# THE CRETACEOUS-TERTIARY TRANSITION ON THE SHALLOW SAHARAN PLATFORM OF SOUTHERN TUNISIA

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ABSTRACT - A multidisciplinary approach to the study of a K/T boundary section on the Saharan Platform based on planktic and benthic foraminifera, calcareous nannofossils, lithology, stable isotopes, mineralogy and geochemistry reveals a biota stressed by fluctuating hyposaline, hypoxic littoral and nearshore environments, productivity changes, and a paleoclimate altering between seasonal warm to temperate and warm/humid conditions. Benthic foraminifera indicate that during the last 300 kyr of the Maastrichtian (CF1, *Micula prinsii*) deposition occurred in a inner neritic (littoral) environment that shallowed to a near-shore hyposaline and hypoxic environment during the last 100-200 kyr of the Maastrichtian. These conditions were accompanied by a seasonal warm to temperate climate that changed to warm/humid conditions with high rainfall, by decreasing surface productivity, and significantly decreasing planktic and benthic foraminiferal species richness. The K/T boundary is marked by an undulating erosional contact overlain by a 10 cm thick sandstone layer which is devoid of any exotic minerals or spherules. Their absence may be due to a short hiatus and the fact that the characteristic clay and red layer (zone P0) are missing. During the earliest Danian (Pla), low sea-levels prevailed with continued low oxygen, low salinity, high rainfall, high erosion and terrigenous sediment influx, accompanied by low diversity, low oxygen and low salinity tolerant species. These environmental conditions abruptly ended with erosion followed by deposition of a phosphatic siltstone layer that represents condensed sedimentation in an open (transgressive) marine environment. Above this layer, low sea-levels and a return to near-shore, hyposaline and hypoxic conditions prevailed for a short interval [(base of Plc(2)] and are followed by the re-establishment of normal open marine conditions (inner neritic) comparable to the late Maastrichtian. This marine transgression is accompanied by increased productivity, and the first diversified Danian foraminiferal assemblages after the K/T boundary event and represents the return to normal biotic marine conditions. Though the K/T Seldja section represents one of the most shallow marginal sea environments studied to date for this interval, it does not represent isolated or atypical conditions. This is suggested by the similar global trends observed in sea-level fluctuations, hiatuses, as well as faunal assemblages. We conclude that on the Saharan platform of southern Tunisia, longterm environmental stresses beginning 100-200 kyr before the K/T boundary and related to climate, sea-level, nutrient, oxygen and salinity fluctuations, were the primary causes for the eventual demise of the Cretaceous fauna in the early Danian. The K/T boundary bolide impact appears to have had a relatively incidental short-term effect on this marine biota.

KEYWORDS: K/T TRANSITION, SAHARAN PLATFORM, PALEOENVIRONMENT.

RÉSUMÉ - Une étude détaillée, multidisciplinaire, incluant foraminifères benthiques et planctoniques, nannofossiles, lithologie, isotopes stables, minéralogie et géochimie, d'une section localisée sur la plate-forme saharienne dans le Sud de la Tunisie, démontre que la transition Crétacé-Tertiaire était caractérisée par des conditions paléoécologiques très extrêmes liées aux fluctuations du niveau marin, de la productivité et du climat. La distribution des foraminifères benthiques montre que les sédiments caractérisant les derniers 300 ka du Maestrichtien (CF1, zone à *Micula prinsii*) se sont déposés dans un milieu hyposalin et hypoxique, en domaine néritique côtier, sous un climat d'abord chaud mais contrasté évoluant vers des conditions plus humides. Une diminution de la productivité des eaux de surface est indiquée par la réduction graduelle des espèces de foraminifères planctoniques et benthiques. La limite Crétacé-Tertiaire est marquée par une surface érosive, surmontée par un banc gréso-silteux de 10cm. La présence de ce hiatus incluant probablement la partie tout à fait terminale du Maastrichtien, la zone P0 et une partie de la zone P1a, expliquerait l'absence d'une couche enrichie en sphérules et en matériel exotique. Le Danien basal (P1a) est marqué par une période de bas niveau marin accompagné par un important flux détritique et de fortes précipitations. Les milieux étaient peuplés par des espèces indiquant une oxygénation déficiente et une faible salinité. La partie supérieure de ce milieu de dépôt est brutalement interrompue par une surface d'érosion et surmontée par le dépôt d'une couche enrichie en phosphate et glauconie indiquant une sédimentation condensée en milieu marin (transgressif) ouvert. Un bref retour à des conditions néritiques côtières, marquées par une faible oxygénation et une basse salinité, est observé par la suite (zone P1c(2), il est suivi par le rétablissement d'un milieu marin ouvert comparable à celui caractérisant le Maastrichien terminal. Cette dernière transgression marine est associée à une augmentation de la productivité, soulignée par la première apparition d'une faune diversifiée de foraminifères, après l'événement Crétacé-Tertiaire, indiquant un retour à des conditions écologiques normales. Même si elle est caractérisée par des milieux marginaux, très peu profonds, la transition Crétacé-Tertaire étudiée dans cette section, n'est donc pas atypique. Elle montre des fluctuations du niveau marin et des assemblages fauniques similaires à ce qui est globalement observé. En conclusion, les milieux de la plate-forme saharienne du Sud de la Tunisie ont fait l'objet de stress environnementaux, débutant 100-200 ka avant la limite Crétacé-Tertiaire, liés aux fluctuations du climat, du niveau marin, de la productivité, de l'oxygénation et de la salinité. Ces changements environnementaux sont les causes principales de la disparition des faunes crétacées. L'impact météoritique Crétacé-Tertiaire ne semble avoir relativement affecté ce type d'environnement que sur une très courte durée de temps.

MOTS-CLÉS: K/T TRANSITION, PLATE-FORME SAHARIENNE, PALÉOENVIRONNEMENT.

# INTRODUCTION

Paleontology is undergoing a period of unprecedented progress as new technologies and analytical approaches are integrated with an ever increasing and detailed database. This progress is due in large part to the Cretaceous-Tertiary (K/T) boundary controversy and the interest it has generated across disciplines. As a result, scientists from many different fields have been brought together to work on the same problems and the integration of the varied datasets has significantly enhanced our understanding of the ancient world as well as provided an additional dimension to the interpretation of paleo-data. At the same time, paleo-data is providing age, environmental information and supporting evidence for many disciplines (e.g., geochemistry, stable isotopes, mineralogy, sedimentology). Thus an integrated multidisciplinary approach to paleoenvironmental problems can revitalize geological research and provide the necessary paleo-database that not only illuminates ancient environmental changes and catastrophes, but also provides the basis for predicting future environmental changes.

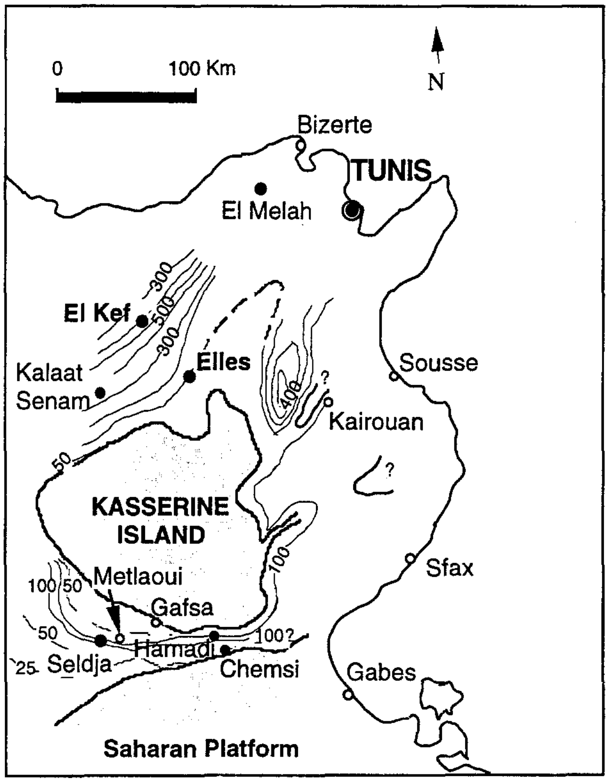

FIGURE 1 - Paleogeographic setting of Tunisia during the late Maastrichtian and early Tertiary with Cretaceous-Tertiary boundary sections (modified after Burollet 1967). Note the shallow water location of Seldja between the Kasserine Island to the north and the Saharan platform to the south. *Position paléogéographique de la Tunisie au Maastrichtien supérieur et Tertiaire inférieur avec emplacement des coupes montrant la limite Crétacé-Tertiaire (d'après Burollet 1967, modifié). Noter la localisation en eau peu profonde de Seldja entre l'île de Kasserine au Nord et la plate-forme saharienne au Sud.*

This report is an example of an integrated multidisciplinary study that combines paleontological, geochemical, mineralogical, lithologic and stable isotopic data to evaluate the environmental conditions in a new K/T section at Oued Seldja in southern Tunisia (Fig. 1). Specifically we integrate paleontologic data from planktic and benthic foraminifera and calcareous nannofossils with lithologic, whole rock and clay mineral data, stable isotopes and various geochemical and trace element parameters. Based on these data, the Seldja section provides a rare glimpse of the environmental conditions and biotic consequences in a shallow marine to coastal environment during the K/T transition.

Biotic and environmental consequences associated with the Cretaceous-Tertiary (K/T) transition are well known from deeper water (shelf, slope) marine environments where sediment accumulation rates are relatively high and exposure to erosion is limited to submarine current activity. In northern Tunisia, a number of such sections are known including from El Kef, Elles, Kalaat

Senam and El Melah (Fig. 1). The most studied of these is the El Kef section which was designated as the K/T boundary stratotype section and point (Perch-Nielsen 1981; Donze et al. 1982, 1985; Smit 1982; Peypouquet et al. 1986; Keller 1988a,b; Brinkhuis & Zachariasse 1988; Méon 1990; Saint-Marc 1992; Pospichal 1995; Ben Abdelkader & Zargouni 1995; Rocchia et al. 1995; Kouwenhoven et al. 1997). The other sections are relatively unknown and no studies comparable to El Kef exist to date (e.g., Said 1978; Robaszynski et al. 1993).

From shallow marine environments in southern Tunisia, no K/T boundary sections have been examined in detail to date, though a number of benthic foraminiferal studies have concentrated on a survey of the paleobiogeography of Tunisian Paleocene assemblages (e.g., Aubert & Berggren 1976; Bou Dagher 1987; Saint-Marc & Berggren 1988; Saint-Marc 1992). In these studies, the shallowest southernmost sections (Hamadi, Chemsi and Oued Seldja) are located between the Kasserine Island to the north and the Saharan platform to the south (Fig. 1). However, no studies are known to us that detail the K/T transition in any of these sections (except El Kef) and the Seldja section is known from only three samples (Aubert & Berggren 1976).

The paleogeographic and tectonic setting of the Seldja section is unique (Fig. 1). During the Maastrichtian and into the Eocene, the Seldja sequence was deposited in the shallow Gafsa basin. This basin was connected to the Sahara platform to the south but separated from the Tethyan realm to the north by the Kasserine Island. The interchange with the open sea was therefore restricted and probably further hampered by small uplifted areas to the east and west which could have acted as barriers to circulation (Burollet 1956; Burollet & Oudin 1980; Sassi 1974). Sediment deposition occurred largely in restricted seas that fluctuated between inner neritic to coastal environments. Tectonic activity and erosion of the Kasserine Island contributed to a constant though variable terrigenous influx of sediments. This unique paleogeographic setting provides a rare glimpse of marine life in shallow nearshore environments during the K/T transition.

The multi-disciplinary nature of this study necessitates a less conventional organization for this report. Instead of the strict separation of sections on results from interpretation, we opt for a sectional approach for each discipline. Sections for each discipline begin with a statement giving the rational for using a given proxy as environmental indicator, followed by the results and end with the interpretation. We devote the *Discussion* section to the integration of results from the various proxies for sea-level, climate and environmental changes and to evaluating these results within the context of published K/T boundary records.

## LOCATION AND LITHOLOGY

Oued Seldja is located in a gorge about 10 km west of the city of Metlaoui and is reached by following the road from Metlaoui to Tozeur. About 10 km south of Metlaoui a signpost marks the unpaved road that leads over 7 km to Oued Seldja. From the end of the road a foot path leads 0.5 km over a plain to the gorge. The gorge is perpendicular to the Tamerza-Metlaoui belt and was formed by a small river that cuts through a sediment sequence of Maastrichtian to Eocene age. The strata form the south flank of a W-E striking anticline and beds dip steeply (60-80 ) to the south.

We collected the K/T boundary transition on the west side of the gorge in a shale sequence that overlies thick bedded shallow water limestones of the Campanian to Maastrichtian Abiod Formation. These limestones form a mountain ridge that is easily recognized within the gorge. Upsection from the Abiod limestones are siltstones, shales and claystones of the late Maastrichtian to Paleocene El Haria Formation as defined by Burollet (1956). Intensive small scale faulting makes it difficult to measure the thickness of these shales. We estimate that the K/T boundary interval is about 15-20 m above the lithological contact between the Abiod and El Haria Formations in sediments that are less affected by tectonic faulting. A 9 m thick interval spaning from 2.4 m below to 6.6 m above the K/T boundary was trenched and 40 samples collected (Fig. 2). Between our first (1996) and second (1997) samplings, another party of geologists trenched the section and labelled seven sample stations (RP0 to RP6) with red paint on the outcrop; these sample stations are indicated on Figure 2 in relation to our samples.

The uppermost Maastrichtian interval of the collected K/T transition consists of 2.4 m of grey to brown silty shales, clays and clayey siltstones that is overlain by a 15 cm thick bed of yellow silty sandstone rich in fish scales and teeth. The undulating contact between these lithologies indicates erosion as also suggested by truncated burrows and the presence of mud clasts from the underlying sediments within the sandstone layer. This sandstone layer marks the K/T boundary event as discussed below. Above this layer are 1.15 m of grey silty shales and clays (Zone Pla) followed by a 25 cm thick bed of grey calcareous bioturbated siltstone rich in phosphatic and glauconitic grains ranging in size from 0.3 to 1.4 mm. The lower contact of this phosphatic layer is mar-

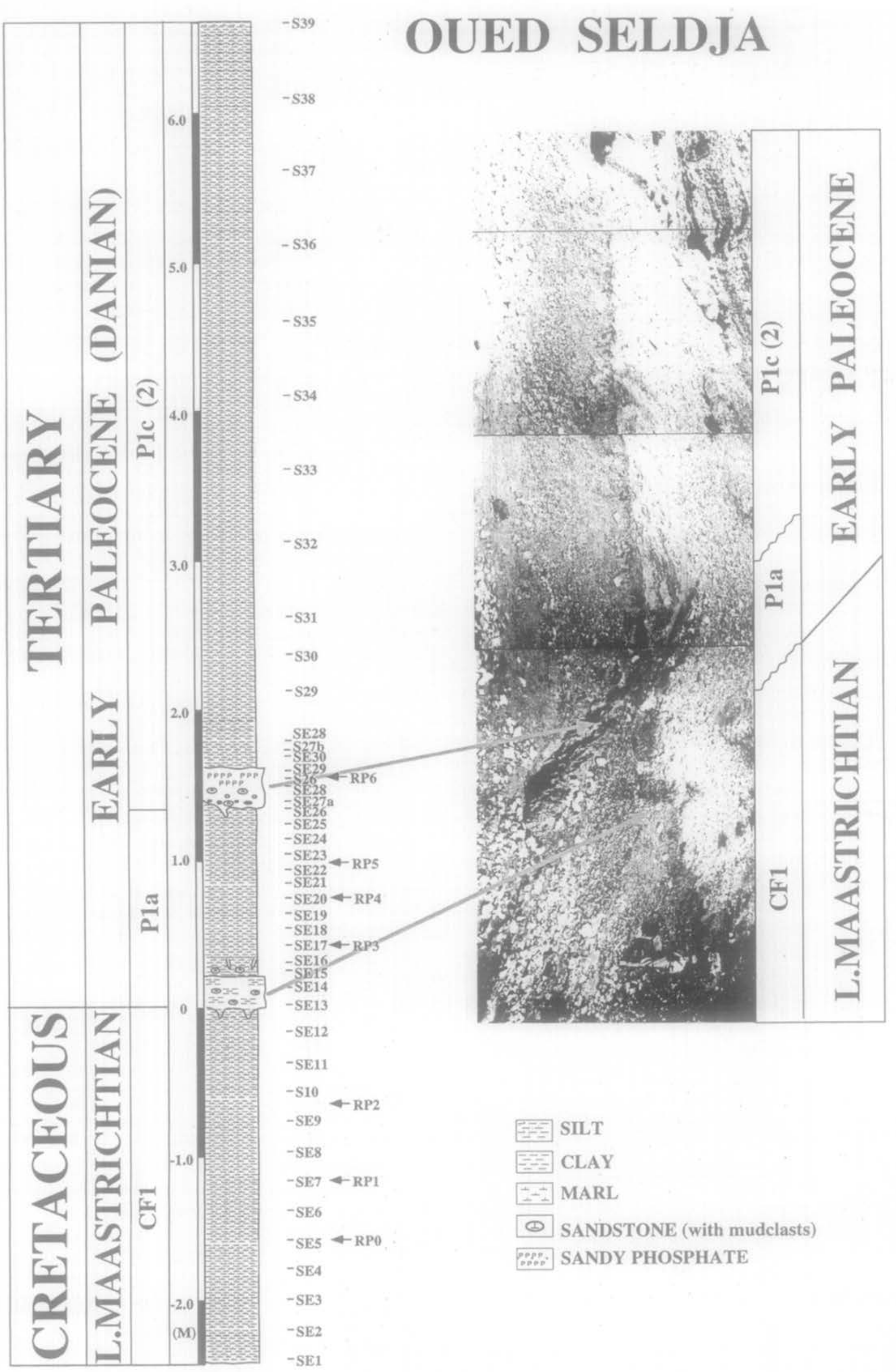

FIGURE 2 - Lithostratigraphic column of the Seldja section with sample locations of this study (SE and S samples) and short arrows and sample numbers marking the location of red painted sample stations painted on the outcrop by another geological party. Long arrows point to location of K/T sandstone and lower Danian (Pla/Plc) phosphate layers on outcrop photo.
*Colonne lithostratigraphique de la coupe de Seldja avec localisation de l'échantillonnage pour cette étude (échantillons SE et S); les flèches courtes avec numéros indiquent la localisation des échantillonnages peints en rouge sur l'affleurement par une autre équipe géologique. Les longues flèches indiquent l'emplacement du grès K/T et des couches phosphatées du Danien inférieur (P1a/P1c) sur la photo de l'affleurement.*

ked by an undulose surface, manganese crusts and nodules that suggest an extended period of erosion and non-deposition (Föllmi 1990; Föllmi et al. 1992). The lower 5 cm of the phosphate layer contains mud clasts and phosphate-filled burrows extend into the underlying shales. The phosphate layer is rich in fish remains (shark teeth, fish scales), small bivalves (mostly nuculanids) and gastropods; preservation of invertebrates as interior moulds impedes precise determination of the fauna. Though prior to dissolution, shells were mostly intact and bivalves closed which indicates a low energy environment and little transportation. The first 5 cm above the phosphate layer consist of grey-green marly siltstone rich in microfossils (foraminifera and ostracods) with small (0.5 to 1 cm) clasts of phosphate. Upsection, marly siltstones grade into brown siltstone with increasingly abundant terrestrial plant debris.

## METHODS

For foraminiferal studies samples were processed by standard methods (see Keller, Li & MacLeod 1995). Population counts were based on sample splits of 300-400 specimens of each benthic and planktic foraminifera from the greater than 63

**Relative percent abundances of planktic foraminifera across the K-T boundary at Oued Seldja, Tunisia**

| Biozones | *P. hantkeninoides* (CFI) | | | | | | | | | | | | | P1a | | | | | | | | | | | | | P1c (2) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample Numbers | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27a | 27b | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 |
| *Globigerinelloides aspera* | | | | | | 6 | 7 | 2 | | 3 | 8 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Globigerinelloides volutus* | | | | | | 2 | 2 | | | | | | 5 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | |
| *Globotruncanella subcarinatus* | | 1 | | 2 | 3 | | | 2 | | 3 | 1 | | | | | | | | | | | | | 1 | | | | | | | | | | | | | | | |
| *G. petaloidea* | | 1 | | | | | | | | | | | | | | | | d | | d | d | d | d | | d | | | | | | | | | | | | | | |
| *Gublerina robusta* | | | | | | | | | | 1 | | | | | | | | i | | i | i | i | i | | i | | | | | | | | | | | | | | |
| *Hedbergella holmdelensis* | 2 | | 1 | 1 | | 3 | | 4 | 2 | | | 4 | 5 | | | | 1 | s | | s | s | s | s | | s | | | | | | | | | | | | | | |
| *H. monmouthensis* | 4 | 5 | 8 | 2 | | 18 | 25 | 19 | 10 | 2 | 5 | 5 | 7 | | 2 | | | s | 2 | s | s | s | s | | s | | | | | | | | | | | | | | |
| *H. complanata* | 7 | 2 | | 3 | 5 | 3 | | | | | | 3 | | | | | | o | | o | o | o | o | | o | | | | | | | | | | | | | | |
| *H. dentata* | 30 | 26 | 32 | 16 | 68 | 97 | 87 | 72 | 47 | 42 | 51 | 28 | 23 | 6 | 1 | 1 | 3 | l | 5 | l | l | l | l | | l | | 3 | 1 | | | | | | | | | | | |
| *H. globulosa* | 37 | 24 | 28 | 20 | 11 | 24 | 11 | 14 | 11 | 23 | 28 | 22 | 11 | 9 | 12 | 4 | 2 | u | 3 | u | u | u | u | | u | 2 | | | | | | | | | | | | | |
| *H. navarroensis* | 11 | 27 | 15 | 25 | 48 | 84 | 62 | 55 | 26 | 21 | 23 | 21 | 27 | 3 | 5 | | 1 | t | 4 | t | t | t | t | 3 | t | 1 | | | | | | | | | | | | | |
| *H. planata* | | 1 | 1 | 3 | 10 | 8 | 2 | 12 | 13 | 21 | 13 | 11 | 11 | | | | | i | 1 | i | i | i | i | | i | | | | | | | | | | | | | | |
| *H. pulchra* | 1 | 1 | | | 2 | 7 | 3 | 1 | | | | 1 | | | | | | o | | o | o | o | o | | o | | | | | | | | | | | | | | |
| *H. striata* | 4 | | 1 | | | | 3 | | | 2 | | | | | | | | n | | n | n | n | n | | n | | | | | | | | | | | | | | |
| *Pseudotextularia carseyae* | 1 | 3 | 13 | 2 | 6 | 2 | 1 | | 4 | 5 | 5 | 4 | 3 | 4 | 4 | | | | | | | | | 3 | | 2 | | | | | | | | | | | | | |
| *Pseudotextularia deformis* | 1 | | | | | 1 | | | | 2 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *P. elegans* | | | | | 1 | | | | | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *P. kempensis* | | | 1 | 3 | | 4 | 4 | | 2 | 2 | | | 1 | 1 | 1 | | | | | | | | | 1 | | | | | | | | | | | | | | | |
| *Pseudoguembelina costulata* | 13 | 9 | 16 | 15 | 23 | 46 | 51 | 26 | 12 | 16 | 13 | 10 | 5 | 4 | 6 | 1 | | | | | | | | | | 1 | | | | | | | | | | | | | |
| *P. palpebra* | | | | | | | 1 | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Plummerita hantkeninoides* | | | | | | | | | 1 | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *P. reicheli* | 2 | 4 | 2 | | 5 | | | | 1 | 1 | | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Rugoglobigerina rugosa* | 3 | | 1 | | | | | | | | 4 | 5 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *R. macrocephala* | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *R. scotti* | | | | | | | | | | | 2 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *R. hexacamerata* | | | | | | | | | | | 3 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Racemiguembelina fructicosa* | 1 | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Globotruncana aegyptiaca* | 1 | | | | | | | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *G. arca* | | | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *G. esnehensis* | | | | | | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *G. rosetta* | | | | | | | | 1 | | 1 | 1 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *G. stuarti* | 2 | | | | | | | | | 1 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Guembelitria cretacea* | 12 | 110 | 2 | 15 | 22 | 9 | 21 | 40 | 34 | 43 | 18 | 85 | 105 | 140 | 142 | 93 | 75 | | 160 | | | | | 138 | | 90 | 21 | 2 | | | | | | | 1 | | | | |
| *G. danica* | | 3 | | | 1 | 2 | 2 | 3 | 2 | 3 | | 2 | 6 | 3 | | | 5 | | 22 | | | | | 8 | | 3 | 1 | | | | | | | 1 | | | | | |
| *G. irregularis* | | 4 | 14 | 10 | 3 | 1 | 4 | 6 | 3 | 2 | 1 | | | | | | | | 3 | | | | | 3 | | 5 | | | | | | | | | | | | | |
| *G. trifolia* | | 2 | | 1 | 2 | 1 | 1 | | 8 | 4 | | 12 | 18 | | 21 | 22 | 13 | | 20 | | | | | 29 | | 11 | 8 | | | | | | | | | | | | |
| *Eoglobigerina edita* | | | | | | | | | | | | | | | | | | | | | | | | | | 4 | 3 | 14 | 2 | 1 | 2 | 10 | | 5 | 6 | | | 1 | |
| *E. fringa* | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | 4 | | | | | | | | | | | | |
| *E. eobulloides* | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | 25 | 10 | 2 | 7 | 6 | 3 |
| *Parvularugoglobigerina eugubina* | | | | | | | | | | | | | | | | | | | | | | | | | | 23 | | | | | | | | | | | | | |
| *Subbotina pseudobulloides* | | | | | | | | | | | | | | | | | | | | | | | | | | 6 | 15 | 64 | 50 | 35 | 45 | 30 | 27 | 57 | 81 | 37 | 66 | 40 | 27 |
| *S. triloculinoides* | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | 19 | 14 | 2 | 12 | 12 | 5 | 49 | 47 | 28 | 40 | 5 | 13 |
| *S. trivialis* | | | | | | | | | | | | | | | | | | | | | | | | | | | 9 | 9 | 8 | 3 | 9 | 9 | 6 | 11 | 17 | 13 | 22 | 4 | 7 |
| *S. varianta* | | | | | | | | | | | | | | | | | | | | | | | | | | | 18 | 50 | 17 | 14 | 20 | 9 | 10 | 22 | 27 | 29 | 52 | 20 | 18 |
| *Globanomalina hemisphaerica* | | | | | | | | | | | | | | | | | | | | | | | | | | | 10 | 23 | 21 | 6 | 17 | 30 | 13 | 32 | 46 | 18 | 20 | 7 | 7 |
| *G. pentagona* | | | | | | | | | | | | | | | | | | | | | | | | | | 4 | 30 | 17 | 31 | 10 | 19 | 15 | 9 | 12 | 2 | 10 | 29 | 13 | 11 |
| *G. taurica* | | | | | | | | | | | | | | | | | | | | | | | | | | | 6 | 5 | 3 | 6 | 3 | 1 | 4 | | 4 | 5 | | 15 | 5 |
| *G. polycamera* | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | | 1 | | | | | |
| *Chiloguembelina midwayensis* | | | | | | | | | | | | | | | | | | | | | | | | | | | 6 | 13 | 9 | 13 | 11 | 6 | 19 | 11 | 18 | 8 | 10 | 10 | 13 |

| Biozones | *P. hantkeninoides* (CFI) | | | | | | | | | | | | | P1a | | | | | | | | | | | | | P1c (2) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample Numbers | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27a | 27b | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 |
| *C. moresei* | | | | | | | | | | | | | | | | | | | | | | | | | | | | 15 | | | | | | | | | | | |
| *Woodringina hornerstownensis* | | | | | | | | | | | | | | | | | | | | | | | | | | 15 | 22 | 12 | 8 | 11 | 12 | 19 | 10 | 3 | 13 | 8 | 5 | 5 | 6 |
| *W. claytonensis* | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | 3 | 7 | | 6 | 1 | 2 | 1 | |
| *W. kelleri* | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | 14 | 17 | 7 | 6 | 9 | 16 | 5 | 7 | 10 | 3 | 2 | 5 | 2 |
| *Globoconusa daubjergensis* | | | | | | | | | | | | | | | | | | | | | | | | | | 40 | 93 | 126 | 130 | 164 | 157 | 142 | 166 | 10 | 42 | 37 | 40 | 140 | 70 |
| *Globoconusa conusa* | | | | | | | | | | | | | | | | | | | | | | | | 2 | | 4 | | | | | | | | | | | | | |
| *Morozovella inconstans* | | | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | 1 | 1 | 1 | | | 2 | 1 | 4 | 10 | 2 | 3 |
| *Planorotalites planocompressus* | | | | | | | | | | | | | | | | | | | | | | | | | | | 33 | 42 | 16 | 24 | 55 | 83 | 50 | 40 | 78 | 64 | 55 | 78 | 47 |
| **Total Number Counted** | 133 | 224 | 136 | 118 | 210 | 320 | 287 | 258 | 176 | 204 | 181 | 219 | 229 | 170 | 195 | 121 | 100 | 0 | 220 | 0 | 0 | 0 | 0 | 188 | 0 | 215 | 297 | 431 | 317 | 296 | 374 | 387 | 333 | 288 | 409 | 267 | 360 | 352 | 232 |

TABLE 1 - Relative percent abundance of planktic foraminifera across the K/T boundary at Oued Seldja, Tunisia. *Abondance relative (pourcentages) des foraminifères planctoniques à la limite K/T à Oued Seldja, Tunisie.*

**Relative percent abundances of benthic foraminifera across the K-T boundary at Oued Seldja, Tunisia**

| Biozones | *P. hantkeninoides* (CFI) | | | | | | | | | | | | | P1a | | | | | | | | | | | | | P1c (2) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample Numbers | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27a | 27b | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 |
| *Ammodiscus sp.* | | 4 | 25 | 13 | 5 | 1 | | 3 | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Arenaceous sp.* | | 10 | 46 | 27 | 6 | 10 | | 6 | 6 | 5 | 1 | | 2 | | | | 4 | | | | | 8 | 23 | | | | 2 | | | | | 3 | 2 | 5 | | | 5 | 1 | 1 |
| *Ammobaculites subcretaceus* | 24 | 26 | 42 | 30 | 2 | 22 | 2 | | | | | | | | | | | | | | | 7 | 2 | | | | | | | | | | | | | | | | |
| *Anomalinoides praeacuta* | 77 | 52 | 28 | 5 | 3 | 2 | 1 | | | | | | | | | 1 | | d | | d | d | | | | d | | | | | | | | | 1 | | 1 | 11 | | |
| *Anomalinoides umbonifera* | 26 | 61 | 34 | 20 | 12 | 38 | 18 | 9 | 22 | 61 | 5 | 7 | 16 | 165 | 139 | 134 | 92 | i | 21 | i | i | 10 | 22 | 118 | i | 20 | 30 | 15 | 25 | 9 | 15 | 7 | 9 | 25 | 4 | 2 | 23 | 3 | 2 |
| *Bolivina decurrens* | | | | | 1 | | 2 | | | | | | | | | | | s | | s | s | | | | s | | | | | | | | | | | | | | |
| *Bulimina asperaaculeata* | | | | | | | 1 | | | | | | | | | | | s | | s | s | | | | s | | | | | | | | | | | 1 | 3 | 11 | |
| *B. reussi* | 3 | | | | 4 | | | | | | | | | | | | | o | | o | o | | | | o | | | 6 | 1 | 30 | 55 | 62 | 44 | 16 | 42 | 52 | 13 | 39 | 30 |
| *B. gr. trigonalis* | 32 | 16 | 17 | 23 | 33 | 65 | 31 | 24 | 43 | 23 | 34 | 39 | 24 | 42 | 45 | 10 | | l | 5 | l | l | 25 | 6 | 50 | l | 30 | 18 | 8 | 8 | 18 | 68 | 53 | 51 | 22 | 32 | 66 | 15 | 39 | 75 |
| *Caucasina minuta* | | | | | | | | | | | | | | | | | | u | | u | u | | | | u | | | | | | | | | 2 | 2 | 7 | 1 | 2 | |
| *Epistominella minuta* | | | | | 1 | | | | | | | | | | | | | t | | t | t | | | | t | 7 | 16 | 7 | 8 | 15 | 1 | 1 | 2 | 2 | 24 | 1 | 23 | 27 | 19 |
| *Fursenkoina nederi* | 1 | | 1 | 5 | 61 | 24 | 42 | 150 | 6 | 29 | 36 | 52 | 65 | 2 | 8 | | 13 | i | 30 | i | i | 77 | 7 | 70 | i | 73 | 22 | | | | | | | | | | | | |
| *Gyroidina nitidus* | | | | | | | | | | | | | | | | | | o | | o | o | | | | o | | | | | | | | 1 | 2 | 2 | | 3 | | |
| *G. planulata* | | 1 | 1 | | 3 | | | | | | | | | | | | | n | | n | n | | | | n | | | | 1 | | | 1 | | | | | | | |
| *G. subangulata* | | | | | | 2 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| *Haplophragmoides excavata/walteri* | 37 | 50 | 82 | 58 | 8 | 43 | 11 | 2 | 9 | | | | | | | | 2 | | | | | 10 | 4 | 2 | | 1 | | | | | | | 1 | 1 | 1 | | | | |
| *Lenticulina midwayensis* | 2 | 1 | | | 1 | | | 1 | | 1 | | | | | | | | | | | | | | | | 2 | 2 | 3 | | | | 2 | 1 | 5 | 1 | | 2 | | |
| *Loxostomoides deadericki* | | | | | | | | | | | | | | | | | | | | | | | | | | 6 | 42 | 100 | 213 | 175 | 85 | 83 | 62 | 132 | 70 | 42 | 61 | 22 | 6 |
| *Nonionella insecta* | | | | | | | | | | | 4 | | | | 1 | | | | 1 | | | | | | | | | | 1 | | | | | | | | | | |
| *Nonionella ovata* | 6 | 1 | | | 4 | 6 | 20 | 10 | 1 | 29 | 41 | 1 | 28 | | | | | | | | | | | | | 26 | 19 | 23 | 6 | 43 | 50 | 35 | 50 | 4 | 22 | 45 | 11 | 54 | 70 |
| *Nodosaria sp.* | | | | | | | | | | | | | | | | | | | | | | | | | | 2 | | 2 | 1 | 3 | | | | | | | | | |
| *Orthokarstenia parva* | 3 | | | | | | | 5 | | 4 | 20 | 13 | 25 | | 2 | | | | | | | | | | | 12 | 1 | | | | | | | | | | | | |
| *Palmula sigmoicostata* | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 1 | | | | | | | | 1 | | |
| *Pyramidina prolixa* | 31 | 12 | 15 | 20 | 44 | 63 | 31 | 41 | 41 | 60 | 21 | 45 | 55 | 30 | 93 | 16 | 24 | | 75 | | | 16 | 1 | 58 | | 28 | 10 | 2 | | | | | | | | | | | |
| *Pyramidina szajnochae* | 13 | 25 | 11 | 7 | 3 | 12 | 6 | 4 | 14 | 28 | 32 | 11 | 17 | 9 | 9 | 1 | | | | | | | | | | 10 | 1 | | | | | | | | | | | | |
| *Quinqueloculina sp.* | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 4 | | | | | | |
| *Stainforthia farafraensis* | 4 | 2 | 4 | 7 | 59 | 80 | 67 | 70 | 24 | 92 | 144 | 180 | 179 | 9 | 13 | 4 | 1 | | | | | 10 | 7 | 5 | | 88 | 78 | 94 | 62 | 43 | 157 | 137 | 140 | 138 | 139 | 193 | 243 | 186 | 179 |
| *Tappanina selmensis* | 4 | | 5 | 5 | 17 | 17 | 14 | 6 | 1 | | | | 1 | | | 3 | 1 | | | | | | | | | 2 | 9 | 1 | 1 | 2 | 3 | | | | | | | | |
| *Trochammina altkpensis* | 10 | 60 | 108 | 71 | 5 | 22 | 12 | 3 | 4 | 1 | 2 | 1 | 1 | | 1 | | 3 | | | | | 13 | 22 | | | | | | | | | | | | | | | | |
| *Valvulineria insueta* | | | 2 | 3 | 1 | 2 | 4 | 6 | | 2 | 3 | 2 | 1 | | | | | | | | | | | | | 3 | | | 2 | 2 | | | | | | | | | |
| *Valvulineria scorbiculata* | | | | 1 | | | | 5 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| **Total Number Counted** | 273 | 321 | 421 | 295 | 273 | 409 | 262 | 345 | 173 | 335 | 343 | 351 | 414 | 257 | 311 | 169 | 140 | 0 | 132 | 0 | 0 | 176 | 94 | 303 | 0 | 310 | 250 | 261 | 330 | 340 | 434 | 384 | 367 | 355 | 339 | 410 | 415 | 386 | 382 |

TABLE 2 - Relative percent abundance of benthic foraminifera across the K/T boundary at Oued Seldja, Tunisia. *Abondance relative (pourcentages) des foraminifères benthiques à la limite K/T à Oued Seldja, Tunisie.*

micron fraction (Tables 1 and 2). Calcareous nannofossils were also processed by standard methods (Keller & v. Salis Perch-Nielsen 1995). Total organic carbon, whole rock and clay mineralogical analyses were carried out at the Geological Institute of the University of Neuchatel, Switzerland, with a CHN Calro-Erba Elemental Analyzer NA 1108 and a SCINTAG XRD 2000 Diffractometer following the analytical methods by Verardo et al. (1990) and Kubler (1987) as described in Adatte et al. (1996). Stable carbon and oxygen isotope data for carbonate were obtained from finely ground bulk samples using a fully automated preparation system ("MultiCarb") connected on-line to an "Optima" Isotope Ratio Mass Spectrometer at the University of Karlsruhe, Germany. All carbon and oxygen isotope values are reported relative to the PDB standard with reproducibility better than 0.1 permill (Appendix, Table 3). Element analysis was carried out at the Institute for Petrography of the University of Karlsruhe, Germany, with a Spectrace5000 (Tracor) equipped with a Rh-tube and Si (Li)-detector (30mm2). To check measurement accuracy, the certified standards MRG-1, AGV-1, SOIL-5 and SOIL-7 were measured. A total of 24 elements were analyzed. Details of the analytical procedure and detection limits are described in Kramar (1984, 1997). Data are presented in Tables 3 and 4.

## BIOSTRATIGRAPHY

**Planktic Foraminifera** - The biostratigraphy of the Seldja section is based on planktic foraminifera and calcareous nannofossils with the former based on the zonal scheme of Keller (1993; Keller et al. 1995) and shown in Figure 3 in comparison with the zonal scheme of Berggren et al. (1995). Contrary to earlier reports (e.g. Aubert & Berggren 1976; Saint-Marc & Berggren 1988), planktic foraminifera are common in the Seldja K/T transition with the exception of some dissolution intervals in the lowermost Danian and most of the lower Danian sediments are present. The lower part of the section (samples 1 to 13) has abundant and well preserved planktic foraminifera and the planktic/benthic ratio averages between 0.3 to 0.6. The faunal assemblages are dominated by heterohelicids and guembelitrids. All other taxa are relatively rare and sporadically present (Fig. 4a,b). The index taxa *Plummerita hantkeninoides* and *P. reicheli* are present though rare and indicate that this interval represents part of the last 300 kyr of the Maastrichtian (Pardo et al. 1996). Though the undulating erosional contact at the base of the sand layer indicates a hiatus with part of this interval missing. Within the sandstone layer and above it, guembelitrids are dominant, heterohelicids are relatively rare and other Cretaceous taxa are generally absent. This is characteristic of early Danian assemblages, though no Danian species were observed

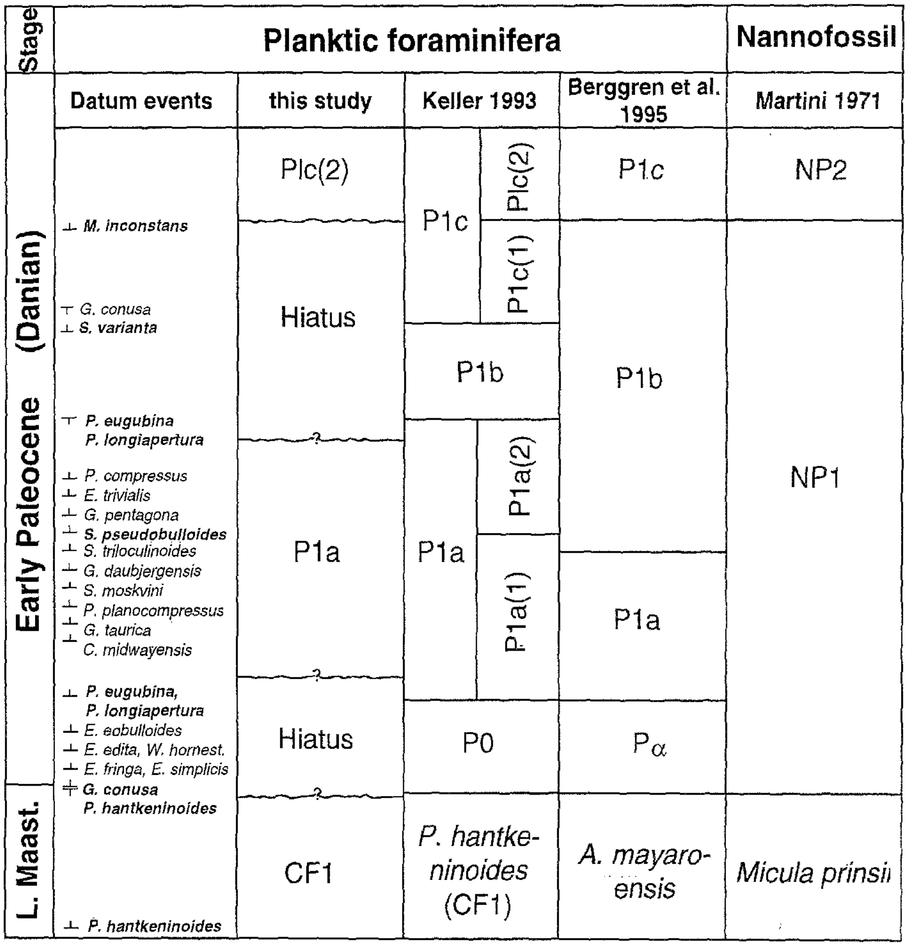

FIGURE 3 - Planktic foraminiferal and calcareous nannofossil biozonations used in this study and their calibration to the Keller (1993) and Berggren et al. (1995) zonal schemes. Note the short hiatuses at the K/T boundary and between the lower Danian Pla and Plc (2) zones. *Biozonations avec foraminifères planctoniques et nannofossiles calcaires utilisées dans cette étude et calibration de celles-ci avec les zones établies par Keller (1993) et par Berggren et al. (1995). Noter les brefs hiatus à la limite K/T et au Danien inférieur entre les zones Pla et Plc(2).*

possibly due to dissolution and poor preservation. We tentatively placed the K/T boundary at the base of the sandstone layer.

In the interval between the sandstone and phosphate layers (samples 16 to 25, Figs 2, 4a,b) planktic foraminifera are relatively rare and many samples are barren due to dissolution. Planktic foraminifera present include heterohelicids, guembelitrids and some reworked Cretaceous species, whereas the delicate Danian species are generally dissolved. The first Danian species, *Globoconusa conusa*, was observed 90 cm above the sandstone layer (sample 24), and *Parvularugoglobigerina eugubina*, the index species for Zone Pla, is common in sample 26 below the yellow phosphatic layer. The interval between the sandstone and phosphate layers is therefore considered as of early Danian Zone Pla age. The 5.5 m upsection from the base of the phosphatic layer contain abundant and well preserved Danian assemblages characteristic of Zone Plc (2) age (upper part of Plc), as indicated by the presence of the marker species *Morozovella inconstans*. The abrupt change in Danian assemblages at the base of the phosphatic layer, the undulating erosional contact and rip-up clasts, all indicate the presence of a hiatus. The juxtaposition of *P. eugubina* and *M. inconstans* indicates that this hiatus spans from the upper part of Pla through the lower part of Plc (Figs 3, 4a,b).

**Calcareous Nannofossils** - Preservation of coccolith assemblages is variable and usually affected by dissolution. Reworking of Campanian (?) species is very rare. *Micula prinsii*, the marker species of the uppermost Maastrichtian zone (Fig. 3) is present, though rare, throughout the interval below the sandstone layer (samples 1-12) and coccolith assemblages are dominated by *Micula decussata*, a dissolution resistant form, but also include a rich and moderately well preserved assemblage containing about 20-40 species. A total of over 80 species were observed in the Maastrichtian interval. In most Maastrichtian samples very rare specimens of *Chiastozygus ultimus, Cyclagelosphaera margerelii, Placozygus sigmoides, Thoracosphaera* sp. and *Biscutum* sp. are present; all of these taxa are known to survive into the Tertiary.

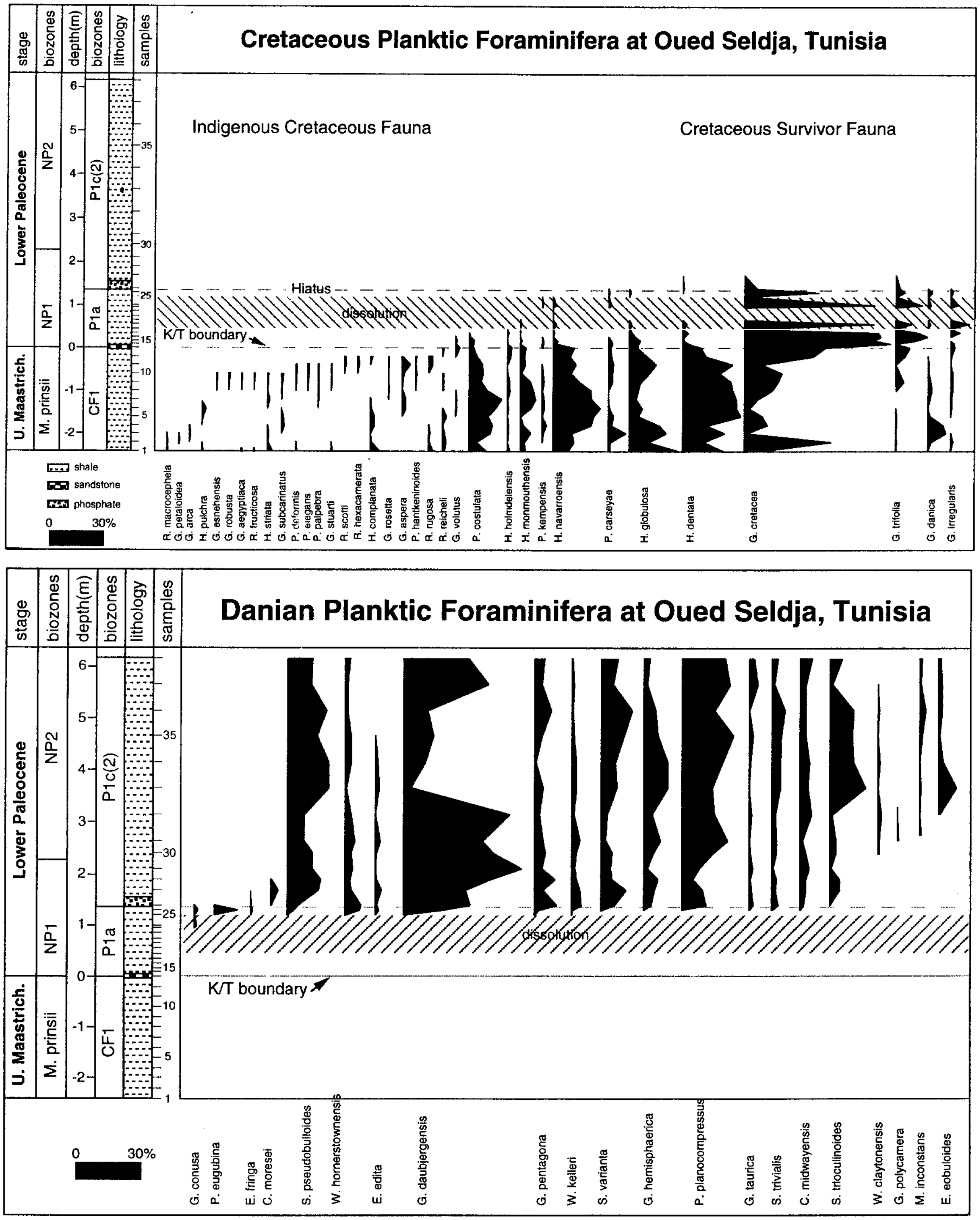

FIGURE 4 - **a.** Ranges and relative abundances of Cretaceous planktic foraminifera across the K/T boundary transition at Oued Seldja. Note that the species labelled indigenous Cretaceous fauna disappear at or below the K/T boundary, whereas species of the Cretaceous survivor fauna range into the early Danian and are also generally more abundant. **b.** Ranges and relative abundances of Danian planktic foraminifera at Oued Seldja. Note that the first Danian species appear in the upper part of Pla because of dissolution. The first common Danian assemblage of Pla age appears just below a phosphate layer and the hiatus. ***a.*** *Répartitions et abondances relatives des foraminifères planctoniques crétacés au passage de la limite K/T à Oued Seldja. Noter que les espèces qualifiées d'indigènes dans la faune crétacée disparaissent à la limite K/T ou sous celle-ci, tandis que les espèces de la faune crétacée survivante passent dans le Danien inférieur et sont aussi généralement plus abondantes.* ***b.*** *Répartitions et abondances relatives des foraminifères planctoniques à Oued Seldja. Noter que les premières espèces daniennes apparaissent dans la partie supérieure de Pla à cause de dissolutions. Le premier assemblage commun du Danien, d'âge Pla apparaît juste sous une couche phosphatée et le hiatus.*

The sandstone layer which marks the K/T boundary contains a very similar assemblage to that of the underlying uppermost Maastrichtian plus small reddish and/or yellow spheres which may represent pseudomorphs after coccospheres of small coccoliths (i.e. *Neobiscutum*). In the interval between the sandstone and the lower Danian phosphate layer (samples 16-25) many samples are barren of calcareous nannofossils and others contain only rare, dissolution resistant, longranging Cretaceous species and the spherules first noted in the sandstone layer. Only samples 19 and 20 contain a rich coccolith assemblage with common delicate specimens of the Cretaceous species *Kamptnerius magnificus*, large (up to 6um) *Placozygus sigmoides*, and specimens of the Danian (?) species *Neobiscutum romeinii* and *N. parvulum*. The large size of *P. sigmoides* suggests that this interval marks the onset of the upper part of zone NP1 (D2 of Perch-Nielsen, 1979). The presence of common *K. magnificus* suggests the survival of this species into the Danian as also suggested by the finding of coccospheres of *K. magnificus* in the Danian of the Netherlands (Mai et al. 1997).

The first appearance of *Cruciplacolithus primus* was observed in a burrow just below the phosphate layer (sample 26). Both *C. primus* and *C. edwardsii* are large (8 µm and 9 µm respectively) in this interval and typical of the upper part of NP1 (Romein 1979), though they are not accompanied by an acme of small *Prinsiaceae*. Maastrichtian and Danian species are equally common in this interval above the phosphate layer. The marker species for the NP1/NP2 zone, *Cruciplacolithus tenuis*, was first observed in sample 29 and morphotypes between *C. edwardsii* and *Chiasmolithus danicus* first appear in sample 36. However, no typical *C. danicus* were observed though *Prinsius dimorphosus* and *Futyama petalosa* are abundant. In samples 30 and 39 rare specimens of *Hornibrookina teuriensis* are present. This Danian genus is believed to be restricted to high latitudes (Varol 1989), though its probable ancestor *H. edwardsii* was observed in Turkey near the base of NP3 together with the first appearance of *C. danicus*.

Calcareous nannofossil stratigraphy differs from other K/T sequences (e.g. El Kef) primarily in the absence of abundant *Neobiscutum romeinii*, *N. parvulum*, *Thoracosphaera* and *Braarudosphaera*. However, considering the hiatuses at the base of the K/T sandstone and early Danian phosphate layers, these intervals could be missing. Surprising for this shallow depositional environment is the high species richness (>80 species) in the uppermost Maastrichtian and relatively high diversity in Danian zone NP2, but also the near absence of some shallow water taxa (e.g., *Kamptnerius magnificus* in the Maastrichtian). It is possible that these isolated rich assemblages represent marine incursions as also observed in planktic foraminifera.

## K/T BOUNDARY MASS EXTINCTION PATTERN

A total of 35 Cretaceous planktic foraminiferal species were found and identified from more than one sample (Fig. 4a, Tab. 1). About half of these taxa are only sporadically present and include nearly all spirally coiled morphotypes (e.g., rugoglobigerinids, globotruncanids, racemiguembelinids) that are generally common in open marine environments. Their sporadic occurrences suggest that these are migratory forms which entered the shallow Seldja environment only during favorable conditions such as a marine transgression, or an open sea connection. Their last occurrences in the Seldja section are therefore local disappearances rather than extinctions. However, in low latitude open marine environments, including El Kef (Keller et al. 1995), about 10-15% of the tropical Cretaceous species disappeared during the last 100-200 kyr of the Maastrichtian, the remainder disappeared at the K/T boundary and only environmentally tolerant generalist taxa such as heterohelicids, guembelitrids, hedbergellids and globigerinellids survived into the Danian (for a recent summary see Keller 1996).

Twelve biserial and four triserial species dominate late Maastrichtian assemblages at Seldja. Among these, the relative abundance of only five species comprises more than 90% of the total populations (e.g., *Pseudoguembelina costulata, Heterohelix navarroensis, H. globulosa, H. dentata, Guembelitria cretacea*). The same biserial species group also dominates at El Kef and in both localities, *H. dentate* is most abundant. This suggests a contiguous seaway to the south and/or similar conditions for these species (possibly low oxygen, see Rohling et al. 1993; Keller 1996). The most significant difference between the dominant late Maastrichtian assemblages at the two localities is the dominance of *Guembelitria* species at Seldja and its near absence at El Kef (Fig. 4a). *Guembelitria* are generally rare in late Maastrichtian open marine environments, but abundant in shallow nearshore waters where they are generally associated with low oxygen tolerant benthic species (see Keller 1996, p. 65-67).

All common and dominant species show a distinct relative abundance pattern with either declining populations in the last 1 m before the K/T boundary (*P. costulata, H. navarroensis, Hedbergella monmouthensis*), or within the last 20 cm (*H. glo-*

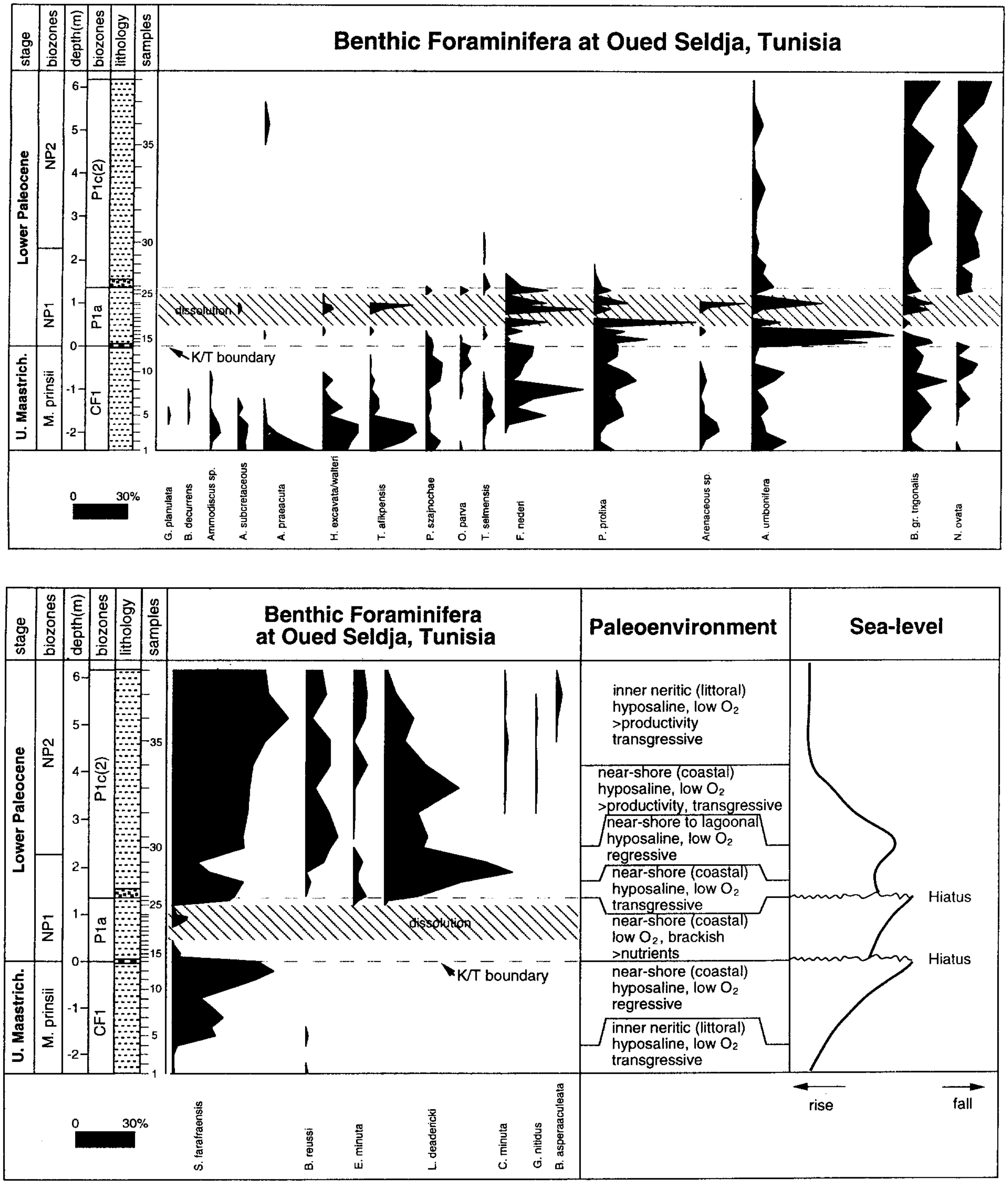

FIGURE 5 - **a.** Ranges and relative abundances of Cretaceous benthic foraminifera across the K/T transition at Oued Seldja. Note the assemblage changes during the latest Maastrichtian and early Danian suggest variations in salinity, oxygen and water depths between inner neritic to near-shore paleoenvironments. **b.** Ranges and relative abundances of Cretaceous benthic foraminifera across the K/T boundary at Oued Seldja continued. Paleoenvironment and sea-level changes are interpreted based on assemblage changes and inferred species affinities to inner neritic and coastal environments. ***a.*** *Répartitions et abondances relatives des foraminifères benthiques crétacés au passage K/T à Oued Seldja. Noter que les changements des assemblages durant le Maastrichtien terminal et le Danien inférieur suggèrent des variations de salinité, d'oxygénation et de profondeur entre les paléoenvironnements néritiques internes et littoraux.* ***b.*** *Répartitions et abondances relatives des foraminifères benthiques crétacés au passage K/T à Oued Seldja (suite). Les variations du paléoenvironnement et du niveau marin sont interprétées d'après les changements des assemblages et les affinités supposées des espèces pour les milieux néritiques internes et côtiers.*

*bulosa, H. dentata*). At the same time *Guembelitria* species are rapidly increasing to over 90% of the faunal assemblages in the early Danian (Fig. 4a). All of these species survived well into the early Danian zone Pla where they are truncated by a hiatus. These relative abundance and survivorship patterns are very similar to those observed at El Kef and suggest that a seaway remained open to the south well into the Danian.

## BENTHIC FORAMINIFERAL ASSEMBLAGES

A total of 30 benthic foraminiferal species were identified, though a number of arenaceous taxa could not be identified to species level because of poor preservation (Tab. 2, Figures 5a,b). Most of the species identified at Seldja have previously been illustrated by various authors from other shallow water Tunisian and Egyptian sections (e.g., Aubert & Berggren 1976; Saint-Marc & Berggren 1988; Saint-Marc 1992; Bou Dagher 1987; Luger 1985). One exception is a very small, but abundant morphotype *Fursenkoina nederi* Sliter which was first recognized and described by Sliter from the Rosario Formation of southern California (Sliter 1968, p. 112). Most of the species identified fall within the inner neritic, coastal and lagoonal bathymetric range as classified by Saint-Marc (1992, p. 481).

Benthic foraminiferal assemblages at Seldja mirror the same changes as those observed in planktic foraminifera. Among the common species, about half are restricted to the late Maastrichtian or early Danian zone Pla, six range through the studied interval, but show abundance variations in the earliest Danian, and six appear restricted to the Danian Plc zone (Fig. 5a,b). Strong variations in the relative abundances of these species imply changes in the environment. At the base of the section the assemblage is dominated by the low oxygen tolerant species *Anomalinoides praeacuta, Trochammina afikpensis* and *Haplophragmoides excavata/walteri.* Saint-Marc & Berggren (1988) interpreted this assemblage as inner neritic (littoral) based on correspondence analysis of eight Tunisian sections. At Seldja, additional common taxa within this assemblage are the low oxygen and low salinity tolerant species *Bulimina* gr. *trigonalis, A. umbonifera, Pyramidina prolixa* and *P. szajnochae* which are characteristic of nearshore or coastal environments (Saint-Marc & Berggren 1988). The transition from an inner neritic to near-shore assemblage occurs about 1.5 m below the K/T boundary as indicated by the decline of *A. praeacuta* and the *Haplophragmoides-Trochammina* group and increase in the *Bulimina-Pyramidina* group. This late Maastrichtian environmental change is accompanied by abundant (>60%) *Stainforthia farafraensis* and *Fursenkoina nederi,* morphotypes which thrive in low oxygen hyposaline nearshore and lagoonal environments (Aubert & Berggren 1976; Bou Dagher 1987). This suggests a generally low oxygen low salinity inner neritic environment shallowing to a near-shore coastal environment with a decreasing sea level during the last 100-200 kyr of the Maastrichtian (Zone CF1). At Seldja, sea level lowering culminates in erosion and deposition of a sandstone layer at or near the K/T boundary.

In the earliest Danian, between the K/T sandstone layer and Pla/Plc phosphate layer, *A. umbonifera* dominates (>90%) along with *F. nederi* and *P. prolixa*, though abundances are sporadic due to dissolution and generally decrease towards the top of this interval (Fig. 5a,b). This low diversity assemblage suggests increasing environmental stress possibly associated with a shallow, low oxygen and generally brackish coastal or lagoonal environment. A more stressful environment is also indicated by relatively low $\delta^{13}C$ values and may have resulted from increased riverine flux (abundant quartz), high rainfall and generally humid climate (discussed below). These conditions abruptly end with erosion and are followed by deposition of a sediment starved phosphate layer rich in post-depositional gypsum. Deposition of the phosphatic biofacies probably occurred in a transgressive open marine environment (Fig. 5b).

The Danian Plc(2) assemblage deposited in the first 60 cm above the phosphate layer is dominated by *Stainforthia farafraensis, Nonionella ovata, Epistominella minuta* and *Loxostoma deadericky* (Fig. 5a,b). Bou Dagher (1987) interpreted similar assemblages as indicative of restricted, hyposaline lagoonal to near-shore regressive facies. At Seldja this biofacies probably represents a nearshore hyposaline, low oxygen regressive environment similar to the latest Maastrichtian as indicated by similar biofacies, primary productivity, oxygen isotope trends (Fig. 6), as well as mineralogical values. Upsection in Plc(2), the benthic assemblages remain relatively constant, though *L. deadericky* decreases, *S. farafraensis* increases and additional low oxygen tolerant species appear (*Bulimina reussi, B.* gr. *trigonalis*) along with increasingly abundant wood and plant debris (Fig. 5a,b). This suggests a shallow, low oxygen, hyposaline near-shore environment though with increased surface productivity as suggested by increased carbon isotope values (Fig. 6). In the upper part of Plc(2), the reappearance of *A. praeacuta*, and the first occurrences of additional inner neritic species (*Gyroidina nitidus, Bulimina asperoaculeata, Caucasina minuta*) suggests a rising sea level and deepening to an inner neritic hyposaline low oxygen environment. The percentage of Danian planktic foraminifera in these Plc (2) sediments is

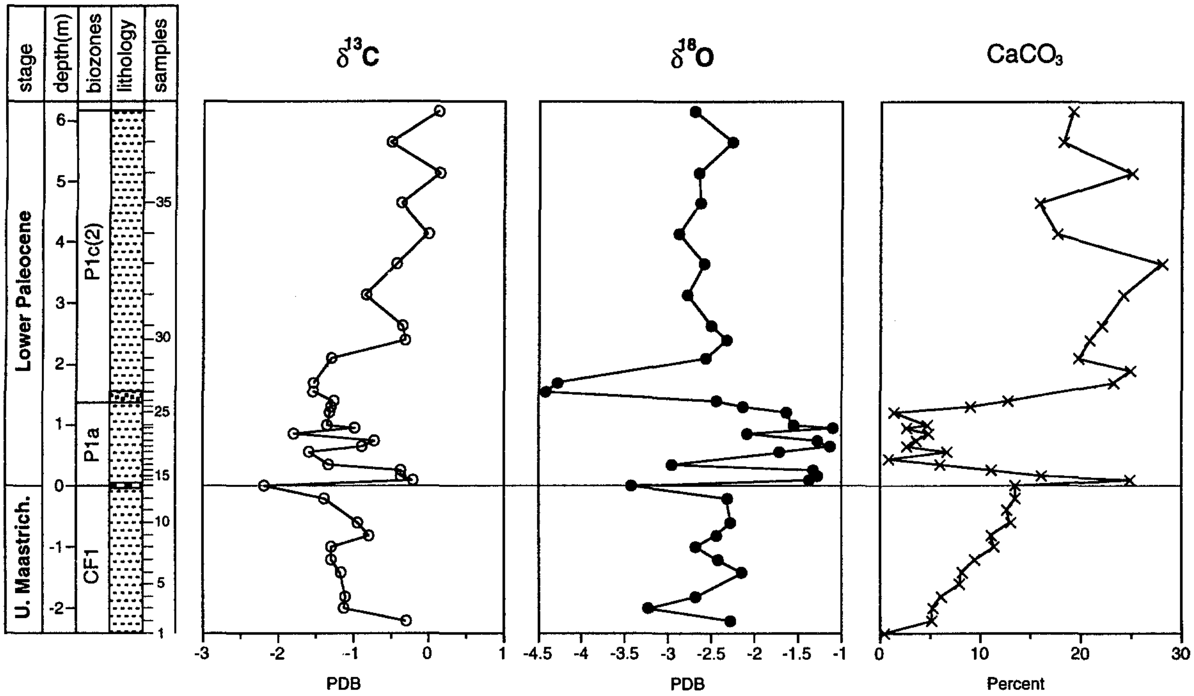

FIGURE 6 - $CaCO_3$, carbon and oxygen isotope records of bulk rock samples at Seldja. Note the pre-K/T boundary decline in carbon isotopes suggests decreased primary productivity near the end of the Maastrichtian. The absence of a major negative carbon-13 shift and the relatively high values during the early Danian (Pla) suggest that environmental conditions in this shallow water Tethys environment were less severe than for more open ocean environments. The rapid increase in Plc(2) signals the return to high productivity similar to the late Maastrichtian and is consistent with this event at El Kef and other open marine environments. Oxygen isotope trends suggest relatively warm late Cretaceous and early Danian climatic conditions. The cooler earliest Danian (Pla) signal may be unreliable because the $CaCO_3$ content is very low (2-6%) in this interval and may have provided insufficient gas. *Données pour $CaCO_3$ et les isotopes du carbone et de l'oxygène sur des échantillons de roches de Seldja. Noter que la chute du carbone isotopique avant la limite K/T suggère une baisse de la productivité primaire vers la fin du Maastrichtien. L'absence de variation négative importante pour le carbone 13 et les valeurs relativement élevées durant le Danien inférieur (Pla) suggèrent que les conditions environnementales dans ce milieu peu profond de la Téthys étaient moins sévères que celles des milieux océaniques ouverts. L'accroissement rapide dans Plc(2) indique le retour d'une productivité élevée identique à celle du Maastrichtien supérieur et s'accorde avec cet événement à El Kef et d'autres milieux océaniques ouverts. Les tendances de l'isotope d'oxygène suggèrent des conditions relativement chaudes pour le Crétacé supérieur et le Danien inférieur. Le signal de rafraîchissement au Danien basal (Pla) peut être non significatif car la teneur en $CaCO_3$ est très faible (2-6%) dans cet intervalle et peut avoir fourni insuffisamment de gaz.*

high which suggests high surface productivity and a connection to the open sea.

## STABLE ISOTOPES

Bulk rock samples were analyzed for all lithologies including the carbonate-poor clayey layers between the K/T sandstone and early Danian phosphate. The Seldja bulk rock $\delta^{13}C$ record is similar to the benthic record at El Kef (Keller and Lindinger 1989) because the carbonate fraction is dominated by benthic foraminifera with planktic foraminifera and nannofossils relatively minor constituents. However, these two sections also differ in important aspects. During the latest Maastrichtian, $\partial^{3}C$ values average -1 to -1.2 permill (Fig. 6) and are comparable to the benthic values for the same interval at El Kef. Though during the last 80 cm of the Maastrichtian $\partial^{13}C$ values decreased by 1.5 permill and suggest decreasing productivity (Fig. 6). Within the K/T sandstone layer and the first 10 cm clayey shale above it, $\partial^{13}C$ values average -0.3 permill, or nearly 2 permill heavier than during the underlying Maastrichtian. In contrast, surface and bulk rock values generally decrease by 2-3 permill at the K/T boundary in low to middle latitudes (Zachos et al. 1989). Above this positive excursion at Selja and through the early Danian Zone Pla (NP1), $\partial^{13}C$ values average -1.3 permill and are comparable to the late Maastrichtian preceding the 1.5 permill decrease. In Zone Plc (NP2), 2 m above the K/T boundary, $\partial^{13}C$ values rapidly increase by 2 permill. This increase coincides with a sea-level transgression and the evolution of the first high diversity and abundant Danian planktic foraminiferal assemblages globally and has been interpreted as the post-K/T recovery in primary productivity (Keller & Lindinger 1989; Zachos et al. 1989).

The major differences between Seldja and El Kef are thus in the decreasing latest Maastrichtian $\partial^{13}C$ values and the absence of a major negative excursion at the K/T boundary. The former suggests that productivity declined prior to the K/T boundary, and the latter implies that productivity was not severely affected by the K/T boundary event. The absence of the negative carbon excursion is not likely due to the short hiatus at Seldja because at El Kef this excursion lasted well into the early zone Plc and hence should be recorded at Selja in zone Pla. It is more likely that the absence of this negative excursion at Seldja is due to the fact that bulk rock carbonate at Seldja during the early Danian Pla consists primarily of benthic foraminifera and hence measures largely bottom water productivity which did not decrease across the K/T transition at El Kef or elsewhere (Keller & Lindinger 1989; Zachos et al. 1989). It is also possible that the high earliest Danian values are biased due to the presence of reworked Cretaceous planktic foraminifera and nannofossils. Though the relative abundance patterns of benthic foraminifera do not indicate major reworking in this group (Fig. 5a,b) and $\partial^{13}C$ values below the disconformity at the base of the sandstone layer from which reworking likely occurred are significantly lower. These differences between El Kef and Seldja may also be due to their respective oceanographic settings. El Kef was located in an upper slope to outer shelf marine environment and subject to upwelling, whereas Seldja was located in a restricted inner neritic to coastal or lagoonal environment subject to nutrient influx from the continent. TOC values remained essentially unchanged during the late Maastrichtian and early Danian (Pla) and significantly increased only within the phosphate layer.

Though oxygen isotope values at Seldja are probably compromised by diagenetic alteration of

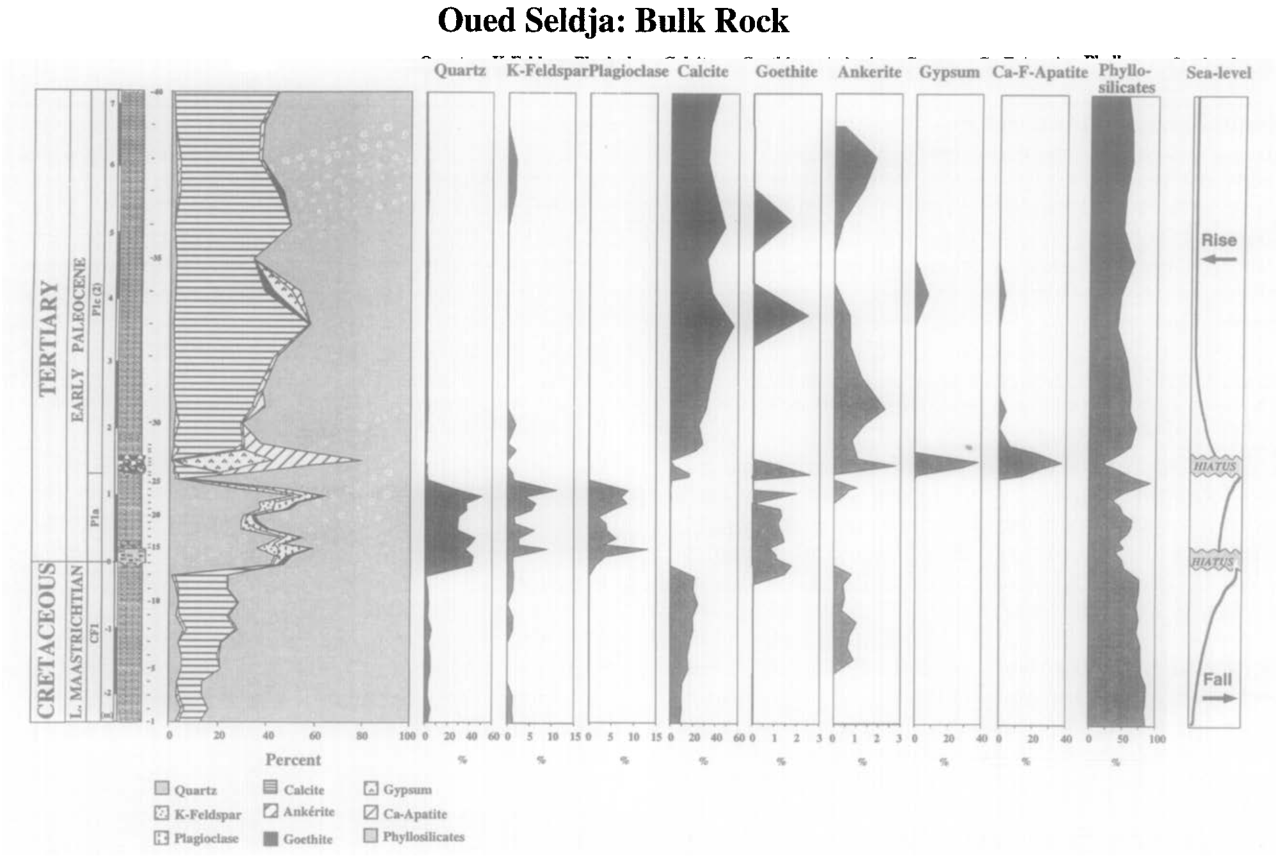
**Oued Seldja: Bulk Rock**

FIGURE 7 - Bulk rock mineral compositions and inferred sea-level changes across the K/T transition at Oued Seldja. Note the increase in quartz and feldspars between the K/T sandstone and early Danian phosphate layers (Pla/Plc) suggest low sea-levels and enhanced erosion. Peak abundance of apatite in the phosphate layer suggests high nutrient levels and probably transgressive seas. *Composition minéralogique d'échantillons de roches et variations du niveau marin déduites au passage K/T à Oued Seldja. Noter l'accroissement en quartz et feldspaths entre le grès K/T et les couches phosphatées du Danien inférieur (Pla/Plc) suggérant de bas niveaux marins et une accentuation de l'érosion. Le pic d'abondance en apatite dans les couches phosphatées suggère des niveaux nutritifs élevés et probablement des mers transgressives.*

carbonate and therefore no absolute temperature values can be interpreted, general climatic trends are apparent. During the late Maastrichtian as well as early Danian Plc (NP2), $\partial^{18}O$ values average about -2.5 permill and are comparable to El Kef. During the earliest Danian Pla zone, $\partial^{18}O$ values average -1.5 permill (Fig. 6). Within the phosphate layer just above the Pla/Plc boundary and hiatus, values decrease to -4.5 permill probably as a result of meteoric waters. These $\partial^{18}O$ trends suggest similar late Maastrichtian and early Danian Plc(2) temperatures in the Seldja area, but a significantly cooler earliest Danian Pla interval. A cooler climate during the early Danian (Pla) has been observed in many marine sequences (e.g., Zachos & Arthur 1986). However, at Seldja the cooler early Danian (Pla) climate signal may be suspect due to salinity fluctuations as well as to insufficient gas for reliable measurements because bulk carbonate averages less than 5% in this interval.

## MINERALOGICAL ANALYSES

**Bulk Rock Composition** - Relative changes in bulk rock composition reflect variations in sediment source, intensity of weathering and erosion under arid and humid climates, and the variable influx of terrigenous sediments into the oceans during high and low sea levels. At Seldja the basal 50 cm of the section are marked by low calcite (<10%), low quartz (<5%) and low feldspar (<2%), but abundant phyllosilicates (>80%, Fig. 7). In the uppermost Maastrichtian (up to 50cm below the KT boundary), calcite increased to 20-25%, phyllosilicates decreased to 70% and a minor component of goethite (1%) is present, though quartz and feldspar remain low. A major change in bulk rock composition occurs between the disconformities at the K/T boundary sandstone and phosphate layer. In this interval calcite is nearly absent, phyllosilicates decreased to <50% whereas quartz increased to 30-50%, and feldspar and plagioclase increased significantly (up to 11% and 13% respectively). Another mineralogical change occurs in the overlying 25 cm thick silty phosphate layer. The lower 15 cm of this phosphate layer is marked by 16% calcite, low quartz and feldspar, 60% phyllosilicates and the first occurrence of phosphate (F-Ca apatite). The upper 10 cm are marked by increased phosphate (to 37%) which persists, though in decreasing abundance in the 30 cm above the phosphate layer. The relatively high gypsum (28-38%) near the top of the phosphate layer is of late diagenetic origin. In the shales above the phosphate layer phyllosilicates (60%) and calcite (40%) dominate.

These bulk rock compositions suggest changes in sea level or tectonic activity and erosion. For example, the increased influx of quartz, K-feldspar and plagioclase beginning at the K/T boundary indicates increased erosion of the nearby Kasserine Island due to a sea-level fall and/or tectonic activity. The phosphate enriched upper 10 cm of the phosphate layer indicate a condensed interval possibly during a rising sea-level (Föllmi 1990; Föllmi et al. 1992). The brief episode of early Danian phosphate deposition reflects the first invasion of nutrient-rich oceanic waters onto the Saharan platform; phosphate deposition dominates the upper Paleocene to Eocene sediments in the Metlaoui region. However, in the upper Danian zone Plc(2), the high calcite and phyllosilicates suggest that normal marine sedimentation resumed during a rising sea level (Fig. 7). These interpretations are in general agreement with the lithological observations, biostratigraphic inferences of hiatuses and the sea level changes interpreted from benthic foraminifera (Fig. 5b) and stable isotope data.

**TOC** - Total organic content (TOC) in sediments may reflect terrigenous influx or increased marine productivity. At Seldja, TOC values are low during the late Maastrichtian (<0.3%) and increased only slightly in the K/T sandstone layer and within the lower Danian zone Pla, or the lower part of zone Plc(2) (Fig. 8). A significant increase occurs within the phosphate layer (>1%) and a sustained increase to 0.4 to 0.6% occurs in the upper part of zone Plc(2). Because organic matter associated with phosphate and glauconite is generally marked by the high H/C ratios indicative of marine origin (Burollet & Oudin 1980), TOC in the phosphate layer suggests high nutrients and/or high productivity and an open marine environment. The 0.4-0.6% TOC values in the upper part of zone Plc(2) represent mean TOC values for the Paleocene-Eocene interval of Tunisia (Burollet and Oudin 1980) and hence suggest normal marine conditions. This interpretation is supported by the appearance of the first high diversity Danian planktic foraminiferal assemblages at Seldja as well as globally at this time.

**Clay Minerals** - Clay mineral assemblages reflect continental morphology and tectonic activity as well as climate evolution and associated sea-level fluctuations (Chamley 1989; Weaver 1989). Mica and chlorite are considered common byproducts of weathering reactions with low hydrolisis typical of cool to temperate and dry climates. Kaolinite is generally a byproduct of highly hydrolitic weathering reactions in constant warm humid climates. The presence of abundant smectite is generally linked to transgressive seas and warm climate with alternating humid and

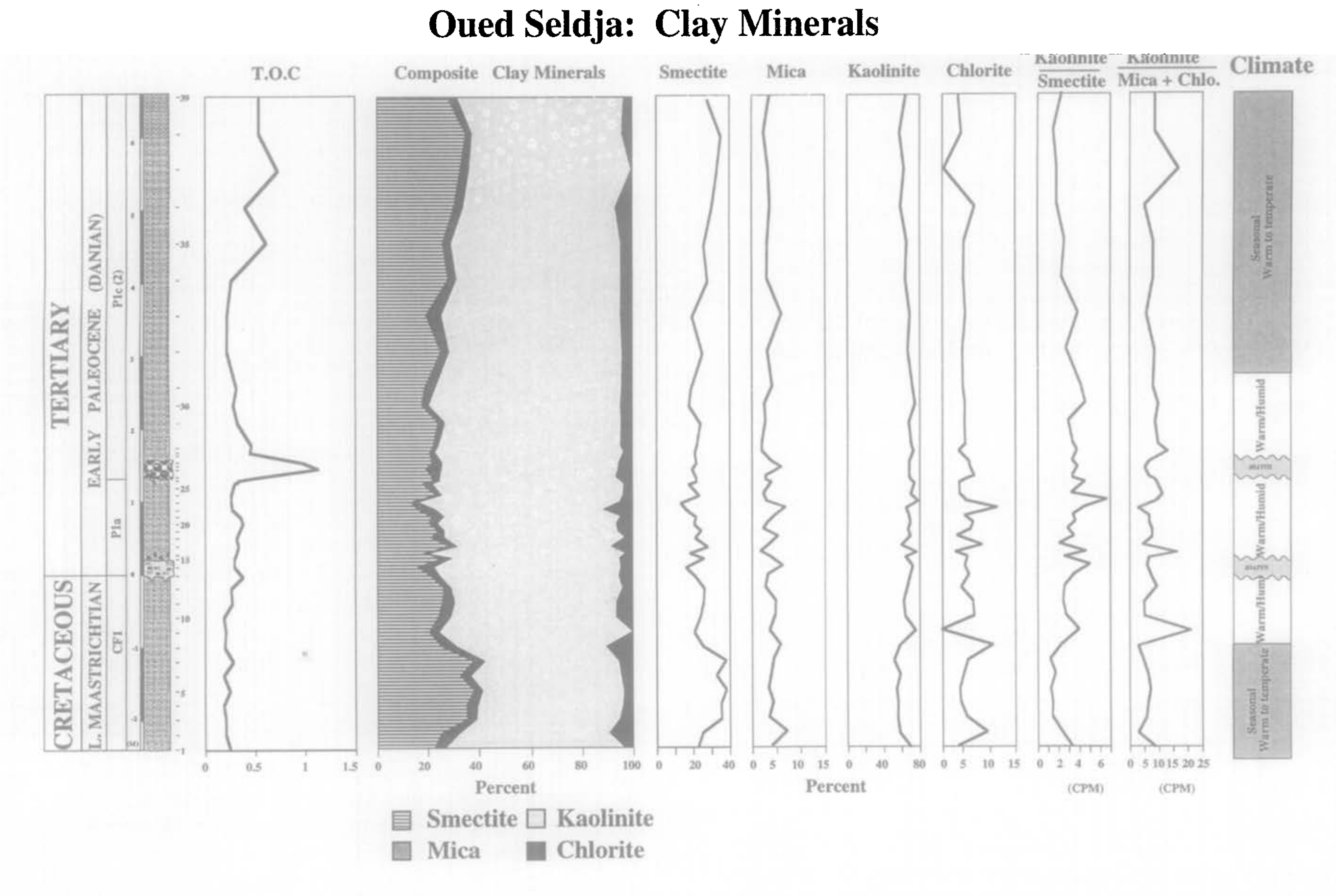

FIGURE 8 - Clay mineral compositions and inferrred climatic conditions across the K/T transition at Oued Seldja. See text for interpretations. *Composition en minéraux argileux et conditions climatiques déduites au passage K/T à Oued Seldja. Voir le texte pour les interprétations.*

arid seasons, but it can also reflect volcanic activity. Thus, the index of kaolinite/(chlorite+mica) represents an estimate of cold to temperate-dry and warm-humid climates, whereas the kaolinite/smectite index reflects climate variations from humid/warm to more seasonal.

During the latest Maastrichtian to early Danian, Seldja was located on a shallow marine platform with little hydrodynamic activity and hence little mineral segregation that could mask or exaggerate the climate signal (Adatte & Rumley 1989; Chamley 1989; Monaco et al. 1982). Since kaolinite and chlorite are more abundant in coastal areas and smectite in open marine environments, the kaolinite/smectite ratio is generally used as indicator for sea-level changes.

At Seldja the clay mineral assemblages are dominated by kaolinite (55-80%) and variable smectite (12-40%), but contain low chlorite (0-11%) and mica (2-6%, Fig. 8). Within this trend smectite reaches maximum mean values in the lower 1.1 m of the section and in the upper 3 m of subzone Plc(2). The low kaolinite/smectite (K/S) ratio in these two intervals suggests warm to temperate seasonal climatic conditions with a relatively high sea-level (inner neritic) during the latest Maastrichtian and during deposition of the upper part of the lower Danian subzone Plc(2) as also suggested by benthic foraminifera (Fig. 5b). Higher K/S ratios are observed beginning 1 m below the K/T boundary, within the lower Danian zone Pla and in the lower 1.5 m of subzone Plc(2). These intervals suggest the presence of a warm and humid climate with prolonged rainfall and relatively lower sea-level (coastal). The abundance of hyposaline benthic foraminifera (Fig. 5a,b) and the increased influx of detritus (Fig. 7) during these intervals suggest increased riverine runoff during sea-level lowstands.

## TRACE ELEMENT ANALYSIS

Finely ground bulk rock samples were analyzed by energy dispersive X-ray fluorescence (ED-XRF) for 24 elements including the trace elements Ni, Cu, Zn, Sr, Mo, Cd, Ba, La and Ce. Nearly all elements show considerable variations in their concentrations in the Seldja section. To aid the interpretation of environmental affinities, bulk rock and clay minerals were included in the data analysis. In a first attempt at evaluating patterns and interpreting environmental signals, the dataset was subjected to hierarchical cluster analysis of the Pearson correlation matrix and then processed by an R-mode factor analysis as discussed below.

**Hierarchical cluster analysis** - The dendrogram for the cluster analysis of the Pearson correlation matrix is given in Figure 9. Elements near the detection limit, or not clearly linked to other elements, are not in the correlation matrix. The dendrogram shows two characteristic groups of elements: one of a more biogenic carbonate origin (e.g., $\partial^{13}$C and $\partial^{18}$O; Sr, Ca and Ni; Cd and Zn), and the second of more terrigenous detrital origin (Ti, Ba, Zr, Nb, Ga, Pb, Rb, Fe, La, Ce, Th and Y). Within the latter group, Ga, Nb, Zr, Ba and Ti show very similar patterns at Seldja (Zr vs Ba, $r = 0.95$, Figure 10a). The low linkage of Cd and Zn to the biogenic growth is an indication that both elements are of biogenic and terrigenous origin. Ba is often used as indicator for nutrients, but detrital components can also be the main source for Ba in sediments. For example, Ga behaves geochemically similar to Al and is contained mainly in feldspars and clay minerals, whereas Nb-, Zr- and Ti-bearing minerals are resistant to weathering (Calvert et al. 1996). The covariation of Ba with these detrital components suggests that the major part of Ba at Seldja is of terrigenous origin and can not be used in this case as indicator for primary productivity.

Sr shows the closest covariance with Ca ($r = 0.81$, Fig. 10b) which indicates that the major part is of biogenic origin and the variations in the Sr/Ca ratio therefore reflect sea-level changes (Stoll & Schrag 1996; Li et al. in press). However, in intervals of very low $CaCO_3$ content, a considerable part of the Sr is likely to be of terrigenous origin. For example in zone Pla, the Sr/Ca ratios may have shifted in favor of Sr due to the Sr content in feldspars or clay minerals of terrigenous origin (Fig. 11).

Heavy metals (HM) can generally be used as indicator for primary production (Shen et al. 1987; Mongenot et al. 1996), especially if an increase in HM contents coincides with decreased $\partial^{13}$C values. However, HM/Ca- ratios can also be modified by detrital sediments and scavenging by Fe-Mn-oxides. At Seldja no correlation between Fe and Mn can be observed and generally high Zn/Ca ratios and Cd/Ca ratios (Fig. 11) occur together with low $\partial^{13}$C values. At very low $CaCO_3$ contents (e.g., zone Pla) these ratios shift due to coprecipitation of HM with Fe-Mn- oxides, or HM influx by detrital material.

**R-mode factor analysis** - The observations above are supported by R-mode factor analysis. This analysis includes, in addition to chemical and isotopic data, the semi-quatitative mineral composition of rock samples as determined by X-

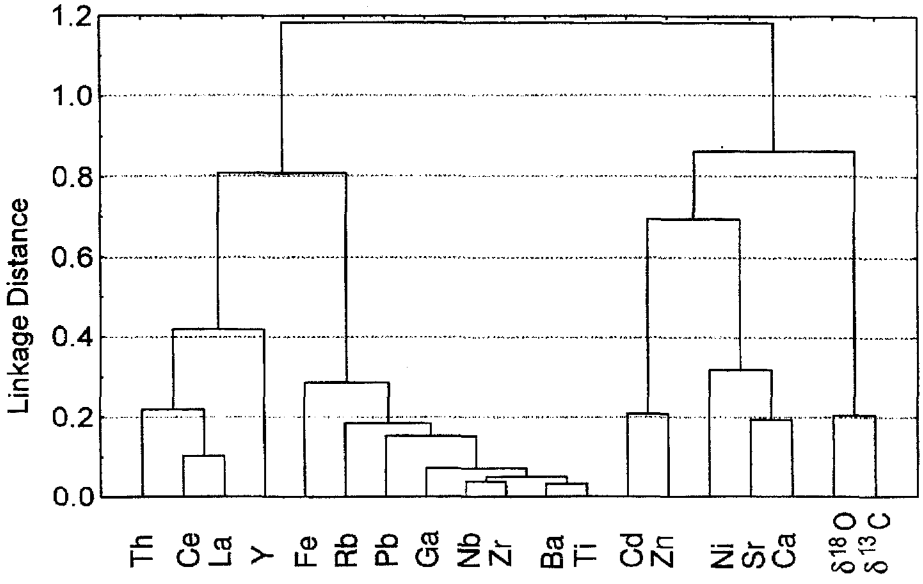

FIGURE 9 - Dendrogram for Pearson correlation coefficients (weighted pair group average) for 42 samples from the Seldja section. Unlinked elements and elements near the detection limit are removed. See text for discussion. *Dendrogramme pour les coefficients de corrélation de Pearson pour 42 échantillons de la coupe de Seldja. Les éléments non liés et ceux à la limite de détection sont supprimés. Voir le texte pour discussion.*

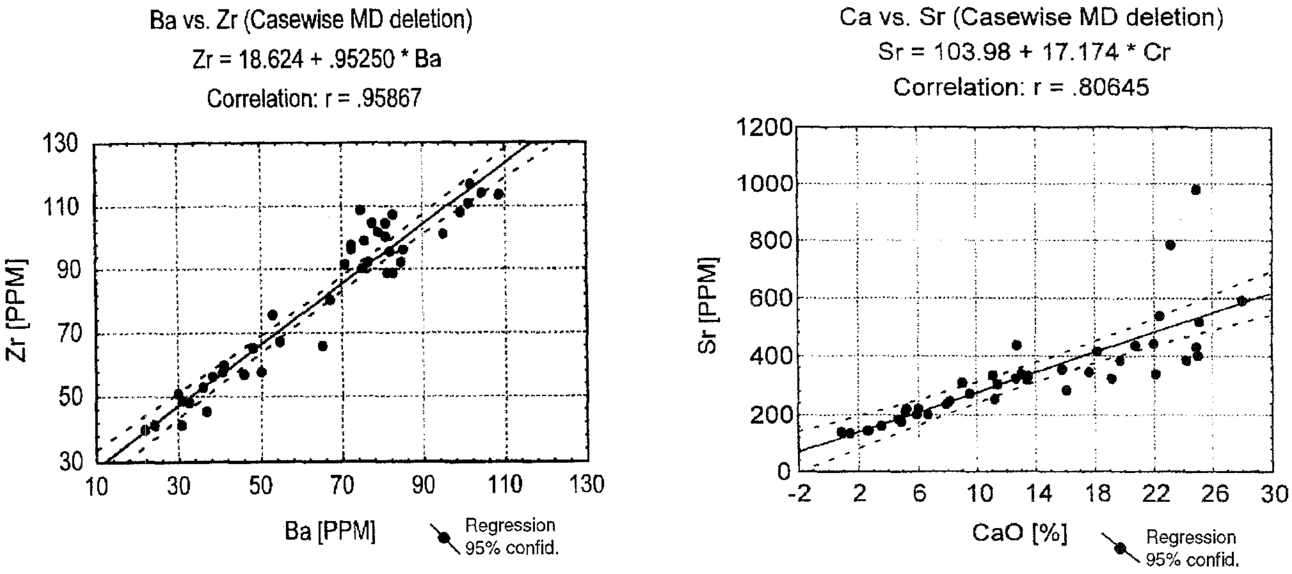

FIGURE 10 - Scatterplots for samples from the Seldja section. a) Ba and Zr. b) Sr and Ca. *Graphes de dispersion pour les échantillons de la coupe de Seldja. a) Ba et Zr. b)Sr et Ca.*

ray diffractometry. Though elements with concentration ranges close to detection limits (As, Mo, Ag, Sb) and some minerals with low contents and only sporadic occurrences were not included in this analysis. The mineral composition was measured from bulk rock samples, except for the clay minerals (mica, kaolinite, chlorite and smectite) which were measured from the <2 µm size fraction. In order to avoid induced correlation among the clay mineral phases which represent a tightly closed data array (just four parameters comprise 100%), the initial values were recalculated to give a sum which equals the amount of the phyllosilicates determined in the bulk samples. The analysis was performed using the statistical software package WINStatQ 3.1. The eigenvalue was set at 1.0 as a threshold in order to limit the number of extracted factors. The 31 initial parameters are reduced in this way to six factors, which account for 87.7% of the total variance. Factors can be interpreted from the loading of the parameters (loading close to ±1 are shaded in, Tab. 5) as discussed below.

**Factor 1** - This factor includes parameters related to the biogenic carbonate component (CaO, Ca, Sr, Ni) and accounts for 39.5% of the variance. In addition to the carbonate specific Sr, Ni is known to be incorporated in the skeletal part of some marine organisms through nutrients (Chester 1990). A set of other elements ($TiO_2$, Zr, Nb, Sn, Ba, Pb, Ga, Th, $Fe_2O_3$) have comparably high absolute loadings, but are opposite in sign. The association of these elements suggests a relation to the heavy mineral fraction of the detrital component which is mineralogically in amounts below the detection limit of XRD. These results suggest that factor 1 represents an efficient indicator for sedimentary environments. Low factor scores suggest relatively high erosion and near-shore deposition enhanced by heavy minerals, whereas high factor scores suggest periods of carbonate sedimentation and high productivity. The moderately high positive loading of $\partial^{13}C$ (indicative of higher primary productivity) and negative loading for detrital minerals (feldspars, quartz, phyllosilicates) further support this interpretation. In the context of the Seldja section, factor 1 suggests terrigenous influx of shaly and silty sediments due to enhanced erosion during sea-level lowstands.

**Factor 2** - This factor is characterized by Y, the REE (La, Ce) and the minerals apatite and gypsum respectively, and accounts for 16.0% of the variance. The element/mineral association is due to the fact that REE and Y are trace constituents of apatite. The generally high U content in some biogenic phosphate is here reflected by the relatively high loading for Th. In the context of the Seldja section, factor 2 represents the open marine environment in which the phosphate formed and subsequently diagenetic gypsum.

**Factor 3** - The mineralogic components of factor 3 illustrate two extremes of detrital sedimentation and account for 11.7% of the variance. One end member represents deposition of coarser sediments in near-shore environments which are composed of mechanically more resistant components (quartz) and feldspars (positive loading). The other end member represents predominantly

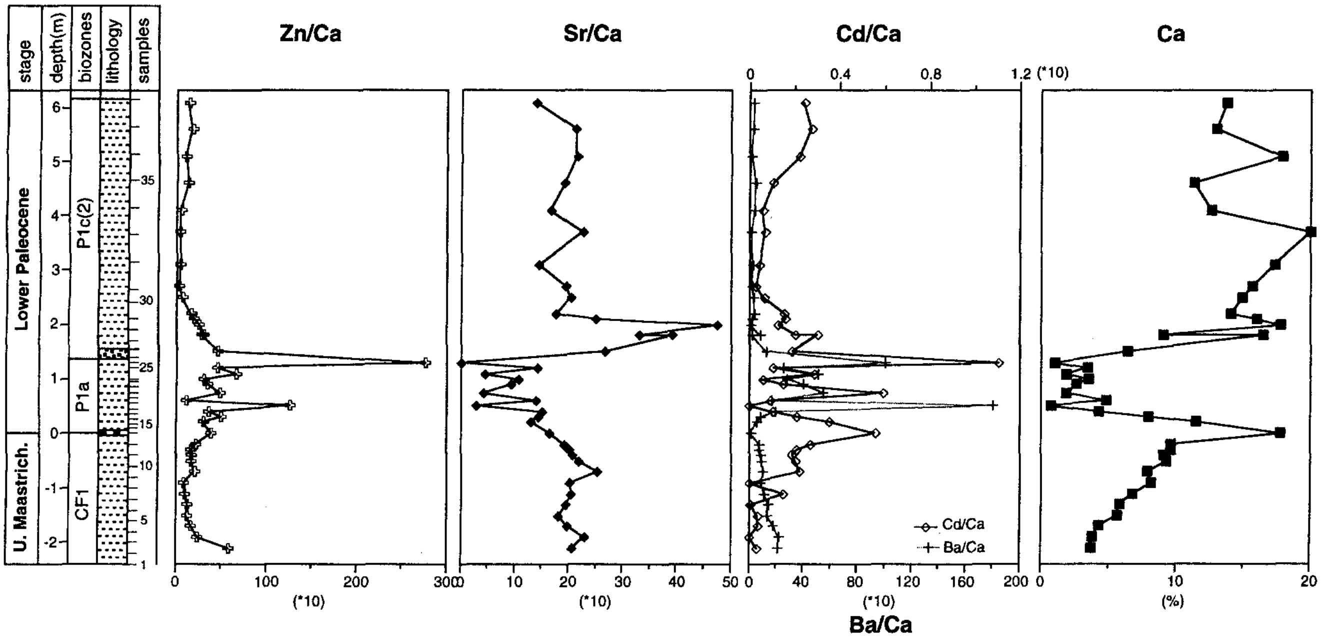

FIGURE 11 - Ratios of Zn/Ca, Sr/Ca, Ba/Ca and Cd/Ca in the Seldja section. Percent Ca is shown for comparison. Note that within the lower Danian Pla interval Ca is very low (5%) and trace element signals are generally compromised by terrigenous influx. *Rapports de Zn / Ca, Sr / Ca, Ba / Ca et Cd / Ca dans la coupe de Seldja. Le pourcentage de Ca est indiqué pour comparaison. Noter que dans l'intervalle Pla du Danien inférieur, le taux de Ca est très bas (5%) et que les signaux des éléments-traces sont généralement diminués par les apports terrigènes.*

sediment deposition in deeper waters (marls, negative loading). In the context of the Seldja section, positive loading of factor 3, or coarser sediment deposition, would occur at the K/T boundary and in the earliest Danian (Pla) (see Fig. 7).

**Factor 4** - This factor (7.6% variance) clusters the mineral components of the clay fraction <2 µm and therefore could be considered the equivalent of clay sedimentation. In the context of Seldja, this factor suggests high clay sedimentation in the late Maastrichtian and Danian zone Plc(2) (see Fig. 8).

**Factor 5** - This factor (6.6% variance) includes the well-known geochemical element association of Zn and Cd. Though in the absence of mineral phases, it is difficult to constrain the concrete sedimentological meaning. These elements could be related to some sulphidic components, with factor 5 indicating low oxygen conditions, or they could be scavenged by iron oxides/hydroxides and hence suggest the opposite conditions. However, the increased abundance of low oxygen tolerant benthic foraminifera associated with these elements suggests that factor 5 indicates low oxygen conditions.

**Factor 6** - Clustering of the oxygen and carbon isotope ratios as an independent factor 6 (6.1% variance) is a consequence of the relatively high correlation between them (r = 0.8). However, this high correlation is due to only two samples (Tab. 3, samples 5 and 11) in which the delta values are very low and the carbonate is diagenetically altered. For further comments see the section on Stable Isotopes.

## DISCUSSION

Our primary objective in this study was to evaluate the paleoenvironmental conditions across the Cretaceous-Tertiary transition in a shallow littoral to coastal setting at the edge of the Saharan platform, and more specifically to determine longterm and shortterm variations which may have been caused by terrestrial and extraterrestrial events respectively. Shallow nearshore depositional environments are difficult to interprete because they are strongly influenced by more factors than deeper water marine settings, including temperature, salinity, oxygen and nutrient fluctuations, terrigenous sediment influx, erosion, tectonic activity and eustatic sea-level changes. In addition, diagenetic alteration, chemical interaction, and mixing of terrestrial and marine parameters in various trace elements (e.g., Sr, Cd, Ba) further challenge paleoenvironmental interpretations. These challenges notwithstanding and to maximize the information obtainable, we utilized a multi-disciplinary approach that includes various faunal, mineralogical and geochemical studies.

TABLE 3 - Stable oxygen and carbon isotope analysis, Ca, Zn/Ca, Sr/Ca and Cd/Ca ratios across the K/T boundary at Oued Seldja, Tunisia. *Analyses pour l'oxygène stable et le carbone isotopique, le Ca et les rapports Zn/Ca, Sr/Ca et Cd/Ca au passage K/T à Oued Seldja.*

| Samples | Depth | Delta 13C | Delta 180 | Ca [%] | Zn/Ca | Sr/Ca | Cd/Ca |
|---|---|---|---|---|---|---|---|
| S40 | 7.20 | 0.720 | -2.796 | 17.9 | 7.2971 | 14.7909 | 0.1426 |
| S39 | 6.60 | 0.052 | -2.607 | 15.8 | 7.7972 | 12.7539 | 0.1448 |
| S38 | 6.10 | 0.134 | -2.699 | 13.7 | 13.6525 | 13.8603 | 0.2429 |
| S37 | 5.60 | -0.506 | -2.263 | 13.0 | 17.6668 | 21.4322 | 0.2761 |
| S36 | 5.10 | 0.158 | -2.654 | 17.9 | 10.0945 | 21.4923 | 0.2248 |
| S35 | 4.60 | -0.362 | -2.634 | 11.3 | 13.0216 | 19.2798 | 0.1088 |
| S34 | 4.10 | -0.004 | -2.881 | 12.6 | 5.1957 | 16.5938 | 0.0603 |
| S33 | 3.70 | -0.423 | -2.579 | 20.0 | 4.2023 | 22.6260 | 0.0714 |
| S32 | 3.10 | -0.840 | -2.781 | 17.3 | 4.1942 | 14.3567 | 0.0450 |
| S31 | 2.70 | -0.348 | -2.504 | 15.7 | 3.7550 | 19.5321 | 0.0292 |
| S30 | 2.50 | -0.306 | -2.329 | 14.9 | 6.7022 | 20.2818 | 0.0658 |
| S29 | 2.20 | -1.287 | -2.568 | 14.1 | 16.3147 | 17.5938 | 0.1561 |
| 528B | 2.00 | 0.024 | -2.686 | 16.0 | 19.3777 | 25.0704 | 0.1627 |
| 527B | 2.00 | -1.539 | -4.414 | 17.8 | 25.9389 | 47.4909 | 0.1310 |
| S28 | 1.80 | -1.530 | -4.291 | 16.5 | 28.3126 | 39.1233 | 0.3034 |
| S27 | 1.80 | -1.266 | -2.445 | 9.1 | 31.5070 | 33.0385 | 0.2072 |
| S26 | 1.50 | -1.303 | -2.131 | 6.4 | 46.6284 | 26.6035 | 0.1909 |
| S25 | 1.30 | -1.308 | -1.623 | 1.0 | 277.1016 | 0.0000 | 1.1057 |
| S24 | 1.20 | -1.344 | -1.556 | 3.4 | 46.7372 | 14.0988 | 0.1070 |
| S23 | 1.10 | -0.976 | -1.096 | 1.9 | 66.5587 | 4.4444 | 0.2888 |
| S22 | 1.00 | -1.794 | -2.077 | 3.5 | 30.7825 | 10.5965 | 0.0597 |
| S21 | 0.90 | -0.723 | -1.281 | 2.6 | 35.1464 | 9.2421 | 0.1479 |
| S20 | 0.75 | -0.879 | -1.134 | 1.9 | 49.5595 | 4.1011 | 0.5934 |
| S 19 | 0.60 | -1.591 | -1.714 | 4.8 | 11. 0427 | 13. 9110 | 0.0962 |
| S18 | 0.50 | -2.722 | -1.654 | 0.6 | 126.7841 | 2.8815 | 0.0000 |
| S 17 | 0.40 | -1.325 | -2.966 | 4.3 | 36.2908 | 15.0015 | 0.1053 |
| S 16 | 0.30 | -0.367 | -1.323 | 8.0 | 50.6533 | 14.2881 | 0.2125 |
| S15 | 0.20 | -0.372 | -1.276 | 11.5 | 30.1904 | 13.0206 | 0.3553 |
| S 14 | 0.00 | -0.209 | -1.372 | 17.8 | 39.0056 | 16.4739 | 0.5591 |
| S13 | -0.20 | -2.183 | -3.432 | 9.6 | 22.0342 | 19.1854 | 0.2742 |
| S 12 | -0.30 | -1.385 | -2.317 | 9.6 | 17.3030 | 20.2271 | 0.2137 |
| S11 | -0.40 | -5.265 | -10.744 | 9.1 | 17.2013 | 20.5995 | 0.1898 |
| S10 | -0.50 | -0.937 | -2.275 | 9.3 | 16.6721 | 21.7743 | 0.2040 |
| S09 | -0.70 | -0.797 | -2.448 | 7.9 | 20.5286 | 25.2519 | 0.2223 |
| S08 | -0.90 | -1.291 | -2.687 | 8.2 | 8.6409 | 20.1899 | 0.0000 |
| S07 | -1.10 | -1.296 | -2.428 | 6.8 | 10.1290 | 20.3699 | 0.1518 |
| S06 | -1.30 | -1.170 | -2.143 | 5.8 | 12.4552 | 19.4202 | 0.0069 |
| S05 | -1.50 | -6.018 | -12.158 | 5.7 | 12.1831 | 18.1318 | 0.0370 |
| S04 | -1.70 | -1.113 | -2.680 | 4.3 | 17.4051 | 19.7610 | 0.0391 |
| S03 | -1.90 | -1.128 | -3.235 | 3.8 | 23.9752 | 22.8854 | 0.0000 |
| S02 | -2.10 | -0.300 | -2.274 | 3.7 | 58.2840 | 20.5849 | 0.0350 |

Our first task was to determine the biostratigraphic age and completeness of the section which was done based on nannofossils and planktic foraminifera. The results indicate the presence of two short hiatuses, one at the K/T boundary and the other in the early Danian. Hiatuses at similar stratigraphic positions have been determined worldwide and mark global sea-level lowstands (MacLeod & Keller 1991a,b; Keller & Stinnesbeck 1996). At Seldja the K/T boundary hiatus spans at a minimum the lowermost Danian zone P0 (approximately 50 kyr) and at a maximum the lower part of zone Pla, P0 and the uppermost part of the latest Maastrichtian zone CF1 (approximately 150-200 kyr). The early Danian hiatus spans the lower part of zone Plc and zone Plb (approximately 150-250 kyr). Both hiatuses are marked by lithological disconformities, undulating erosional surfaces, rip-up clasts and truncated burrows. Critical to this study is the K/T boundary hiatus because any direct impact signal (e.g., Ir, spinels, spherules, red layer, clay) that may have been present was eroded. The Seldja section therefore can not address the shortterm effects of the impact event. However, longterm trends beginning before and continuing long after the K/T boundary event can be evaluated.

Within these limitations we evaluated the faunal turnover and extinction pattern in planktic foraminifera, the microfossil group most severely affected by the K/T boundary mass extinction (Figs 4a,b). The mass extinction eliminated generally large, ornate, tropical and subtropical taxa which lived at depths at or below the thermocline (for a review see Keller 1996). At Seldja, there is no clear mass extinction pattern because these extinction-prone taxa are rare and only sporadically present in this shallow water environment.

Though they comprise about half of the species, they are less than 10% in combined relative abundance, and most disappear at or below the K/T boundary hiatus. Their last appearances most likely represent marine incursions, rather than extinctions. However, the faunal turnover pattern of the dominant fauna is similar to that in deeper water environments to the north (El Kef, Elles), though relative species abundances differ. Most notable is the similarity in the Cretaceous survivor fauna which is dominated by environmentally tolerant biserial and triserial species that range well into the early Danian zones Pla to Plc. This fauna survived the K/T boundary event worldwide (MacLeod & Keller 1994) and is particularly abundant in high latitudes and shallow seas. The latter is the probable reason for their success at Seldja where this group dominated (>90%) the faunal assemblages during the late Maastrichtian. However, biserial taxa begin to decline and triserial taxa to dominate during deposition of the last meter below the K/T boundary. This suggests increasing environmental stress beginning well before the K/T boundary impact event.

Sea-level, climate and productivity fluctuations appear to be the major external causes for biodiversity variations at Seldja, with low sea-levels, warm humid climate and low productivity generally associated with decreased diversity. This is clearly observed in both planktic and benthic foraminifera at Seldja where species richness dramatically declined during the latest Maastrichtian (50-100 cm below KT), remained low during the time of low sea-levels and low productivity of the early Danian (Pla), and returned to normal late Maastrichtian levels with the rising sea level and rising productivity during Danian zone Plc(2) (Fig. 12). Though the effects of oxygen on biodiversity are less well understood, the Seldja section suggests that oxygen (based on low oxygen tolerant faunas and the association of Zn and Cd, see R-mode factor 5) remained low at times of low productivity and was highest at times of sea level inflection points (Fig. 12). Biotic effects of salinity changes (here inferred from benthic faunas and rainfall inferred from clay minerals) are poorly understood, though low salinity trends mirror low sea-level and low productivity conditions. This suggests that on the shallow Saharan platform adverse environmental conditions beginning in the latest Maastrichtian and including freshwater influx, low oxygen, low sea-levels and decreasing productivity, conspired against the survivorship of the tropical Cretaceous fauna.

Sea-level changes can be evaluated by a number of faunal, geochemical, and mineralogical proxies, though the signal may be overprinted by tectonic activity and diagenesis. For the Seldja section we

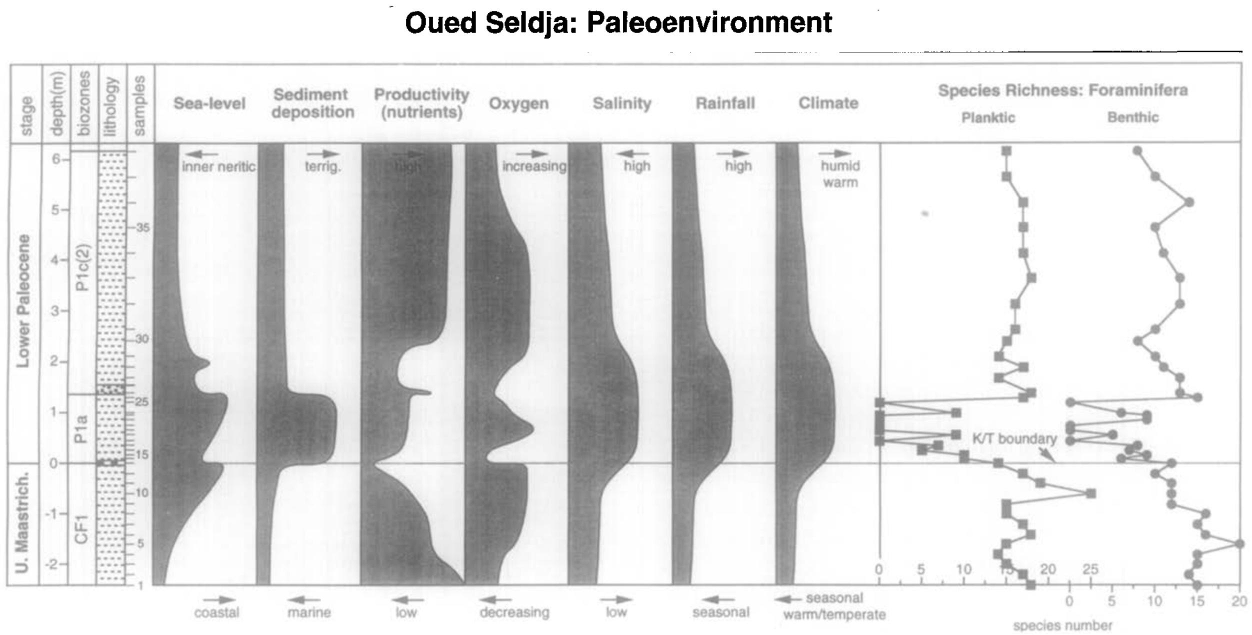

FIGURE 12 - Summary graph of paleoenvironmental conditions across the K-T transition at Seldja as interpreted from faunal, mineralogical, geochemical and trace element studies. Note that in the shallow Saharan platform region of Tunisia low sea-levels, low productivity and low species richness generally coincide with high rainfall and humid/warm climates, low salinity, low oxygen and high terrigenous influx. *Graphique résumant les conditions paléoenvironnementales au passage K/T à Seldja, interprétées d'après les études fauniques, minéralogiques, géochimiques et des éléments-traces. Noter que sur la plate-forme saharienne peu profonde de Tunisie les bas niveaux marins, la faible productivité et la faible richesse spécifique coïncident généralement avec une forte pluviosité et des climats chauds et humides, une faible salinité, une faible oxygénation et d'importants apports terrigènes.*

| | factor loadings | | | | | | |
|---|---|---|---|---|---|---|---|
| | F1 | F2 | F3 | F4 | F5 | F6 | Communalities |
| CaO | 0,97 | 0,00 | -0,07 | -0,12 | 0,14 | 0,02 | 0,97 |
| $TiO_2$ | -0,96 | -0,08 | 0,04 | 0,14 | -0,15 | -0,01 | 0,97 |
| Ga | -0,95 | -0,05 | 0,09 | 0,11 | -0,14 | -0,04 | 0,94 |
| Ba | -0,95 | -0,05 | 0,09 | 0,13 | -0,16 | -0,01 | 0,95 |
| Zr | -0,93 | -0,05 | -0,10 | 0,17 | -0,15 | -0,13 | 0,95 |
| Nb | -0,92 | -0,15 | -0,07 | 0,19 | -0,13 | -0,05 | 0,93 |
| Ni | 0,84 | -0,20 | -0,18 | -0,15 | -0,15 | 0,08 | 0,83 |
| $Fe_2O_3$ | -0,83 | 0,14 | 0,39 | 0,08 | 0,19 | 0,05 | 0,89 |
| Pb | -0,83 | -0,28 | 0,02 | 0,05 | -0,34 | -0,03 | 0,88 |
| Rb | -0,82 | -0,20 | 0,28 | -0,04 | -0,14 | -0,01 | 0,81 |
| Sr | 0,79 | 0,54 | -0,13 | -0,17 | 0,08 | -0,05 | 0,96 |
| Sn | -0,77 | -0,09 | 0,09 | 0,24 | 0,02 | -0,12 | 0,68 |
| calcite | 0,73 | -0,35 | -0,41 | -0,13 | -0,28 | 0,02 | 0,92 |
| Th | -0,72 | 0,60 | 0,07 | -0,03 | -0,08 | -0,18 | 0,92 |
| Y | 0,16 | 0,94 | -0,00 | -0,13 | 0,25 | -0,05 | 0,98 |
| apatite | 0,33 | 0,86 | -0,05 | -0,18 | 0,07 | -0,06 | 0,89 |
| La | -0,38 | 0,84 | 0,05 | -0,01 | 0,17 | -0,01 | 0,88 |
| gypsum | 0,29 | 0,79 | 0,03 | -0,02 | -0,17 | -0,04 | 0,73 |
| Ce | -0,55 | 0,75 | 0,12 | 0,04 | 0,23 | -0,02 | 0,94 |
| plagioclase | -0,31 | -0,03 | 0,90 | 0,01 | 0,07 | 0,07 | 0,91 |
| quartz | -0,38 | -0,05 | 0,81 | 0,09 | 0,22 | 0,07 | 0,86 |
| phyllosilicates | -0,44 | -0,13 | -0,81 | 0,13 | 0,04 | -0,10 | 0,89 |
| K-feldspar | -0,40 | -0,01 | 0,75 | -0,11 | 0,03 | 0,05 | 0,74 |
| smectite | -0,15 | -0,35 | -0,50 | 0,42 | -0,01 | -0,24 | 0,63 |
| mica | -0,19 | -0,09 | -0,08 | 0,90 | 0,03 | -0,05 | 0,87 |
| chlorite | -0,20 | -0,01 | 0,06 | 0,84 | -0,20 | -0,02 | 0,80 |
| caoline | -0,28 | -0,39 | -0,27 | 0,55 | 0,27 | 0,02 | 0,67 |
| Cd | 0,50 | 0,02 | 0,15 | -0,01 | 0,81 | 0,04 | 0,94 |
| Zn | 0,26 | 0,42 | 0,16 | -0,12 | 0,79 | 0,08 | 0,91 |
| $\delta^{18}O$ | -0,11 | -0,06 | 0,22 | -0,03 | 0,06 | 0,95 | 0,97 |
| $\delta^{13}C$ | 0,34 | -0,11 | 0,04 | -0,06 | 0,03 | 0,91 | 0,96 |
| percent of variance | 39,55 | 16,07 | 11,67 | 7,68 | 6,61 | 6,12 | 87,70 |

TABLE 4 - Factor analysis of trace elements across the K/T boundary at Oued Seldja, Tunisia. *Analyse factorielle des éléments-traces à la limite K/T à Oued Seldja, Tunisie.*

have used three proxies: benthic foraminifera (faunal associations of inner neritic vs. coastal), bulk rock compositions (terrigenous influx suggests erosion and nearshore deposition), and Sr/Ca ratios (reflecting eustatic sea-level changes).

Benthic foraminiferal assemblages indicate a change from an inner neritic to coastal environment during the latest Maastrichtian, a nearshore coastal environment during the early Danian (Pla) and a return to offshore inner neritic depths during the middle Danian (Plc, Fig. 5b). Bulk rock compositions generally support this sea-level history (see also R-mode factors 1and 2) and show a strong influx of terrigenous sediments (quartz, feldspars) during the early Danian (Pla) and predominantly carbonate deposition during offshore inner neritic phases (Fig. 7). Sr/Ca ratios, which reflect eustatic sea-level changes in the deep-sea where Ca is predominantly of biogenic origin (Stoll & Schrag 1996; Li et al. in press), confirms the faunal and mineralogical proxies indicating rising seas during the late Maastrichtian and Danian (Plc(2), Fig. 12). Though in nearshore environments, such as during the earliest Danian (Pla), this method must be applied with caution because of the influx of Sr from terrigenous sources (e.g., Sr in feldspars and clays) and very low (<5%) $CaCO_3$ content which results in the opposite signal at Seldja. Though Sr/Ca ratios and benthic faunas also indicate a strong sea-level regression in the lower part of Plc(2) above the phosphate layer. In addition, a good correlation is observed between high sea-levels and high positive $d^{13}C$ values and low sea-levels and negative values related to detrital influx (see also R-mode factor 3). Though sea-level changes at Seldja may be influenced by tectonic activity of the Kasserine Island, this appears not to have been a major influence during the K/T transition.

Oxygen isotopes are most commonly used as climate and temperature proxies, though in the diagenetically altered carbonate at Seldja only climatic trends can be interpreted. However, climate is also generally related to sea-level changes as well as weathering and erosion. Thus clay minerals provide a useful proxy for cool to temperate and dry climates (mica and chlorite), warm humid climates (kaolinite), and alternating humid and arid seasons (smectite, Fig. 8). At Seldja, climatic trends interpreted from clay minerals and oxygen isotopic trends generally support each other and suggest seasonal warm to temperate climates coinciding with high sea-levels during the late Maastrichtian and Danian zone Plc(2), and warm/humid climates with high rainfall correlating with low sea-levels in the earliest Danian zone Pla (Fig. 12).

This multi-disciplinary approach revealed the power of interdisciplinary studies to decipher the complex environmental conditions that prevailed during the Cretaceous-Tertiary transition. Though each discipline revealed environmental information, the veracity of interpretations was significantly strengthened by corroborating data from other disciplines, and original interpretations in some cases proofed misleading. Despite some gaps in the Seldja record due to two short hiatuses, a relatively complete environmental history could be determined. Direct comparison of this paleoenvironment with other sections is not possible at this time because no such integrated multi-disciplinary studies exist for other sections. However, individual faunal, isotopic and sea-level records do exist for many other K/T sections and offer a basis for comparison. The planktic foraminiferal K/T record was recently summarized by Keller (1996) and shows very similar low latitude trends as at Seldja. The only significant difference is the lower abundance and presence of deeper dwelling large, tropical species during the late Maastrichtian at Seldja. The history of eustatic sea-levels across the K/T transition was summarized by Keller and Stinnesbeck (1996) and shows the same sea-level pattern as at Seldja, suggesting that local tectonic activity of the Kasserine Island was not a major influence at this time.

## SUMMARY AND CONCLUSIONS

On the shallow Saharan platform of southern Tunisia, a normal inner neritic marine environment shallowed to a nearshore environment during the last 100-200 kyr of the Maastrichtian. This shallowing was accompanied by a warm/humid climate with increased rainfall, lower salinity and decreased productivity, and significantly decreased biodiversity in both benthic and planktic foraminifera. Near the K/T boundary the sea-level regression culminated in erosion and deposition of a sandstone layer. During the earliest Danian (Pla), low sea-levels prevailed with continued low oxygen, low salinity, high rainfall, high erosion and terrigenous sediment influx, accompanied by low diversity, low oxygen and low salinity tolerant species. These environmental conditions abruptly ended with erosion followed by deposition of a phosphatic siltstone layer that represents condensed sedimentation in an open (transgressive) marine environment. Above this layer, low sea-levels and a return to near-shore, hyposaline and hypoxic conditions prevailed for a short interval (base of Plc(2) and are followed by the re-establishment of normal open marine conditions (inner neritic) comparable to the late Maastrichtian base of the section. This marine transgression is accompanied by increased productivity and TOC, and the first diversified foraminiferal assemblages after the K/T boundary event and represents the return to normal biotic conditions.

The results of this multi-disciplinary study indicate that longterm environmental changes, beginning in the latest Maastrichtian (last 200 kyr) and continuing through the early Danian, resulted in a highly stressed physical and biotic environment at the edge of the Saharan platform. Sea-level fluctuations, climate changes and variations in salinity, oxygen, and nutrients were the primary stress inducing factors that lead to the faunal turnover across the Cretaceous-Tertiary transition. There is no evidence of catastrophic effects of a bolide impact at Seldja partly because some sediments that may have contained such evidence are missing due to a short hiatus (P0 missing). However, the absence of the K/T boundary clay does not hinder the evaluation of the biotic consequences across the K/T transition, whether due to a bolide impact or other environmental stresses, because survivor taxa are present above the K/T boundary and extinct taxa are not. Planktic foraminifera, the group most severely affected by the K/T boundary event globally, began to decline both in number of species and population size during the last 100-200 kyr of the Maastrichtian. Survivor species comprised 90% of the total population during this time and continued to dominate during the early Danian (Pla), though their relative abundance decreased. The return to normal faunal assemblages occurred about 500 kyr after the K/T boundary (Plc) coincident with the return of high primary productivity, rising sea-levels and open marine conditions.

Though the K/T Seldja section represents one of the most shallow marginal sea environment studied to date for this interval, it does not appear to represent isolated or atypical conditions. This is suggested by the global trends observed in sea-level fluctuations, hiatuses, as well as faunal assemblages. We conclude that on the Saharan platform of southern Tunisia, longterm environmental stresses beginning 100-200 kyr before the K/T boundary and related to climate, sea-level, nutrient, oxygen and salinity fluctuations were the primary causes for the eventual demise of the Cretaceous fauna in the early Danian. The K/T boundary bolide impact appears to have had a relatively incidental shortterm effect on this marine biota.

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