The Cretaceous-Palaeogene (K/P) boundary in the Aïn Settara section (Kalaat Senan, Central Tunisia): lithological, micropalaeontological and geochemical evidence

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Abstract

The Cretaceous-Palaeogene (K/P) boundary, until recently known as the "Cretaceous-Tertiary" or K/T boundary, is well exposed at Aïn Settara in the Kalaat Senan area (Central Tunisia), 50 km south of the El Kef section. Micropalaeontological and geochemical studies led to the identification of six main features tentatively named "events", which characterise the K/P boundary interval, and of which at least two (B and C) have global significance. The lowermost event A located at about 14 cm below the base of the Dark Boundary Clay is marked by a sudden increase in tiny bioturbations, by small nodules and a few macrofossils, a 50% drop in calcareous nannofossil abundance and an increase in Scytinascias (organic linings of foraminifera). It is thought to witness a slowdown in sedimentation. Event B is characterised by a burrowed surface, separating the ca 60-cm thick Dark Boundary Clay from the underlying Aïn Settara marls. It indicates an episode of non-deposition, just before a major change in lithology from marls to clays, corresponding to a major flooding. No substantial palaeontological changes have been recorded in relation to this event. Event C is characterised by maximum concentrations of Ir and Ni-rich spinels, which have been observed in platy nodules, similar to the level at El Kef (K/P boundary *sensu* ODIN, 1992). It coincides with a major extinction in planktonic foraminiferal species (71%) and a 60% drop in nannofossil abundance. The change in lithology (occurrence of small ripples and channel-like structures) recorded at event D, a few cm up-section, might be related to a locally recorded storm activity. Events E and F, which are situated higher up in the Dark Boundary Clay, are mainly determined by palaeontological changes (palynomorphs and nannofossils), probably resulting from small sea-level variations. The coincidence of the cosmic markers with the major biotic changes at event C pleads for the asteroid impact hypothesis. Their disjunction from the base of the Dark Boundary Clay shows that the change of lithology usually used to determine the K-P boundary is distinct from the major extinction (in the planktonic realm), classically referred to this boundary and linked to the presence of cosmic markers. These results argue the need for the revaluation of the K-P boundary GSSP at El Kef. It is suggested to redefine the K-P boundary at the level of coincidence of the major biotic changes and the cosmic markers.

Key words: K/P boundary, Aïn Settara, Tunisia, lithology, micropalaeontology, geochemistry

Résumé

La limite Crétacé/Paléogène (K/P), connue jusqu'à maintenant comme la limite "Crétacé/Tertiaire" (K/T) est particulièrement bien exposée à l'Aïn Settara dans la région de Kalaat Senan, quelques 50 km au sud de la section type d'El Kef. Une étude pluridisciplinaire micropaléontologique et géochimique de l'intervalle de la limite K/P aboutit à l'identification de six événements, parmi lesquels deux au moins (B et C) ont une signification globale. Le plus inférieur, l'événement A, localisé à 14 cm en dessous de la limite K/P, est marqué par quelques petites concrétions et de rares petits macrofossiles, par une chute de 50% de l'abondance des nannofossiles calcaires et par une augmentation des Scytinascias (restes organiques de foraminifères). Il est rapporté à une réduction du taux de sédimentation dont l'origine reste jusqu'à présent incertaine. L'événement B, à 3 cm en dessous de la limite K/P, est caractérisé par une surface bioturbée qui sépare les 60 cm de l'Argile Limite des marnes de l'Aïn Settara sous-jacentes. Il indique un épisode de non-dépôt, précédant immédiatement le début d'une transgression majeure, globalement reconnue. Aucun changement paléontologique n'est enregistré à ce niveau. L'événement C est caractérisé par des concentrations maximales d'iridium et de spinelles nickelifères apparaissant dans les nodules jarositiques aplatis qui marquent la limite K/P comme au Kef (la limite K/P *sensu* ODIN, 1992). Il coïncide avec une extinction majeure des espèces de foraminifères planctoniques (71%) et avec une chute de 60% de l'abondance des nannofossiles. Le changement lithologique (petits chenaux et rides) enregistré par l'événement D, quelques cm plus haut, est relié à un dépôt de tempête de signification locale. Les événements E et F, qui prennent place plus haut dans l'Argile Limite sont essentiellement revelés par des modifications paléontologiques (palynomorphes et nannofossiles) et résultent probablement de légères fluctuations du niveau marin. La coïncidence des marqueurs cosmiques avec les changements biotiques majeurs à la limite K/P de l'Aïn Settara plaide pour l'hypothèse de l'impact météoritique. Leur séparation par rapport à la base de l'Argile Limite indique que la succession est légèrement plus complète qu'au Kef, ce qui justifierait une réévaluation du stratotype de la limite K/P et du Point Stratotype Global (PSG). Il paraît maintenant opportun de redéfinir la limite K/P au niveau où coïncident les changements biotiques majeurs et les marqueurs cosmiques.

Mots-clefs: la limite K/P, Aïn Settara, Tunisie, lithologie, micropaléontologie, géochimie

Introduction

After 20 years of intensive research, much debate and controversy, the Alvarez impact hypothesis (ALVAREZ *et al.*, 1980, 1982) has been widely accepted to explain the anomalously high abundances of iridium and the mass extinctions recorded in some microfossil groups at the palaeontologically identified Cretaceous/Palaeogene (K/P) boundary, until recently known as the K/T boundary (SMIT & HERTOGEN, 1980; KELLER & BARRERA, 1990; several papers in SILVER & SCHULTZ, 1982, in SHARPTON & WARD, 1990 and in RYDER *et al.*, 1996; ROCCHIA & ROBIN, 1998). However, other phenomena, such as the sudden release of large amounts of volcanic ashes and gasses and major sea-level changes, have also been invoked for mass extinctions (COURTILLOT, 1994; GLASBY & KUNZENDORF, 1996). The discovery of Ni-rich

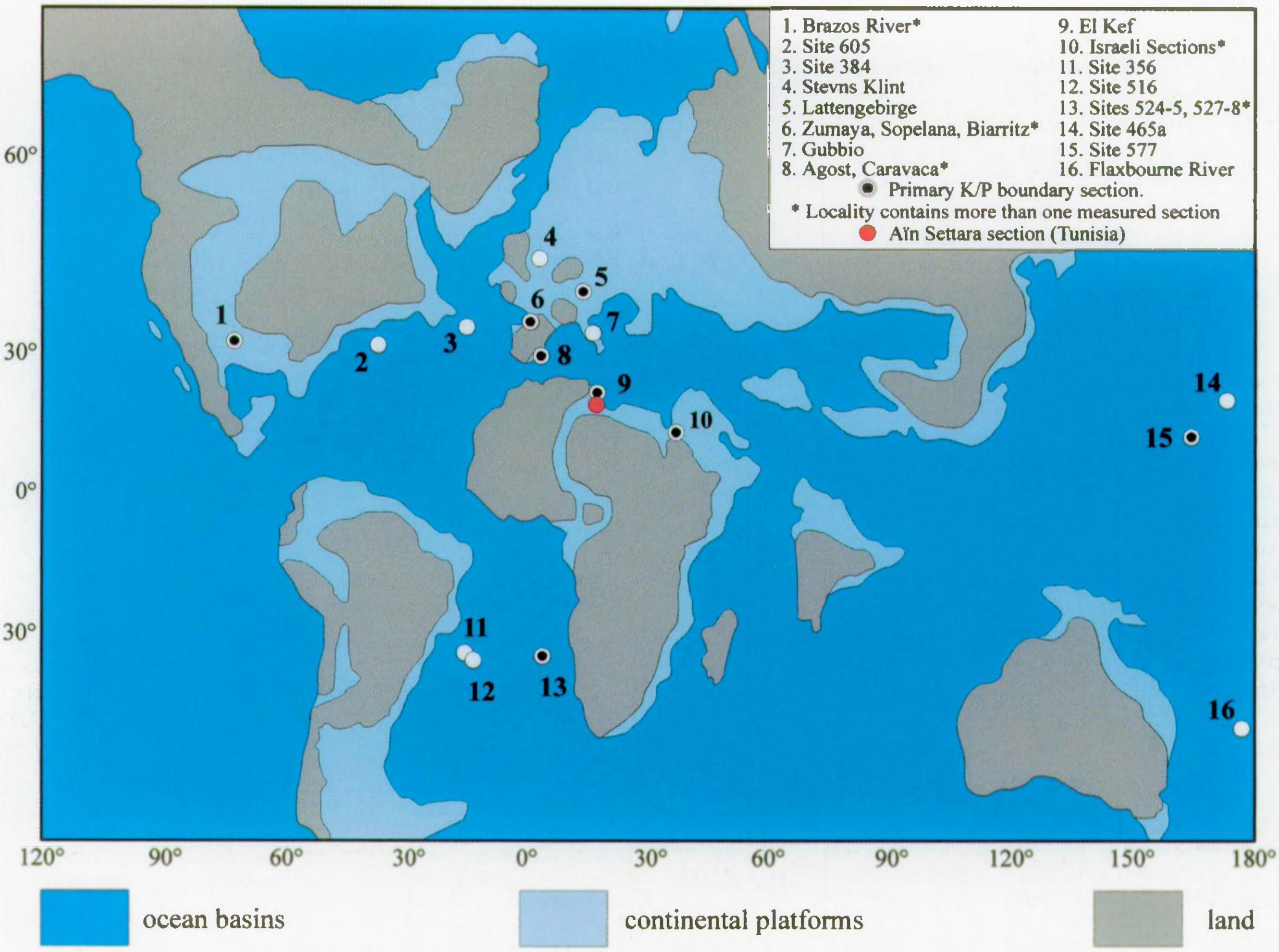


Plate 1 — Locations of the most famous K/P boundary sections worldwide, including the Aïn Settara section, plotted on a palaeogeographic reconstruction of continental positions at the time of the K/P boundary (65.0 Ma) (after MACLEOD & KELLER, 1991).

spinel, a mineral formed by fusion and oxidation in the atmosphere of meteoritic objects (KYTE *et al.*, 1980; SMIT & KYTE, 1884; KYTE & SMIT, 1986; ROBIN *et al.*, 1991, 1992; ROCCHIA *et al.*, 1996; ROBIN & ROCCHIA, 1998) and of shocked minerals at the K/P boundary (BOHOR, 1990; GRIEVE *et al.*, 1996; CLAEYS *et al.*, 1998), seem to be in favour of the asteroid impact hypothesis.

During the last decade, compared to other famous K/P boundary sections worldwide (GARTNER, 1996; see also Pl. 1), most attention has been paid to the El Kef section in northwest Tunisia (KELLER *et al.*, 1996; OLSSON, 1997 and SMIT & NEDERBRAGT, 1997), because it includes the formally accepted Boundary Stratotype and Global Stratotype Section and Point (= GSSP) for the Cretaceous/Palaeogene Boundary (Minutes IUGS, 1991, p. 23). The base of the Dark Boundary Clay at El Kef, represented by a rusty-coloured layer (BEN ABDELKADER & ZARGOUNI, 1995, figs 1 & 2) in which the maximum concentration of Ir and Ni-rich spinels (ROBIN *et al.*, 1991; ROCCHIA *et al.*, 1998) and the major species extinction in planktonic foraminifera (KELLER *et al.*, 1996) were observed, is the accepted boundary criterion (ODIN, 1992, p. 13), in spite of problems related to the exact location and preservation of the original GSSP locality (REMANE *et al.*, 1999, p. 48).

During their fieldwork campaigns in the Kalaat Senan area the present authors recorded an orange-coloured level at Aïn Settara, which they associated with the rusty-coloured level occurring at the base of the boundary clay in the El Kef reference section. However, at Aïn Settara, situated in the same basin as the El Kef section ("le Sillon tunisien": ROBASZYNSKI *et al.*, 1993b, fig. 2), although somewhat more proximally (50 km southward), this coloured layer did not coincide with the base of the clay, but occurred a few cm higher up. In order to solve the discrepancies between the El Kef and the Aïn Settara sections it was decided to set up a multidisciplinary investigation at Aïn Settara, including micropalaeontological (planktonic foraminifera, calcareous nannofossils, dinoflagellate cysts), mineralogical and geochemical analyses.

Geological setting

A five thousand meter thick, fossiliferous and predominantly marly sequence is outcropping in Central Tunisia, in the region between Kalaat Senan, Tajerouine and Kalaa Khasba (Fig. 1). This sequence, which ranges in age from the Aptian to the middle Ypresian, was measured and sampled during the last decade by ROBASZYNSKI, DUPUIS, CARON and STEURBAUT. The Cenomanian to Maastrichtian sequences were reported in ROBASZYNSKI *et al.* (1990, 1993a, 1993b, 1993c, 2000) and HARDENBOL *et al.* (1993), the Danian/Selandian boundary interval in STEURBAUT *et al.* (2000).

At Aïn Settara, the Dark Boundary Clay lies within the lower part of the marly El Haria Formation, at about 180 m above the top of the limestone-rich Abiod Formation, and 400 m below the base of the carbonate and phosphate-rich Metlaoui Formation (Fig. 1). For a description of these formations the reader is referred to BUROLLET (1956). The El Haria Formation consists of several (at least 5) mappable, lithologically and faunally distinct units. Two of these units, located within the middle of the El Haria Formation, are exposed at Aïn Settara (Fig. 2): they are the 150 m thick Sidi Nasseur marls, consisting of alternating blue grey marls and thin whitish limestone beds, and the underlying Aïn Settara marls which are composed of dark grey jarositic marls, with alternating 0.2 to 0.8 m thick whitish more carbonate-rich beds (carbonate content between 25 and 50%). The lower part of the Sidi Nasseur marls is marked by two dark clayey layers, of which the lowermost represents the "Dark Boundary Clay" and encompasses the K/P boundary.

The K/P boundary is exposed in a 100 m high very steep flank of a deeply incised gully at about 80 m above the base of the gully, and horizontally traceable over more than 200 m. There is almost no vegetation on this steep slope and therefore exposure is excellent (Pls 2 & 3).

Samples and methods

Samples, labeled STW (Settara West), were taken at 2 to 5 m intervals in the 100 m vertical section along the western flank of the gully (Fig. 2). The 1 m thick K/P boundary section was studied at several points along the outcrop in order to unravel the stratigraphic succession and its lateral variations.

Mineralogy and geochemistry

Carbonate content was determined with a Bernard calcimeter on 42 samples (Fig. 2), among which 21 were focused to the 1 m thick section spanning the K/P boundary (Fig. 3). Analytical precision is about 5%.

Geochemical analyses have been carried out on the detailed section (Fig. 3 and Table 1). Major element and trace element contents were determined using SEM-EDS analysis upon pressed powder and ICP spectrometry, respectively (Table 2). The precision of the SEM-EDS analysis is 3-5% for major elements whose abundance

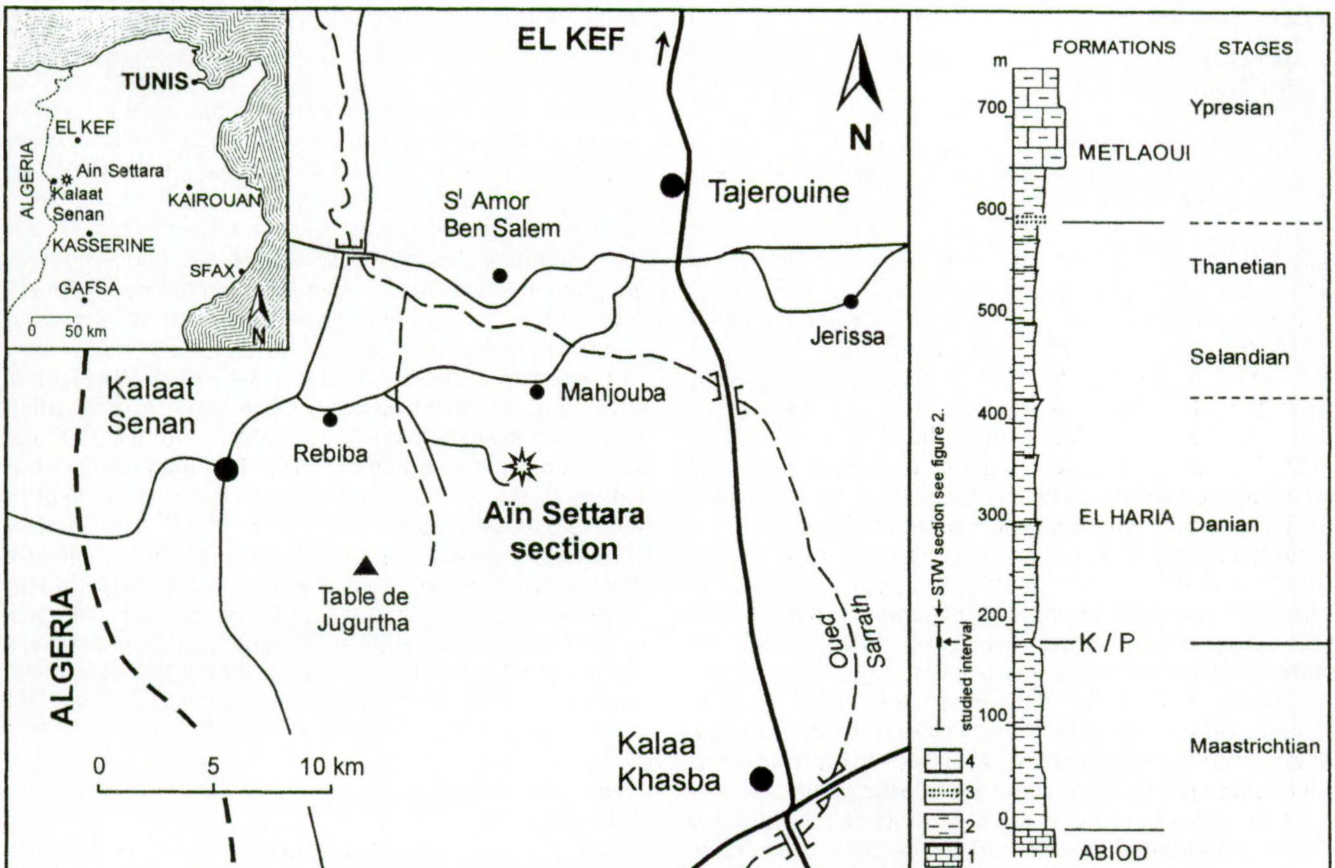


Fig. 1 — Location maps and general stratigraphical context of the studied intervals. The Abiod Formation is composed of limestones (1). The El Haria Formation is dominantly marly, sometimes clayey, with few calcareous beds (2). The Metlaoui Formation is dominantly calcareous (4); its base contains several phosphatic beds (3).

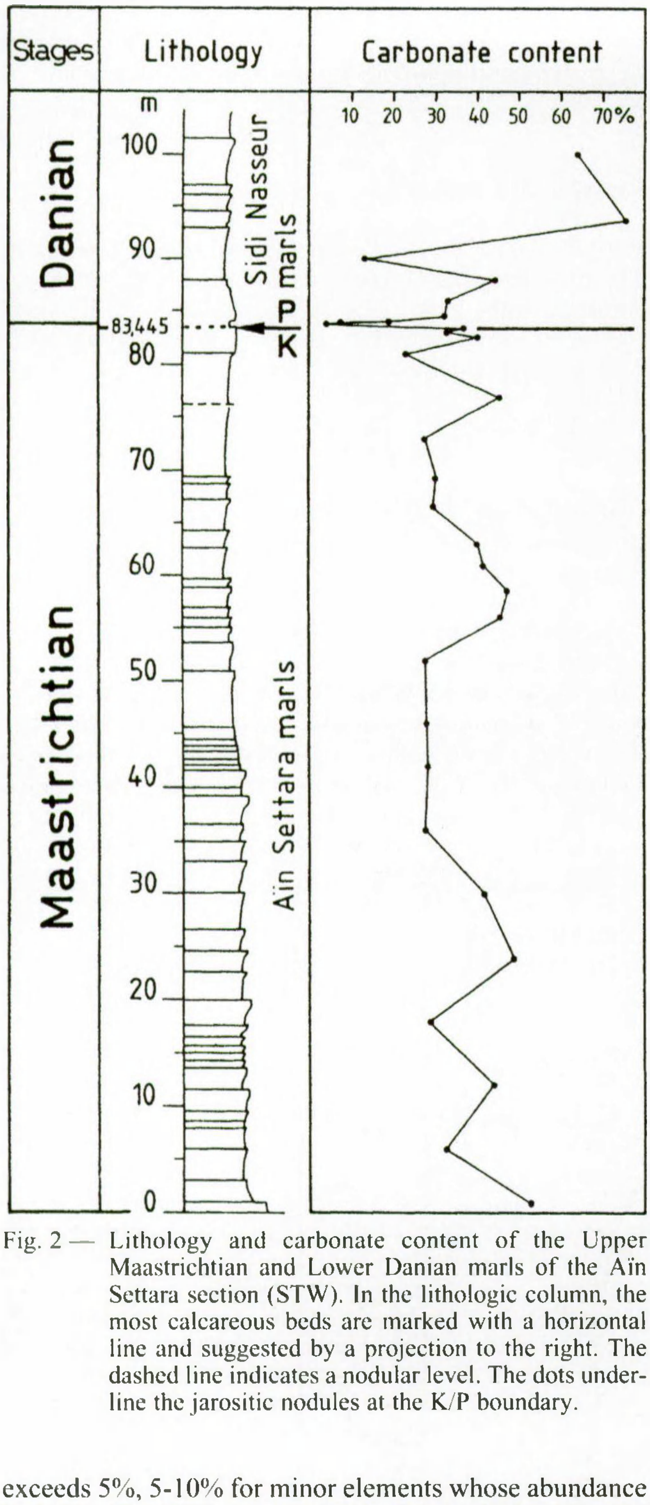


Fig. 2 — Lithology and carbonate content of the Upper Maastrichtian and Lower Danian marls of the Aïn Settara section (STW). In the lithologic column, the most calcareous beds are marked with a horizontal line and suggested by a projection to the right. The dashed line indicates a nodular level. The dots underline the jarositic nodules at the K/P boundary.

exceeds 5%, 5-10% for minor elements whose abundance is 1-5%. For ICP spectrometry, the studied sediments were analysed after dissolution of 200 mg sample with 2 ml HF plus 2 ml $HClO_4$ plus 5 ml HNO_3. The precision of the method is 1-10%, depending on the element analysed. Rock Eval pyrolysis has been performed upon bulk rocks. Rock Eval parameters, including the total organic carbon (T.O.C.), the Hydrogen Index (HI) and Tmax, as defined in ESPITALIÉ (1993), have been measured.

Ten samples were taken and processed for cosmic marker analysis (Fig. 4). Iridium was measured by Instrumental Neutron Activation Analysis (INAA), following the method described by MEYER *et al.* (1993). About 100 mg of ground and homogenised whole-rock sample was dried, sealed in pure quartz vials, and then irradiated for 4 hours in the 10^{14} neutrons $cm^{-2}.s^{-1}$ flux of the OSIRIS reactor at the Pierre Süe Laboratory, Saclay. After 1 month cooling, iridium was measured at Gif-sur-Yvette, with a γ-γ; spectrometer detecting, without anti-Compton device, the 316-468 keV γ-ray coincidence resulting from the decay of ^{192}Ir. The detection limit of the instrument is lower than 0.05 $ng.g^{-1}$. Ni-rich spinel was measured following the procedure described by ROBIN *et al.* (1991). About 1 to 2 g of whole sample was treated with 10 % hydrochloric acid and the magnetic fraction was separated from the aqueous suspension in a Frantz magnetic separator and subsequently dispersed on a nuclepore filter. The composition of individual mineral grains thus recovered was determined by X-ray microanalysis, using a high purity germanium detector and digital pulse processing from Princeton Gamma-Tech (PGT) attached to a JEOL JSM 840 scanning electron microscope. Ni-rich spinel crystals larger than 0.5 µm are counted and sorted according to their size with an automatic search routine supplied by PGT. The detection limit depends on the abundance of other magnetic grains but is generally lower than 0.1 spinel crystal mg^{-1}.

Planktonic foraminifera, calcareous nannofossils and palynomorphs

A total of 24 samples were analysed for the study of the planktonic foraminifera (Figs 5 and 6). All samples were disaggregated in tap water and diluted H_2O_2, then washed through a 63 µm sieve and dried at 50°C. Quantitative analyses were based on representative splits of 300 or more specimens from the size fraction larger than 63 µm, obtained using a modified Otto micro-splitter. All the representative specimens were picked, identified and mounted on micro-slides for a permanent record. The remaining sample was scanned for rare species in different fractions larger than 63, 100 and 150 µm. The tables including detailed quantitative data are presented elsewhere (MOLINA *et al.*, 1998).

Fourteen samples were processed for calcareous nannofossil investigations (Fig. 7). Smear-slides were made following standard procedures and examined with the light microscope at 1250 magnification. Each sample was also analysed on a semi-quantitative basis (magnification 1000 x), based on the method described by BACKMAN & SHACKLETON (1983). Various samples from unit 6 and the base of unit 7 were studied with the scanning electron microscope.

Fourteen samples were processed for palynology using the standard procedure of the "Laboratoire de Palynologie de l'Institut de Géologie de Strasbourg" (RAUSCHER & SCHMITT, 1990; RAUSCHER *et al.*, 1992).

Lithology

The K/P boundary interval is marked by a layer of yellowish, jarositic platy nodules, 2 to 5 cm long and a few mm thick in which cosmic markers were found. This layer lies approximately 3 cm above the base of the ca 60

Plate 2 — The Aïn Settara section, looking northwest, with location of the K/P boundary. The rocks of the left upper corner are capping the Aïn Settara spring.

cm thick jarosite-rich Dark Boundary Clay (= DBC). The base of the latter is located at 83.445 m in the section at the base of the Sidi Nasseur marls (Figs 2 and 3).

Eight lithological units are identified in the approximately 1 m thick K/P boundary interval (Figs 3 and 4). Some of these (especially units 3 and 4) are locally missing. Units 1 to 6, which are dark-coloured and characterised by low carbonate content (less than 10%), constitute the DBC (Pl. 4). The lowermost unit 0, which consists of blue grey bioturbated marl, represents the top of the Aïn Settara marls. Its carbonate content ranges between 35 and 45% and equals that of the underlying Maastrichtian marls. A few small nodules, bivalves, brachiopods, and solitary corals occur at about 14 cm below the top of unit 0. The upper contact of unit 0 is strongly burrowed. The burrows, a few cm long and 0.5 cm wide are flattened by compaction. They are filled with dark clayey material from the overlying unit 1. The latter is a 2 to 3 cm thick, slightly bioturbated dark clay, heavily burrowed into the underlying unit 0.

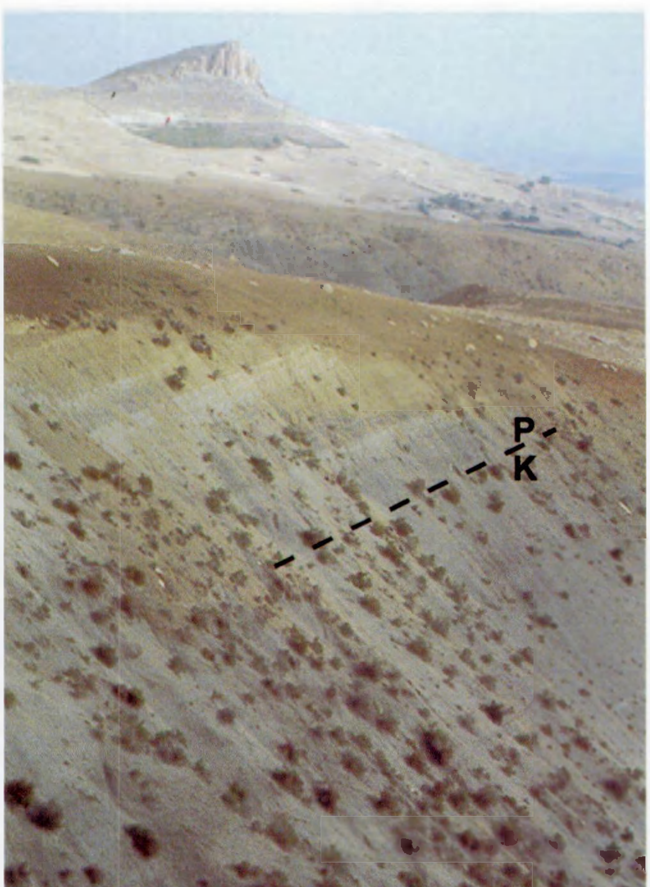


Plate 3 — The Aïn Settara section, looking north, with in the background the nummulitic limestone cliffs of Sidi Nasseur.

Unit 2, which yields the cosmic markers, consists of very thin (a few mm), 2 to 5 cm long, yellowish to orange-coloured platy nodules made up of jarosite, gypsum, and iron oxides (goethite and hematite of low crystallinity), resulting from pyrite oxidation. The overlying part of the DBC is lithologically complex, and includes three thin beds. At the base occurs dark brown clay, 0 to 3 cm thick (= unit 3), overlain by a discontinuous pale grey carbonate-rich (40%) silt, deposited in channel-like structures and containing rare pyritised molluscs (= unit 4). This silt is covered with unit 5, consisting of heterogeneous breccia-like brown clay forming small elevations (ripples?). Units 4 and 5 are interpreted as a single storm deposit. Units 3 and 4 can be locally missing due to ravination. This heterogeneous complex is characterised by very low carbonate contents (4 to 5%, Figs 3 and 4), except unit 4. It is covered by an almost 55 cm thick jarosite-rich dark clay, in which the carbonate content is slightly increasing upward from 5 to 20% (= unit 6) (Fig. 3). The base of unit 7, which marks the top of the DBC, is represented by light grey marl showing a strong upward increase in carbonate content (35% at 85 m, Fig. 2). There is a slight increase in the total organic carbon content (= T.O.C.) in unit 3, as well as in unit 5, just

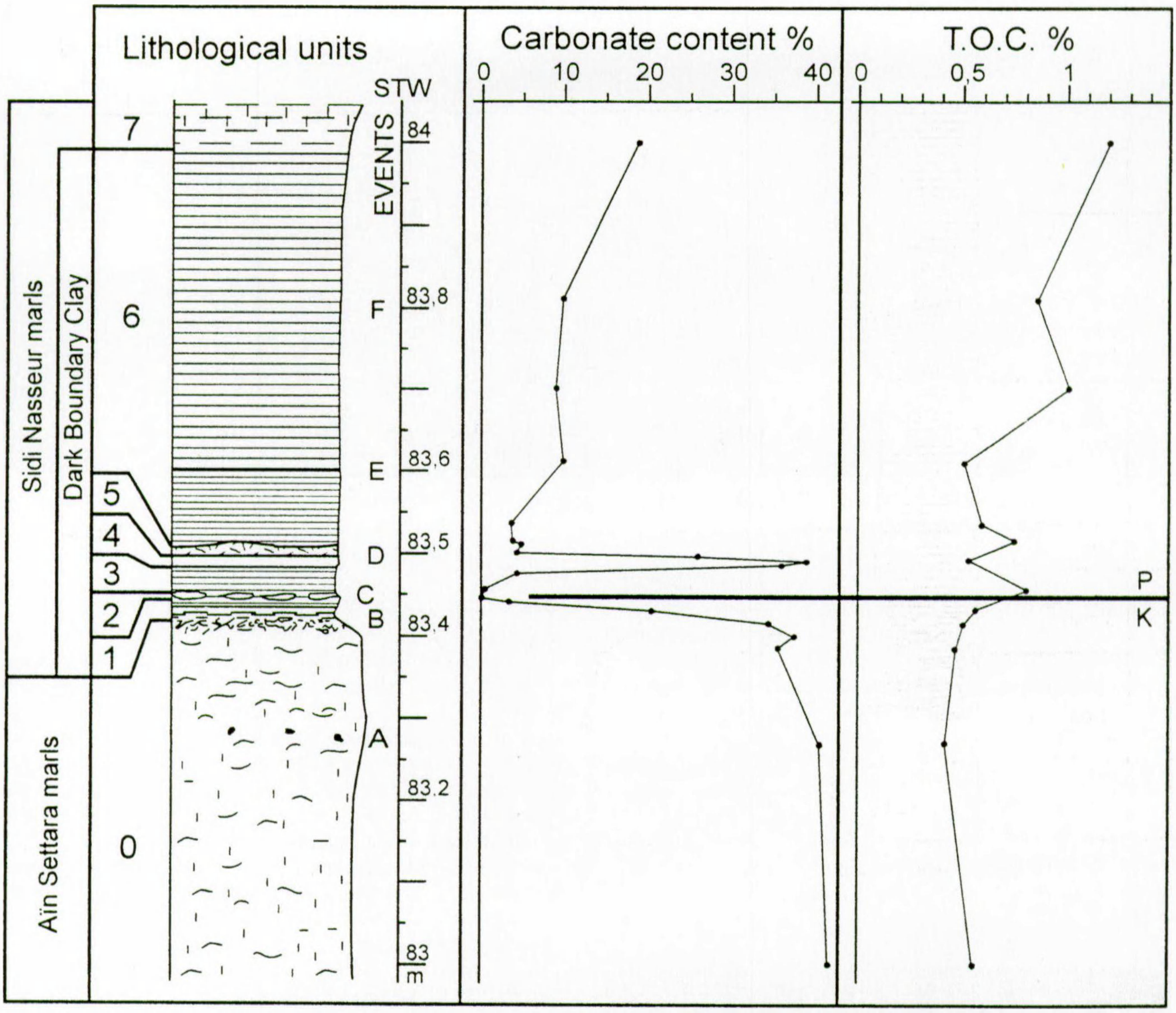


Fig. 3 — Description of the Dark Boundary Clay. Carbonate and total organic carbon (T.O.C.) contents.

above the K/P boundary (from 0.5 to 0.8%) (Fig. 3). From this level to approximately 10 cm above the base of unit 6 the T.O.C. progressively decreases to about 0.5%, from which it rapidly rises again to ca 1.2% at the base of unit 7.

Cosmic markers

The stratigraphic distributions of iridium and Ni-rich spinel are displayed in Fig. 4 and Table 2. A maximum concentration of 2.7 $ng.g^{-1}$ of Ir is observed in the jarositic layer (unit 2). The Ir content decreases rapidly and almost symmetrically on both sides of this layer, reaching a value of 0.2 $ng.g^{-1}$ at about 10 cm below and above it. The Ir flux integrated over the 20 cm of section studied here is 35 $ng.cm^{-2}$. This value is about 2 times lower than these measured in the KD and KR sections at El Kef (80 and 70 $ng.cm^{-2}$, respectively, see Rocchia *et al.*, 1998), which are located about 50 km Northeast of Aïn Settara. However, at El Kef, as at many K/P boundary sites, the Ir peak is superimposed on a low-amplitude shoulder (Ir concentrations of 100-200 $ng.g^{-1}$), extending over 1-2 m in the Danian and the Maastrichtian, and contributing to more than 40 wt% of the total Ir flux (Rocchia *et al.*, 1987; Robin *et al.*, 1991; Rocchia & Robin, 1998). Supposing a similar contribution of the Ir shoulder at Aïn Settara, we can expect a minimum value of 60 $ng.cm^{-2}$ for the total Ir flux. This value is close to the total Ir fluxes measured in many other K/P sections.

The stratigraphic distribution of Ni-rich spinel is a pulse-like function, with a maximum abundance in the jarositic layer (unit 2). Spinel is almost absent (less than 0.1 spinel mg^{-1}) below and above this layer (unit 1). The abundance and total flux of spinel (about 150 crystals mg^{-1} and 5.10^4 crystals cm^{-2}, respectively) is comparable to the abundance and total flux of this mineral at El Kef (about 200 crystals mg^{-1} and 4.10^4 crystals cm^{-2}, respectively, see Robin *et al.*, 1991; Robin & Rocchia, 1998).

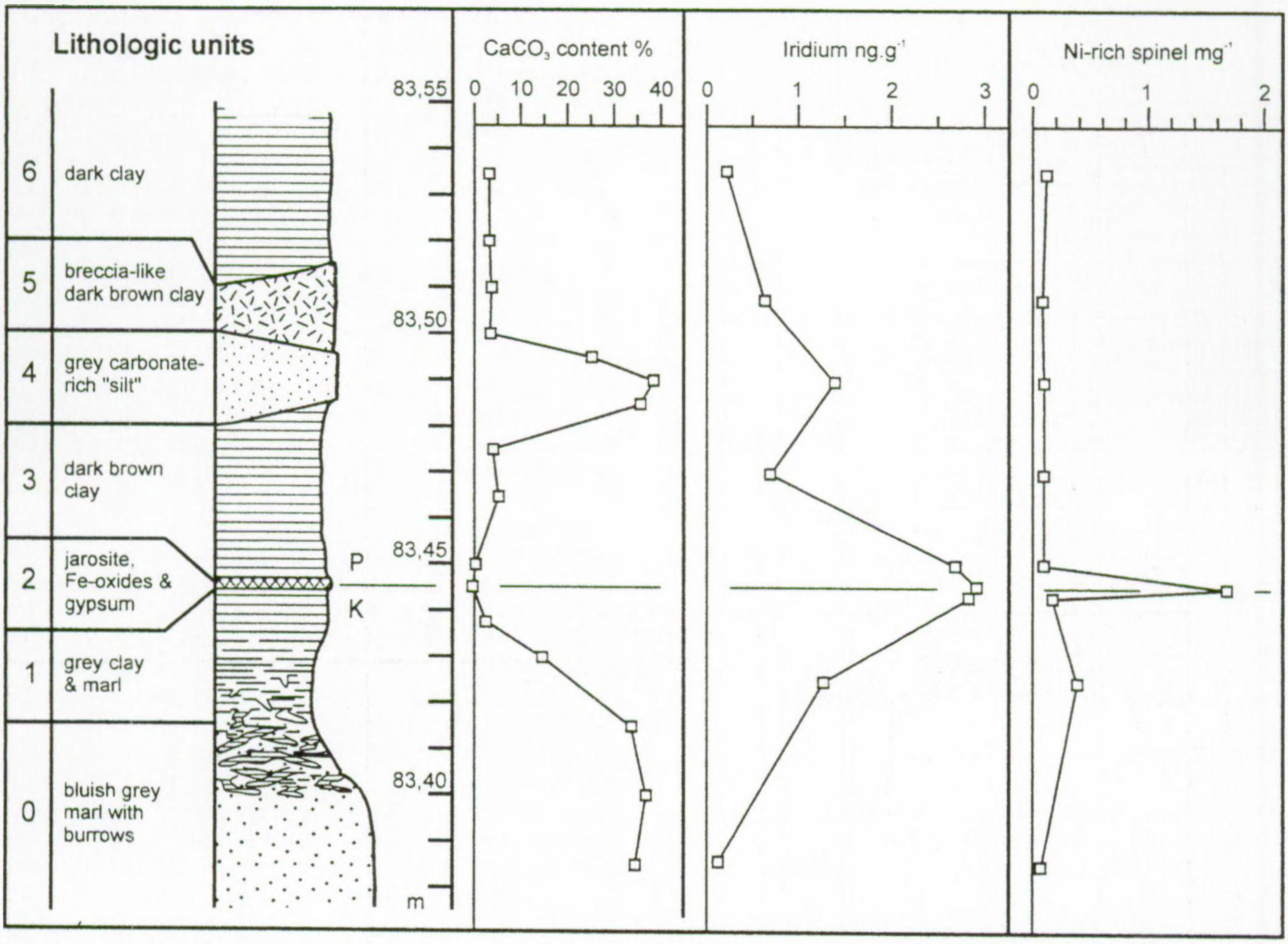


Fig. 4 — Detailed lithological succession of the K/P boundary interval. Carbonate content and stratigraphical distribution of the cosmic markers.

Plate 4 — The K/P boundary interval in the Aïn Settara section, with the lateral distribution of the different units (0 = top Aïn Settara marls; 1-6 = Dark Boundary Clay, including unit 2 with the cosmic marker bearing, orange-coloured platy nodules).

Table 2 — Cosmic marker, iridium and Ni-spinel contents in the Aïn Settara K/P boundary interval. Level in m is referred to Fig. 4.

Units	Sampling level (cm)	Iridium (ng.g^{-1})	Ni-rich spinel mg^{-1}
6	8353.5	0.212±0.093	-
6	8351.5	-	0.10±0.10
5	8351.0	-	0.560.58
5	8350.7	0.638±0.064	-
5	8350.0	-	0.760.50
4	8349.0	1.392±0.096	0.09±0.06
4	8348.5	-	0.05±0.06
3	8347.5	-	0.03±0.03
3	8347.0	0.704±0.067	1.11±0.86
3	8345.3	-	0.88±0.39
3	8345.0	2.714±0.247	-
3	8344.7	-	50.44±8.87
2	8344.5	2.687±0.213	154.85±53
1	8344.3	2.86±0.13	19.93±3.99
1	8343.8	-	0.72±0.19
1	8343.0	-	0.32±0.34
1	8342.5	1.295±0.121	-
0	8338.5	0.187±0.127	-

Geochemistry and depositional conditions

Major elements

The samples studied show very monotonous distributions for the Si/Al, K/Al, Mg/Al and Ti/Al ratios (Table 1). The Si/Al ratio reveals no variation neither in the siliceous productivity (diatoms, radiolarians) nor in the grain-size distribution. The most variable sediment component seems to be the carbonate content. The Mg/Ca ratio does not allow the differentiation of dolomite or Mg-calcite. The vertical distribution of the values of the Mg/Ca ratio and of the Ca content reveals that these two data are negatively correlated. This indicates that the Mg input is diluted by the carbonate flux, and that most of the Mg content is probably land derived. Rock Eval pyrolysis shows that organic matter (OM) is present in low amounts. T.O.C. values do not exceed 1.2 wt% but are generally much below 1 wt% (Table 1). The values of the Tmax and HI indices show that the K/P samples contain immature type III organic matter, which according to ESPITALIÉ (1993) is believed to be land derived, as confirmed by the palynofacies analyses.

Trace elements

The samples from the K/P boundary interval do not reveal strong variations in their chemical composition (Table 1). The Th/K and Th/Al ratios (VAN BUCHEM *et al.*, 1992) do not show any tendency that could be interpreted in terms of grain-size variation within the sediment matrix. Relative to earth crust abundances, the samples appear to be depleted in some trace elements, e.g. V, Mo, Cr, Cd, Ni, Cu, Mn, Ba and P, except for samples (STW 1 to 4 for Ni and STWA 40-42 for Cr). Assuming that sulfur is only present in the form of iron sulfide, a normative calculation allows to

Table 1 — Geochemical content of the sediments across the K/P boundary in the Aïn Settara section. [1] - HI is expressed in mg hydrocarbon per g T.O.C. Fe* content was determined with ICP-OES. DOP' = Degree of pyritization, i.e. the pyrite Fe/total Fe ratio. Molybdenium and cadmium contents measured but the values were below the detection thresholds.

Lithol. units	*Samples*	SiO_2 wt %	TiO_2 wt %	Al_2O_3 wt %	Fe0 wt %	MgO wt %	CaO wt %	Na_2O wt %	K_2O wt %	P_2O_5 wt %	S wt %	V ppm	Cr ppm	Th ppm	Ni ppm	Cu ppm	Mn ppm	Fe* wt %	Ba ppm	P ppm
Unit 7	STW 84	45.08	0.86	24.63	5.27	2.00	10.64	0.88	1.23	0.00	0.46	193	138	12	62	15	123	4.52	90	1598
Unit 6	STWA 40-42	46.86	1.07	24.98	5.75	2.18	8.66	1.08	1.38	0.69	0.53	204	189	12	65	15	119	4.47	93	1768
Unit 6	STWA 20-22	47.70	0.85	25.06	6.16	2.14	8.37	0.84	1.42	0.47	0.41	194	112	12	56	15	158	4.50	90	1331
Unit 6	STWA 8-10	52.04	1.44	28.22	6.66	2.06	3.86	0.77	1.54	0.00	0.39	221	89	13	68	19	99	4.36	102	1005
Unit 6	STWA 3-5	51.61	1.11	27.63	7.01	2.03	4.16	0.97	1.58	0.00	0.66	224	106	12	75	19	65	4.31	117	824
Unit 5	STWA 5	50.88	0.99	27.3	6.09	1.81	5.27	0.94	1.57	0.00	0.93	206	107	13	101	20	86	4.54	98	722
Unit 4	STWA 4	33.79	0.61	18.09	4.97	1.34	21.53	0.85	1.02	0.00	0.87	123	89	8	189	14	409	3.47	57	441
P / Unit 3	STWA 3	44.58	1.01	24.62	8.51	1.93	8.07	0.81	1.22	0.00	2.90	165	112	10	209	26	116	4.77	310	575
K / Unit 1	STWA 1	39.12	0.69	20.78	7.46	1.55	15.24	0.00	1.18	0.00	1.99	162	119	10	176	23	109	4.81	91	633
Unit 0	STWA 0-3	33.88	0.79	17.77	4.95	1.31	21.91	0.57	0.98	0.00	0.63	142	88	8	77	14	120	3.46	70	743
Unit 0	STWA 5-7	33.17	0.97	17.81	5.27	1.67	21.75	0.82	0.91	0.00	0.54	135	70	9	56	15	126	3.36	67	789
Unit 0	STWA 12-14	39.11	0.82	20.31	6.12	1.60	29.60	0.00	1.03	0.00	0.78	120	94	7	43	13	129	3.56	60	1240
Unit 0	STW 83	37.43	0.76	17.09	5.12	1.84	19.77	0.00	1.20	0.00	0.12	102	72	7	43	13	111	3.41	67	721

Lithol. units	*Samples*	V/Al x 10^4	Cr/Al x 10^4	Th/Al x 10^4	Th/K x 10^4	Ni/Al x 10^4	Cu/Al x 10^4	Mn/Al x 10^4	Ba/Al x 10^4	P/Al x 10^4	Si/Al	K/Al	Mg/Al	Ti/Al	DOP'	TOC wt%	HI [1]	Tmax °C
Unit 7	STW 84	14.78	10.57	0.91	11.61	4.79	1.15	9.43	6.93	122.62	1.62	0.08	0.09	0.04	0.12	1.20	102	429
Unit 6	STWA 40-42	15.41	14.28	0.90	10.37	4.91	1.13	8.99	7.03	133.57	1.66	0.04	0.10	0.05	0.30	0.93	98	427
Unit 6	STWA 20-22	14.60	8.43	0.91	10.30	4.22	1.13	11.89	6.78	100.20	1.69	0.04	0.10	0.04	0.38	0.50	52	425
Unit 6	STWA 8-10	14.77	5.95	0.86	10.09	4.55	1.27	6.62	6.82	67.19	1.64	0.04	0.08	0.06	0.20	0.57	56	423
Unit 6	STWA 3-5	15.30	7.24	0.85	9.47	5.12	1.30	4.44	7.99	56.27	1.66	0.05	0.08	0.05	0.17	0.68	71	424
Unit 5	STWA 5	14.20	7.38	0.87	9.65	6.96	1.38	5.93	6.76	49.78	1.65	0.05	0.08	0.04	0.14	0.79	79	426
Unit 4	STWA 4	12.83	9.28	0.81	9.17	19.71	1.46	42.66	5.95	46.00	1.66	0.04	0.08	0.04	0.10	0.52	80	426
P / Unit 3	STWA 3	12.64	8.58	0.73	9.36	16.01	1.99	8.89	23.75	44.06	1.61	0.04	0.09	0.05	0.11	0.75	90	425
K / Unit 1	STWA 1	14.71	10.81	0.91	10.24	15.98	2.09	9.90	8.26	57.48	1.67	0.04	0.08	0.04	0.07	0.52	60	421
Unit 0	STWA 0-3	15.07	9.34	0.88	10.19	8.17	1.49	12.74	7.43	78.87	1.69	0.04	0.08	0.05	0.14	0.51	70	424
Unit 0	STWA 5-7	14.30	7.42	0.96	12.01	5.93	1.59	13.35	7.10	83.60	1.65	0.04	0.11	0.06	0.07	0.46	63	422
Unit 0	STWA 12-14	11.15	8.73	0.63	7.98	4.00	1.21	11.99	5.57	115.21	1.71	0.04	0.09	0.05	0.10	0.39	69	424
Unit 0	STW 83	11.29	7.97	0.81	7.35	4.77	1.47	12.25	7.42	79.71	1.94	0.11	0.12	0.05	0.12	0.54	50	427

infer the proportion of iron trapped as pyrite. The pyrite Fe/total Fe ratio may thus be looked at as a simplified expression of the degree of pyritisation, as defined by BERNER (1970). This permits to envision in how far iron was sequestered as sulfides, of which low values are observed here.

Nickel and copper are present in weak proportion. A small relative Ni enrichment may be seen at the K/P boundary s.s. (samples STW 1 to 5), accompanied by some relatively higher Cu content (Cu remains however depleted relative to average proportions in the earth crust). This may be accounted for by the presence of some type III organic matter (i.e. land derived).

Interpretation

The Al-normalised abundances of Si, K, Mg, Ti and Th bear witness of the very homogenous nature of the terrestrial supply. The trace elements studied may provide information about the palaeoenvironmental conditions during deposition and early diagenesis. Ni and Cu may reflect the presence of sedimentary organic matter. Other elements, such as V, Mo, Cr, Cd and Mn may help to decipher the palaeo-redox conditions. Lastly, Ba and P may represent palaeoproductivity. All of this is detailed in CALVERT & PEDERSEN (1993), DISNAR (1980), BRUMSACK (1986), BREIT & WANTY (1991), DYMOND *et al.* (1992) and references therein. Here, the depletion in V, Mo and Cd for all samples indicates that depositional conditions (bottom/interstitial waters) were not reducing. This is confirmed by the low values of the Fe_{pyrite}/Fe_{total} ratio.

Two samples (STW 1 and 3) show a higher S content than the others (ca 2 and 3% respectively). Taking into account the Mo and Cd absence and the V depletion, this relative S enrichment cannot be accounted for by sulfide precipitation during early diagenesis (it must have occurred during later diagenesis).

For what the Ba and Mn content is concerned, some samples show extremely high values (samples STW 3 for Ba, and STW 4 for Mn, see Table 1). These relatively high values may be interpreted as the result of remobilisation-migration processes under reducing conditions, followed by trapping of the migration front when oxidising conditions were met. If that were the case, it would have been reflected by the contents in V and Mo. However, this is not so, and, as the result, this hypothesis has to be rejected. Therefore, the anomalies in Ba and Mn must also have a late diagenetic origin. As a conclusion, one can put forward that the geochemical contents of the sediments across the K/P boundary do not provide evidence that the depositional conditions were anoxic at Aïn Settara at this time.

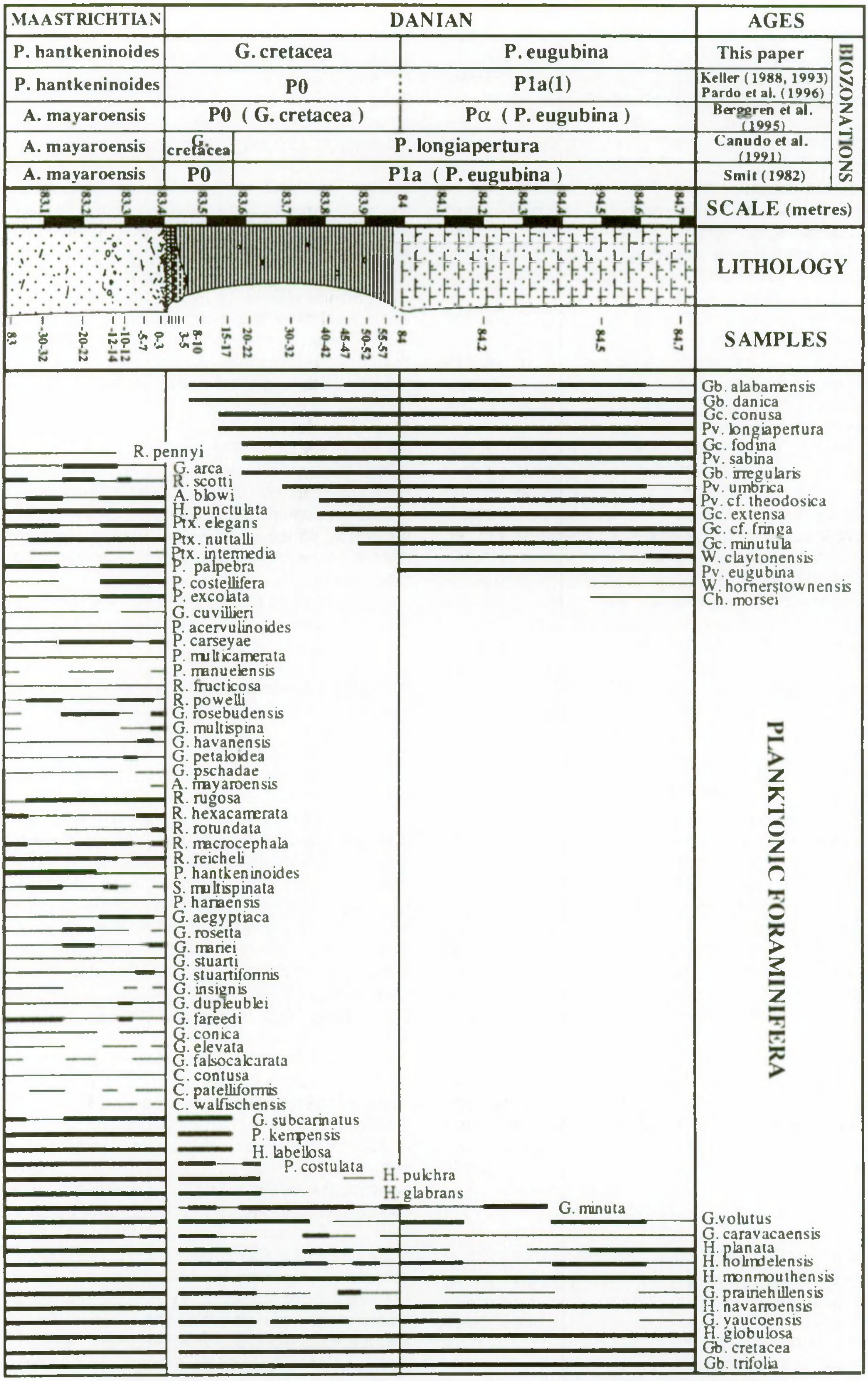
Jarosite nodules (hydrous iron sulfate) are frequently occurring in the studied section. These concretions contain no carbonate and are devoid of identifiable fossil remains. They probably result from the weathering of pyrite nodules and reflect redox conditions, allowing sulfide precipitation. This could be interpreted as the development of reducing conditions at the K/P boundary (unit 2), as generally stated in the literature for this boundary. However, such reducing conditions are not echoed at all in the adjacent units (0, 1, 3, 4, 5, 6). Actually, the arguments derived from trace element distribution (see above) support non-reducing conditions for these units. As a consequence two interpretations may be put forward: (1) reducing conditions did occur, but only for the short time interval during which the nodules formed. This episode would not have left any geochemical witness in the sediment containing the nodules. (2) The nodules may have formed later during diagenesis. Diagenetic nodules generally occur during the sulfate-reduction diagenetical stage or the anaerobic methane oxidation stage (RAISWELL, 1988). The first hypothesis is unlikely in the present case because sulfate reduction would have left an imprint upon the sediment, recorded by the trace element distribution and the Fe_{pyrite}/Fe_{total} ratio (Table 1). The second is more plausible: nodule formation does not imply that the conditions were reducing during deposition, and its formation can occur without any other geochemical echo within the sediment. However, some sediment feature must explain the location of the nodules at the K/P boundary. The methane must have been trapped there for a long time, enough to be bacterially degraded (anaerobic methane oxidation). In conclusion, the presence of the jarosite nodules might witness episodes of reducing palaeoenvironmental conditions at the K/P boundary, although no strong evidence for this is available. However, the trace element content indicates that the environment was not reducing and, therefore, the nodules should rather be linked up with a subsequent diagenetic event.

Planktonic foraminifera

Biozonation

LUTERBACHER & PREMOLI SILVA (1964) began to study the K/P boundary in a high resolution way. Nevertheless, the K/P boundary remained not completely zoned in the classical biozonation of BOLLI (1966). BERGGREN (1969, 1971) proposed to use a biostratigraphical system of numerical nomenclature for the biozones, which has been used and modified by different authors (BLOW, 1979; SMIT, 1982; KELLER, 1988, 1993; BERGGREN *et al.*, 1995; KELLER *et al.*, 1996). This numerical system can be confusing and we prefer to use the classical system of nomenclature biozonation. Thus, in this study the following biozones have been recognised:

- *Plummerita hantkeninoides* Biozone (= *Plummerita reicheli* subzone *in* ROBASZYNSKI *et al.*, 2000): this biozone was defined by ION (1993) in Romania and has also been recognised by PARDO *et al.* (1966) in the Agost section in Spain. This biozone is defined by the total range of *Plummerita hantkeninoides* and is used in this paper because of the scarcity of *Abathomphalus mayaroensis* in the terminal Maastrichtian. Nevertheless, in the uppermost Cretaceous sample (unit 1) some specimens of *A. mayaroensis* have been found. Almost all large tropical Cretaceous taxa suddenly disappear at the top of this biozone in the Aïn Settara section (Fig. 5).
- *Guembelitria cretacea* Biozone: SMIT (1982) defined this biozone in the Caravaca section (Spain) to replace his former unnamed "intermediate" zone (SMIT, 1977). The base of this zone, which is considered to represent the


MAASTRICHTIAN
DANIAN
AGES
P. hantkeninoides
G. cretacea
P. eugubina
This paper
P. hantkeninoides
P0
P1a(1)
Keller (1988, 1993) Pardo et al. (1996)
A. mayaroensis
P0 (G. cretacea)
Pα (P. eugubina)
Berggren et al. (1995)
A. mayaroensis
G. cretacea
P. longiapertura
Canudo et al. (1991)
A. mayaroensis
P0
P1a (P. eugubina)
Smit (1982)
BIOZONATIONS
83.1 83.2 83.3 83.4 83.5 83.6 83.7 83.8 83.9 84 84.1 84.2 84.3 84.4 84.5 84.6 84.7
SCALE (metres)
LITHOLOGY
83 -30-32 -20-22 -12-14 -10-12 -5-7 0-3 3-5 8-10 15-17 20-22 30-32 40-42 45-47 50-52 55-57 84 84.2 84.5 84.7
SAMPLES
Gb. alabamensis
Gb. danica
Gc. conusa
Pv. longiapertura
Gc. fodina
Pv. sabina
Gb. irregularis
Pv. umbrica
Pv. cf. theodosica
Gc. extensa
Gc. cf. fringa
Gc. minutula
W. claytonensis
Pv. eugubina
W. hornerstownensis
Ch. morsei
R. pennyi
G. arca
R. scotti
A. blowi
H. punctulata
Ptx. elegans
Ptx. nuttalli
Ptx. intermedia
P. palpebra
P. costellifera
P. excolata
G. cuvillieri
P. acervulinoides
P. carseyae
P. multicamerata
P. manuelensis
R. fructicosa
R. powelli
G. rosebudensis
G. multispina
G. havanensis
G. petaloidea
G. pschadae
A. mayaroensis
R. rugosa
R. hexacamerata
R. rotundata
R. macrocephala
R. reicheli
P. hantkeninoides
S. multispinata
P. hariaensis
G. aegyptiaca
G. rosetta
G. mariei
G. stuarti
G. stuartiformis
G. insignis
G. dupleublei
G. fareedi
G. conica
G. elevata
G. falsocalcarata
C. contusa
C. patelliformis
C. walfischensis
G. subcarinatus
P. kempensis
H. labellosa
P. costulata
H. pulchra
H. glabrans
G. minuta
G.volutus
G. caravacaensis
H. planata
H. holmdelensis
H. monmouthensis
G. prairiehillensis
H. navarroensis
G. yaucoensis
H. globulosa
Gb. cretacea
Gb. trifolia
PLANKTONIC FORAMINIFERA

K/P boundary, is correlated with the "red oxidized layer" present in many sections worldwide (SMIT & HERTOGEN, 1980; SMIT, 1982, 1990; SCHMITZ, 1994; KELLER, 1994; LÓPEZ-OLIVA & KELLER, 1996). In the Aïn Settara section it spans the interval between the last appearance datum (LAD) of *Plummerita hantkeninoides*, and the first appearance datum (FAD) of *Parvularugoglobigerina eugubina*, and is thus equivalent to Zone P0 of KELLER (1988, 1993), KELLER *et al.* (1996) and PARDO *et al.* (1996). At Aïn Settara it coincides with the jarositic layer (unit 2), containing the cosmic markers, and not with the base of the Dark Boundary Clay. Carbonate dissolution is only notable in the basal layers of the DBC (units 3 to 5). The remaining part of the DBC (unit 6), which contains a very well preserved autochthonous fauna, is entirely attributable to the *G. cretacea* Biozone. The first Tertiary planktonic foraminifera are present in the lower half of this biozone.

- *Parvularugoglobigerina eugubina* Biozone: This biozone was defined by LUTERBACHER & PREMOLI SILVA (1964) by the total range of the nominate taxon, but in this paper it is used as the interval between the *P. eugubina* FAD and the *Parasubbotina pseudobulloides* FAD, which is equivalent to Zone P1a(1) of KELLER (1993), KELLER & VON SALIS PERCH-NIELSEN (1995) and KELLER *et al.* (1996).

Faunal turnover and causes of extinction

The Aïn Settara section appears to be continuous, because all the planktonic biozones are present and the "Tertiary" species appear sequentially. The thickness of the *G. cretacea* Biozone or P0 Zone at Aïn Settara (55 cm) equals that at El Kef (55 cm and 65 cm respectively at El Kef I and El Kef II, KELLER *et al.*, 1996, p. 225). It clearly exceeds that at Caravaca (16 cm) and at Agost (14 cm) (CANUDO *et al.*, 1991; ARENILLAS, 1996; MOLINA *et al.*, 1996, 1998), that are among the most complete sections known worldwide (MACLEOD & KELLER, 1991; KELLER *et al.*, 1996).

During the tropical to subtropical climate of the latest Maastrichtian, deposition at Aïn Settara took place on an outer platform, deep enough to yield a very diversified planktonic foraminiferal fauna of 64 species. Nevertheless, the index species *A. mayaroensis* is absent in the upper 14 m of the section (ROBASZYNSKI *et al.*, 2000), with the exception of the uppermost Cretaceous sample in unit 1. The temporary absence of this deep dwelling species may be due to a sea-level fall (KELLER, 1988, 1989a,b, 1993; HUBER, 1990; ARZ *et al.*, 1992; KELLER & STINNESBECK, 1996). The scarcity of other deep dwellers (*Contusotruncana contusa, C. plicata, Gublerina cuvillieri, Globotruncanita falsocalcarata, Planoglobulina carseyae*, etc.) may also be related to the relative shallow

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Fig. 5 — Stratigraphical ranges of planktonic foraminifera across the K/P boundary at Aïn Settara and correlation with other biozonations established in different sections. Thick lines indicate presence in quantitative splits and thin lines presence in the remaining sample.

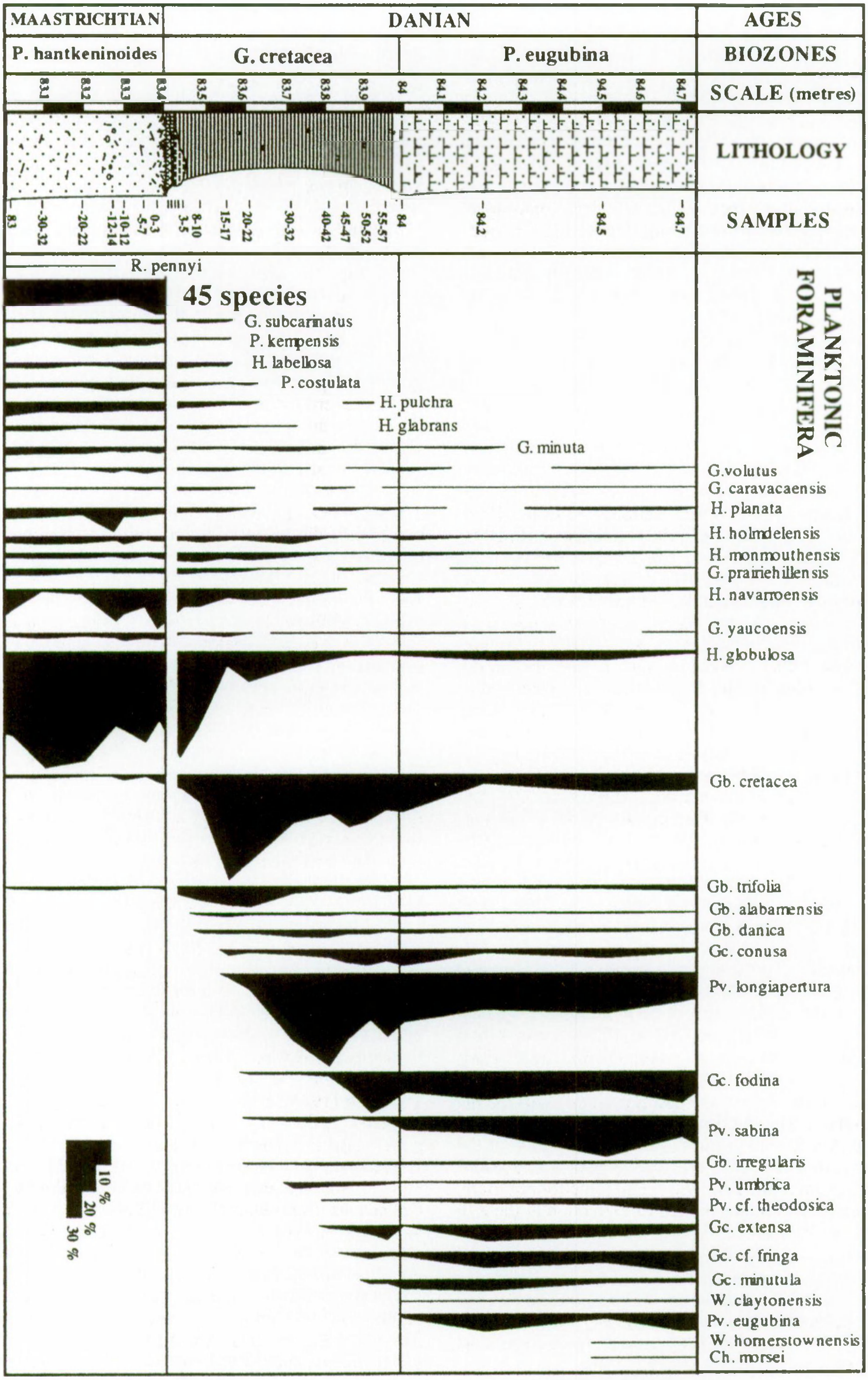
deposition depth at Aïn Settara. The reappearance of *A. mayaroensis* just below the K/P boundary could be associated with a sea-level rise during the last 50 ky of the Maastrichtian (KELLER *et al.*, 1993; PARDO *et al.*, 1996; STINNESBECK & KELLER, 1996), which seems to coincide here with the major flooding at the base of the DBC.

Only one species, *Rugoglobigerina pennyi*, disappears within the 4 m interval studied for the uppermost Maastrichtian, whereas a total of 45 large low latitude species disappear at the cosmic marker yielding jarositic K/P boundary layer (unit 2). The presence of rare species was investigated by intensively scanning the residue of all samples of different size fractions (it is easier to find the rare larger species in the fractions larger than 100 and 150 µm than in the fraction larger than 63 µm). We believe that this search minimizes the SIGNOR-LIPPS (1982) effect, which may suggest that rare species become extinct before their real moment of extinction. However, it is not possible to eliminate the Signor-Lipps effect completely and therefore we cannot be sure that *R. pennyi* really becomes extinct below the K/P boundary. Alternatively, we cannot exclude the possibility that some very rare specimens may be reworked.

Quantitative planktonic foraminiferal analysis of the uppermost 45 cm of the Cretaceous at Aïn Settara shows little variation among the relative abundances of different species (Fig. 6; ARENILLAS *et al.*, 2000). The detailed sampling (18 samples in a 80 cm thick interval spanning the K/P boundary, Fig. 5) and intensive search for rare species in every sample indicate that 45 species suddenly disappeared at the jarositic K/P boundary layer. This extinction event represents 71% of the species, although, they account for only about 20% of the population in the fraction larger than 63 µm (Fig. 5).

The extinction of 71 % of the species of the Maastrichtian assemblage exactly coincides with the layer containing the cosmic markers (unit 2). At present, it is generally assumed that a meteorite impacted at the K/P boundary, which probably caused the mass extinction in planktonic foraminifera (ALVAREZ *et al.*, 1980, 1982; SMIT & HERTOGEN, 1980; SMIT, 1982, 1990, 1994; D'HONDT, 1994; LIU & OLSSON, 1994; MOLINA, 1994, 1995; MOLINA *et al.*, 1996, 1998; ARENILLAS, 1996; ARZ, 1996; ARZ & ARENILLAS, 1996; ARENILLAS *et al.*, 1998). Nevertheless, the hypothesis of a single catastrophic impact event as sole cause for the mass extinction is still controversial and various studies propose scenarios in which climate, volcanism and an impact may account for the extinction pattern in planktonic foraminifera (KELLER 1988, 1989a,b, 1993, 1994, 1996; KELLER *et al.*, 1993, 1996; MACLEOD & KELLER, 1991, 1994; PARDO *et al.*, 1996).

In the Early "Tertiary" the small, cosmopolitan forms were very abundant (e.g. *Heterohelix globulosa* and *H. navarroensis*). The guembelitrids (*Guembelitria trifolia* and *G. cretacea*) are rare in the Upper Cretaceous but are very abundant in the lowermost "Tertiary", just after the main planktonic foraminiferal extinction event. In the *G. cretacea* and *P. eugubina* Biozones a total of 18 small Cretaceous species are present that can be considered Cretaceous survivors (KELLER, 1988, 1989a,b, 1993; MACLEOD & KELLER, 1994; KELLER *et al.*, 1993, 1996; MOLINA *et al.*, 1996; ARZ, 1996). The possible


MAASTRICHTIAN
DANIAN
AGES
P. hantkeninoides
G. cretacea
P. eugubina
BIOZONES
SCALE (metres)
LITHOLOGY
SAMPLES
PLANKTONIC FORAMINIFERA
R. pennyi
45 species
G. subcarinatus
P. kempensis
H. labellosa
P. costulata
H. pulchra
H. glabrans
G. minuta
G. volutus
G. caravacaensis
H. planata
H. holmdelensis
H. monmouthensis
G. prairiehillensis
H. navarroensis
G. yaucoensis
H. globulosa
Gb. cretacea
Gb. trifolia
Gb. alabamensis
Gb. danica
Gc. conusa
Pv. longiapertura
Gc. fodina
Pv. sabina
Gb. irregularis
Pv. umbrica
Pv. cf. theodosica
Gc. extensa
Gc. cf. fringa
Gc. minutula
W. claytonensis
Pv. eugubina
W. hornerstownensis
Ch. morsei
10 %
20 %
30 %

Cretaceous survivors disappeared gradually during the early Danian, whereas at the same time "Tertiary" species evolved (Figs 5 and 6).

The question of how many species survived the K/P boundary event constitutes one of the most controversial topics. According to SMIT (1982, 1990) only *Guembelitria cretacea* survived. In contrast, KELLER (1988, 1989a,b, 1994), MACLEOD & KELLER (1994) and KELLER *et al.* (1996) reported that about 1/3 of the species survived. Historically, most of the micropaleontologists assumed that almost all planktonic foraminifera became extinct at the K/P boundary and, consequently, they considered all Cretaceous specimens found in the basal Danian as reworked. However, isotopic analyses of *Heterohelix globulosa, H. navarroensis, Guembelitria danica, G. cretacea, G. trifolia* and *Chiloguembelina waiparaensis* present in earliest Palaeogene sediments allowed BARRERA and KELLER (1990, 1994), KELLER *et al.* (1993) and KELLER (1993) to conclude that these species are Cretaceous survivors. Furthermore, they assumed that other species consistently present in "Tertiary" sediments are survivors as well, based on their constant presence in several samples and their geographic distribution in other sections (KELLER, 1988, 1989a,b, 1993; CANUDO *et al.*, 1991; KELLER *et al.*, 1993; MACLEOD & KELLER, 1994). Not all Cretaceous specimens present in earliest "Tertiary" samples can be considered survivors. For example, in samples from the basal Danian we found some isolated globotruncanid specimens with different preservation, which are very probably reworked. Other Cretaceous species that are present in several samples and are frequent can be considered as autochthonous, but isotopic analyses of the rare species (*Pseudoguembelina costulata, P. kempensis, Heterohelix glabrans*, etc.) are necessary to demonstrate that they also are survivors. Recently, some foraminiferal specialists that have criticised the Cretaceous species survivorship data, are now accepting that certain species, such as *Hedbergella holmdelensis* and *H. monmouthensis*, survived in addition to *Guembelitria cretacea* (LIU & OLSSON, 1994). SMIT (1994) also accepts some, "unimportant", survivorship above the K/P boundary and believes that the final extinctions may have lingered on for a while.

In conclusion, the model of extinction in planktonic foraminifera is composed of two superimposed patterns (MOLINA, 1994, 1995; MOLINA *et al.*, 1996): a gradual extinction pattern of less than 30% of the species (small cosmopolitan), which mainly became extinct in the early Danian and the catastrophic mass extinction pattern of more than 70% of the species (large tropical) at the K/P boundary. The sudden pattern of extinction of 45 species at Aïn Settara section exactly coincides with the layer containing the cosmic markers and is the major extinction event in the history of planktonic foraminifera. Consequently, this major pattern of extinction at the K/P boundary is very compatible with the catastrophic effects of a large meteorite impact. The gradual pattern of extinction in the early Danian, although it should be compatible with a less sudden cause, could also be the long-term effect of the meteorite impact.

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Fig. 6 — Relative abundance of planktonic foraminifera in percent across the K/P boundary at the Aïn Settara section.

Calcareous nannofossils

Biostratigraphy

The biozonation used in this paper is that of BRINKHUIS *et al.* (1994), which is based on PERCH-NIELSEN (1981, 1985) (Fig. 7). Units 0 and 1, which directly underlie the K/P boundary layer (unit 2), are attributable to the upper part of SISSINGH's nannofossil zone CC 26 (the *Micula prinsii* subzone) because of the co-occurrence of *Micula prinsii* (2 to 3%), *Lithraphidites quadratus* (1 to 2%) and sporadic *Nephrolithus frequens*. Consequently, they represent the terminal Maastrichtian.

Several nannofossil events have been recognised above the K/P boundary. Among these are a slight increase in abundance of calcareous dinoflagellate cysts (from less than 0.1% to 2%) at 3 cm above the base of unit 6 (STW 3-5), the FO of *Neobiscutum* cf. *romeinii* (slightly to moderately dissolved and recrystallised specimens) and of *Braarudosphaera bigelowii* 5 cm higher up in unit 6 (STW 8-10) and the absence of *Cruciplacolithus primus* and *Neobiscutum parvulum* in the uppermost sample studied (STW 84, Fig. 7). These data suggest that units 6 and the base of unit 7 belong to the *Neobiscutum romeinii* subzone or subzone CP1b of BRINKHUIS *et al.* (1994), which is of Early Danian age. The underlying units 4 and 5 are marked by poor and slightly dissolved nannofossil assemblages, exclusively consisting of Cretaceous coccoliths, including *M. prinsii* and *N. frequens*. But, as the lowermost Danian unit 3 contains a few *Obliquipithonella operculata* (formerly *Thoracosphaera operculata*, for an overview see WILLEMS, 1996), these three units should be attributed to subzone CP1a or the *Obliquipithonella operculata* subzone.

Main characteristics of the nannoflora

Calcareous nannofossils occurring across the K/P boundary have traditionally been classified into three broad groups: a Cretaceous assemblage, a "survivor" assemblage, and a "Tertiary" assemblage (PERCH-NIELSEN *et al.*, 1982, p. 355; JIANG & GARTNER, 1986, p. 236; POSPICHAL, 1994, p. 100 and 1996, p. 344). These correspond roughly to the three groups commented on by GARTNER (1996), respectively the assemblage of declining species, the assemblage of persistent species and the assemblage of incoming species.

The nannofossil assemblages of the basal Danian units 3, 4, 5 and the extreme base of 6 are dominated by Cretaceous taxa (generally over 99.9%) (Fig. 7). There is an abrupt decrease of these taxa at 8 cm above the base of unit 6 (from 98 % to 64 %). This decrease progressively continues up-section to about 37% at 60 cm above the K/P boundary. The abundance pattern of *Micula decussata* (10 to 20%) and *Watznaueria barnesae* (generally between 5 and 10%) is almost identical in the lower part of the section (unit 0 to base unit 6). These patterns are

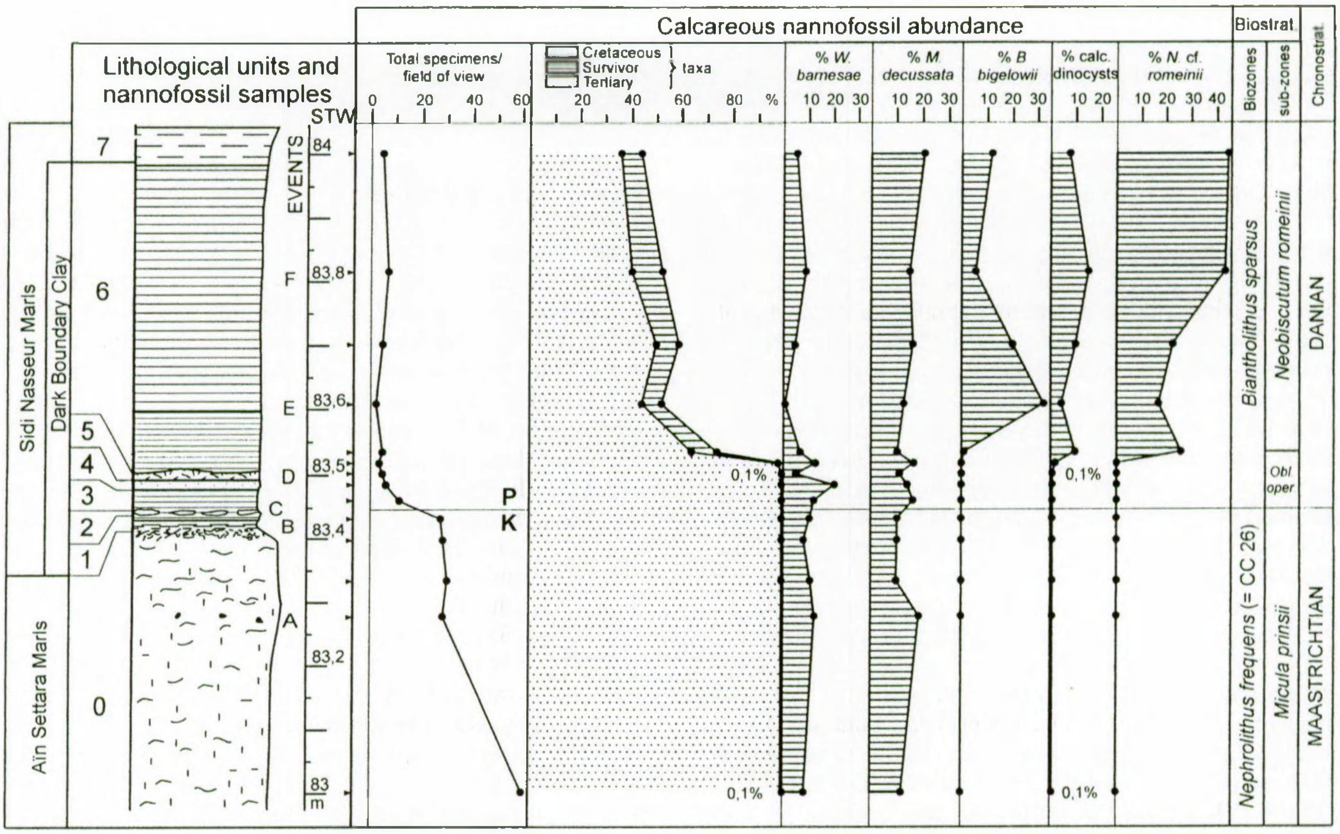

Fig. 7 — Abundance patterns of calcareous nannofossils.

strongly diverging higher up, probably because of selective dissolution. The marker species *Micula prinsii* and *Lithraphidites quadratus* disappear almost simultaneously within the lower part of unit 6 (between 8 and 20 cm above its base).

Most of the calcareous dinoflagellate cysts, until recently referred to as *Thoracosphaera* spp., and the nannofossil species *Markalius inversus* and *Cyclagelosphaera reinhardtii* are traditionally considered to represent survivor taxa. They are extremely rare in units 0 to 5 (less than 0.1%). Calcareous dinoflagellate cysts, including *Obliquipithonella operculata*, are consistently occurring with frequencies higher than 2% from the base of unit 6 onwards. They do not make up more than 10%, and hence may not represent real blooms. The other survivor forms, known from unit 6 onwards are less common (generally less than 2 %).

Neobiscutum cf. *romeinii* and *Braarudosphaera bigelowii*, which are generally considered to represent "Tertiary" forms (KELLER & VON SALIS PERCH-NIELSEN, 1995, fig. 4.5), first occur at ca 8 cm above the K/P boundary layer in the Aïn Settara section. High frequencies of *Braarudosphaera bigelowii*, which may indicate an episode of shoaling (STEURBAUT & KING, 1994), are recorded in the lower part of unit 6 (32 % at 20-22 cm above the K/P boundary), just before the acme of *N.* cf. *romeinii* (Fig. 7).

Survivorship of Cretaceous taxa

Cretaceous coccoliths are present in variable quantities above the K/P boundary in every section studied up to now (PERCH-NIELSEN *et al.*, 1982; SMIT & ROMEIN, 1985; KELLER & VON SALIS PERCH-NIELSEN, 1995; POSPICHAL, 1996). Stable isotope studies of bulk samples from various K/P boundary sections have shown that the Cretaceous coccoliths above the K/P boundary have isotopic values that are significantly different from those below the boundary. Based on these results it was concluded that Cretaceous nannofossils must have survived the K/P boundary events and have continued to reproduce in the earliest "Tertiary" oceans (PERCH-NIELSEN *et al.*, 1982). These conclusions have been contested by POSPICHAL (1994, 1996), who, based on studies of the El Kef section, suggested that the presence of Cretaceous coccoliths in Early Danian deposits is entirely due to reworking and that there is no evidence for survivorship.

The nannofossil data from the Aïn Settara section do not support POSPICHAL's theory of reworking. If all the supra-boundary Cretaceous taxa are reworked, one should expect to find *Micula prinsii* and *Lithraphidites quadratus*, just like the other Cretaceous forms, throughout the section, up to the base of unit 7, and not to have disappeared in the lower part of unit 6. These disappearances are not believed to result from selective dissolution, because otherwise both species should reappear in the better-preserved assemblage of the topmost sample. Moreover, as it is generally assumed that reworking prevails during shallowing conditions, one should find maximum percentages of Cretaceous taxa in sample 20-22, which according to the acme of *Braarudosphaera* *bigelowii* reflects the most proximal conditions. As this is not so, it is suggested that a substantial number of Cretaceous species could survive into the "Tertiary". However, the abundance peaks of *W. barnesae, M. prinsii* and *Arkhangelskiella* spp. in units 4 and 5 and at the base of unit 6, just above the K/P boundary (Fig. 7), might be due to reworking.

Interpretation

On the whole, the calcareous nannofossil distribution in the K/P boundary interval of the Aïn Settara section is very similar to that recorded at El Kef (PERCH-NIELSEN, 1981), up to now considered to yield one of the most complete K/P boundary sequences (KELLER & VON SALIS PERCH-NIELSEN, 1995, fig. 4.3; KELLER *et al.*, 1996). The minor differences in nannoflora of both sections (e.g. absence of nannofossils in the basal 7 cm of the boundary clay at El Kef, due to a presumably more pronounced dissolution; absence of *B. bigelowii* and occurrence of blooms of calcareous dinoflagellate cysts in the *N. romeinii* subzone at El Kef; data from PERCH-NIELSEN, 1981, fig. 2) are interpreted as the result of palaeoenvironmental differences, El Kef occupying a more distal position in the basin. The nannofossil data suggest that the K/P boundary interval at Aïn Settara is at least as complete as that of El Kef.

In the Aïn Settara section there is a stepwise reduction in nannofossil abundance across the K/P boundary, including a first drop in abundance during the latest Maastrichtian (50% reduction), a second and major drop at the K/P boundary (60% reduction) and a third drop slightly above the boundary (50% reduction between units 3 and 4). These abundance drops do not result from a single cause (e.g. successive sea-level changes), because they do not always coincide with the major lithological changes. The major shifts in lithofacies, located respectively at the base of the boundary clay and at the base of unit 7, had no apparent effect on the nannoplankton. The carbonate abundance pattern mirrors nearly exactly that of the nannofossil abundance, except for the carbonate peak in unit 4 (compare Fig. 3 with Fig. 7). As a consequence the carbonate content may be an indication of biotic surface productivity. The anomalous carbonate peak in unit 4 is probably the result of huge quantities of minute calcitic material (present in the nannofossil fraction), brought in the deposition area by currents.

The Late Maastrichtian nannofossil assemblages are very rich and diversified, reflecting a high biotic surface productivity. These favourable and stable conditions disappeared near the K/P boundary. The nannofossil assemblages from the oldest Danian layers (units 3 to 5) are poor. They are entirely made up of Cretaceous coccoliths and this is assumed to result, at least partly, from reworking. The Cretaceous taxa up-section are believed to have survived into the Palaeogene, although generally with rapidly declining numbers (Fig. 7). The earliest new Palaeogene species seem to appear at about 4.000 to 5.000 years above the K/P boundary, if one assumes that the 60 cm thick DBC represents deposition over about 30 ky (interval K/P boundary to FO of *Parvularugoglobigerina eugubina*; see BERGGREN *et al.* 1995, p. 146).

Palynology

General comments

All studied samples are sufficiently fossil-rich to support quantitative analysis of the successive palynological associations. Organic-walled microfossils are well preserved. Four main groups are recognised: (1) pollen and spores (some rare Normapolles and more often spores), (2) dinoflagellate cysts, (3) acritarchs ("leiospheres" and *Micrhystridium*) and (4) Scytinascias (= organic linings of foraminifera *sensu* COURTINAT, 1989). Palambages (algae), tasmanitids and scolecodonts are also sporadically present.

The relative proportions of the 4 main groups reported in Fig. 8 allow the following remarks: 1) the marine constituents, dinoflagellate cysts, acritarchs and Scytinascias always dominate over the continental ones (pollen and spores); 2) the continental input of pollen-spores (with abundant cuticular and lignitic debris) is weakly represented, reaching a maximum (7 %) just below the DBC (83.39 m); 3) the number of dinoflagellate cysts increases progressively across the K/P boundary (83.27 m to 83.49 m) and then decreases up to 83.61 m, whereas Scytinascias shows an opposite trend.

The organic-walled microfossils in the studied interval are mainly of marine origin, just as in the Maastrichtian and the Danian marls not studied here. No major pollen and spore maximum was observed. This might be surprising considering the organic geochemistry data that reveal a type III and occasionally a type II organic matter (Table 1). However, this can be easily explained taking into account that the organic-walled microfossils only represent a very small part of the total organic matter. The amorphous organic matter constitutes the major part of the insoluble residues and is of continental origin according to the organic geochemistry (see above).

Dinoflagellate cyst distribution

The dinoflagellate cysts represent the most diversified group among the organic-walled microfossils studied here. Fifty-seven taxa were identified in the K/P boundary interval, between 83 m and 84 m. According to their respective distribution they can be assembled into three main groups, respectively consisting of - 1: ubiquitous taxa, occurring throughout the entire Aïn Settara section, such as *Spiniferites* and *Achomosphaera* which are more or less regularly present in the association; - 2: taxa with a more restricted distribution, ranging from the lower part of the section and overstepping the K/P boundary, such as *Fibrocysta licia* (last appearance at 83.46 m), *Andalusiella gabonensis, Cerodinium diebelii, Cribroperidinium* (?) *pyrum, Dinogymnium* spp., *Disphaerogena carposphaeropsis, Exochosphaeridium bifidum, Glaphyrocysta* spp., *Manumiella seelandica, Phelodinium magnificum*; - 3: taxa appearing just before, or just after the K/P boundary and extending a little higher in the section: *Kenleyia, Cordosphaeridium fibrospinosum, Tanyosphaeridium xanthiopyxides, Diphyes spinulum, Damassadinium, Fibrocysta* spp. (except *F. licia*), *Alisocysta circumtabulata, Duosphaeridium rugosum* and *Exoscho-*

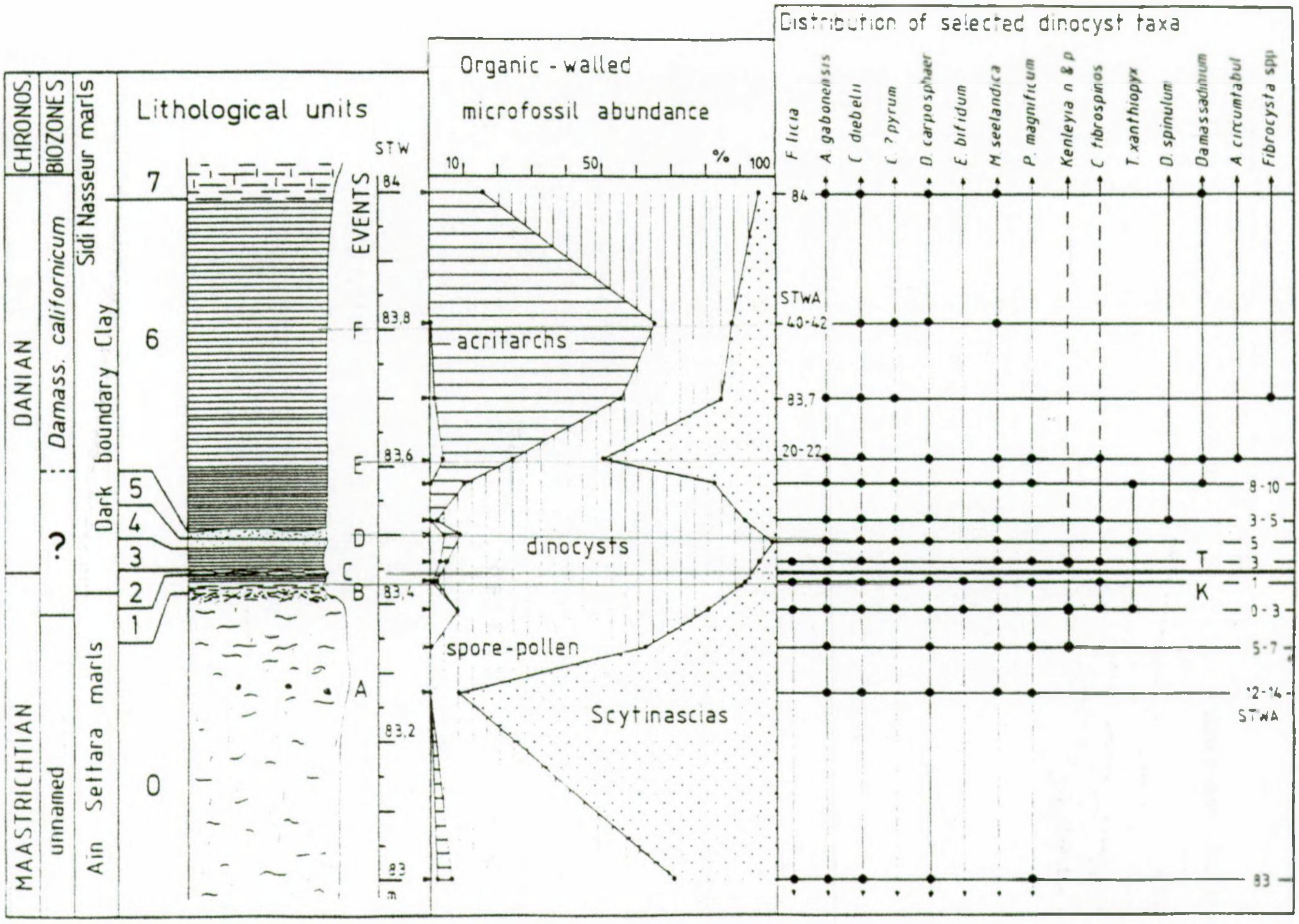

Fig. 8 — Distribution of main palynomorph groups and distribution of selected stratigraphically significant dinoflagellate cyst taxa.

sphaeridium phragmites. The two last species appear 4 m above the top of the studied section (88 m).

From the qualitative and quantitative distribution of the dinoflagellate cysts along the Aïn Settara section (Fig. 8) it is quite clear that the K/P boundary events did not affect their distribution. Not a single species disappears at this limit. Some first appearances have been recorded slightly below (*Kenleyia nuda = Carpatella cornuta, K. lophophora*) or just above the K/P boundary. However, the analysis of the palynomorphs of the entire Aïn Settara section has led to the identification of a major change in the composition of the assemblages, from associations with abundant *Spiniferites-Achomosphaera* and *Glaphyrocysta*, to associations dominated by *Fibrocysta* and *Exochosphaeridium phragmites*. This substantial change does not occur at the limit itself, but a few meters higher up, in the Lower Danian.

Completeness of the Aïn Settara K/P boundary section

Brinkhuis & Zachariasse (1988) and Brinkhuis & Leereveld (1988) sampled and analysed a 10 m thick interval of the El Kef type section, from ca 4.5 m below to about 5 m above the K/P boundary. There are some similarities in the palynomorph sequence of both the El Kef and the Aïn Settara sections, among which the increase in sporomorphs just below the K/P boundary (Aïn Settara sample at 83.39 m and sample 540 at El Kef) and the absence of a break in the dinocyst distribution across the boundary. On the basis of palynomorphs it is possible to correlate samples taken from 83 m and 84 m at the Aïn Settara section with respectively samples 538 and samples 552-553 from El Kef. The main difference between the two sections concerns the slightly earlier appearance of *Kenleyia (K. nuda = Carpatella cornuta, K. lophophora)* in the Aïn Settara section (at 83.39 m, a few cm below the K/P boundary, Fig. 8). At El Kef, these species appear only 20 cm above this boundary. These earlier occurrences are easy to explain bearing in mind the occurrence of lithological units in the Aïn Settara section which have not been reported from El Kef (unit 1) and assuming that the uppermost part of unit 0, containing the first *Kenleyia* at Aïn Settara, is missing at El Kef.

The Aïn Settara K/P boundary sequence

Main features

Lithological, geochemical and palaeontological data highlight the interest of the Aïn Settara section which exhibits a well exposed and expanded K/P boundary

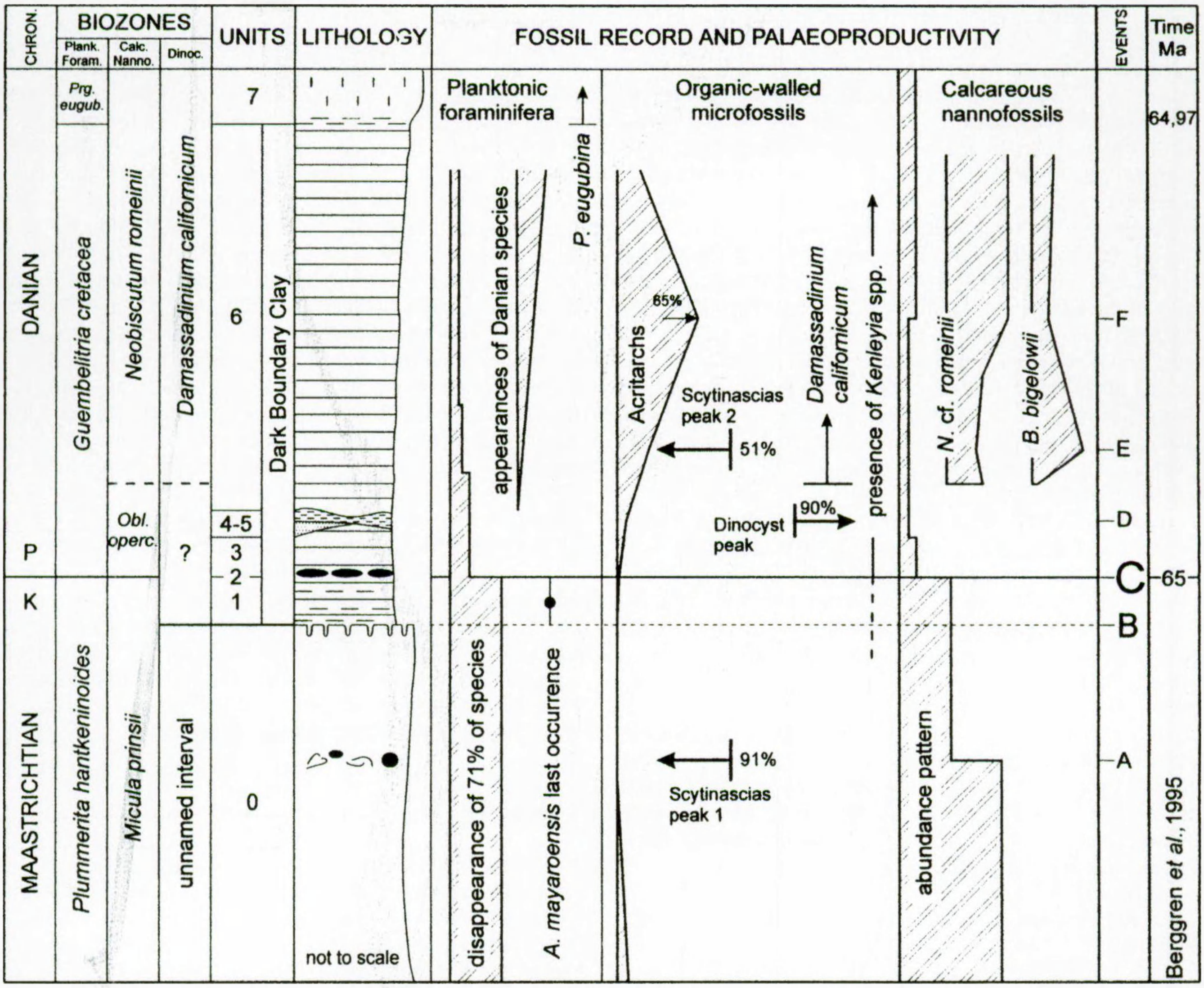

Fig. 9 — The main events compared to the fossil record and palaeoproductivity, calibrated to the lithological column. The dinoflagellate cyst, acritarch and Scytinascias contents are expressed as % of the total number of organic-walled microfossils (= 100 %).

interval, close to the well known El Kef reference section. Because of its almost continuous and complete depositional history the Aïn Settara section allows us to differentiate discrete events and to clarify and refine parts of the palaeobiologic record.

Six major geological events, labeled A to F in ascending order, have been identified in the studied 1 m thick K/P boundary interval, demonstrating important palaeoenvironmental changes (Fig. 9). These events are of diverse magnitude and origin. Three of these events (D, E and F) seem to be minor. Event D had only little effect on the palaeontological signal, despite a clear lithological expression. On the contrary, events E and F, which are evidenced by substantial palaeontological changes, are not characterised by prominent lithological shifts. Event D is characterised by an abrupt change in lithology (income of silt in channel-like structures) and a drop in nannofossil abundance. The occurrence of microchannels and ripples might refer to a storm deposit that occurred in the earliest Danian. Event E, located at about 22 cm above the K/P boundary, within the lower part of unit 6, is defined by a substantial increase in the abundance of *Braarudosphaera bigelowii* (from ca 2% to 32%) (Fig. 7). This might reflect an episode of shallowing. The changes in the Palaeogene nannofossil-assemblage (rise in *Neobiscutum* cf. *romeinii*, drop in *B. bigelowii*) marking event F are believed to result from a deepening of the depositional environment.

Comparison with other K/P boundary sections (Keller & von Salis Perch-Nielsen, 1995; Stinnesbeck & Keller, 1996; Adatte *et al.*, 1996; Gartner, 1996) suggests that at least two of the three lowermost events (B and C) have a global significance. Event A, at about 14 cm below the K/P boundary, is marked by a sudden substantial increase in tiny bioturbations and by the occurrence of small nodules and a few macrofossils (bivalves, brachiopods, solitary corals, but no ammonites). This event, which coincides with a substantial drop in nannofossil abundance (50%), seems not to have affected the planktonic foraminiferal abundance and species richness (only *Rugoglobigerina pennyi* apparently disappeared). The major increase in Scytinascias at this level (from 30% to

93%) probably results from a major enrichment in benthic foraminifera. All these data refer to a slowdown in sedimentation rate, of which the origin is not clearly understood up to now. The first appearance of the Danian dinoflagellate cyst taxa *Kenleyia nuda* and *K. lophophora* definitely lies just above this junction, and, thus, is of terminal Maastrichtian age. At about 3 cm below the K/P boundary occurs a burrowed surface, separating underlying carbonate-rich marls (35%) from grey poorly calcareous clays. It represents an episode of non-deposition, referred to as event B. This junction, which forms the base of the ca 60 cm thick Dark Boundary Clay (DBC), is believed to correspond to a major flooding surface. No substantial palaeontological changes have been observed at this level (no abundance drops nor extinctions). The reappearance of the planktonic foraminiferid *Abathomphalus mayaroensis* just above the junction is probably related to a substantial deepening of the depositional environment.

Event C is marked by a bed of platy orange-coloured jarositic nodules, in which relatively high maximum concentrations of iridium (2.7 $ng.g^{-1}$) and Ni-rich spinel (about 150 crystals mg^{-1}) have been recorded (Pl. 4). These Ni-rich spinel and Ir spikes, which characterise the K/P boundary, are coinciding with major biotic changes: major extinction in planktonic foraminifera, mainly complex forms adapted to deep and intermediate environments (71% of the species) and a 60% drop in calcareous nannofossil abundance. This mass extinction cannot be caused by anoxia, because no unequivocal evidence for anoxia has been found in the DBC. As a consequence, event C has to be related to the well-known impact event that occurred at the end of the Cretaceous period.

The "K/P boundary" in the Aïn Settara section: a reflection

In the El Kef reference section the cosmic markers are included in the"red clay layer" (sic), a jarositic layer, which coincides with the base of the boundary clay. In the auxiliary section of Aïn Settara (REMANE *et al.*, 1999), the cosmic markers imbedded in platy jarosite nodules (event C) are located a few cm above the deeply burrowed surface which clearly marks the base of the boundary clay. In both sections extinctions are linked to the cosmic marker bearing jarositic layer. At El Kef, the "K/P boundary" is marked by the coincidence of three geological distinct phenomena: a change in lithology (base of the boundary clay), a geochemical-mineralogical signal (pyrite-derived jarositic layer with the Ir-anomaly and Ni-spinels) and biotic events (extinctions of planktonic taxa). In the Aïn Settara section only the geochemical-mineralogical and biotic criteria coincide. The base of the boundary clay occurs a few cm below the cosmic marker bearing jarositic layer and is, as a consequence, definitely older. Thus, following the concept of COWIE *et al.* (1986), the base of the Dark Boundary Clay at Aïn Settara, which represents the K-P boundary at El Kef, is hence separate from the two other "diagnostic" criteria. Therefore, placement of the K-P boundary at Aïn Settara should take into account the concomitant cosmic and biotic events, instead of the lithological change at the base of the "Dark Boundary Clay".

The discrepancies between the two sections can be explained as resulting from minute differences in the sedimentary record. As stated above, the base of the boundary clay (event B) is interpreted as a short non-deposition interval, which duration could have been a little bit longer in the El Kef section. The deposition of the boundary clay could have begun later at El Kef, where the impact products were sprinkled directly on the underlying marls. Indeed, at El Kef, immediately below the "red layer" we have frequently observed burrows filled with black clay that are equivalent with the ones at Aïn Settara ("event B") but less developed or eroded. It is believed that these burrows, well represented in the Aïn Settara section, are only preserved in the uppermost part of the underlying Maastrichtian marls in the El Kef section. This observation confirms our interpretation that these burrows are equivalent to "event B" of the unit 1. Consequently, we are convinced that the Aïn Settara is more complete than the others known sections in Tunisia not in the lowermost Danian but in the uppermost Maastrichtian.

The concomitant biotic and cosmic signals are believed to be indicative for the K/P boundary, because they can be considered as independent indicators of the global event (this in contradiction to the sedimentological variations). The adoption of these two coinciding phenomena as boundary criteria is justified because it remains consistent with the current general agreement of the causal relationship between impact and extinction.

Conclusions

High-resolution lithological, micropalaeontological and geochemical investigations at Aïn Settara have led to the identification of six events within the studied 1 m thick K/P boundary interval. The base of this interval, lying in the topmost part of the Aïn Settara marls at about 45 cm below the K/P boundary, falls within the *Plummerita hantkeninoides* and the *Micula prinsii* biozones, and is of terminal Maastrichtian age. The top of the studied interval, located at about 55 cm above the K/P boundary, just above the top of the Dark Boundary Clay, lies at the base of the *Parvularugoglobigerina eugubina* biozone (= P1a1 or Pα) and within the *Neobiscutum romeinii* nannofossil subzone (= CP1b), and is dated as Early Danian. Comparison with other K/P boundary sections suggests that at least two of the three lowermost events (B and C) have a global significance. The three uppermost events (D, E and F), which are located in the Dark Boundary Clay, seem to have only local or regional significance.

The study of the stratigraphic distributions of iridium and Ni-rich spinel shows that the cosmic imprint reported worldwide at the K/P boundary is also recorded in the Aïn Settara section. The stratigraphic coincidence of the spinel and Ir peaks and the major extinction of planktonic foraminiferal species clearly establish a causal link between the K/P biological crisis and the cosmic event. Their disjunction from the base of the Dark Boundary Clay shows that the change of lithology usually used to determine the K/P boundary is distinct from the major extinction (in the planktonic realm), classically referred to this boundary and linked to the presence of cosmic markers. These results argue the need for the revaluation of the K/P boundary GSSP at El Kef. It is suggested to redefine the K/P boundary at the level of coincidence of the major biotic changes and the cosmic markers. This coincidence is not fortuitous since it has now been observed in many K/P boundary sites all around the globe. The Aïn Settara data support the view of a giant asteroid impact triggering the global mass extinction at the end of the Cretaceous.

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