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Cyclostratigraphy and chronometric scale in the Campanian – Lower Maastrichtian: the Abiod Formation at Ellès, central Tunisia

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ABSTRACT

The Campanian to Lower Maastrichtian Abiod Formation of the Ellès section, central Tunisia, has been analyzed bed by bed for cyclostratigraphic purpose. Based on the "20 kyr" precession and "100 kyr" eccentricity cycles, sedimentation rate profiles were generated, which were then transformed into cumulative time scales. The resulting synthetic time scale places identified sedimentary and biological events in a new time-based framework floating around the Campanian-Maastrichtian boundary. This new time scale was compared with previously published geological time scales.

1. Introduction

The time resolution of biozonation may vary extensively according to the group of organisms and the period of time considered. For the Cretaceous Period the resolution of pelagic fossil zonations can be as high as 0.3 Myr (Cope, 1993).

On another side, progress has been made in the recognition of the Milankovitch cyclicity – i.e., the orbital periods of precession ($\sim$21 kyr), obliquity ($\sim$41 kyr) and eccentricity ($\sim$100 kyr and $\sim$400 kyr) in geological series. As a result, very accurate and precise astrochronologic time scales can be produced, determining duration and age of geological events (see for example: Gale, 1989; Einsele et al., 1991; Hilgen et al., 1993; Schwarzacher 1993; Herbert et al., 1995; House and Gale, 1995; Sageman et al., 1997; Caron et al., 1999; Hennebert and Dupuis, 2003). This astrochronologic approach has been used here in the aim to determine the absolute timing of the biological events intervening in the chronology of the Campanian – Lower Maastrichtian interval. This work also aims at showing that a fast and inexpensive field approach of "white box" type can solve, at least within favourable cases, a problem that otherwise necessitates time consuming and expensive methods such as geochemistry, magnetic susceptibility and time-series analysis.

The study begins with the description of the diverse aspects of the studied section (e.g., geological setting, sedimentology, palaeoenvironment, location of the Campanian-Maastrichtian boundary; section 2: the studied section). It continues with the description of the different bed types observed and their vertical enchainment (section 3: stratonomy). Then, the stratonomic characteristics are interpreted according to the known data about the primary orbito-climatic signal (section 4: cyclostratigraphic interpretation). Then, two chronometric scales are built by using the "100 kyr" cycle of the eccentricity and the "20 kyr" cycle of the precession. The time scales are compared between them and with the already published time scales (section 5: the chronometric scale). The paper ends with the conclusions (section 6).

2. The studied section

2.1. Geological setting

The village of Ellès is situated in the Central Tunisian Atlas, between the towns of El Ksour and Maktar, about 137 km from Tunis, 43 km from El Kef and 65 km from Kalaat Senan (Fig. 1A). The studied section is located in the Ellès syncline, showing a NE-SW axial direction. It shows a quasi complete succession from the Upper Cretaceous to the Eocene (Pervinquière, 1903). The Campanian to Maastrichtian interval of the Ellès section consists of the Abiod Formation: two stratified-limestone bars (Haraoua and Ncham Members) separated by a marly facies with sparse

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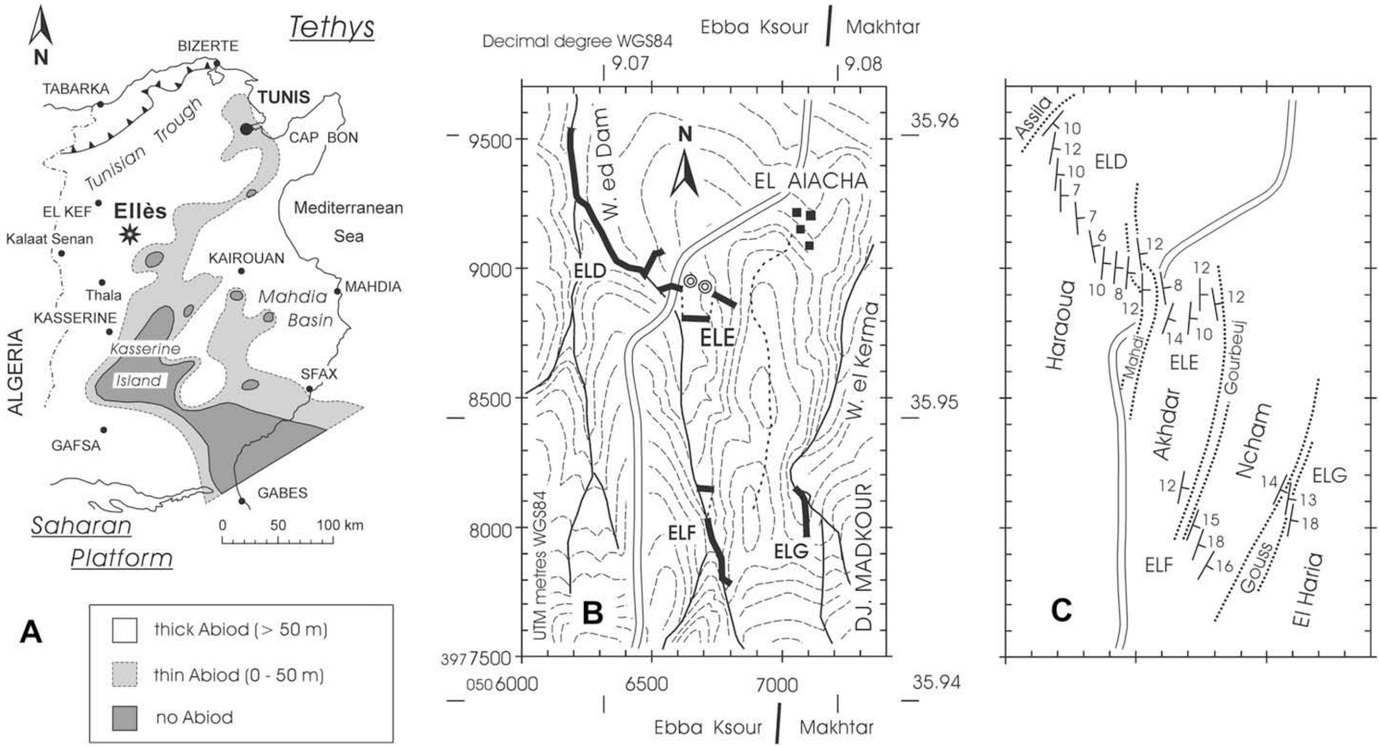

Fig. 1. Location of the Ellès section. A, Palaeogeography and location of the section (from Robaszynski et al., 2000, modified). B, Detailed location of the studied sections. Surveyed with a GPS (map datum = WGS84) and supplemented with the aim of the topographic map of Tunisia (contour interval 10 metres). The partial sections are in thick line. The double circles correspond to the place of the residue-basins of olive-pressing. The black squares locate the hamlet of El Aiacha. W. = wadi (oued), Dj. = djebel. C, Geological sketch of the studied area. For the member and formation names see Fig. 2.

limestone beds (Akhdar Member). The bases and tops of the two limestone bars are characterized by transitional facies, with dense limestone-marl alternations (Assila, Mahdi, Gourbeuj and Gouss Members). The Abiod Formation is followed by the thick marly El Haria Formation.

This was already the subject of several studies (Li and Keller, 1998; Li et al., 1999, 2000; Robaszynski and Mzoughi, 2004, in press). The stratigraphic interpretation of Li and Keller and the one presented in this work are compared in detail in Robaszynski and Mzoughi (in press). The Ellès section is especially known as a parastratotype section of the Cretaceous-Paleogene boundary (Remane et al., 1999), and has already been studied in many papers (e.g., Zaghbib-Turki et al., 2000, 2001; Abramovitch and Keller, 2002; Gardin, 2002; Karoui-Yaakoub et al., 2002; Keller et al., 2002).

Central Tunisia was located during the Cretaceous Period north of the Saharan Platform, on the south-western border of the Tethyan Ocean. More precisely it occupied the southernmost margin of the Tunisian Trough, at the north of the "Kasserine Island". This situation is illustrated on Fig. 1A by the isopach map of the Abiod Formation (which is the studied formation). During the Campanian – Early Maastrichtian, central Tunisia was exposed to tectonic constraints (Africa – Eurasia relative movement) driving to synsedimentary faults, noticeable thickness-variations in some places, intraformational conglomerates, slumping and turbidites (Kadri et al., 1999; Robaszynski et al., 2000; Dlala, 2002; Bouaziz et al., 2002). The Ellès section was quite unaffected from these tectonic features, except for a slump present near the base of the Maastrichtian.

According to recent plate-tectonic models, at the Campanian-Maastrichtian boundary, central Tunisia was located close to the Northern Tropic (which itself varies within the Late Cretaceous from 22.1° to 24.2° N according to the obliquity value; Laskar et al., 2004). The calculated palaeolatitudes are, for Ellès area: 18–19° N according to the *Peri-Tethys Atlas* (Philip and Floquet, 2000), 21–22° N according to the *Plate Tectonic Reconstructions – On-line Paleogeographic Mapper* (Schettino and Scotese, 2000), 22–23° N according to the *Plate Tectonic Reconstruction Service* of the *Ocean Drilling Stratigraphic Network* (Hay et al., 1999).

2.2. Local geography

The four studied sections are named: ELD, ELE, ELF and ELG (Fig. 1B; as in Robaszynski and Mzoughi, in press). These are located in an area called Argoub el Aiacha, SW of the hamlet of El Aiacha, on the NW side of Djebel Madkour (or Madhkour). This area lies between the Wadi ed Dam and the Wadi el Kerma. Section ELD (90 m thick) starts in the Wadi ed Dam bed, downstream from the road, and follows the wadi in the SE direction. Section ELE (98 m thick) begins in the Wadi ed Dam, just west of the road, and continues zigzagging eastwards beyond the ponds containing olive-pressing residues. The ELF section (122 m thick) starts upstream in the wadi which leaves the road towards the south and goes up towards the Djebel Madkour. Section ELG (37 m thick) is situated east from the hill which prolongs El Aiacha in the south. It starts in the bed of the Wadi el Kerma and is prolonged southwards (upstream lies the well-known Cretaceous-Paleogene boundary section). The studied area is for its largest part on the eastern part of the Ebba Ksour 1/50 000 geological-map sheet. ELG is located just on the western edge of the Makhtar sheet.

2.3. General description

2.3.1. Formations and members

The sedimentary sequence contains limestones and marls mainly belonging to the Abiod Formation (Campanian-Maastrichtian,

Fig. 2A). This is well known in the central Tunisian landscape as it brings out splendid reliefs by its two limestone bars framed by thick marly sequences below (Kef Formation, Turonian-Campanian) and above (El Haria Formation, Maastrichtian-Paleocene). The Abiod Formation was introduced by Burollet et al. (1954) and its content and lateral variation was described in Burollet (1956), Ben Ferjani et al. (1990), Negra and Purser (1996), Robaszynski et al. (2000) and Jarvis et al. (2002). According to Robaszynski et al. (2000) the Abiod Formation can be divided at Kalaat Senan into seven members: the Assila Member (marl-limestone alternation), the Haraoua Member (limestone bar), the Mahdi Member (marl-limestone alternation), the Akhdar Member (marly facies), the Gourbeuj Member (marl-limestone alternation), the Ncham Member (limestone bar) and the Gouss Member (limestone-marl alternation). All seven have been recognized at Ellès (Fig. 1C and 2A; Robaszynski and Mzoughi, 2004, in press).

2.3.2. Composite section

The four sections ELD, ELE, ELF and ELG are used to built a composite-section Z (Fig. 2B) which includes almost the entire Abiod Formation; only its base can not be studied in continuous sections and was not been considered in this work (Assila Member and base of the Haraoua Member as shown by the two small sections ELB and ELC; see, Robaszynski and Mzoughi, in press). The study extends upwards into the El Haria Formation to the second prominent structural surface (ELG 17 m to ELG 37 m, in Fig. 2).

Sedimentary sequence can be followed on almost all its thickness, because the individual partial sections share overlapping exposures (Figs. 1B and C and 2B). The overlapping partial sections were correlated exclusively by the means of the bedding characteristics of the exposed rocks (thicknesses of the beds and the interbeds).

However, discontinuities of exposure caused some difficulties in the cyclostratigraphic interpretation. The two most problematic intervals are described below:

(1) The first interval is ELD 48 m to ELD 65.5 m. The section is not well exposed in the wadi. Only resistant beds can be observed, the others are covered by the alluvia. The interval between ELD 55 m and 57.5 m is partially usable (Fig. 2B, see later).

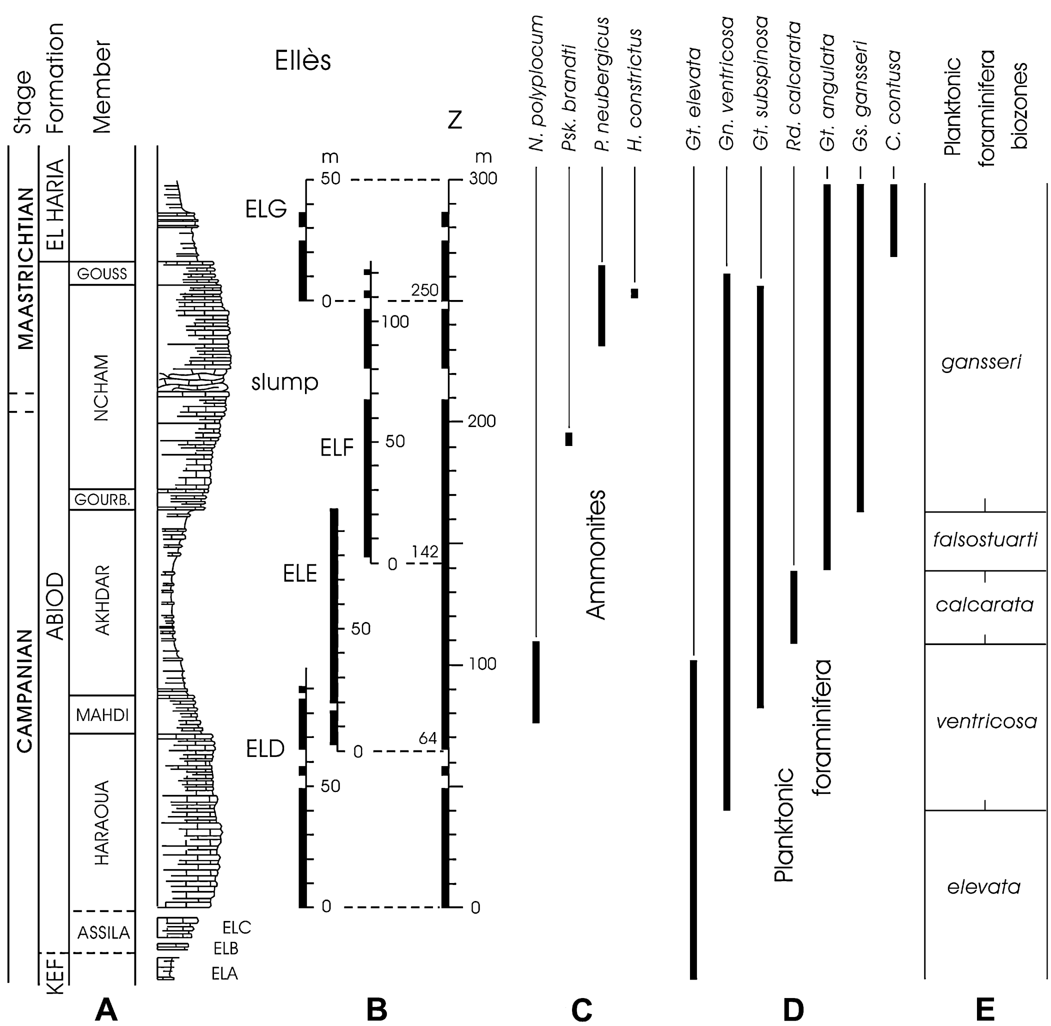

Fig. 2. Composite section of the Ellès Abiod Formation. A, Lithological column according to Robaszynski and Mzoughi, in press, simplified. Gourb. = Gourbeuj. B, Partial sections (ELD, ELE, ELF, ELG) and composite section (Z). Black bars indicate where a continuous cyclostratigraphic interpretation could be made in the field. C, Ammonite distribution. *N.* = *Nostoceras* (*Bostrychoceras*), *Psk.* = *Pseudokossmaticeras*, *P.* = *Pachydiscus*, *H.* = *Hoploscaphites*. D, Planktonic foraminifera distribution according to Robaszynski and Mzoughi, in press, simplified. *Gt.* = *Globotruncanita*, *Gn.* = *Globotruncana*, *Rd.* = *Radotruncana*, *Gs.* = *Gansserina*, *C.* = *Contusotruncana*. E, Planktonic foraminifera biozones (Robaszynski and Mzoughi, in press). *falsostuarti* = *Globotruncana falsostuarti* Zone.

(2) The second interval corresponds to a large slump in the ELF section, which severely disturbed the original beds. Moreover, they mostly consist of massive limestone with few discernible interbeds. It has been assumed that this intraformational deformation did not involve significant thickness variations in the series.

The studied composite section Z is about 300 metres in thickness (Fig. 2B). The survey of the section was carried out in great detail (5 cm/m) by F. Robaszynski and M. Mzoughi in May 1999, May 2001 and May 2002. It was examined and interpreted in the field for the cyclostratigraphy by M. Hennebert in May 2004 and sampled for the ammonites by S. Goolaerts in May 2001, 2003, and 2004.

2.4. Facies and petrography

The studied section shows stratified limestones (Haraoua and Ncham Members), limestone-marl alternations (Mahdi, Gourbeuj and Gouss Members) and marls with limestone beds (Akhdar Member and base of the El Haria Formation). The limestones are generally very pale, white or cream-coloured (*abiod* means white). They are particularly pale in the very pure limestone beds. They are brownish in the more argillaceous and altered beds. The marls vary from bluish-grey, turquoise, in the Akhdar Member to dark-grey almost black in the El Haria Formation.

Limestones are generally fine grained (mudstone and wackestone), without obvious structures, except in those levels where *Zoophycos* are abundant. They normally contain few discernible fossils. Particularly, in the Haraoua Member the fossils are very rare (inoceramids in some beds, scattered irregular echinids and some *Zoophycos*). The fossils become more abundant higher up in the series in the Mahdi Member and particularly in the Akhdar Member. The latter contains macrofauna of diverse types: both heteromorph, *Nostoceras (Bostrychoceras) polyplocum* (Fig. 2C), and non heteromorph ammonites, irregular echinids, brachiopods, bivalves and rare serpulids, bryozoa and corals. The Ncham Member contains many fossil trace *Zoophycos* and several species of inoceramid bivalves (some may reach very big sizes). Irregular echinids and ammonites can also be found. In the Ncham Member, limestones contain some ribbon-like flint-levels particularly in the slump, where the limestone is almost massive.

The Abiod Formation was often described as being made up of "chalky" limestones (Burollet, 1956; Jarvis et al., 2002; Mabrouk et al., 2005). In central Tunisia they are genuine, often hard, limestones that are significantly different from boreal-realm chalks.

The Abiod limestones are mainly composed of micritic mud, mudstones and wackestones, containing small sized elements which often consist of (fragmented) planktonic foraminifera. Calcispheres, small calcareous and agglutinated benthic foraminifera, echinoderm fragments by inoceramid bivalves and sponge spicules can also be found. Textures have been modified into "blows of brushes" by *Zoophycos*.

It has been suggested that calcareous mud of the Abiod Formation was at the beginning mainly made up of coccoliths on which sparry overgrowths and microspar further developed (Negra and M'Rabet, 1992, 1994; O'Hearn et al., 1993; Negra, 1994; Mabrouk et al., 2005).

2.5. Palaeoenvironment

The fine grained nature of the rocks, limestones (mudstone and wackestone) and marls, suggests that the sediments were deposited under weak energy conditions.

Zoophycos are common in fine-grained sediments that are deposited below the level of storm-waves action, in zones unaffected by bottom currents. It thrives in the presence of quite abundant organic matter and in scarcely oxygenated environments (e.g.: Seilacher, 1967; Frey and Pemberton, 1984; Ekdale, 1988; Ekdale and Mason, 1988; Savrda and Bottjer, 1986, 1989, 1991; Savrda et al., 1991; Bromley, 1996; Savrda et al., 2001).

The inoceramid bivalves are known to colonize also unfavourable environments. They are frequently found under oxygen deficient conditions, even in black shales that are highly rich in organic matters (Thiede and Dinkelman, 1977; Elder, 1987; Kauffman, 1988; Sageman, 1989; Kauffman and Sageman, 1990; MacLeod and Hoppe, 1992; Harries and Schopf, 2003; MacLeod, 2003; Henderson, 2004).

The co-occurrence of the inoceramid bivalves and *Zoophycos*, and the scarcity of others macrofossils (irregular echinids, brachiopods, bivalves, and rare serpulids, bryozoa and corals), suggest very calm sedimentary conditions, in relatively deep (below the level of storm-waves action) environment. A quite low oxygen content is possible, although the limestone beds appear pervasively bioturbated.

2.6. Location of the Campanian-Maastrichtian boundary

From a general point of view, the exact placement of the Campanian-Maastrichtian boundary is controversial. Different boundary criteria have been used. Time scales published before 1995 (e.g., Haq et al., 1987; Harland et al., 1990) used the disappearance of the planktonic foraminifera *Radotruncana calcarata* (Cushman, 1927) as the best boundary proxy.

Today, after the 1995 Brussels Symposium on Cretaceous Stage Boundaries (Odin, 1996), the Campanian-Maastrichtian boundary was placed close to the first appearance of the ammonite *Pachydiscus (Pachydiscus) neubergicus* (von Hauer, 1858) in the ratified multi-event criterion concept of Odin (Odin, 1996, 2002; Odin and Lamaurelle, 2001). The disappearance of *Radotruncana calcarata* is now placed 1.5 to 4 Myr before the boundary (Schönfeld and Burnett, 1991; Hancock et al., 1992; Obradovich, 1993; Robaszynski and Caron, 1995).

In central Tunisia the Campanian-Maastrichtian boundary can be located with high confidence when the limestone deposits of the Ncham Member delivers sufficient index ammonites. This is the case of the Kalaat Senan section (Robaszynski et al., 2000; Fig. 3) where uppermost Campanian could be recognized by the co-occurence of *Pseudokossmaticeras brandti* (Redtenbacher, 1873) and *Nostoceras (Nostoceras)* cf. *hyatti* Stephenson, 1941, and where Early Maastrichtian is defined by the first occurrence of Nostoceras (*Nostoceras*) aff. *magdadiae* Lefeld and Uberna, 1991 and higher up section is characterized by the presence of *Hoploscaphites constrictus* (Sowerby, 1817), *Nostoceras (Nostoceras) alternatum* (Tuomey, 1854) and *Pachydiscus (Pachydiscus) neubergicus* (von Hauer, 1858) (Robaszynski et al., 2000).

The first appearance of *Pachydiscus (Pachydiscus) neubergicus* (von Hauer, 1858) is normally used to define the base of the Maastrichtian according to Odin (1996) and Odin and Lamaurelle (2001). But since only a single specimen was found at Kalaat Senan (Robaszynski et al., 2000) it remains questionable that it can be regarded as a true first appearance. The presence of *P. (P.) neubergicus* at Kalaat Senan higher than the base of the Maastrichtian is supported by the fact that *N. (N.) alternatum* is known to appear somewhat above the base of the Maastrichtian in the Northern Gulf Coast sections (Robaszynski et al., 2000). Moreover, the low number of stratigraphically well collected specimens of *P. (P.) neubergicus* in other basins than the Tercis Global Boundary Stratotype Section and Point (Odin et al., 2001) is probably responsible for the observed diachronism in the first occurrence of the taxon (Wagreich et al., 1998; Jagt and Felder, 2003).

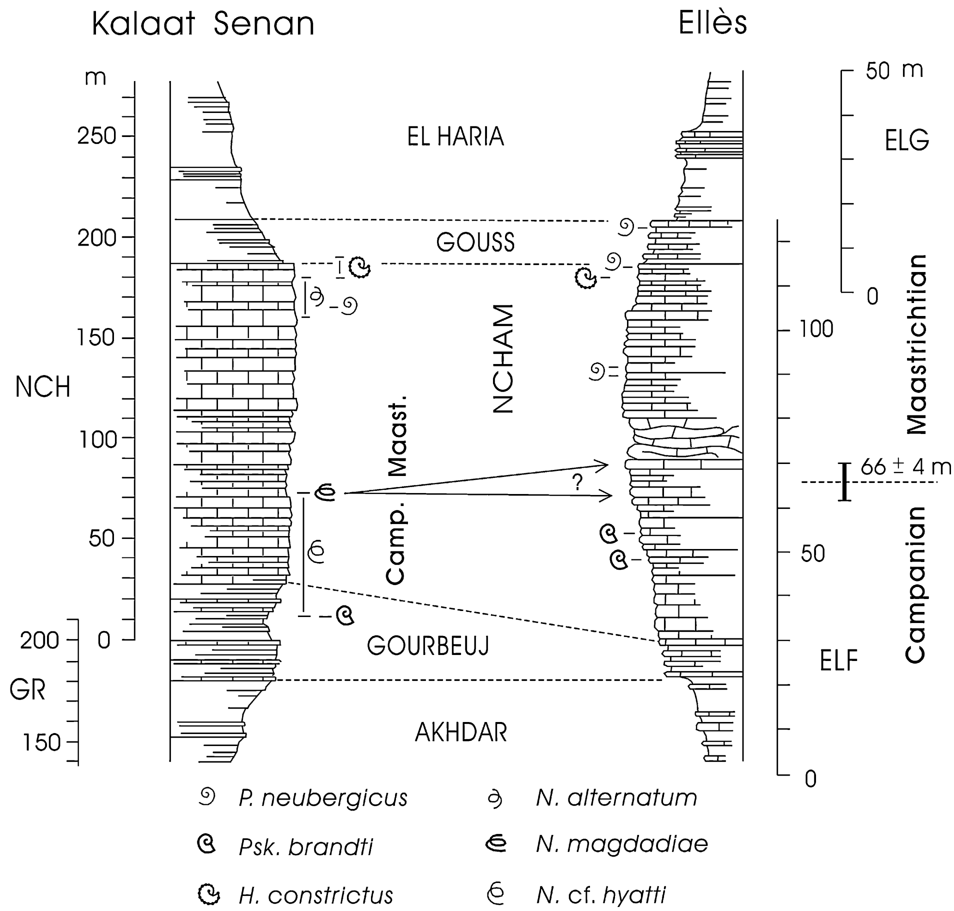

Fig. 3. Determination of the Campanian-Maastrichtian boundary position in Ellès, partly by correlation with the Kalaat Senan section. *P.* = *Pachydiscus*, *Psk.* = *Pseudokossmaticeras*, *H.* = *Hoploscaphites*, *N.* = *Nostoceras* (*Nostoceras*).

At Ellès, Nostoceratidae Hyatt, 1894 have not yet been observed in the Ncham Member, but the presence of *Psk. brandti* in its lower part and *H. constrictus* and *P. (P.) neubergicus* shows that the age of the sedimentary succession of Ellès is fully comparable to the one at Kalaat Senan, as can be also observed in the proportionality of the lithostratigraphic units among Gourbeuj, Ncham and Gouss members in both areas, although the Kalaat Senan series is 2.3 times thicker than the Ellès series.

It is thus on the basis of this correlation and proportionality that the Campanian-Maastrichtian boundary is placed at level ELF 66 ± 4 m (Fig. 3).

3. Stratonomy

The Abiod Formation is made up of a marl-limestone alternation in which two carbonated episodes (the Haraoua and Ncham limestone bars) are separated by a marly interval (the Akhdar marls). Fig. 4 shows how beds and interbeds are related, and how beds are grouped. Three types of sequences can be distinguished, which correspond to a progressive evolution from a mainly marly sedimentation to a carbonate-dominant one. The marly type (type 1) corresponds to the Akhdar Member (Fig. 5) and to the base of the El Haria Formation. The carbonated type (type 3) corresponds to the Haraoua and Ncham Members. The intermediate type (type 2) corresponds to the Mahdi, Gourbeuj and Gouss Members.

In the marly type 1, *marly interbeds* (0.3–3.0 m thick) appear grey, sometimes bluish or turquoise. On the one hand the limestone levels correspond to *main limestone beds* (0.2–0.5 m), pale grey or beige when altered, hard, often a weakly argillaceous, clearly highlighted by present day erosion, individuated by sharp lower and upper bedding planes; on the other hand, they correspond to *intermediate beds* (0.2–0.4 m) where appearing between the hereabove described interbeds and beds. These intermediate beds consist of limy marls or very argillaceous limestones, bluish grey, slightly highlighted by erosion. Their base and top are usually hardly discernible. The groupings of intermediate beds were called “diffuse zones” because of the difficulty to resolve in well defined beds and interbeds by Hennebert and Dupuis (2003).

The main limestone beds and the intermediate beds are not randomly distributed. They appear to be grouped, generally by two, sometimes by three, more rarely alone.

Where the limestone/marl ratio increases (type 2) interbeds become thinner (0.1–0.5 m) and the main limestone beds become thicker (0.4–0.8 m) and less argillaceous. The intermediate beds are transformed into main beds (0.2–0.3 m), in hollow compared to the prominent beds of type 1, but remain thinner.

Where the limestone/marl ratio further increases (type 3), marly interbeds become thinner (0.01–0.15 m), the limestone beds become thicker and start to show a higher carbonate content. However, “the old” groupings of main beds and of intermediate beds can still be distinguished. The main beds are the thickest (0.6–1.0 m) and the most massive ones, and have the highest carbonate content. They are often separated by well marked thin marly interbeds or by well marked bedding planes. The intermediate beds remain thinner (0.1–0.3 m), less prominent and often more argillaceous. They tend to show more undulating joints and even to be amalgamated.

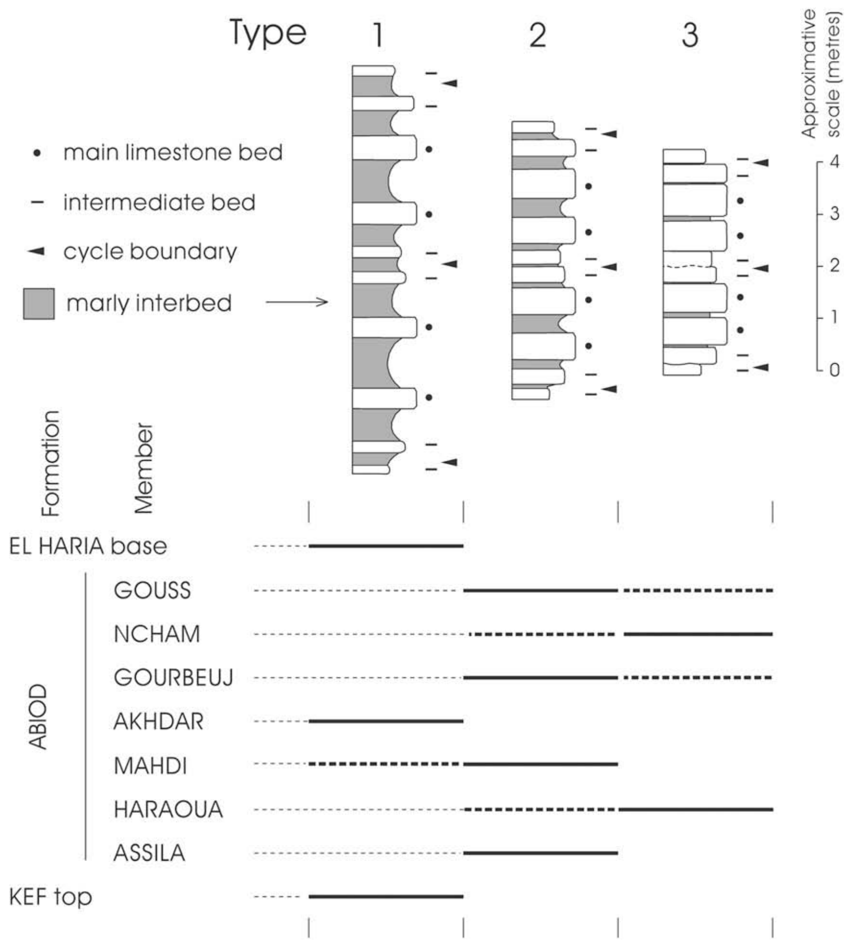

Fig. 4. Stratonomic description of the cycle types recognized in the studied section and their occurrence in the members and formations. The thick continous lines indicate the dominant stratonomic type present in each lithostratigraphic unit, the dashed lines indicate the occasional types.

4. Cyclostratigraphic interpretation

4.1. The orbito-climatic signal

The amount of solar energy flux that penetrates at a particular place the top of the atmosphere, shows cyclic variations related to the fluctuations of the Earth-orbit parameters: eccentricity, obliquity and precession (Milankovitch, 1941; Berger, 1976, 1978a,b). Variations in these parameters (orbital signals) induce climatic variations (climatic signal) recorded in the sedimentary record (sedimentary signal; Fig. 6).

It is important to note that the obliquity exerts a strong climatic influence in the high latitude zones, but a negligible one in the low latitudes (Berger, 1978a). In the Late Cretaceous Period, this is reinforced by the (probable) absence of a significant snow or ice cover on the poles (Berger, 1989). With central Tunisia located around 21° North during the Campanian and Maastrichtian, a clear prevalence of the precession on climatic variations (Berger, 1978a) and thus on sedimentation is to be expected. By leaving the obliquity component in the signal out will largely simplify the data interpretation without compromising the result (see Section 4.2.).

In order to visualise the correlation between orbital, climatic and sedimentary signal (Fig. 6), the characteristics of the orbital signal, as calculated by astronomers, will be considered (Berger, 1978a,b, 1984; Berger and Loutre, 1991; Laskar et al., 1993, 2004). The eccentricity, by itself, cause very slight climatic variations, although it induces significant amplitude variations of the precession component in the signal (Berger 1978a, 1984).

4.2. Precession versus obliquity

It has been stated previously that the obliquity effect in the studied section was most likely negligible compared to the precession. The fact of not taking into account the obliquity represents of course a crucial simplification in the present work. This is the reason it is largely discussed below.

Changes in the monsoon regime were suggested by Barron et al. (1985) as a link between Milankovitch orbital forcing and the periodicity observed in the Cretaceous sediment record. Prell and Kutzbach (1987) stated that precession should dominate obliquity in affecting low- to mid-latitude monsoons.

This is consistent with the prevalence of the precession (accompanied by the eccentricity of 100 kyr) often observed in the Cretaceous especially Tethyan record (Schwarzacher and Fischer, 1982; Fischer and Herbert, 1986 ; Gale, 1989, 1995; Rio et al., 1989; Herbert and D'Hondt, 1990; Park et al., 1993; Ten Kate and Sprenger, 1993; Fiet, 1998; Caron et al., 1999; Gale et al., 1999; Herbert et al., 1999; Herbert, 1999; Mutterlose and Ruffell, 1999; Stage, 1999; Fiet and Gorin, 2000; Fiet et al., 2001; Wendler et al., 2002; Felder et al., 2003; Hennebert and Dupuis, 2003; Herrle et al., 2003; Negri et al., 2003; Gale et al., 2004; Beckmann et al., 2005).

One interesting case is from the Cenomanian-Turonian of the Western Interior Seaway, USA (Sageman, et al., 1997, 1998; Meyers et al., 2001). Park and Oglesby (1990, 1991) used an atmospheric general circulation model to investigate changes in the modelled atmospheric climate resulted from imposed orbital insolation changes. They found that for most regions and

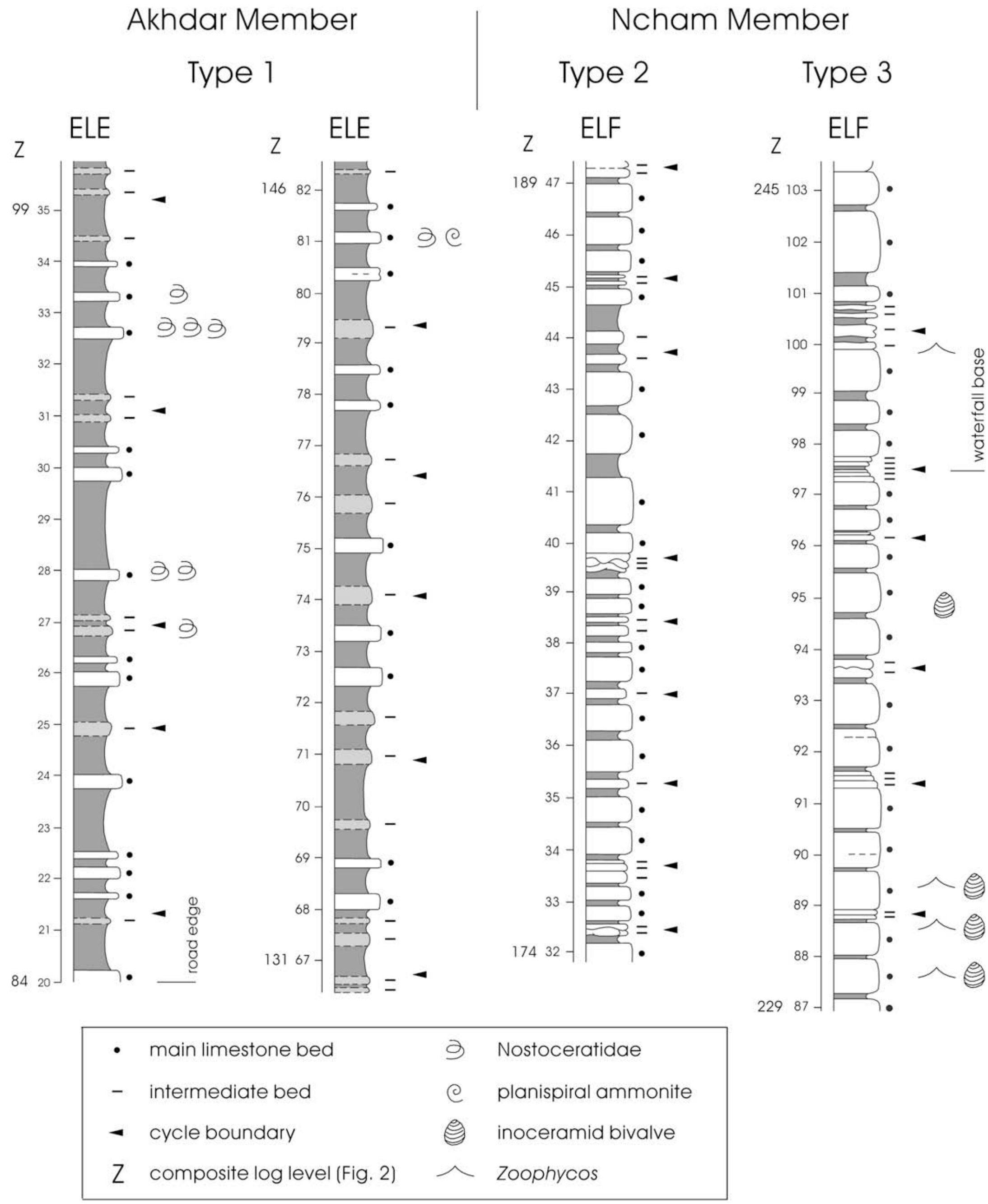

Fig. 5. Lithological succession examples illustrating the stratonomic types 1, 2 and 3. Scales in metres.

modelled quantities, the response due to changes in precession is considerably larger than the one due to changes in obliquity. Glancy (1992) used a computer based climate model to explain the observed rhythmic sedimentation pattern within the Bridge Creek Limestone Member of the Greenhorn Limestone Formation (Cenomanian-Turonian of the Cretaceous Western Interior Seaway, USA). He found that the rhythmic pattern is "controlled by climatic change produced by cyclic variation in the precession of the equinox and eccentricity insolation forcing, rather than by periodic change in obliquity insolation forcing." Several authors studying the same rock unit in the same region, using time-series analysis techniques, found that obliquity as well as precession was present in the sedimentary signal (Sageman, et al., 1997, 1998; Meyers and Sageman, 2000; Meyers et al., 2001). They proposed the following explanation: carbonate productivity was controlled by orbital precessional cycles, which affected evaporation and nutrient upwelling in the southern part of the basin and the Tethyan realm. However, the sedimentary cycles reflect over more carbonate dilution by clastic sediments, which were driven by the influence of obliquity cycles on high-latitude precipitation and riverine sediment influx. The constructive and destructive interference of these two mechanisms results in the complex bedding patterns seen on the outcrop (Sageman, et al., 1998). These north-south relationships along the Western Interior Seaway are supported by the existence of a strong counter clockwise gyre occupying the entire north-south extent of the basin (Slingerland et al., 1996). Following Floegel et al. (2005) bedding couplets can be explained essentially by the precession, but the effect of precession and obliquity is variable according to the areas.

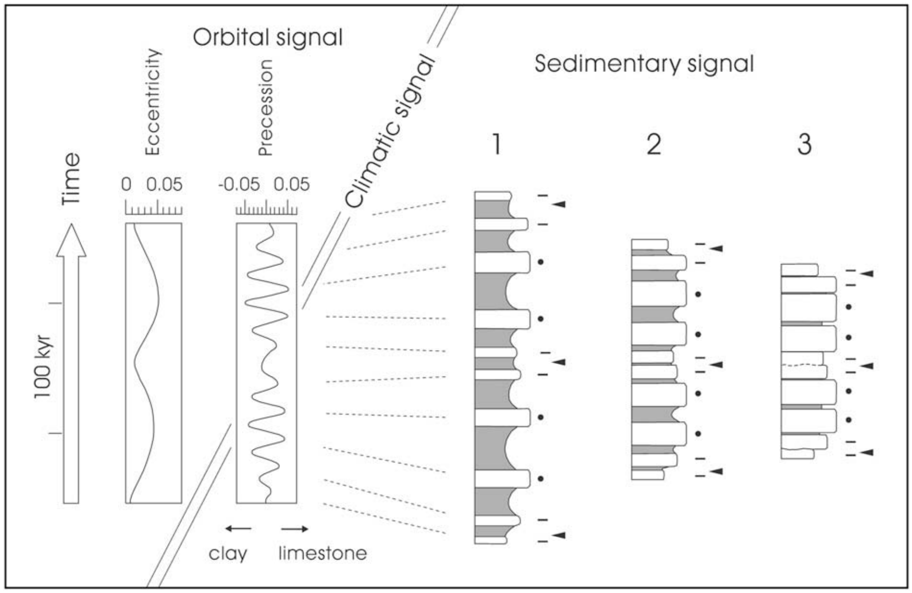

Fig. 6. Orbito-climatic interpretation of the stratonomic observations.

In our case, the presence of the Tethys Ocean (and its own circulation pattern) northwards from central Tunisia (Fig. 1A) certainly blocked such high-latitude northern influences. During the Pangea continent configuration, a large clockwise surface current went over the Tethys, resulting in a northwards circulation along the south-western border of the ocean (Röhl et al., 2001). In the Cretaceous time, this clockwise current persisted (Barron and Peterson, 1989, 1990; Föllmi et al., 1991). In addition, due to the opening of Atlantic Ocean and of the passage to the Pacific through the Central American Seaway, a wind-driven circumglobal current possibly strengthened the Tethyan clockwise gyre (Brush, 1997; Cousin-Rittemard et al., 2002; Pucéat et al., 2005).

4.3. Periods of the orbito-climatic signal

Despite the proven chaotic behaviour of the solar system, eccentricity periods are known to be very stable in time and have not varied significantly during the last 100 Ma (Berger et al., 1992; Laskar, 1989, 1999). The "100 kyr" period is in fact made up of several quasi-periods, whose average is about 95.8 kyr (Berger, 1976).

The precession band has two quasi-periods of approximately 19 and 23 kyr, with an average of about 21.74 kyr (Berger, 1976). The precession period is known to show peaks of variation. For the last 5 Myr, for example, the period had varied between a minimum of 13.9 kyr and a maximum of 31.3 kyr (Berger, 1976).

In addition, the progressive lengthening of the day length and of the Earth-Moon distance, as well as the reduction in the dynamic ellipticity of the Earth, result in the lengthening of precession and obliquity periods (Berger et al., 1989a, b; Berger and Loutre, 1994). The current precession periods of 19 and 23 kyr were estimated to be respectively 18.645 and 22.481 kyr at −72 Ma (Berger and Loutre, 1994). A simple "rule of three" calculation gives an average period of the precession, passing from 21.74 ka (its current value) to 21.27 ka to −72 Ma (Campanian-Maastrichtian boundary). This gives an average of 4.5 precession cycles of 21.27 kyr for each eccentricity cycle of 95.8 kyr.

The eccentricity shows, superimposed on the 100 kyr period, a very stable "400 kyr" periodic component. Recently published values for this period are 404.103 ka (Laskar, 1990), 404.178 kyr (Berger and Loutre, 1991) and 405.091 kyr (Laskar et al., 2004). The "400 kyr" eccentricity component has not been identified yet in the Ellès Abiod. However, it is important to note in the frame of this work that the precession period undergoes important duration variations, as a function of its position in the "400 kyr" cycle.

4.4. Interpretation of the stratonomic characteristics

Fig. 6 gives first of all a typical example of the precession signal of which the amplitude is modulated by eccentricity (period of about 100 kyr). It shows that, when applying a "climatic filter" (the precession minima correspond to a maximum insolation), a sedimentary signal could be obtained. This sedimentary signal corresponds to a marl-limestone alternation, whose detailed characteristics depend on the curve of the "orbito-climatic" signal. The stratonomic expression of this signal is different according to the general trend of the limestone/marl ratio, as has been discussed previously in the definition of types 1, 2 and 3.

In the marliest series (type 1) the precession maxima which correspond at the same time to eccentricity maxima, deliver the main limestone beds. The precession maxima corresponding to the eccentricity minima give the intermediate beds. The precession minima give marly interbeds, which are thicker and more argillaceous when the eccentricity is high. The 100 kyr eccentricity cycles were identified in the field using the following criteria: the doublets (or triplets) of main limestone beds indicate a high eccentricity, the intermediate beds, which separate the main limestone beds indicate a low eccentricity.

When the limestone/marl ratio increases (types 2 and 3), interpretation becomes a little more complicated. One can however still distinguish the doublets of thick beds and the sets of smaller beds (usually more argillaceous) that always correspond respectively to eccentricity maxima and minima.

4.5. Dilution versus productivity cycles

Within a limestone-marl alternation it is often difficult to say *a priori* which component varies in sedimentation rate as the other remains constant, or if they vary together. There are either periodic fluctuations of terrigenous sediment supply (dilution cycles), or periodic fluctuations of pelagic carbonate supply (productivity cycles). In the first case the limestone bed thickness remains fairly constant while those of the marly interbeds vary much more, in the second case the limestone bed thickness varies while the interbeds thickness remain constant (Einsele, 1982; Arthur et al., 1984; Einsele and Ricken, 1991).

In the Abiod Formation cycles both mechanisms might be working at the same time: the marly alternation type 1 (Fig. 6) does correspond to mixed dilution-productivity cycles, where clays certainly play an active role by their abundance, the carbonated alternation type 3 (Fig. 6) does correspond to productivity cycles as shown by the variation of the limestone bed thicknesses and the scarcity of clay supply. The type 2 alternation is an intermediate situation.

In dilution cycles, the climatic orbitally-induced variations depend on the continental climatic conditions prevailing on the Saharan Platform, on the contrary, in the productivity cycles it depends predominantly on those on the Tethyan Ocean. This narrow relationship between continent and ocean is consistent with the proposed hypothesis that the monsoon systems were already an influencial factor in the Cretaceous greenhouse realm (Barron et al., 1985; Beckmann et al., 2005; Floegel and Wagner, 2006).

5. The chronometric scale

5.1. Use of the “100 kyr” cycle

Fig. 6 shows a theoretic model. The recognition of the minima of the 100 kyr eccentricity cycles in the field is shown on Fig. 5. As the maxima are difficult to locate precisely in thick beds and interbeds, the eccentricity minima will be sought as it usually corresponds to a thin easy to locate interval.

Fig. 7C shows the 100 kyr cycle thickness expressed in metres. Each data point corresponds to one 100 kyr cycle recognized in the field. On the horizontal axis is represented the thickness of the cycle and its elevation is represented on the vertical axis, corresponding to the average between the base and the top of the cycle. The dashed line gives a smoothing average curve of the whole recognized points. In this way, a continuous variation of the “sedimentation rate” in metres by 100 kyr can be obtained for the whole composite section Z (it is not a true sedimentation rate because the series is not decompacted). This averaged procedure limits the influence of possible mistakes in the interpretation of the field data. It also compensates the lack of information caused by the presence of some hiatuses in exposure.

The two main hiatuses correspond: to a badly outcropping segment in the ELD section (it acts as a simple observation hiatus), and to the presence of the ELF slump. The last one is the most problematic since we do not know if it corresponds to a thickening or on the contrary to a thinning of the stratigraphic sequence. For the purpose of this work, the simplest option has been chosen: the thickness of the series have been considered not to be affected by this intraformational deformation (see hereabove).

Fig. 7D gives the time spent per metre of sedimentary sequence, expressed in kyr/m. The “100 kyr” period is in fact made up of several quasi-periods, whose average is about 95.8 kyr (Berger, 1976). The values presented in Fig. 7D have been obtained by dividing the 95.8 kyr value by the thicknesses of the “100 kyr” cycles shown in the Fig. 7C. As for Fig. 7C, the dashed curve represents a smoothing average curve of the whole points.

Fig. 7G presents the correlation between the studied sedimentary sequence and a time-scale expressed in million years (Myr). This curve was obtained by cumulating the “kyr/metre” value (Fig. 7D) for each metre of the stratigraphic sequence. The zero figure of the time-scale does correspond to the 0 metre level in Z. The various durations existing between given events can be obtained by substraction.

5.2. Use of the “20 kyr” cycle

Theoretically, it is a matter of simply counting the beds (or interbeds) which correspond to the “20 kyr” precession-cycle, having disregarded the difference in aspect they may show because of the eccentricity variations. At first sight that seems easier than to delimit bundles induced by the “100 kyr” cycle. But the beds and interbeds are not easily discernible around the minima of the “100 kyr” cycles. This certainly will result in an underestimation of the number of precession cycles. That is particularly true in two extreme cases: the disappearance of beds (by dilution) in the marliest sequences and the disappearance of interbeds (by amalgamation) in the limestone sequences (Fig. 6). This will result in an underestimation of the elapsed time.

It has been discussed hereabove that the precession period has significant duration variations, which are a function of the location in the “400 kyr” eccentricity cycle. More exactly, the maxima peaks of duration of the precession are located on one half of the cycle of “400 kyr”, the minima peaks are located on the other half of the cycle.

This problem caused by duration variation of the precession can be solved by measuring the stratigraphic thickness corresponding to 404 kyr/21.27 kyr = 19 cycles. To make it easy, 20 precession-cycles packages have been used. If this is done with the aim of correcting the inherent skew of the astronomical signal, there is a risk, on another side, to smooth the sedimentary signal too much. Both risks have been taken into account by counting packages of 20 cycles shifted 10 by 10 (Fig. 7E).

5.3. Comparison of the two time scales

Fig. 7G shows the comparison of the two time scales produced by cumulating the “duration per metre” obtained by using the 100 kyr and 20 kyr cycles. As it is the upper part of the Haraoua Member that has the most serious interpretation uncertainties, the two scales diverge quickly (Z segment from about 40 to 70 m) but then tend to stabilize upward. To reduce the uncertainty caused by the Haraoua Member, time scales were recalculated by placing the origin of the time scale at the Campanian-Maastrichtian boundary as defined in Fig. 3. The result is presented in Fig. 7H. For the rest of this work the two time scales will be named by T100 and T20 respectively.

5.4. Use of the chronometric scale

The approach explained above makes it possible to place the ammonite and planktonic foraminifera biozones (Fig. 2) on an absolute time scale floating around the proposed Campanian-Maastrichtian boundary (Fig. 8A). The planktonic foraminifera distribution and the corresponding biozonation come from Robaszynski and Mzoughi (2004 and in press). The ammonite distribution in the Ellès section is based on the later and on the work of one of us (SG). *N.* cf. *hyatti*, *N. magdadiae* and *N. alternatum* are projected (Fig. 3) from their distribution in the Kalaat Senan area (Robaszynski et al., 2000).

The positions of each event in the Ellès section or of events projected on this same section (Fig. 3) are recomputed by using the Fig. 7H data. As an example, the top of the planktonic foraminifera biozone *Radotruncana calcarata* appears at Ellès at −2.75 Myr according to T20 and at −3.18 Myr according to T100. The figure already published varies between 1.5 and 4 Myr before the

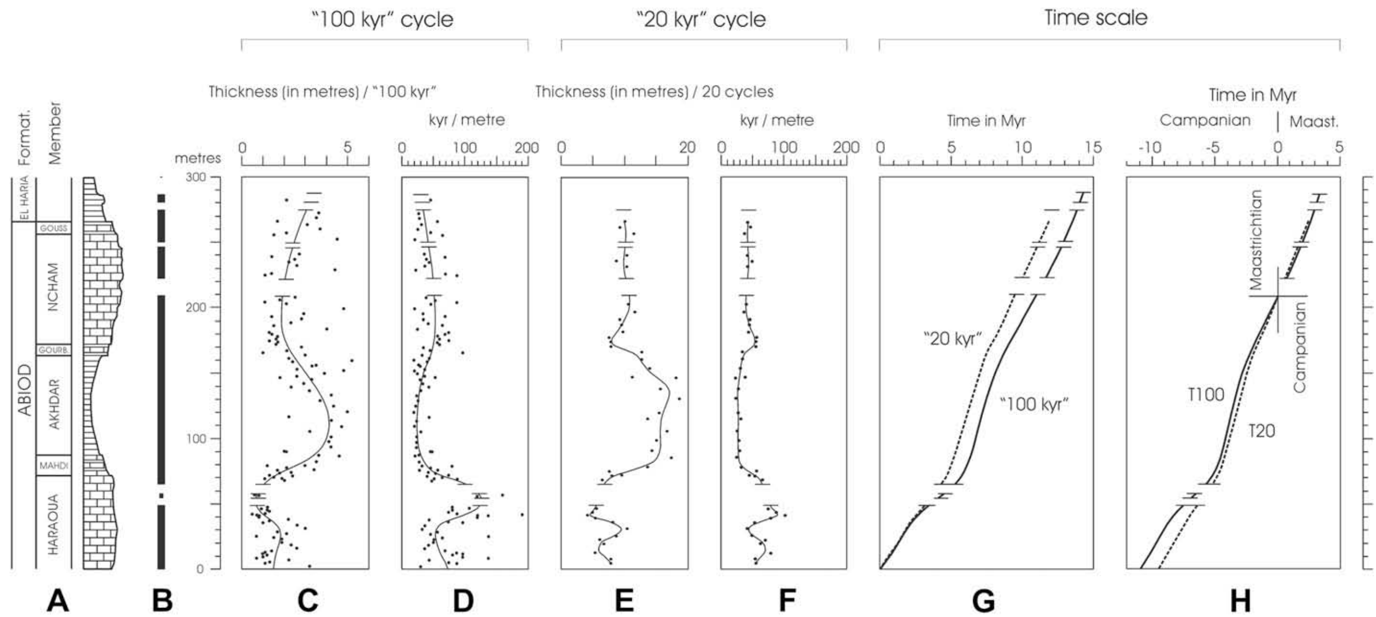

Fig. 7. Use of the "100 kyr" eccentricity cycle and the "20 kyr" precession cycle to draw up time curves. A, Lithological column of the studied section. B, Continuity of the section showing the cyclostratigraphic hiatuses. C, Thickness of the cycles of 100 kyr, in metres. D, Elapsed time per metre of sedimentary sequence (in kyr/m). E, Thickness of the cycles of 20 kyr, in metres. F, Elapsed time per metre of sedimentary sequence (in kyr/m). G, Correlation between an arbitrary time scale (in Myr) and the studied sedimentary sequence. H, Recalibration of the two time curves (T100 and T20) to the Campanian-Maastrichtian boundary datum in Ellès section.

boundary (Schönfeld and Burnett, 1991; Hancock et al., 1992; Obradovich, 1993; Robaszynski and Caron, 1995).

The chronometry based on T100 is slightly more expanded in time than that based on T20. The figure also visualises the difference (absolute value) between the T100–T20 scales (Fig. 8B), and shows that this difference between both scales is lower or equal to 0.5 Myr for ages more recent than −5 Myr, below the zero point. For ages older than −5 Myr, the difference quickly increases

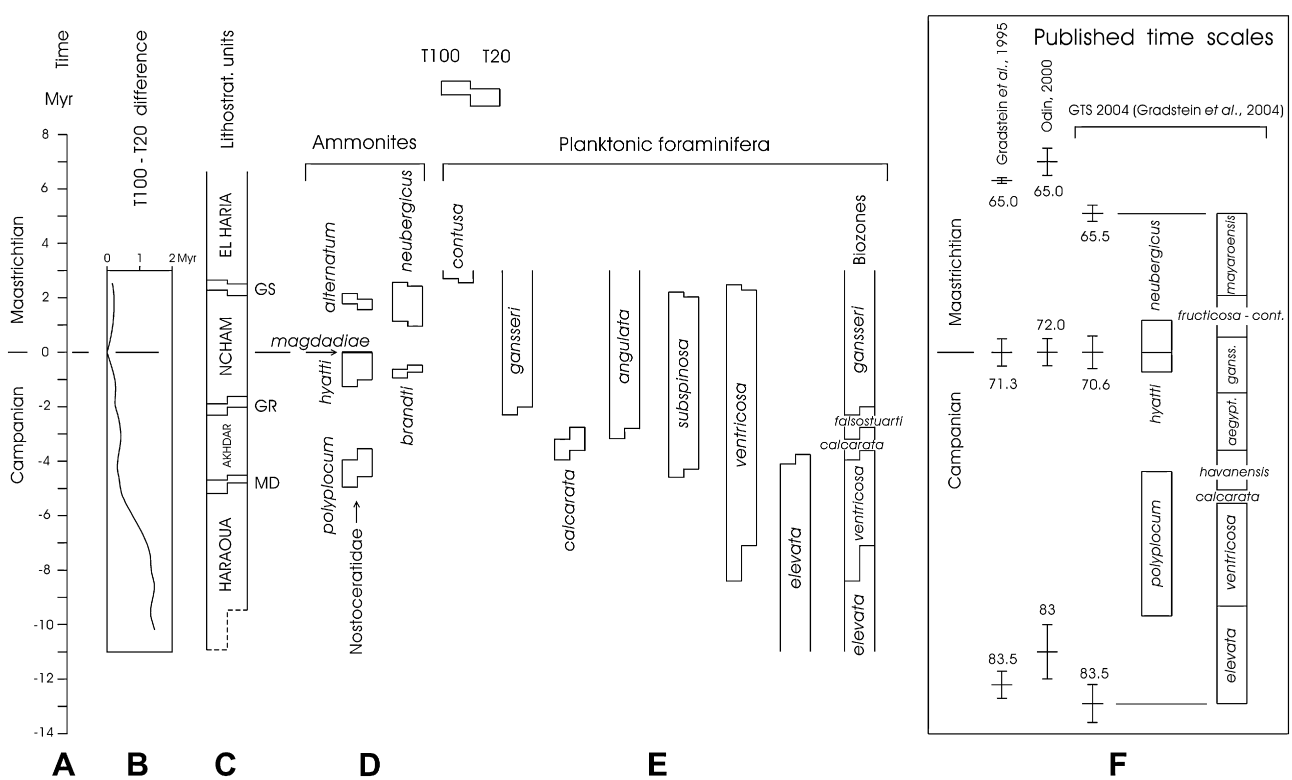

Fig. 8. Use of the time scales to date the lithostratigraphic units and the distribution of ammonites and planktonic foraminifera of the Ellès section. A, Time scale. B, Difference between T100 and T20 in absolute value (Myr). C, Age of the lithostratigraphic units. Both T100 and T20 values are drawm. MD = Mahdi, GR = Gourbeuj, GS = Gouss. D, Ammonite distribution. Taxa as on Fig. 2 and 3. *N. polyplocum*, *Psk. brandti* and *P. neubergicus* are located according to their distribution in the Ellès section. *N.* cf. *hyatti*, *N. magdadiae* and *N. alternatum* are projected from their distribution in the Kalaat Senan area. E, Planktonic foraminifera distribution and biozones. Taxa as on Fig. 2. F, Comparison with several published time scales by readjusting their Campanian-Maastrichtian boundary to the one defined at Ellès (Fig. 3).

Table 1

Boundary	Maastrichtian		Campanian	
	Duration	Boundary	Duration	Boundary
65.0 ± 0.1	6.3	71.3 ± 0.5	12.2	83.5 ± 0.5 Gradstein et al. (1995a,b)
65.0 ± 0.5	7.0	72.0 ± 0.5	10.0	83 ± 1 Odin in: Remane et al. (2000)
65.5 ± 0.3	5.1	70.6 ± 0.6	12.9	83.5 ± 0.7 Gradstein et al. (2004)

to about 1.5 Myr. The boundaries between lithostratigraphic units are dated in the same method (Fig. 8C).

5.5. Comparison with published time scales

For fifteen years Cretaceous time scales have been continuously refined and finally stabilized (Harland et al., 1990; Obradovich, 1993; Gradstein et al., 1995a,b; Odin, 1994, 2002; Gradstein et al., 2004; Table 1). Moreover, duration of stages can usually be better estimated than the age of the stage boundaries themselves (Gradstein et al., 1995b). The durations of the Campanian and Maastrichtian stages were thus estimated to be about 10–13 and 5–7 Myr respectively. Since the base of the Campanian and the top of the Maastrichtian are not included in this study, radiometric durations can not be used to verify in an absolute way our results (Fig. 8F). However, one can estimate if the obtained durations represent acceptable proportions of the published figures.

5.5.1. Campanian

The base of the studied section (ELD = 0 m; Z = 0 m) is dated (Fig. 7H) from −10.929 Myr (T100) to −9.467 Myr (T20): that is to say 10.198 Myr of average time. The position of the Santonian-Campanian boundary can not be precisely located at Ellès (Robaszynski and Mzoughi, 2004 and in press), at Kalaat Senan the boundary has been located below the base of the Abiod, near the top of the Kef Formation (Robaszynski et al., 2000). As the whole Campanian presents an estimated duration (by radiometric dating) spanning from 10 to 13 Myr (Table 1), the obtained value of 10.198 Myr for almost the entirety of the stage appears coherent (see Fig. 2).

5.5.2. Maastrichtian

The top of Abiod Formation (ELG = 17 m; Z = 267 m) is estimated from 2.660 Myr (T100) to 2.503 Myr (T20): that is to say 2.582 Myr of averaged time. The total duration of the Maastrichtian stage is estimated to 5 to 7 Myr. The Abiod part of the Maastrichtian could correspond to 37 to 52% of the total duration of the stage. The thickness of the Maastrichtian Abiod is, according to our work, of 58 metres (Fig. 3). The thickness of the El Haria marls comprised between the top of the Abiod and the Cretaceous-Paleocene boundary, is of approximately 96 metres. The proportion of 37 to 52% of time thus corresponds to about 1/3 the total thickness of the Maastrichtian. As one can suppose that the "sedimentation rate" in the marls of El Haria is higher than in the Abiod limestones (see the marls of the Akhdar Member; Figs. 7, 8) the time estimate here obtained is still plausible.

6. Conclusions

The depositional environment of the studied rocks is favourable for the good recording of orbito-climatic cycles: it was a fairly deep environment, with very low agitation and moderate oxygen-content. The (not decompacted) "sedimentation rate" is quite high (from 1 to 4 cm/kyr), which ensures a continuous deposition of sediment. Furthermore, the accomodation space (i.e. the space made available for potential sediment accumulation; Jervey, 1988) was largely sufficient.

During the Campanian to Early Maastrichtian, central Tunisia underwent tectonic constraints related to the Africa - Eurasia relative movement. The area was affected by the deformation and re-mobilisation of sediments which often occur in relatively deep deposits: synsedimentary faulting, intraformational conglomerates, slumping and turbidites. At Ellès the sedimentary recording was quite saved from these tectonically-induced features, except for the presence of a slump near the base of the Maastrichtian, which introduces an uncertainty into the Maastrichtian part of the built time-scale.

The limestone-marl alternation shows variations in carbonate-content and in bed (and interbed) thickness, where the precession-cycle, modulated in its amplitude by the eccentricity, can be easily recognized. This transformation from an orbital cyclicity to a sedimentary cyclicity mimics a quasi-linear relation. The situation is such that obliquity-variations can be neglected. This is corroborated by many studies undertaken on the Milankovitch cyclicity in the Western-Tethys Cretaceous.

Precession cycles (circa 20 kyr) and eccentricity cycles (circa 100 kyr) were used separately to build up two distinct time scales. These scales gradually diverge, but are usable to evaluate the duration of deposition of the various lithostratigraphic units and the duration of the ammonite and planktonic foraminifera biozones (Fig. 8). Any particular stratigraphic level in the composite section can be dated relative to the Campanian-Maastrichtian boundary.

The methodology here presented can be used to develop accurate and useful time scales, if the following favourable conditions are present:

(1) a geographical area where precession and eccentricity dominate the orbito-climatic signal;
(2) the depositional environment was rather deep (low depositional energy environment and sufficient accommodation);
(3) the sediment exhibits an intermediate limestone/clay ratio, typical limestone-marl alternations constitutes the best case;
(4) the deposits underwent as less syn-sedimentary (or post-sedimentary) deformations as possible (faults, slides, slumps) and as less remobilisation and resedimentation (breccias, turbidites) as possible;
(5) a good biozonal control or other events suitable for long-distance correlations are available;
(6) favourable outcrop conditions, particularly the continuity of exposure, are important.

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