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Late Cretaceous sea-level changes in Tunisia: a multi-disciplinary approach

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Abstract: A multi-disciplinary study of sea-level and climate proxies, including bulk rock and clay mineral compositions, carbon isotopes, total organic carbon (TOC), Sr/Ca ratios, and macro- and microfaunal associations, reveals seven major sea-level regressions in the southwestern Tethys during the last 10 million years of the Cretaceous: late Campanian (*c.* 74.2 Ma, 73.4–72.5 Ma and 72.2–71.7 Ma), early Maastrichtian (70.7–70.3 Ma, 69.6–69.3 Ma, and 68.9–68.3 Ma), and late Maastrichtian (65.45–65.3 Ma). Low sea levels are generally associated with increased terrigenous influx, low kaolinite/chlorite+mica ratios, high TOC and high Sr/Ca ratios, whereas high sea levels are generally associated with the reverse conditions. These sea-level changes may be interpreted as eustatic as suggested by the global recognition of at least four of the seven major regressions identified (74.2 Ma, 70.7–70.3 Ma, 68.9–68.3 Ma and 65.45–65.3 Ma). Climatic changes inferred from clay mineral contents correlate with sea-level changes: warm or humid climates accompany high sea levels and cooler or arid climates generally accompany low sea levels.

Keywords: Late Cretaceous, Tunisia, regression, geochemistry, mineralogy.

The most commonly used eustatic sea-level curves are based on seismic stratigraphy pioneered by a group of Exxon geologists and others (e.g. Vail *et al.* 1977; Haq *et al.* 1987; Donovan *et al.* 1988; Van Wagoner *et al.* 1990). Although these sea-level curves are widely used, it is generally recognized that their resolution is relatively low (e.g. based on lithological changes, hardgrounds, etc.) and the effects of regional tectonic activity may be underestimated (e.g. Christie-Blick *et al.* 1990; Pitman & Golovchenko 1991; Hallam 1992). In this report we consider relatively short-term sea-level fluctuations, on the order of 10^4 to 10^6 years for the late Campanian and Maastrichtian, that can be readily recognized in continental shelf and upper slope areas of southwestern Tethys. Such short-term eustatic sea-level fluctuations are generally expressions of global cooling and possibly polar ice growth, whereas long-term sea-level fluctuations are generally related to plate tectonic movements and particularly mid-ocean ridge spreading rates (e.g. Pitman & Golovchenko 1983; Miller *et al.* 1991).

Sea-level fluctuations are recognized based on a variety of sedimentological, geochemical, clay mineralogical and trace element proxies, as well as various macro- and microfaunal palaeodepth indecies; though most studies concentrate on one or the other. In this study, we use a multi-disciplinary approach to integrate these proxies. This approach has several advantages over single discipline studies, though the most important is that each proxy uses independent methods to identify sea-level change, which serves as cross-check for the various data sets.

The main objective is to test a multi-disciplinary approach to sea-level fluctuations that integrates proxies based on bulk rock, clay mineralogical, geochemical (total organic carbon (TOC) and $\delta^{13}C$) and trace element (Sr/Ca) analyses and compares these with macro- and microfaunal palaeodepth indecies (Li *et al.*, 1999). These proxies are applied to the late Campanian and Maastrichtian sequences at El Kef and Elles, Tunisia, and provide a high resolution record of climate and sea-level change. Specifically, we measured (1) bulk rock and clay mineral compositions to evaluate variations in terrigenous influx and climatic changes; (2) total organic carbon content to evaluate variations in carbon preservation; (3) $\delta^{13}C$ values in monospecific benthic and planktic foraminifera to evaluate variations in productivity; and (4) Sr/Ca ratios in monospecific planktic foraminifera to evaluate variations in seawater chemistry related to sea-level fluctuations.

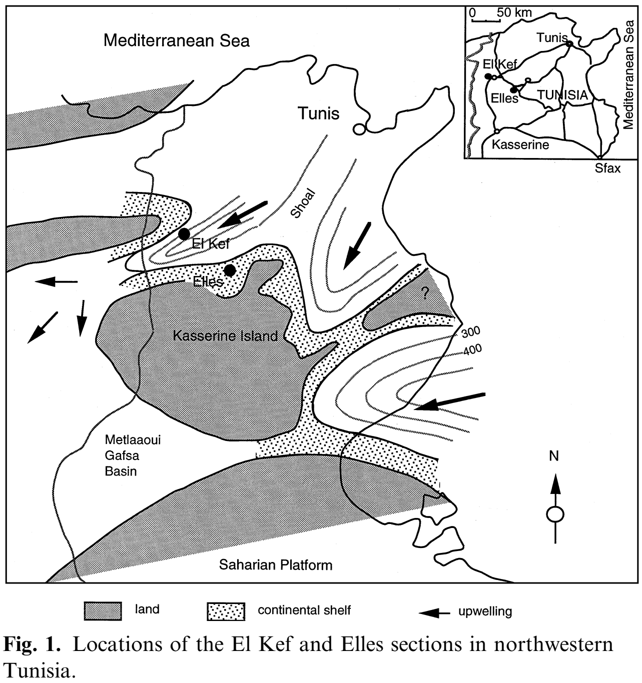

Fig. 1. Locations of the El Kef and Elles sections in northwestern Tunisia.

Material and methods

Sections and sampling

Two sedimentary successions spanning the late Campanian and Maastrichtian were sampled at El Kef and Elles, Tunisia, located 7 km and 75 km respectively from the city of El Kef (Fig. 1). At the El Kef

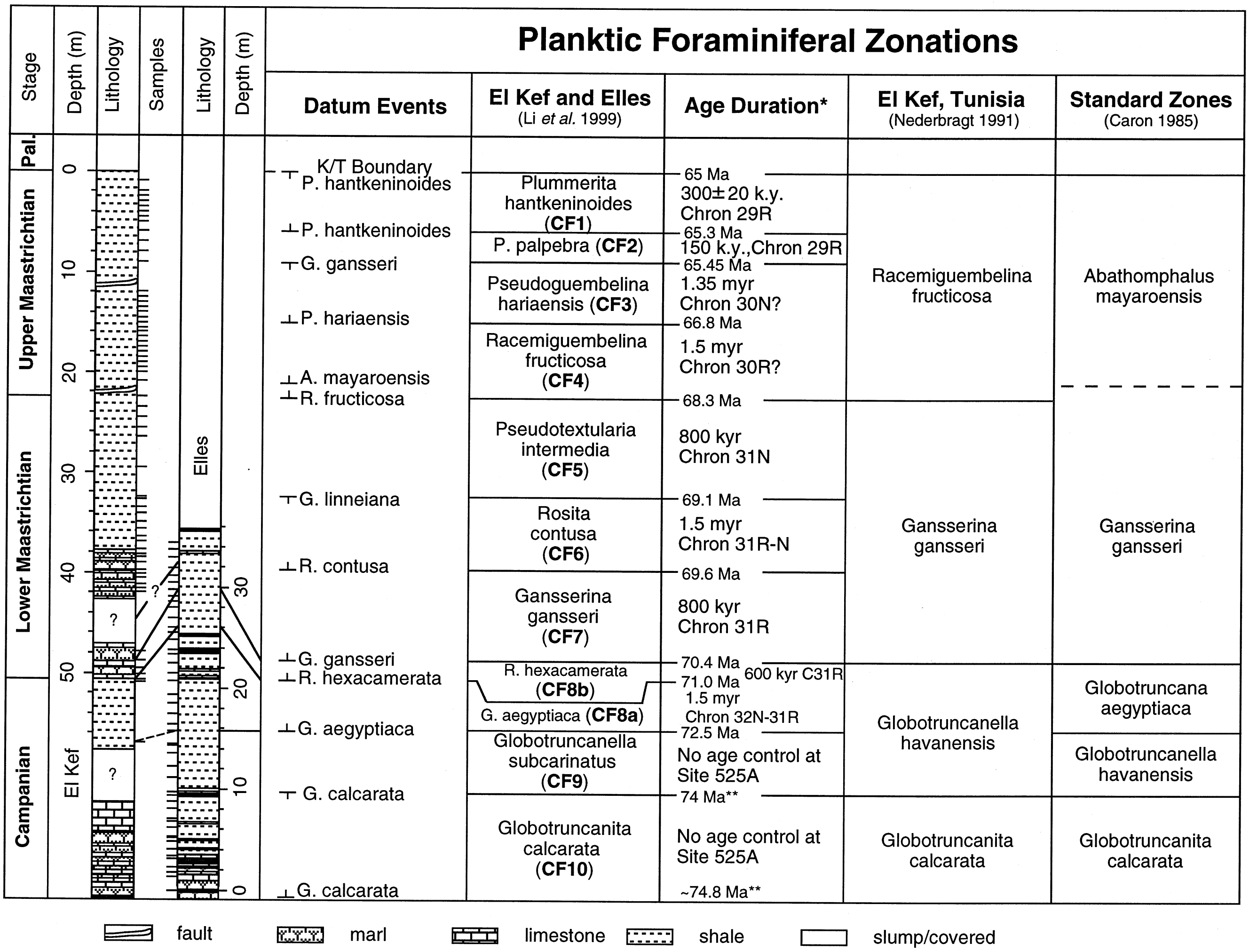

Fig. 2. Commonly used Late Cretaceous planktic foraminiferal zonations in low latitudes along with higher resolution biozonation for Tunisian sections which divides the late Maastrichtian into eight foraminiferal zones (CF1–CF8b). Note that characteristics of each biozone are summarized, including zonal index species, thickness of zone in m, presence of faults and age duration of each zone estimated based on graphic correlation of the Tunisian sections with DSDP Site 525 and its palaeomagnetic record. * Age duration and absolute age estimates are based on graphic correlation with DSDP Site 525 which has a good palaeomagnetic record and the revised time scale of Cande & Kent (1995).
** Estimated ages for the first appearance of *G. calcarata* from Bralower *et al.* (1995).

section, the Maastrichtian is about 50 m thick and 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 interval of unknown thickness is missing. The lower part of the Maastrichtian consists of marls interlayered with nine limestone beds (Figs 2, 3). A slump covers about 5 m of the section between limestone beds 3 and 4 (42.4–47.5 m). A total of 47 samples was collected for the El Kef Maastrichtian through the limestone beds with samples spaced at 20 cm, except in intervals with poor exposure. Below the limestone beds are Campanian grey shales, which are covered by vegetation and could not be sampled, and a thick sequence of limestones.

The discontinuous outcrop exposure for the Campanian–Maastrichtian transition at El Kef necessitated collecting this interval in a valley near the hamlet of Elles located about 75 km southeast of El Kef (Fig. 1). At this location the sedimentary sequence is similar to El Kef but continuously exposed. The upper Campanian interval consists of thick limestone beds interlayered with marls, followed by thick beds of marls interlayered with limestones. Forty-eight samples were collected at sample intervals of 30–50 cm for the upper Campanian and 50–100 cm for the lower Maastrichtian (Figs 2, 3).

Analyses

Stable isotopic analyses were conducted on monospecific planktic (*Rugoglobigerina rugosa*) and benthic (*Anomalinoides acuta*) foraminifera. About 15–20 tests of *A. acuta* were picked from each sample in the 150–250 μm size fraction, and 20–30 tests of *R. rugosa* in the 150–200 μm size fraction. All isotopic data were measured at Princeton University using a VG Optima gas source mass spectrometer equipped with a common acid bath. Isotopic results were calibrated to the PDB standard with errors of 0.04‰ for $\delta^{18}O$ and 0.02‰ for $\delta^{13}C$.

Sr/Ca ratios were measured on sonically cleaned planktic foraminifer *Rugoglobigerina* spp. for the El Kef samples and *Heterohelix globulosa* for the Elles samples (*Rugoglobigerina* spp. is rare at Elles). For Sr/Ca analysis, about 10 tests of *Rugoglobigerina* spp. and 20 tests of *Heterohelix globulosa* were picked and dissolved in hydrochloric acid (HCl). Sr and Ca measurements were conducted by atomic absorption on an Inductively Coupled Argon Plasma Spectrometer (ICP) at Princeton University.

Whole rock, clay mineral and organic carbon analyses were conducted at the Geological Institute of the University of Neuchatel,

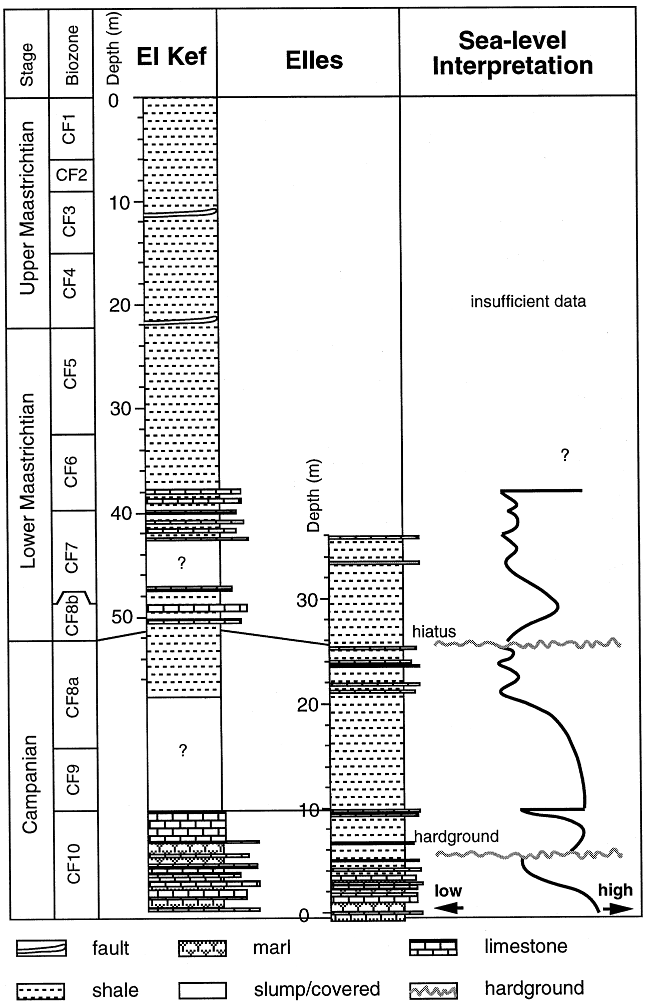

Fig. 3. Field-based observations of lithological variations and their inferred sea-level changes at El Kef and Elles, Tunisia.

Switzerland. Sample processing for whole rock and clay mineral analyses followed the procedure outlined by Kübler (1987) and discussed in Adatte *et al.* (1996). Organic carbon analysis was done using a CHN Carlo-Erba Elemental Analyzer NA 1108. Total carbon was first measured on bulk samples (0.01–0.02 g). TOC was determined after removing carbonate by acidification with hydrochloric acid (10%), assuming that dissolved organic matter in ancient sediments is nearly absent. The obtained values were compared with a standard reference sample. Analytical precision for a standard is ± 0.003% and reproductibility for the Maastrichtian samples is 0.01% for bulk rocks (total carbon) and 0.02% for insoluble residues. Total organic content (TOC) analysis was also performed with a Rock Eval 6 pyrolyser on seven selected bulk samples characterized by high TOC contents. The hydrogen index (HI, mg HC/g TOC) and oxygen index (OI, mg CO_2/g TOC) values were calculated based on TOC data and the maximum pyrolyses temperature (T_{max}) and used to characterize the type of organic matter (kerogen I, II and III) based on the analytical methods of Espitalie *et al.* (1986 and references therein) and Lafargue *et al.* (1996). Organic matter Type I is mainly derived from lacustrine algal lipids. Type II is usually related to marine organic matter, whereas Type III is mostly derived from terrestrial plants.

Biostratigraphy

The biostratigraphy and correlation of the Elles and El Kef sections is based on planktic foraminifera as discussed in Li & Keller (1998*a*, fig. 2). Numeric ages for zone boundaries are estimated based on the geomagnetic time scale of Site 525 (time scale of Cande & Kent 1995) and extrapolation to the Tunisia sections based on correlation of planktic foraminiferal datum events (Li & Keller 1998*a*, *b*). Assigning numerical ages to biostratigraphical datum levels worldwide is a questionable practice because first and last appearances of species are often diachronous across latitudes. We have adopted this convention in this study because preliminary analysis suggests that the amounts of diachroneity exhibited by the dated datum levels appears to be small (Li & Keller 1998*a*).

Campanian–Maastrichtian boundary

The Campanian–Maastrichtian boundary has not been formally defined, although Gradstein *et al.* (1995) proposed the top of the *Baculites jenseni* ammonite Zone, or overlying *B. eliasi* Zone, with an estimated age of 71.6 ± 0.7 Ma (base of C32N.1n) for the Campanian–Maastrichtian Stage boundary. In our zonal scheme and based on the palaeomagnetic record of Site 525, this interval corresponds to within the upper *G. aegyptiaca* Zone, near the first appearance of the planktic foraminifer *Rugoglobigerina hexacamerata* (base of Subzone CF8b, Fig. 2) estimated at 71 Ma. In this study we tentatively adopt the *R. hexacamerata* datum level to approximate the Campanian–Maastrichtian boundary.

Early–Late Maastrichtian boundary

Odin (1996) proposed that the Maastrichtian stage be formally divided into two substages (early and late), though there is no agreement on the boundary criteria. Planktic foraminiferal workers have generally placed this boundary at the first appearance of *Gansserina gansseri* (Caron 1985; Li & Keller 1998*a*, *b*), *Abathomphalus mayaroensis* and/or *Racemiguembelina fructicosa* (Nederbragt 1991). In this study we follow the practice of placing this boundary at the first appearance of *R. fructicosa* because *A. mayaroensis* is very rare and the first and last appearances are diachronous (Huber 1992; Pardo *et al.* 1996, fig. 2).

Lithology micro- and macro-faunas

Lithological variations are generally indicative of environmental changes with faunas and floras within the sedimentary rocks providing more specific information on the nature and tempo of these changes. Here we briefly summarize the lithological, micro- and macro-faunal characteristics of the Elles and El Kef sections and interpret these in terms of sea level fluctuations (Fig. 3; Li *et al.* 1999).

In the upper Campanian interval (0–5 m) at Elles, sedimentary rocks consist of alternating 20–60 cm thick beds of white marls and white marly limestones rich in macrofossils. Inoceramids are common as well as irregular echinoids (*Stegaster altus* and *S. chalmesi*) and ammonites (*Diplomoceras*) are very rare. Trace fossils of large *Cancellophycos* (up to 1 m) are abundant. The surface of the limestone layer at 5 m marks an unconformity and hardground as suggested by the undulating erosional contact and abundant inoceramids, echinoids, wood fragments, *Ophiomorpha* with large (*c.* 3 cm in diameter) horizontal branching tubes, *Rhizocorallium* and unspecified small vertical tubes filled with dark marl from the overlying sediment. The hardground undulating surface and presence of these fossils suggest that the sea floor was consolidated prior to deposition of the overlying sediment and hence indicates a period of erosion and/or non-deposition during a sea level lowstand as also suggested by the decreased abundance of deeper-dwelling benthic foraminiferal species (Li *et al.* 1999, Fig. 3).

The hardground surface marks a lithologic change from white marly limestone to grey marly shale which contains several thin (10–20 cm) resistant beds of marly limestone (about 10 m of marly shale at El Kef are covered by vegetation). Macrofossils and trace fossils are rare in the marly shales, but common in the limestone beds. In addition, there is a decrease in outer neritic to upper slope benthic foraminifera in the marly limestone beds which suggests that the fossil-rich limestone layers mark lower sea levels. The abundance of macrofossils in these limestones suggests that deposition occurred within the photic zone (outer neritic) which favored benthic macrofossils. In contrast, the marly shale layers seem to be poor in macrofossils largely because they were deposited at depth below the photic zone (upper bathyal depth) as indicated by benthic foraminifera (Li *et al.* 1999). A hiatus is present at Elles (base CF8b, Fig. 3) marked by truncated *Ophiomorpha* burrows at the top of the limestone. Another period of low sea levels is marked by a further decrease in deeper dwelling benthic foraminifera at several resistant marly limestone layers in the lower Maastrichtian (CF7/CF6) which contain a similar macrofauna including the last inoceramids and ammonites (Fig. 3). In the Maastrichtian grey shales, macrofossils are rare though the disappearance of many deeper dwelling benthic foraminifera (e.g. *Allomorphina halli, A. cretacea, Stensioina beccariiformis, Praebuliminella lajollaensis, Gyroidina nonionoides, G. nitidus, Cibicidoides praecursoria, Nonionella cretacea, Globorotalites tappanae,* and *Pullenia cretacea*) in zones CF5 and CF2 suggests lower sea levels (Li *et al.* 1999).

Bulk rock composition

Relative changes in bulk rock compositions indicate (1) variations in sediment sources that reflect the variable intensity of weathering and erosion under arid and humid climates (Chamley 1989; Weaver 1989), and (2) the variable influx of terrigenous sediments into the oceans during high and low sea levels. High detrital influx (phyllosilicates and quartz) is generally associated with increased erosion and transport during a sea-level regression and seasonally cool climate. In contrast, high carbonate deposition is generally associated with humid warm climates and transgressive seas.

In marine sediments at El Kef and Elles, bulk rock compositions were analysed to evaluate sediment sources, proximity to terrigenous sediments and intensity of erosion and transport associated with sea-level changes (Fig. 4). In upper Campanian to lower Maastrichtian sedimentary rocks at Elles, four major changes in bulk rock compositions, marked by increased phyllosilicates and quartz and decreased calcite, suggest low sea-levels and increased erosion (stippled intervals, Fig. 4). The decrease in calcite is likely to be a function of increased dissolution, dilution by terrigenous input and changes in primary productivity. No significant dissolution is evident in planktic foraminifera (Li & Keller, 1998*b*) and the near absence of a surface-to-deep gradient in δ^{13}C values suggests that productivity changes may be a significant factor in the calcite variations.

The first significant bulk rock change occurred in alternating marl and limestone beds in the middle of Zone CF10, where phyllosilicates increased by 38% (*c.* 10% to 48%), quartz doubled (from 3% to 7%) and calcite briefly decreased by 40% (Fig. 4). The second and third bulk rock changes in zones CF9 and lower CF8a occurred in marls and are more pronounced with 47–50% increases in phyllosilicates, comparable decreases in calcite and doubling of quartz. A small amount of plagioclase and K-feldspar is present in CF9. The fourth bulk rock change in zones CF8b-CF7 is comparable in magnitude to that in CF10, though more expanded. Phyllosilicates increased from 20% to 50–60% in two distinct peaks at Elles, accompanied by decreased calcite and increased quartz. This double peak may indicate two distinct, but closely spaced depositional events as suggested by the stippling in Fig. 4. Neither of these bulk rock changes is related to lithological changes observed in the field hich suggests that lithological observations alone provide a relatively poor and incomplete record of environmental changes.

At the El Kef section, the lowermost Maastrichtian (zones CF8b–CF7) is poorly exposed and sampling resolution is insufficient to determine changes in bulk rock compositions. A distinct though relatively minor bulk rock change coincides with the last limestone bed at the CF7/CF6 transition and is marked by increased phyllosilicates (from 15% to 40%), increased quartz (from 2% to 4%) and a 20% decrease in calcite (Fig. 4). Two major changes in bulk rock compositions occur in zones CF5 and CF2, coincident with low sea levels inferred from the benthic foraminifera. Zone CF5 is marked by a sustained increase in phyllosilicates from 25% to 65%, concomitant decrease in calcite, nearly doubling of quartz (4% to 7%) and influx of K-feldspar. In Zone CF2 phyllosilicates increased by 40%, calcite decreased and there was an influx of plagioclase.

Benthic foraminifera indicate that during the Late Cretaceous, El Kef and Elles were located at upper slope to outer neritic depths (Li *et al.* 1999) and received variable amounts of detrital influx from nearby continental areas (Fig. 1). Elles was located close to the emergent areas of the Kasserine Island (Burollet 1956) as indicated by the generally higher influx of quartz. The variations in the observed detrital influx primarily indicate variable rates of weathering and erosion of terrestrial sediments associated with climate and sea-level fluctuations. High detrital abundance generally reflects increased erosion and transport during low sea-levels. The rare occurences of plagioclase and K-feldspar, which are diagenetically unstable and subject to intense hydrolysis, correlate mainly with low sea levels and suggest periods of rapid and active erosion. Thus, bulk rock compositions suggest seven major sea-level lowstands in the late Campanian and Maastrichtian (stippled pattern, Fig. 4) which correlate with low sea levels inferred from lithological observations (marl/limestone transitions), macrofossils (in limestones) and benthic foraminifera (in shales and marls).

Clay minerals

Clay mineral assemblages reflect continental proximity and tectonic activity as well as climate evolution and associated sea-level fluctuations (Chamley 1989; Weaver 1989). In relatively deep marine environments (e.g. middle and outer shelf to upper slope depths), such as at El Kef and Elles, clay mineral assemblages can provide reliable climate and/or sea-level

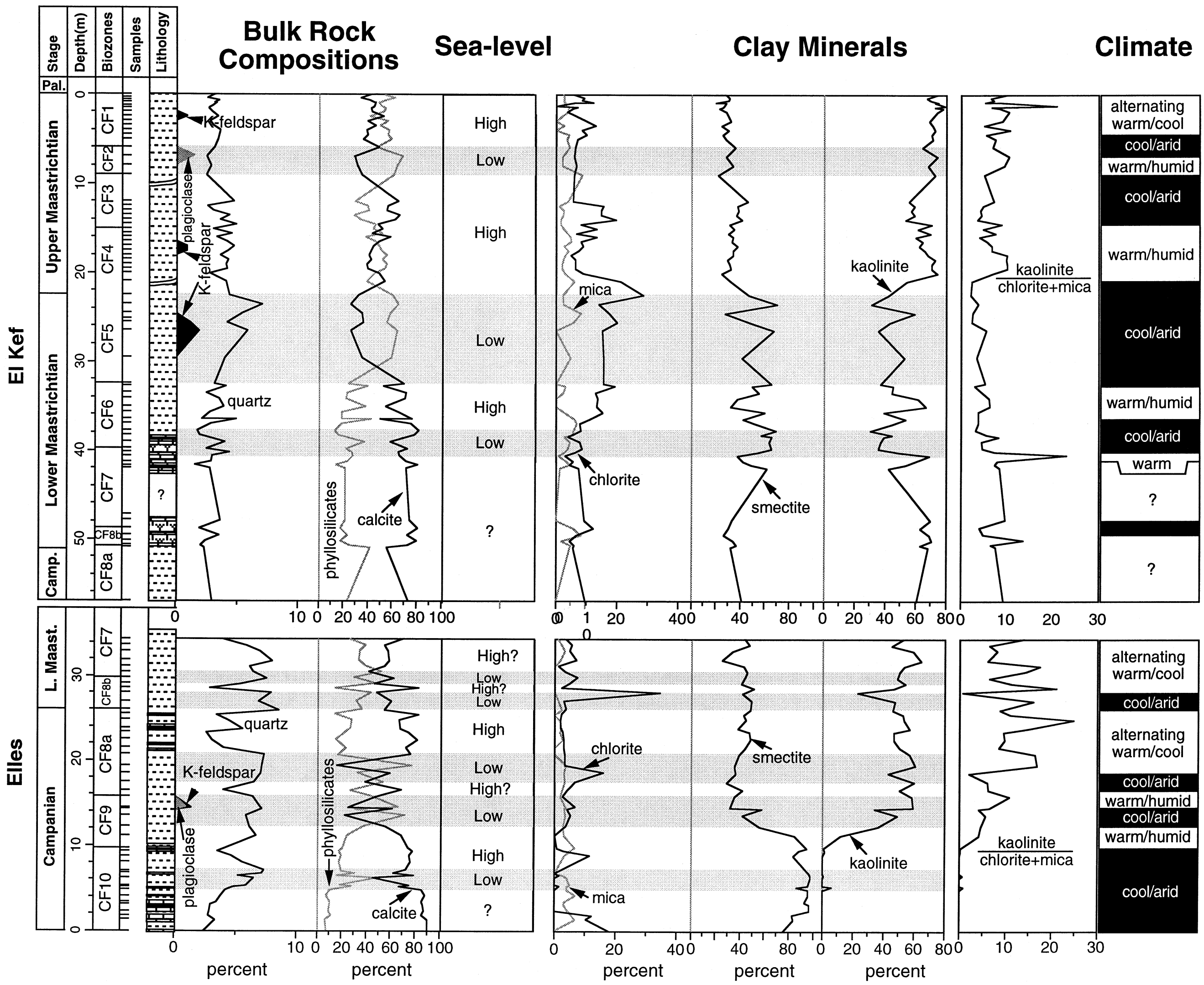

Fig. 4. Late Cretaceous bulk rock and clay mineral compositions at Elles and El Kef. Note that seven major peaks in phyllosilicates mark major sea-level lowstands, whereas cool/arid and warm/humid intervals are inferred from clay mineral compositions. Note the generally good correlation between low sea-levels and cool/arid climates, except in the latest Maastrichtian.

change information (Adatte & Rumley 1989; Chamley 1989; Monaco *et al.* 1982). For example, high abundance of kaolinite generally indicates warm, or humid climates, well-drained continental areas with high precipitation and accelerated leaching of parent rocks (Millot 1970; Weaver 1989). In contrast, high smectite content suggests warm climates with alternating humid and arid seasons and weathering of continental areas with restricted drainage, or weathering of volcanoclastic material (Paquet 1970). Increased chlorite and mica contents suggest cool or arid (desert) conditions with poorly developed soils and reduced chemical weathering, but active mechanical erosion (Millot 1970). High ratios of kaolinite to chlorite+mica in the Kasserine Island region indicate humid and/or warm climates, whereas low ratios indicate a change to a more seasonal climate with less precipitation.

The results of clay mineral analyses at El Kef and Elles allows the interpretation of both long-term and short-term climate trends in the southwestern Tethys (Fig. 4). A distinct long-term climatic trend is apparent in the increasing kaolinite and decreasing smectite abundances upsection. During the late Campanian (Zone CF10, 74.8–74 Ma), the dominance of smectite (>90%), high mica and chlorite and near absence of kaolinite suggest seasonally cool or arid climatic conditions. This interval was followed by alternating warm/humid and cool/arid (or seasonally cool with less precipitation) climates in zones CF9–CF7 (74–69.6 Ma) as indicated by the high abundance of kaolinite (*c.* 60%), low chlorite, mica and smectite. Relatively less humid conditions prevailed during the early Maastrichtian (zones CF6–CF5, 69.6–68.3 Ma) as suggested by the lower kaolinite (*c.* 45%) and increased mica and chlorite (Fig. 4). The last 2 million years of the Maastrichtian appear to have been increasingly humid, though variable, with increased precipitation, as suggested by high kaolinite (*c.* 70%) and variable mica and chlorite abundances.

Within these long-term climatic trends, variations in kaolinite, mica and chlorite suggest alternating arid and humid climates. One way to evaluate these short-term variations is by the ratio of kaolinite (warm and/or humid) to chlorite+mica (less humid/ cooler, Fig. 4, last column). Based on this ratio, as well as individual clay mineral abundances, a series of intervals with distinct climatic changes can be identified. For example, the arid or seasonally cool late Campanian (Zone CF10, marked by low or absent kaolinite/chlorite+mica ratios) changed to an alternating warm/cool latest Campanian to earliest Maastrichtian as suggested by the frequent high amplitude variation in the clay mineral ratios (Fig. 4). Judging from these high clay mineral ratios, the latest Campanian was warmer on average than the Maastrichtian. The early Maastrichtian was generally cooler though humid with less frequent temperature oscillations. Seasonally cool temperatures with less precipitation occurred in the lower part of CF6 (*c*. 69.3–69.6 Ma), CF5 (*c*. 67–68 Ma), CF3 (65.45–66.8 Ma), and CF2 (65.3–65.45 Ma, Fig. 4). The intervening warm and/or humid climates are generally of shorter duration than in the late Campanian (e.g. parts of zones CF7, CF6, CF4 and CF1). The last 300–400 ka of the Maastrichtian are marked by very high kaolinite but variable mica and chlorite and suggest alternating warm/humid and less humid conditions. Generally high, but fluctuating kaolinite/chlorite+mica ratios during the last 100 ka of the Maastrichtian, suggest alternating warm/humid and seasonally cool climates (Fig. 4). The kaolinite distribution indicates that the overall climate in Tunisia was generally more humid during the late Maastrichtian with peak warming in zone CF1.

The correlation between sea-level fluctuations inferred from bulk rock compositions (stippled intervals) and climate changes inferred from clay mineral contents (black/white intervals, Fig. 4) is generally good. Less humid climates coincide with low sea levels and warm/humid climates with high sea levels. An exception is the low sea level inferred in CF2 which correlates with warm/humid conditions inferred from clay minerals. Without further information it is not possible to determine whether local tectonic or local climatic conditions account for this discrepancy. Correlation with sea-level interpretations based on lithology and benthic fossils is also good (Fig. 3). Low sea-level periods correlate generally with seasonally cool climates as inferred from clay mineralogy, though additional climatic variations are evident in shale deposition (e.g. CF4–CF3 transition).

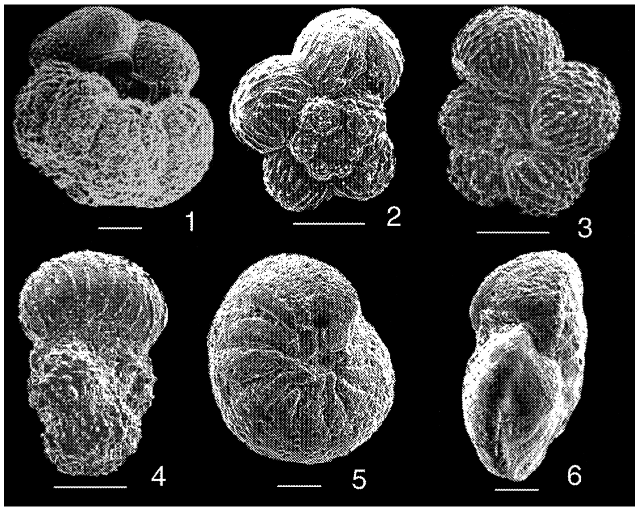

Fig. 5. SEM illustrations of foraminiferal species used for stable isotope analyses and Sr/Ca ratios at El Kef. In all samples scale bar is 100 µm. 1, *Rugoglobigerina rotundata* (Sample 20–25 cm below the K–T boundary). 2–4, *Rugoglobigerina rugosa* (sample 10–15 cm below the K–T boundary). 5–6, *Anomalinoides acuta* (sample 6 m below the K–T boundary).

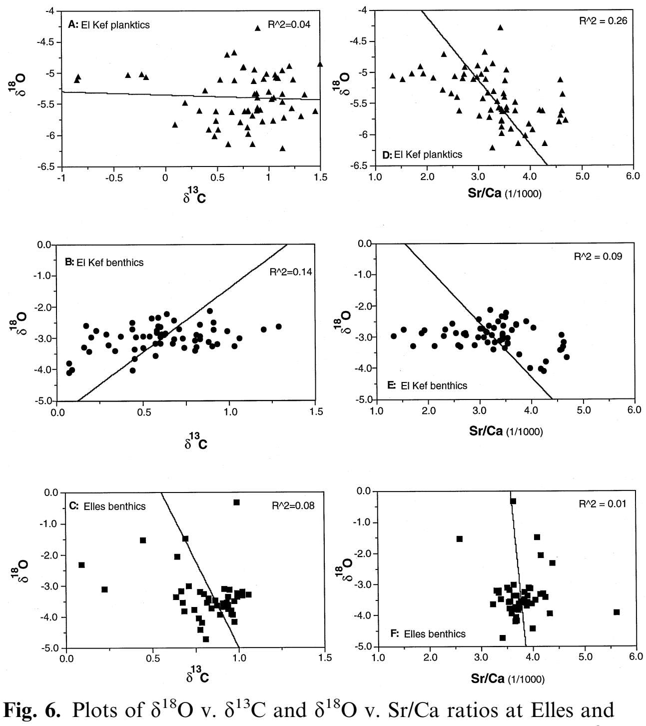

Fig. 6. Plots of $\delta^{18}O$ v. $\delta^{13}C$ and $\delta^{18}O$ v. Sr/Ca ratios at Elles and El Kef. Note that the correlation between these data is weak (R^2 values between 0.01 and 0.26) and that the cluster of $\delta^{18}O$ and Sr/Ca values at Elles suggests a high degree of diagenetic alteration in the Elles samples. However, high Sr/Ca ratios correlate with more negative $\delta^{18}O$ values at El Kef and suggest that diagenetic alteration alone can not explain the more negative $\delta^{18}O$ values in the El Kef samples. It is likely that diagenetic alteration due to meteoric waters and salinity effects account for the unusually negative $\delta^{18}O$ values.

Carbon isotopes

Oxygen isotope records of well-preserved monospecific foraminifera, or fine fraction sediment, are currently the most accurate and useful records of climate change. This record, however, is diagenetically altered in most continental shelf sections and only high frequency temperature trends are generally preserved (Schrag *et al.* 1995 and references therein). Although foraminifera in the Tunisian sections are well preserved, as evident in SEM photos (Fig. 5), diagenesis seems to have altered the original signals. This is also evident in the plots of $\delta^{18}O$ v. $\delta^{13}C$, which show a weak correlation ($R^2=0.04$ for planktic foraminifera, $R^2=0.14$ for benthic foraminifera) and cluster around a very narrow range reflecting a higher degree of recrystallization for Elles as compared with El Kef (Fig. 6A–C). Because of the uncertain effects of diagenesis on $\delta^{18}O$ values, we only use $\delta^{13}C$ records for this study.

Variations in carbon isotopes of seawater can be used indirectly to infer sea-level changes, because the composition of $\delta^{13}C$ in seawater is generally controlled by surface productivity and organic influx from land (e.g. Kroopnick 1985; Broecker & Maier-Reimer 1992). Since the $\delta^{13}C$ in terrestrial organic matter is significantly lighter (−25‰) than in organic matter generated by marine surface productivity (2–5‰, Zachos *et al.* 1994), a major influx of terrestrial organic matter will cause a major negative shift in seawater $\delta^{13}C$ values of both surface and deep waters. Such terrestrial organic influxes commonly occurred at times of increased precipitation and

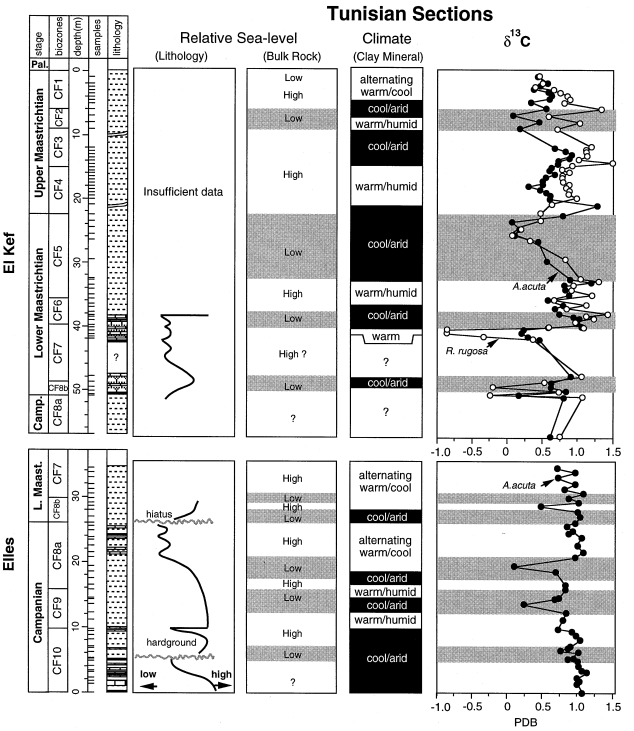

Fig. 7. δ^{13}C records from the continental shelf sections at Elles and El Kef and inferred sea-level and climate fluctuations based on lithology, bulk rock and clay minerals. Note that the Tunisian sections has a primarily regional δ^{13}C record with periods of high terrestrial organic influx of lighter carbon (negative δ^{13}C excursions) due to high precipitation, weathering and erosion during sea-level lowstands.

erosion as seen in Fig. 7. Unlike δ^{18}O, δ^{13}C values are little affected by recrystallization processes because pore waters have low concentrations of carbon (Magaritz 1975; Brand & Veizer 1980; Scholle & Arthur 1980). However, there are also secular variations in seawater carbon isotopes that could be contributing to the δ^{13}C record, particularly in neritic environments such as the Tunisian sections.

Comparison of the deep-sea record with that of the Tunisian sections generally suggests the presence of regional signals. During the late Campanian the deep-sea δ^{13}C record shows relatively low values between 0.5‰ and 1.0‰, as also observed at Elles, and minimum values at the Campanian/Maastrichtian transition (not observed at Elles, though possibly present at El Kef) coincident with maximum global cooling (Barrera *et al.* 1997; Li & Keller 1998*b*). However, deep-sea signals and Tunisian neritic signals diverged during the Maastrichtian. In the deep sea, δ^{13}C values increased by 1.5–2‰ in bottom and surface waters in the early Maastrichtian (CF8b–CF6) and remained relatively high through the late Maastrichtian (Fig. 7). But in the Tunisian sections there was high variability in surface and deep waters during the Maastrichtian and δ^{13}C values are 2–3‰ more negative relative to the open ocean (see also D'Hondt & Lindinger 1994; Barrera 1994). This suggests a primarily regional record with the latter reflecting a relatively constant terrestrial organic influx of lighter carbon.

Although the δ^{13}C signals in the Tunisian sections primarily reflects local conditions, there appears to be a good correlation between negative excursions and generally cool climates or the transition from warm to cool/arid or seasonal climates (Fig. 7). For example, at El Kef four major negative shifts occurred

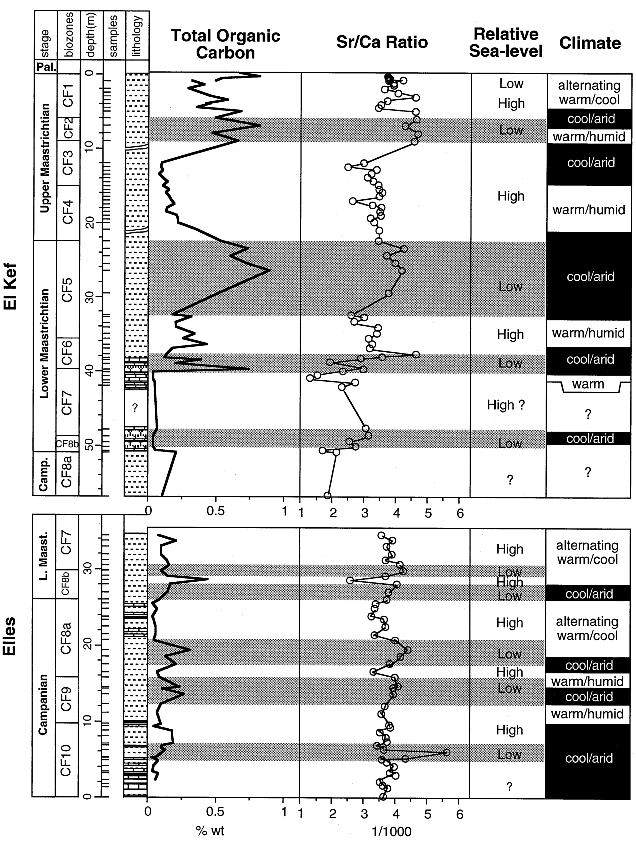

Fig. 8. Late Cretaceous total organic carbon (TOC) and Sr/Ca ratios at Elles and El Kef. Note that high TOC and high Sr/Ca ratios correlate with low sea levels and low TOC, whereas low Sr/Ca values correlate with high sea levels.

during the Maastrichtian in both benthic and planktic foraminifera. The first two negative shifts at the CF8b–CF7 and CF7–CF6 boundaries are associated with warm, humid climates immediately preceding low sea levels and erosion (Fig. 7). The upper two δ^{13}C shifts (zones CF5 and CF2) coincided with low sea levels and cool or alternating cool/warm climates. This suggests that the negative δ^{13}C excursions reflect increased terrestrial organic matter influx due to high precipitation and weathering and possibly erosion, as also suggested by high TOC values (Fig. 8). The absence of a vertical δ^{13}C gradient (coincident with high TOC values, Fig. 8) suggests either increased riverine runoff or increased upwelling, and hence high nutrient influx and increased surface productivity. There is thus good agreement between low sea levels, cool/arid climates and negative, albeit local δ^{13}C excursions.

Organic carbon

Carbon occurs in marine sediments as organic carbon linked with metabolic processes of plants and animals, and as carbon contained within biogenic and abiogenic carbonate minerals (Parsons & Takahashi 1973). Total organic carbon (TOC) in marine sediments is a geochemical proxy for primary productivity and carbon burial linked to erosion and sea-level fluctuations. During low sea levels, TOC values are generally high either as a result of enhanced primary productivity, or high terrestrial organic matter influx.

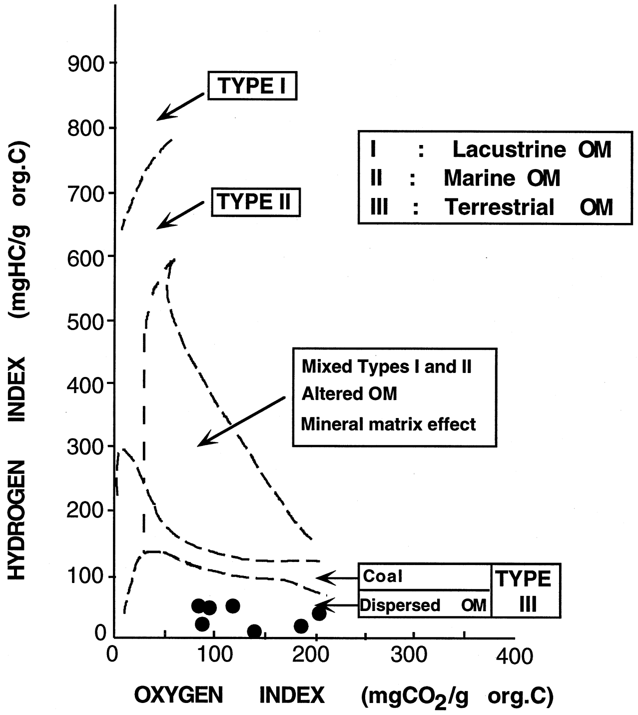

Fig. 9. General HI–OI diagram used for the classification of organic matter type I, II and III. Note that all the high TOC samples analyzed from Tunisian sections are located in the area corresponding to terrestrial OM (Espitalie *et al.* 1977).

TOC values in sediments at Elles and El Kef reflect this relationship. Though TOC values are relatively low (0.01–0.1 wt%), there is a strong signal with peak values generally coinciding with low sea levels inferred from bulk rock compositions (Fig. 8, stippled intervals). In contrast, high sea levels generally correspond to low TOC values. The high TOC values in CF10 and CF8a are associated with a hardground and erosion (Fig. 3). A contrary example is the high TOC values observed between the two sea-level lows in Zone CF8b at Elles which are associated with a warm climate (inferred from clay minerals) and high sea level (bulk rocks). However, in general there is a close association of peak TOC values with low sea levels, lithological changes, hardgrounds, hiatuses, erosion and cool climates. This suggests that the high TOC values are primarily due to enhanced terrestrial organic influx and secondarily to increased surface productivity.

Rock eval pyrolysis permits evaluation of this observation (Fig. 9). Kerogen (organic matter) is characterized by two indices, the hydrogen index (HI) and the oxygen index (OI). These indices are independent of the organic matter (OM) abundance and strongly related to the elemental composition of kerogen (Tissot & Welte 1984; Espitalié *et al.* 1985, 1986; Lafargue *et al.* 1996). There is a good correlation between HI and elemental H/C and between OI and O/C ratio respectively (Fig. 9). The two indices can therefore be used in place of the classical Van Krevelen diagram to determine the nature of the kerogen (types I, II and III). Type I is mainly derived from lacustrine OM algal lipids; Type II is usually related to marine organic matter, whereas Type III is characterized by low HI and relatively high OI and refers to kerogen that is mostly derived from terrestrial plants. The maximum pyrolyses temperature (T_{max}) values indicate the maturation of the analysed sample (Espitalie *et al.* 1985).

In the seven samples analysed with high TOC contents for the Tunisian sections, T_{max} values are low (<437°C) and indicate that the sediments have not been deeply buried, as also suggested by the systematic presence of smectite. Stable isotopes and clay mineral data have therefore not been overprinted by burial diagenesis. The Hydrogen Index (HI, 10–71 HC/g TOC) and Oxygen Index (OI, 75–200 mg CO_2/g TOC) indicates a terrestrial origin (Type III) for the organic carbon (Fig. 9). This supports our observation that the high TOC values (Fig. 8) are due to enhanced terrestrial organic influx at times of low sea levels and increased erosion. There is also a good correlation between high TOC and high kaolinite content (Figs 4, 8). Long-term high terrestrial influx of OM corresponds to high amounts of kaolinite. This reflects increased precipitation and consequently increased runoff of OM derived from soils eroded during sea-level lowstands. Note that the overall TOC content is low (<1%) and not comparable to that from marine black shales (e.g. near the Cenomanian–Turonian boundary); it represents normal OM influx into the ocean which increased slightly during low sea levels.

Foraminiferal Sr/Ca ratio

Strontium concentration in marine sediments is rarely used as a proxy for sea-level fluctuations, though this method holds strong promise, especially for the Cretaceous (Graham *et al.* 1982; Renard 1986; Stoll & Schrag 1996). During the Cretaceous, continental shelves were the major sources and sinks for Sr accumulation with up to 90% of marine carbonates deposited there, as compared with only 20% in the modern ocean (Schlanger 1988; Opdyke & Wilkinson 1988). Moreover, because of this huge Sr sink on shelves, the residence time of Sr in seawater was greatly reduced (about four times shorter than in the modern ocean) which amplified the ocean's response to changes in flux (Opdyke & Wilkinson 1988).

Strontium concentrations in seawater reflect the diagenesis of Sr-rich aragonite to calcite on continental shelves (Schlanger 1988). During low sea levels, Sr-rich aragonite on shelves is exposed to weathering and releases up to 90% of its Sr to the oceans in less than 100 ka producing a rapid increase in the Sr concentration of seawater (Gavish & Friedman 1969). Thus, short-term changes in sea level, over less than 1 Ma, are accompanied by rapid changes in Sr concentrations. These short-term Sr fluctuations differ from hydrothermal Sr flux by their short duration (<1 Ma) as compared to several million years for the latter. Because the residence time of Sr in seawater is very long (*c.* 1 Ma) relative to ocean mixing time (*c.* 1 ka), the Sr concentration is uniform through the water column and provides a useful tool to infer global changes in sea level (Bernat *et al.* 1972; Brass & Turekian 1974). Therefore, short-term variations in Sr/Ca ratios of calcareous microfossils or deep sea carbonate oozes may provide a good proxy for global sea-level changes.

Sr is removed from seawater by pelagic marine organisms which incorporate Sr in their $CaCO_3$ shells in equilibrium with its concentration in seawater. Upon death, the shells are preserved in continental and deep-sea carbonates. Measurement of Sr concentrations in well-preserved planktic foraminiferal shells thus yields a relatively accurate record of Sr fluctuations in seawater. However, diagenetic alteration of the original Sr in calcite shells is a potential problem. Recrystallization of foraminiferal calcite decreases the Sr concentration because Sr^{2+} is preferentially removed from calcite into pore waters due to the similar chemistry of Sr and Ca (Baker *et al.* 1982). In addition, differential diagenesis may have occurred in sediments where the clay content is highly variable (higher clay content leads to better preservation and higher Sr/Ca ratios). In the Maastrichtian carbonates of El Kef and Elles, foraminiferal shells are partly or wholly recrystallized. However, cross-plots of Sr/Ca v. $\delta^{18}O$ shows insignificant correlations (R^2 values of 0.26, 0.09 and 0.01) for El Kef and Elles (Fig. 6d–f), which suggests that differential release of Sr due to diagenesis was not the primary source of Sr/Ca variability in clay-rich shales, though it may have been significant in the clay-poor limestones. Recently, Stoll & Schrag (1996) analyzed Sr concentrations in diagenetically altered carbonates of three deep-sea sections and concluded that the reproducibility of the Sr variability is evidence against a diagenetic origin.

Shallow continental shelf areas provide the major sources and sinks for strontium during sea-level transgressive-regressive cycles (Schlanger 1988). During low sea levels, the Sr/Ca ratios are higher as Sr-rich aragonite on shelves is exposed to weathering, whereas during high sea levels the Sr/Ca ratios are low as Sr is incorporated in aragonite sedimentation on shelves.

Results from the Tunisian sections indicate major Sr/Ca ratio increases (between 30% and 53%) during the Maastrichtian at 70.5–70.3 Ma (CF8b/CF7 boundary), 69.6–69.3 Ma (base of Zone CF6), 68.9–68.3 Ma (Zone CF5) and 65.45–65.3 Ma (Zone CF2, Fig. 8). All of the Sr/Ca maxima coincide with major sea level regressions identified from sedimentological, bulk rock, TOC and isotopic indicators. The intervening high sea levels correspond to relatively low Sr/Ca ratios. During the last 300 ka of the Maastrichtian (Zone CF1), Sr/Ca values are relatively high though fluctuating.

The Maastrichtian record at El Kef suggests an overall increasing trend in the Sr/Ca ratio upsection, though this is likely to be an artifact of differential diagenesis and sampling, rather than a long-term change in the Sr cycle. This is indicated by on average 1×10^{-3} lower values at El Kef than coeval Sr/Ca ratios at Elles (Fig. 8). The lower Sr/Ca ratios at El Kef are partly due to low sample resolution (covered shale interval between limestone beds and hence incomplete record), and the fact that sampling was restricted to limestones where diagenetic alteration is at a maximum. This is reflected by the very low Sr/Ca ratios in these limestone layers at El Kef where recrystallization of foraminiferal tests is high leading to lower Sr/Ca ratios, and the clay content is low also leading to lower Sr/Ca ratios.

At Elles, late Campanian to earliest Maastrichtian Sr/Ca variability is low, though systematic variations coincide with sea-level changes. Similar to El Kef, all major increases in Sr/Ca values (between 15% and 33%) coincide with sea-level regressions inferred from other proxies (stippled intervals) at 74.2 Ma (Zone CF10), 73.4–72.5 Ma (Zone CF9), 72.2–71.8 Ma (Zone CF8) and 70.7–70.3 Ma (Zone CF8/CF7 transition, Fig. 8). Our Sr/Ca records from the Tunisian shelf sections thus correlate with sea-level fluctuations interpreted from a variety of other proxies (e.g. bulk rock and clay minerals, $\delta^{13}C$ and TOC values). This suggests that Sr/Ca ratios are a useful proxy for sea-level change.

Discussion

Our primary objective in this study was to develop a high resolution record of sea-level fluctuations from the late Campanian through Maastrichtian in the southwestern Tethys ocean based on various independent sea-level proxies. Field observations (e.g. lithological changes, presence of macro- and microfossils, trace fossils and hardgrounds) were initially used to establish a first order sea-level history. The second sea-level proxy, based on terrigenous influx measured from bulk rock compositions, confirmed the sea-level changes inferred from field observations and benthic faunas, but also yielded a higher resolution record with seven episodes of major sea-level regressions identified (stippled intervals, Fig. 9). This record was tested against climatic variations inferred from clay mineral contents on the assumption that high sea levels should correlate with warm climates and low sea levels with cooler climates. Indeed, the correlation is very strong between all but one high–low sea-level cycle (Fig. 8). The anomaly is in the latest Maastrichtian (zones CF2–CF1) and seems to be related to the generally higher precipitation in the Tethys region that accompanied the global cooling and sea-level regression.

The inferred climate variations were then tested against the $\delta^{18}O$ temperature record, but failed due to diagenesis. There is a strong correlation between sea-level lows and high TOC weight percent in sedimentary rocks that reflect high terrestrial organic influx via erosion and/or increased productivity. The correlation between sea levels and $\delta^{13}C$ variations is also strong (Fig. 8), with major negative $\delta^{13}C$ shifts in both surface and bottom waters at El Kef coinciding with low sea levels or high/low inflection points. These negative $\delta^{13}C$ shifts appear to be largely driven by erosion and enhanced terrestrial organic influx. An equally strong correlation exists between high Sr/Ca ratios and low sea-levels, probably due to erosion of carbonate-rich shelves (Figs 6, 10). Thus, each of the five independent parameters (bulk rock composition, clay mineral content, $\delta^{13}C$, TOC and Sr/Ca ratio) is a useful and relatively reliable proxy for sea-level variations (Fig. 10).

Are the observed sea-level fluctuations in the southwestern Tethys due to eustatic variations or local tectonic controls? Although one might argue with the Exxon sea-level curve (see Christie-Blick *et al.* 1990; Hallam 1992), which identified three major eustatic sea-level regressions during the late Campanian, at the Campanian–Maastrichtian boundary and in the late Maastrichtian (Fig. 10), these three regressions correspond with low sea-levels at 68.8–68.3 Ma, 71–70.3 Ma and *c.* 74.2 Ma in the Tethys record, respectively. This suggests that these regressions are of eustatic origin. The latest Maastrichtian sea-level low at 65.45 Ma is also likely of eustatic origin as indicated by its presence in sedimentological sequences worldwide (Haq *et al.* 1988; Keller & Stinnesbeck 1996). We have no records from other regions to date of low sea-levels at 73.4–72.5 Ma, 72.2–71.8 Ma and 69.6–69.3 Ma to confirm their eustatic nature. However, since Sr variations in marine carbonates reflect global sea-level changes and all seven sea-level lows in the Tethys are reflected in the Sr/Ca record, they may all be of eustatic origin.

Are these sea-level changes caused by continental glaciation? $\delta^{18}O$ values from South Atlantic Sites 690C and 525 provide a detailed temperature record for the Maastrichtian (Barrera 1994; Barrera *et al.* 1997; Li & Keller 1998*b*). These records indicate a relatively cool late Campanian coincident with a low sea level at about 74.2 Ma (Fig. 10) and a cool/arid climate in the Tethys (Fig. 4). Brief warming during the latest Campanian resulted in maximum warm surface temperatures, for the late Campanian, coincident with a sea-level transgression (base CF8a, Fig. 10) and a warm/humid climate in the Tethys. Thereafter, a long-term trend in climate cooling began.

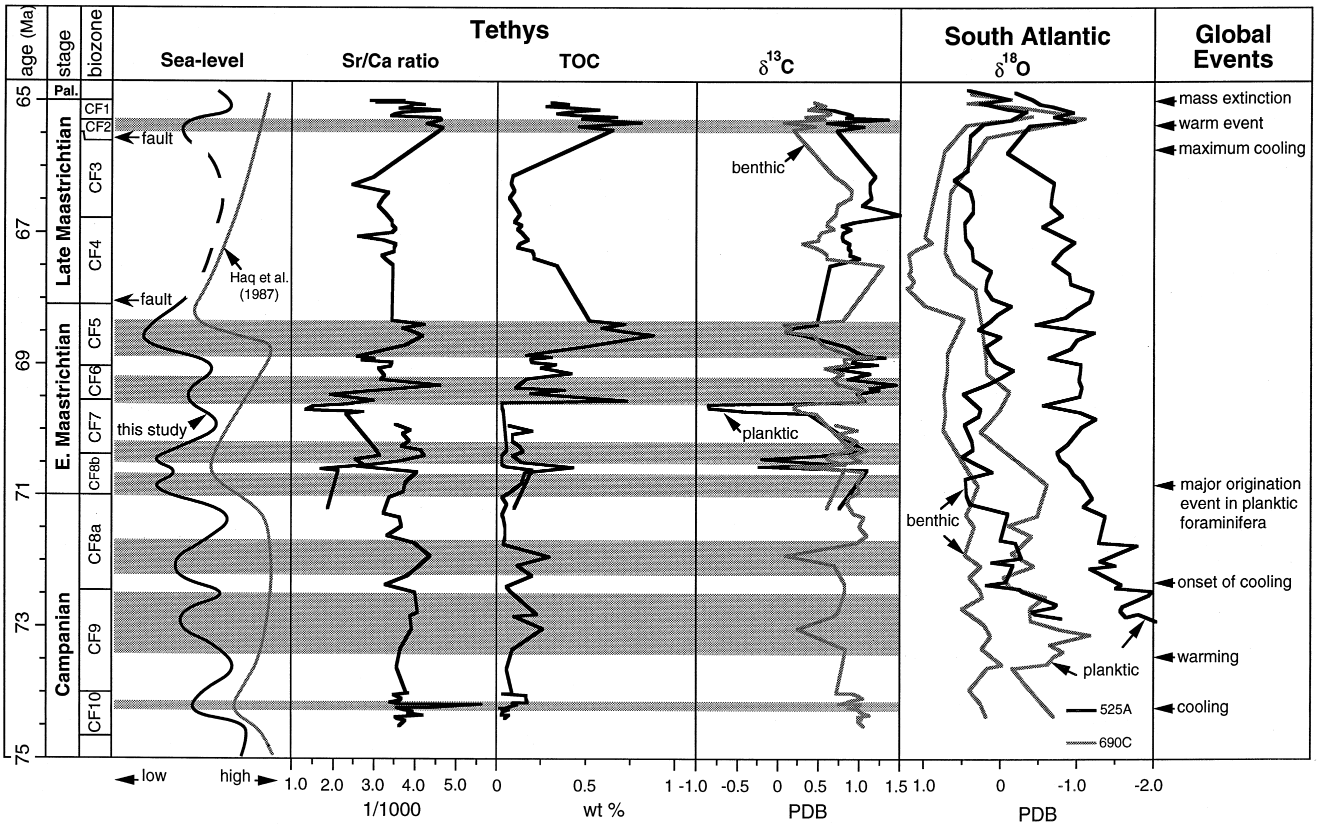

Fig. 10. Summary of Late Cretaceous sea-level fluctuations inferred from various proxies including Sr/Ca ratios, TOC and $\delta^{13}C$, benthic macrofaunas, lithologic markers and bulk rock compositions (stippled intervals), and their comparison with the sea-level curve of Haq *et al.* (1987) and the $\delta^{18}O$ records from South Atlantic Sites 525 and 690 (Barrera 1994; Li & Keller 1998*b*). Note that major sea-level regressions generally correlate with high Sr/Ca ratios, high TOC, high terrigenous influx and global cooling. In the Tunisian sections these variables generally coincide with negative excursions in $\delta^{13}C$ values except in the early late Maastrichtian where the $\delta^{13}C$ shifts precede sea-level lows and appear to be due to high precipitation and weathering as suggested by clay mineral data.

The first major cooling coincided with the Campanian–Maastrichtian transition, and a major sea-level regression in the Tethys at 70.7–70.3 Ma. Surface temperatures continued to decline gradually during the late Maastrichtian, although with some rapid oscillations, whereas bottom water temperatures (at Site 690) reached maximum cooling coincident with the late Maastrichtian regression at 68.9–68.3 Ma and cool climate in the Tethys. High and middle latitude cooling continued into the latest Maastrichtian marked by a low sea-level at 65.45 Ma in the Tethys and a regression globally (Keller & Stinnesbeck 1996). The last 300–400 ka of the Maastrichtian are marked by a major short-term warming in the $\delta^{18}O$ record and a rising sea-level, followed by cooling and falling sea-level up to the K–T boundary in the southern and northern high latitudes (Stott & Kennett, 1990; Schmitz *et al.* 1992; Li & Keller 1998*b*, *c*).

Thus, within the constraint of correlating the Tethys record to Sites 690C and 525 (accomplished based on high resolution biostratigraphic correlations, Li & Keller 1998*b*, *c*), periods of low temperatures and high latitude cooling coincide with episodes of sea-level regressions reflected by high Sr/Ca ratios, high TOC, high $\delta^{13}C$ and high terrigenous influx. Whether these periods of low sea levels during the Maastrichtian correspond to episodes of glaciation is unknown. Cretaceous climates have generally been considered as too warm to accommodate large continental ice sheets (Barron *et al.* 1984), although this view is changing. Recently, Stoll & Schrag (1996) suggested that short-term sea-level variations inferred from Sr concentrations in early Cretaceous deep-sea carbonates are glacially controlled, though this work is controversial. Abreu *et al.* (1998) also proposed an ice house of the Late Cretaceous, based on comparison of the stable isotopic data between the Cretaceous and Cenozoic. Recent GCM studies suggest an increase of 10 in evaporation during the Maastrichtian with seasonal freezing in high latitudes (Pirrie & Marshall 1990; Bush & Philander 1997), that provides a possible source for ice formation. The $\delta^{18}O$ record from Site 525 on Walvis Ridge (Li & Keller 1998*b*, *c*) suggest that the rapid eustatic sea-level changes during the late Campanian through Maastrichtian are related to high latitude cooling and possibly ice growth.

Summary

(1) A multi-disciplinary approach that includes field-based lithological observations, benthic macro- and microfossils, bulk rock compositions, clay mineral assemblages, stable isotopes, TOC and Sr/Ca ratios reveals seven major sea-level regressions in the southwestern Tethys Sea during the last 10 Ma of the Cretaceous.

(2) Low sea levels are associated with major lithological changes, increased terrigenous influx, low kaolinite/chlorite+mica ratios, high TOC and high Sr/Ca ratios, whereas high sea levels are generally associated with the reverse.

(3) The overall climatic changes inferred by clay mineral contents in the southwestern Tethys during the late Cretaceous are similar to those inferred from stable isotopes in the South Atlantic. The observed climatic patterns correlate with sea-level fluctuations recognized in the Tunisian sections.

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