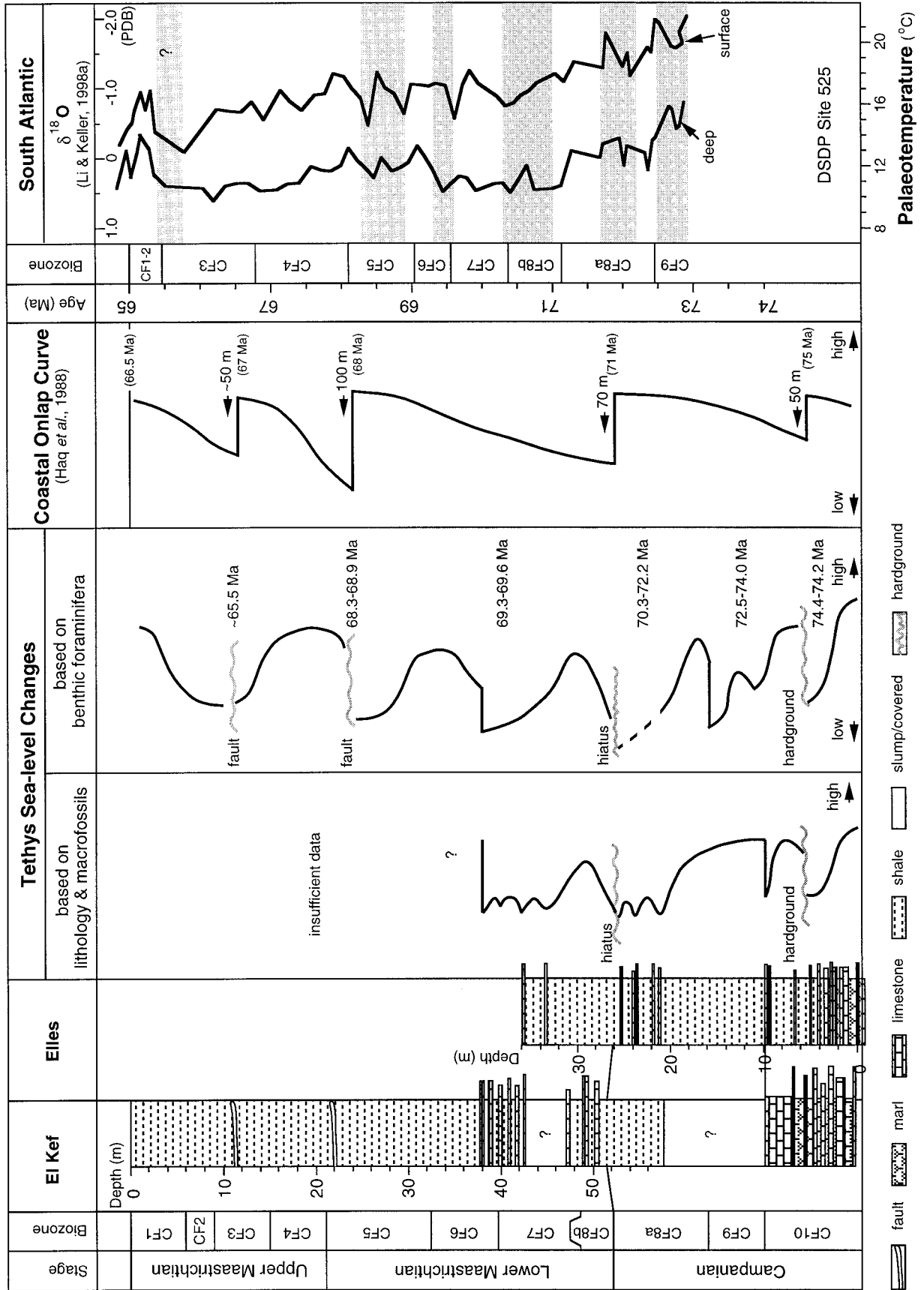
species richness in the outer neritic-bathyal group occurs in the upper part of CF9. This sea-level lowstand may also be associated with a hiatus, as suggested by the nearly simultaneous first appearance of five planktic foraminiferal species at the CF9/CF8b boundary (e.g., *Globotruncana aegyptiaca*, *G. rosetta*, *Guembelitra cretacea*, *Gublerina acuta*, and *Rugoglobigerina rugosa*; Li & Keller, 1998b).

Above this sea-level lowstand is an interval with increased outer neritic-bathyal species richness (base of CF8a) followed by low species richness (middle of CF8a). There are no major planktic changes associated with this interval. The limestone/marl layers in the upper CF8a interval, however, have relatively high species richness and suggest a rising sea level, contrary to the low sea level interpreted from lithology and macrofossils. The top of this interval is marked by a hiatus and erosion surface, as also suggested by the simultaneous first appearance of several planktic

foraminifera (e.g., *Globotruncana angulata*, *G. stuartiformis*, *Planoglobulina brazoensis*, *R. hexacamerata*, and *R. scotti*; Li & Keller, 1998b). This suggests that the high benthic species richness may be due to erosion and the influx of reworked specimens when the sea-level was low. Benthic species richness fluctuations thus must be interpreted with caution, particularly in intervals of low sea levels when erosion and reworking of species was likely.

6. Comparison of sea-level changes based on microfaunas, macrofaunas and lithology

Comparison of sea-level changes inferred from benthic foraminifera with those inferred from macrofaunas and lithology (Figures 3, 6, 9) reveals a generally good agreement. Both faunal groups mark changing sea levels coincident with major lithological transitions from limestone to marl, which may be



abrupt and coincide with a hardground or erosion surface. In the field, an abundance of shells, shell fragments (sometimes wood fragments) and burrows, which are often truncated, mark these surfaces. In microfaunas, the presence of fewer, predominantly bathyal, species and increased abundance of shallower water species mark lower sea levels. There may also be an influx of reworked species which, if not recognized, may obscure the true benthic foraminiferal changes.

There are, however, also significant differences. For example, sea-level changes in relatively deep waters are not easily identified based on macrofaunas or lithology, because the former are rare or absent and major lithological changes are generally absent. This appears to be the case for most of the upper Maastrichtian at El Kef, which was deposited at depths ranging from 200–500 m (Peypouquet *et al.*, 1986). The absence of lithological changes and near absence of macrofaunas in Zones CF6 to CF1 do not permit any evaluation of sea-level changes based on these indices. However, the outer neritic-bathyal benthic foraminiferal group reveals major fluctuations (Figures 6, 9). Similarly at Elles, benthic foraminifera indicate sea-level variations within the grey marly shales of Zones CF9–CF8 (Figure 8). The combined results from micro- and macrofaunas, and lithology may thus provide the best results for the interpretation of sea-level fluctuations during the Late Cretaceous.

7. Discussion

In this study we set out to evaluate late Campanian–Maastrichtian sea-level variations in the southwestern Tethys region of El Kef and Elles based on lithology, and macro- and microfaunas. These data suggest at least eight intervals of significantly lower sea levels as shown in the sea-level curves of Elles and El Kef (Figure 9), though there may be more, yet unrecognized, sea-level changes within the incomplete (two fault zones) upper Maastrichtian interval at El Kef. In order to evaluate whether these sea-level fluctuations were the result of regional tectonic activity, eustatic sea-level changes, or both, we compare this record with the Haq *et al.* (1988) coastal onlap curve and the oxygen isotope record from the middle latitude South

Atlantic DSDP Site 525, which spans 73 Ma to 65 Ma (Figure 9).

Oxygen isotope studies in southern middle and high latitudes (Sites 525 and 690) have indicated the onset of a major climatic cooling at about 73 Ma and maximum cooling by 71 Ma, possibly associated with continental ice accumulation on Antarctica (Barrera & Huber, 1990; Barrera, 1994; Barrera *et al.*, 1997; Li & Keller, 1998a). High latitude climatic cooling continued through the late Maastrichtian reaching maximum low temperatures about 500 Kyr before the K-T boundary. During the last 200–400 Kyr of the Maastrichtian, the climate warmed with temperatures rising 3°C in surface and 4°C in deep waters of Sites 525 and 690, but cooling again before the K-T boundary (Stott & Kennett, 1990; Barrera, 1994; Li & Keller, 1998a, c). These climatic changes suggest a Maastrichtian marked by major eustatic sea-level fluctuations as documented by Haq *et al.* (1987, 1988).

How do sea-level changes inferred from benthic faunas and lithology compare with climatic changes? We would expect a good correlation because low eustatic sea levels are generally associated with cool climates and high sea levels with warm climates. Figure 9 shows that there is excellent agreement between low sea levels and cool climates in Zones CF8a, CF8b, CF7, CF6 and CF5. However, in some intervals sea-level changes at El Kef and Elles do not correlate with climate changes. For example, relatively cool conditions in CF4–CF3 coincide with relatively high sea levels at El Kef, and precede the sea-level lowstand in Zone CF3–CF2. In addition, the end-Maastrichtian cooling indicated in the oxygen isotopes in the upper part of CF1 is not apparent in the current benthic foraminiferal analysis by a sea-level regression, probably because of low sample resolution. For the late Campanian no good oxygen isotope data is available at this time. Despite these shortcomings, the overall cool climates of the Maastrichtian generally correlate with low sea levels, and frequently with erosion and hiatuses.

Are the observed sea-level fluctuations in the southwestern Tethys due to eustatic variations or local tectonic controls? The Exxon sea-level curve (Haq *et al.*, 1987, 1988) identified four major sea-level

Figure 9. Composite sea-level curve for the late Campanian through Maastrichtian based on the Elles and El Kef sections and sea-level interpretations based on lithology, macrofossils and benthic foraminifera. Stippled intervals indicate sea-level lowstands as suggested by changes in benthic foraminifera. The Haq *et al.* (1987, 1988) sea-level curve is shown for comparison. The oxygen isotope record is from DSDP Site 525 in the middle latitude South Atlantic (Li & Keller, 1998a) and shows a close correlation between episodes of climatic cooling and sea-level regressions in the southwestern Tethys.

regressions during the studied interval (e.g., 75 Ma, 71 Ma, 68 Ma, 67 Ma, Figure 9). These four regressions correspond with low sea levels at 74.4–74.2 Ma, 72.2–70.3 Ma, 68.9–68.3 Ma, and ~65.5 Ma in our Tethys record. This suggests that these regressions are of eustatic origin. The latest Maastrichtian sea-level low at ~65.5 Ma is also of eustatic origin, as indicated by its presence in sedimentological sequences worldwide (Keller & Stinnesbeck, 1996). The sea-level lowstand at 69.6–69.3 Ma coincides with a cold deep-water temperature at Site 525. We have no records from other regions to date of low sea level at 74.0–72.5 Ma.

We conclude that within the constraints of correlating the Tethys sea-level record to the oxygen isotope record of Site 525 (accomplished on the basis of high resolution biostratigraphic correlation by Li & Keller, 1998a, b), periods of high latitude cooling coincide with episodes of sea-level regressions as inferred from benthic micro- and macrofaunal assemblages and lithological changes, including hardgrounds, erosion surfaces and hiatuses.

8. Conclusions

An integrated approach to interpreting sea-level changes during the late Campanian through Maastrichtian based on benthic macro- and microfaunas and lithological field observations suggests a history of sea-level regressions that correlate with major episodes of middle and high latitude cooling. Six major sea-level regressions are identified during the late Campanian (74.4–74.2 Ma, 74.0–72.5 Ma), the Campanian-Maastrichtian transition (72.2–70.3 Ma), early Maastrichtian (69.6–69.3 Ma, 68.9–68.3 Ma), and late Maastrichtian (~65.5 Ma). Five of these Campanian-Maastrichtian sea-level regressions correlate with global cooling episodes observed in the oxygen isotope record of Site 525 in the middle latitude South Atlantic. For the late Campanian sea-level regression between 74.4–74.2 Ma, no stable isotope data are available.

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References

- Armentrout, J. M., Echols, R. J. & Lee, T. D. 1991. Patterns of foraminiferal abundance and diversity; implication for sequence stratigraphic analysis. *American Association of Petroleum Geologists, Bulletin* 75, 535.
- Armentrout, J. M., Becker, R. C., Fearn, L. B., Ali, W. M., Hudson, D. G., O'Neill, W. A., Tyrrell, T. E. & Vonderhoya, H. A. 1993. Exploration applications of integrated biostratigraphic analysis, Plio-Pleistocene, offshore southern Trinidad. *American Association of Petroleum Geologists, Bulletin* 77, 303.
- Armentrout, J. M., Becker, R. C. & Fearn, L. B. 1997. Biostratigraphic definition of depositional cycles and environments, Plio-Pleistocene, offshore southern Trinidad. *American Association of Petroleum Geologists, Annual Meeting Abstracts* 6, 5.
- Aubert, J. & Berggren, W. A. 1976. Paleocene benthic foraminiferal biostratigraphy and paleoecology of Tunisia. *Bulletin des Centre de Recherches, Pau-SNPA* 10, 379–469.
- Barrera, E. 1994. Global environmental changes preceding the Cretaceous-Tertiary boundary: early-late Maastrichtian transition. *Geology* 22, 877–880.
- Barrera, E. & Huber, B. T. 1990. Evolution of Antarctic waters during the Maastrichtian: foraminiferal oxygen and carbon isotope ratios, Leg 113. In *Proceeding of the Ocean Drilling Program, Scientific Results* (eds Barker, P. F. & Kennett, J. P., *et al.*) 113, 813–827.
- Barrera, E. & Keller, G. 1994. Productivity across the Cretaceous-Tertiary boundary in high latitudes. *Geological Society of America, Bulletin* 106, 1254–1266.
- Barrera, E., Savin, S. M., Thomas, E. & Jones, C. E. 1997. Evidence for thermohaline-circulation reversals controlled by sea-level change in the latest Cretaceous. *Geology* 25, 715–718.
- Berggren, W. A. & Miller, K. G. 1989. Cenozoic bathyal and abyssal benthic foraminiferal zonations. *Micropaleontology* 35, 308–320.
- Boersma, A. 1984. Campanian through Paleocene paleotemperature and carbon isotope sequence and the Cretaceous-Tertiary boundary in the Atlantic Ocean. In *Catastrophes and Earth history* (eds Berggren, W. A. & Van Couvering, J. A.), pp. 247–277 (Princeton University Press, Princeton, NJ).
- Bolli, H. M., Beckmann, J. P. & Saunders, J. B. 1994. *Benthic foraminiferal biostratigraphy of the south Caribbean region*, 408 pp. (Cambridge University Press, Cambridge).
- Bottjer, D. J. & Droser, M. L. 1992. Paleoenvironmental patterns of biogenic sedimentary structures. In *Trace fossils* (eds Maples, Ch. G. & West, R. R.), *Paleontological Society, Short Courses in Paleontology* 5, 238 pp.
- Bralower, T. J., Leckie, R. M., Sliter, W. V. & Thierstein, H. R. 1995. An integrated Cretaceous microfossil biostratigraphy. In *Geochronology, time scale and global stratigraphic correlation* (eds Berggren, W. A., Kent, D. V., Aubry, M. P. & Hardenbol, J.), *Society of Economic Paleontologists and Mineralogists, Special Publication* 54, 65–79.
- Burollet, P. F. 1967. General geology of Tunisia. In *Guidebook to the geology and history of Tunisia* (ed. Martin, L.), *Petroleum Exploration Society of Libya, 9th Annual Field Conference*, 67 pp.
- Cande, S. C. & Kent, D. V. 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research* 100, 6093–6095.
- Caron, M. 1985. Cretaceous planktic foraminifera. In *Plankton stratigraphy* (eds Bolli, H. M., Saunders, J. B. & Perch-Nielsen, K.), pp. 17–86 (Cambridge University Press, Cambridge).
- Coccioni, R. & Galeotti, S. 1994. K-T boundary extinction; geologically instantaneous or gradual event? Evidence from deep-sea benthic foraminifera. *Geology* 22, 779–782.
- Coccioni, R. & Galeotti, S. 1998. What happened to small benthic foraminifera at the Cretaceous-Tertiary boundary. *Geological Society of America, Bulletin* 109, 271–279.
- Corliss, B. H. 1991. Morphology and microhabitat preferences of benthic foraminifera from the northwest Atlantic Ocean. *Marine Micropaleontology* 17, 195–236.

- Corliss, B. H. & Emerson, S. 1990. Distribution of Rose Bengal stained deep-sea benthic foraminifera from the Nova Scotian continental margin and Gulf of Maine. *Deep-Sea Research* **37**, 381–400.
- Donze, P., Jardine, S., Legoux, O., Masure, E. & Méon, H. 1985. Les événements à la limite Crétacé-Tertiaire: au Kef (Tunisie septentrionale), l'analyse palynoplantologique montre qu'un changement climatique est décelable à la base du Danian. *Actes du Premier Congrès National des Sciences de la Terre*, Tunis, Sept. 1, 1981, pp. 161–169.
- Douglas, R. G. 1979. Benthic foraminiferal ecology and paleoecology: a review of concepts and methods. In *Foraminiferal ecology and paleoecology* (eds Lipps, J. H., Berger, W. H. & Buzas, M. A.), *Society of Economic Paleontologists and Mineralogists, Short Course* **6**, 21–53.
- Douglas, R. G. & Woodruff, F. 1981. Deep-sea benthic foraminifera. In *The oceanic lithosphere: the sea* (ed. Emiliani, C.), **7**, pp. 1233–1327 (John Wiley & Sons, New York).
- Ekdale, A. A. 1988. Pitfalls of paleobathymetric interpretations based on trace fossil assemblages. *Palaio* **3**, 464–472.
- Gooday, A. J. 1993. Deep-sea benthic foraminiferal species which exploit phytodetritus; characteristic features and controls on distribution. *Marine Micropaleontology* **22**, 187–205.
- Gradstein, F. M., Agterberg, F. P., Ogg, J. G., Hardenbol, J., Van Veen, P., Thierry, J. & Huang, Z. 1995. A Triassic, Jurassic and Cretaceous time scale. In *Geochronology, time scale and global stratigraphic correlation* (eds Berggren, W. A., Kent, D. V., Aubry, M. P. & Hardenbol, J.), *Society of Economic Paleontologists and Mineralogists Special Publication* **54**, 95–128.
- Groot, J. J., de Jonge, R. B. G., Langereis, C. G., ten Kate, W. G. H. Z. & Smit, J. 1989. Magnetostratigraphy of the Cretaceous-Tertiary boundary at Agost (Spain), *Earth and Planetary Science Letters* **92**, 385–397.
- Haig, D. W. 1979. Global distribution patterns for mid-Cretaceous foraminiferids. *Journal of Foraminiferal Research* **9**, 29–40.
- Hag, B. U., Hardenbol, J. & Vail, P. R. 1987. Chronology of fluctuating sea levels since the Triassic. *Science* **235**, 1156–1167.
- Hag, B. U., Hardenbol, J. & Vail, P. R. 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level changes. In *Sea-level changes: an integrated approach* (eds Wilgus, C. K., Hastings, B. S., St. Kendall, C. G. C., Posamentier, H. W., Ross, C. A. & Van Wagoner, J. C.), *Society of Economic Paleontologists and Mineralogists, Special Publication* **42**, 71–108.
- Hermelin, J. O. R. & Shimmield, G. B. 1990. The importance of the oxygen minimum zone and sediment geochemistry in the distribution of recent benthic foraminifera in the northwest Indian Ocean. *Marine Geology* **91**, 1–29.
- Huber, B. T. 1990. Maastrichtian planktonic foraminifer biostratigraphy of the Maud Rise (Weddell Sea, Antarctica), ODP Leg 113 Hole 689B and 690C. *Proceeding of the Ocean Drilling Program, Scientific Results* (eds Barker, P. F. & Kennett, J. P. et al.) **113**, 489–514.
- Ingle, J. C. 1980. Cenozoic paleobathymetry and depositional history of selected sequences within the southern California continental borderland. *Cushman Laboratory of Foraminiferal Research, Special Publication* **19**, 163–195.
- Kaiho, K. 1994. Benthic foraminiferal dissolved-oxygen index and dissolved-oxygen level in the modern ocean. *Geology* **22**, 719–722.
- Keller, G. 1988. Biotic turnover in benthic foraminifera across the Cretaceous/Tertiary boundary at El Kef, Tunisia. *Palaogeography, Palaeoclimatology, Palaeoecology* **66**, 153–171.
- Keller, G. 1989. Extended Cretaceous/Tertiary boundary extinctions and delayed population change in planktic foraminifera from Brazos River, Texas. *Paleoceanography* **4**, 287–332.
- Keller, G. 1992. Paleocological response of Tethyan benthic foraminifera to the Cretaceous-Tertiary boundary transition. In *Studies in benthic foraminifera*, Benthos'90 (eds Takagayanagi, Y. & Saito, T.), pp. 77–91 (Tokyo University Press, Tokyo).
- Keller, G. & Stinnesbeck, W. 1996. Sea-level changes, clastic deposits and megatsunamis across the Cretaceous-Tertiary boundary. In *Cretaceous/Tertiary boundary mass extinction: biotic and environmental changes* (eds MacLeod, N. & Keller, G.), pp. 415–450 (W.W. Norton & Co., New York).
- Keller, G., Lopez-Oliva, J. G., Stinnesbeck, W. & Adatte, T. 1997. Age, stratigraphy, and deposition of near-K/T siliciclastic deposits in Mexico: relation to bolide impact? *Geological Society of America, Bulletin* **109**, 410–428.
- Kennedy, W. J., Cobban, W. A. & Scott, G. R. 1992. Ammonite correlation of the uppermost Campanian of Western Europe, the U.S. Gulf Coast, Atlantic Seaboard and Western Interior, and the numerical age of the base of the Maastrichtian. *Geological Magazine* **129**, 497–500.
- Koutsoukos, E. A. M. & Hart, M. B. 1990. Cretaceous foraminiferal morphogroup distribution patterns, palaeocommunities and trophic structure; a case study from Sergipe Basin, Brazil. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **81**, 221–246.
- Kurihara, K. & Kennett, J. P. 1988. Bathymetric migration of deep-sea benthic foraminifera in the southwest Pacific during the Neogene. *Journal of Foraminiferal Research* **18**, 75–83.
- Li, L. & Keller, G. 1998a. Maastrichtian climate, productivity and faunal turnovers in planktic foraminifera in South Atlantic DSDP Sites 525 and 21. *Marine Micropaleontology* **33**, 55–86.
- Li, L. & Keller, G. 1998b. Maastrichtian diversification of planktic foraminifera at El Kef and Elles, Tunisia. *Eclogae Geologicae Helveticae* **91**, 75–102.
- Li, L. & Keller, G. 1998c. Abrupt deep-sea warming at the end of the Cretaceous. *Geology* **26**, 995–998.
- Luger, P. 1985. *Stratigraphie der marinen Oberkreide und des Altertiars im südwestlichen Oberrhein-Becken (SW-Ägypten) unter besonderer Berücksichtigung der Mikropalaontologie. Palökologie und Paläogeographie*, 151 pp. (Verlag Von Dietrich Reimer, Berlin).
- MacArthur, J. M., Thirlwall, M. F., Chen, M., Gale, A. S. & Kennedy, W. J. 1993. Strontium isotope stratigraphy in the late Cretaceous: numerical calibration of the Sr isotope curve, and intercontinental correlation for the Campanian. *Paleoceanography* **8**, 859–873.
- Méon, H. 1990. Palynologic studies of the Cretaceous/Tertiary boundary interval at El Kef outcrop, northwestern Tunisia: paleogeographic implication. *Review of Palaeobotany and Palynology* **65**, 85–94.
- Miller, K. G. & Katz, M. E. 1987. Oligocene to Miocene benthic foraminiferal and abyssal circulation changes in the North Atlantic. *Micropaleontology* **33**, 97–149.
- Nederbragt, A. J. 1991. Late Cretaceous biostratigraphy and development of Heterohelicidae (planktic foraminifera). *Micropaleontology* **37**, 329–372.
- Odin, G. S. 1996. Definition of a Global Boundary Stratotype Section and Point for the Campanian/Maastrichtian boundary. *Bulletin de l'Institut Royal des Sciences Naturelles de Belgique, Sciences de la Terre* **66**-Supplement, 111–117.
- Pardo, A., Ortiz, N. & Keller, G. 1996. Latest Maastrichtian foraminiferal turnover and its environmental implications at Agost, Spain. In *Cretaceous/Tertiary boundary mass extinction: biotic and environmental changes* (eds MacLeod, N. & Keller, G.), pp. 139–172 (W.W. Norton & Co., New York).
- Peypouquet, J. P., Grousset, F. & Mourguiart, P. 1986. Paleoceanography of the Mesogean Sea based on ostracods of the northern Tunisian continental shelf between the late Cretaceous and early Paleogene. *Geologische Rundschau* **75**, 159–174.
- Robaszynski, F., Caron, M., Gonzalez Donoso, J. M., Wonders, A. A. H. & the European Working Group on planktonic foraminifera 1983–1984. Atlas of late Cretaceous Globotruncanids. *Revue de Micropaléontologie* **26**, 145–305.
- Sliter, W. V. 1968. Upper Cretaceous foraminifera from southern California and northwestern Baja California, Mexico. *University of Kansas, Paleontological Contributions* **49**, 1–141.
- Sliter, W. V. & Baker, R. A. 1972. Cretaceous bathymetric distribution of benthic foraminifera. *Journal of Foraminiferal Research* **2**, 167–183.

- Speijer, R. P. 1994. Extinction and recovery patterns in benthic foraminiferal paleocommunities across the Cretaceous/Paleogene and the Paleogene/Eocene boundaries. *Geological Ultralectina* **124**, 191 pp.
- Speijer, R. P. & Van Der Zwaan, G. J. 1996. Extinction and survivorship of southern Tethyan benthic foraminifera across the Cretaceous/Paleogene boundary. In *Biotic recovery from mass extinction events* (ed. Hart, M. B.), *Geological Society, London, Special Publication* **102**, 343–371.
- Stinnesbeck, W., Keller, G., Adatte, T., Lopez-Oliva, J. G., & MacLeod, N. 1996. Cretaceous-Tertiary boundary clastic deposits in northeastern Mexico: impact Tsunami or sea-level lowstand? In *Cretaceous-Tertiary boundary mass extinction: biotic and environmental changes* (eds MacLeod, N. & Keller, G.), pp. 471–518 (W.W. Norton & Co., New York).
- Stott, L. D. & Kennett, J. P. 1990. The paleoceanographic and climatic signature of the Cretaceous/Paleogene boundary in the Antarctic: stable isotopic results from ODP Leg 113. *Proceedings of the Ocean Drilling Program, Scientific Results* (eds Barker, P. F. & Kennett, J. P., *et al.*) **113**, 829–848.
- Thomas, E. 1990. Late Cretaceous through Neogene deep sea benthic foraminifera (Maude Rise, Weddell Sea, Antarctica). *Proceedings of the Ocean Drilling Program, Scientific Results* **113**, 571–594.
- Tjalsma, L. & Lohmann, G. P. 1983. Paleocene-Eocene bathyal and abyssal benthic foraminifera from the Atlantic Ocean. *Micro-paleontology, Special Publication* **4**, 1–90.
- Van Morkhoven, F., Berggren, W. A. & Edwards, A. S. (eds) 1986. *Cenozoic cosmopolitan deep-water benthic foraminifera*, 421 pp. (Elf Aquitaine, Pau).
- Widmark, J. G. V. 1995. Multiple deep water sources and tropic regime in the latest Cretaceous deep sea: evidence from benthic foraminifera. *Marine Micropaleontology* **26**, 361–384.
- Widmark, J. G. V. & Malmgren, B. 1988. Differential dissolution of Upper Cretaceous deep-sea benthonic foraminifera from the Angola Basin, South Atlantic Ocean. *Marine Micropaleontology* **13**, 47–78.