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The Paleocene-Eocene transition in the southern Tethys (Tunisia) : climatic and environmental fluctuations

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Key words. – Climate, Environment, Tunisia, Biostratigraphy, Phosphate, Clay-minerals, Stable isotopes.

Abstract. – This study, based on a multidisciplinary approach including micropaleontology, sedimentology, mineralogy and geochemistry, evaluates the Paleocene-Eocene transition in Tunisia. At Foum Selja, sediment deposition occurred in the shallow, restricted Gafsa Basin influenced by the adjacent Saharan Platform. During the early Paleocene this area experienced a warm and humid climate that changed to warm but arid climatic conditions during the Paleocene-Eocene transition. At Elles the sediment deposition in the El Kef Basin occurred in an open marine environment connected to the Tethys. During the late Paleocene, the Tethyan region was submitted to a seasonal warm climate changing to a warm and humid climate across the P/E transition and becoming seasonal/arid in the early Eocene. From Africa to northern Europe, kaolinite, a strong marker of warmth and humidity disappeared diachronously suggesting a latitudinal shift in the source area of this mineral and consequently in the climatic zones, from lower to higher latitudes. The P/E transition observed at Elles corresponds to a 2.7 m thick clay layer and is marked by a drastic decrease in carbonate sedimentation, a negative $\delta^{13}C$ excursion of 1.3‰ and increased detrital input. The presence of a condensed interval, the accumulation of phosphate deposits after the P/E event, which obliterate the original isotopic signal and strong dissolution of the planktic fauna and flora in these phosphatic layers, all are criteria that prevent the Elles section to be a potential GSSP candidate for the P/E boundary.

La transition Paléocène-Éocène dans la partie sud de la Téthys (Tunisie) : fluctuations climatiques et environnementales

Mots clés. – Climat, Environnement, Tunisie, Biostratigraphie, Phosphates, Minéraux argileux, Isotopes stables.

Résumé. – Cette étude, basée sur une approche multidisciplinaire incluant micropaléontologie, sédimentologie, minéralogie et géochimie, a pour objet l'évaluation de la transition Paléocène-Eocène en Tunisie. A Foum Selja, les sédiments, sous influence de la plate-forme saharienne adjacente se sont déposés dans le bassin peu profond de Gafsa. Au Paléocène précoce, cette région est marquée par un climat chaud et humide qui devient aride à la transition Paléocène-Eocène. Au contraire, à Elles, les sédiments se déposent dans le bassin d'El Kef sous influence téthysienne. Au Paléocène tardif, cette région est soumise à un climat saisonnier qui devient chaud et humide au Paléocène-Eocène et franchement aride à l'Eocène. De l'Afrique au nord de l'Europe, la kaolinite, indicatrice d'humidité et de chaleur, disparaît diachroniquement suggérant un déplacement latitudinal de la zone de production de ce minéral et par conséquent des zones climatiques chaudes et humides, des basses vers les hautes latitudes. La transition Paléocène-Eocène observée à Elles se marque lithologiquement par un intervalle argileux d'une épaisseur de 2,7 mètres. Cet intervalle est caractérisé par une importante diminution de la sédimentation carbonatée, une excursion négative de 1,3‰ du $\delta^{13}C$, et par une augmentation des apports détritiques. Toutefois, en raison de la présence d'un intervalle condensé, de l'apparition de dépôts phosphatés surmontant la transition Paléocène-Eocène et d'une forte dissolution affectant la faune et flore planctoniques dans ces niveaux phosphatés, la coupe d'Elles ne peut être considérée comme une candidate potentielle de la limite Paléocène-Eocène.

VERSION FRANÇAISE ABRÉGÉE

La transition Paléocène-Eocène est caractérisée par des changements environnementaux globaux qui incluent un réchauffement de 6°C des eaux océaniques de surface sous les hautes latitudes [Zachos *et al.*, 1994], et la présence de faunes et flores tempérées à sub-tropicales dans les régions subpolaires des deux hémisphères [Estes et Hutchison, 1980; Wolfe, 1980; Axelrod, 1984]. Ce réchauffement coïncide également avec une excursion négative du $\delta^{13}C$ et une extinction massive des foraminifères benthiques [Thomas, 1990; Kennett et Stott, 1991]. La composition des minéraux argileux reflète une période de précipitations exceptionnellement élevées en Antarctique [Robert et Kennett, 1994] mais au contraire un climat aride dans une partie de la région téthysienne [Adatte et Lu, 1995].

La Téthys, bassin restreint entouré de vastes mers épicontinentales et soumis à une activité tectonique intense constitue une région clé dans la recherche des mécanismes responsables des changements climatiques et environnementaux globaux qui ont eu lieu durant la transition Paléocène-Eocène (P/E) [Kennett et Stott, 1990, 1991; Lu *et al.*, 1996].

L'étude de deux profils, Foum Selja et Elles (marge sud de la Téthys), basée sur une approche pluridisciplinaire, sédimentologique, micropaléontologique, géochimique (isotopes stables) et minéralogique fournit ainsi une nouvelle base de données nécessaires à la compréhension des phénomènes se produisant à la transition P/E.

Le profil de Foum Selja est situé dans le bassin peu profond de Gafsa entre l'île de Kasserine au nord et la plate-forme saharienne au sud (fig. 1). L'absence de communications avec la Téthys durant la transition P/E est due à la présence de petites zones surélevées et de golfes qui agissaient comme barrières. La sédimentation dans ce bassin est principalement influencée par la plate-forme saharienne adjacente. La partie étudiée de ce profil comprend les zones de nannofossiles NP(4)-5 à NP10 (fig. 2 et photo 1). Le profil de Foum Selja se divise en trois formations; Thelja (séquence évaporitique), Chouabine (séquence phosphatique) et Kef Eddour (séquence évaporitique) [Regaya *et al.*, 1991]. Le profil d'Elles est situé dans le bassin d'El Kef, au nord de l'île de Kasserine (fig. 1). La sédimentation dans cet

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environnement marin ouvert est principalement influencée par la région téthysienne. La partie étudiée de ce profil comprend les zones de nannofossiles NP7 à NP10 et de foraminifères planctoniques P4a à P6a. Trois bancs sableux riches en glauconie séparent une alternance de marnes, argiles et petits bancs calcaires noduleux (fig. 2 et photo 2).

A Elles, la transition P/E correspond à un intervalle argileux d'une épaisseur de 2,70 mètres. Cet intervalle se marque minéralogiquement par une diminution importante de la sédimentation carbonatée de 30 % à 7 %. Cette chute des carbonates coïncide avec une augmentation des phyllosilicates et l'apparition de feldspath potassique. La présence de ce minéral et le rapport détritique/carbonate maximal (fig. 5) suggèrent une augmentation des apports détritiques durant cette période. Ces changements minéralogiques reflètent probablement une diminution de la productivité biologique primaire et/ou de la dissolution ainsi qu'une augmentation de l'érosion dans la région téthysienne. La transition P/E se marque également par une diminution graduelle du $\delta^{13}C$ de 1,6 ‰ de la zone P4 à la partie inférieure de la zone P5, suivie par une excursion négative de 1,3‰ du $\delta^{13}C$ (fig. 8). La présence d'apatite fluoro-carbonatée (francolite) dans le banc glauconieux qui surmonte l'intervalle argileux P/E (fig. 2 et 5) coïncide avec des valeurs très négatives du $\delta^{13}C$ et du $\delta^{18}O$ (fig. 8 et tab. II). La francolite formée durant la diagenèse primaire se caractérise par des valeurs fortement négatives du $\delta^{13}C$ (– 12‰) et du $\delta^{18}O$ (– 11‰) [Kastner *et al.*, 1984; Mertz, 1984] masquant ou oblitérant ainsi le signal isotopique originel. La présence de cet intervalle glauconieux coïncidant avec l'apparition de dépôts phosphatés, la forte dissolution qui affecte la faune et flore planctoniques rend difficile le choix du profil d'Elles comme candidat potentiel GSSP de la limite Paléocène/Eocène.

A Foum Selja, les valeurs négatives du $\delta^{13}C$ (entre –2 et –12‰) et du $\delta^{18}O$ (entre – 0,7 et – 5,5 ‰) coïncident également avec les plus fortes teneurs en phosphates (fig. 8 et tab. III). Dans ce profil, la diagenèse primaire caractérisée par la présence de francolite masque l'excursion négative du $\delta^{13}C$ observée dans la majeur partie des profils P/E [Thomas, 1990; Kennett et Stott, 1991; Bolle *et al.*, 1998].

A Foum Selja, la distribution des minéraux argileux reflète les variations climatiques sur la plate-forme saharienne. Le rapport kaolinite/smectite très élevé, observé dans les premiers 20 mètres indique un climat chaud et humide sur la plate-forme pendant l'intervalle biozonal NP4-5 (fig. 6). La disparition de kaolinite et l'abondance de smectite associée à la formation d'évaporites suggèrent le développement d'un climat saisonnier, voir aride, devenant très aride sur la plate-forme à la transition P/E comme l'indique l'abondance de palygorskite et de sépiolite (fig. 6).

A Elles, la faible représentation de la kaolinite, mais l'abondance de smectite suggèrent un climat saisonnier dans la région téthysienne de P4a à P4c. Le rapport kaolinite/smectite maximal à la transition P/E implique un climat chaud et humide pour cette période. L'abondance de smectite et la disparition de kaolinite à l'Eocène inférieur indiquent le retour à un climat plus aride dans cette région (fig. 7).

A Elles, mais également dans le sud de l'Espagne, à Caravaca et Alamedilla, le cortège des minéraux argileux indique des conditions climatiques humides et chaudes à la transition Paléocène-Eocène qui coïncident avec l'excursion négative du $\delta^{13}C$. L'abondance de smectite indique une augmentation de l'aridité dans la région téthysienne juste après l'événement P/E. Du sud au nord, la kaolinite disparaît diachroniquement, dans la zone NP5 à Foum Selja, dans la zone NP9 à Elles et Caravaca et seulement dans la zone NP11 à Zumaya (nord de l'Espagne). Cette disparition diachronique de la kaolinite suggère donc un déplacement latitudinal de la zone de production de ce minéral et par conséquent des zones climatiques chaudes et humides, des basses vers les hautes latitudes (fig. 9).

Au Paléocène terminal, la marge sud de la Téthys pourrait avoir été affectée par l'activité intermittente de courant d'upwellings. A Foum Selja, l'accumulation de phosphates est favorisée par des conditions climatiques arides sur la plate-forme saharienne et par un apport détritique réduit dans le bassin de Gafsa (figs. 4 and 6). Le développement d'un climat plus aride dans la région téthysienne et l'apport réduit de détritiques après l'événement P/E (figs. 5 and 7) pourraient être la principale cause de l'accumulation tardive des phosphates dans le bassin d'El Kef (zone NP9) en comparaison du bassin de Gafsa où les dépôts phosphatés apparaissent dans la zone NP4/5 (fig. 4).

INTRODUCTION

The Paleocene-Eocene transition is marked by major global environmental changes, which caused various palaeontological, sedimentological and isotopical variations that include a 6°C warming in high latitude surface waters of the southern oceans [Zachos *et al.*, 1994], and the presence of sub-tropical to temperate faunas and floras in subpolar regions of both hemispheres [Estes and Hutchison, 1980; Wolfe, 1980; Axelrod, 1984]. In addition, the high latitude warming coincides with a major rapid negative $\delta^{13}C$ excursion and the extinction of 35 to 50 % of deep-sea benthic foraminiferal species [Thomas, 1990; Kennett and Stott, 1991; Speijer, 1994].

The rapid negative $\delta^{13}C$ excursion implies a significant addition of ^{12}C into the combined ocean-atmosphere inorganic carbon reservoir which cannot be explained by the two conventional hypotheses of the addition of volcanogenic CO_2 and/or transfer of ^{12}C from the terrestrial biomass because mantle CO_2 is insufficiently enriched in ^{12}C and the biomass is insufficiently large [Dickens *et al.*, 1995; Thomas and Shackleton, 1996]. Dickens *et al.* [1997] suggest that the release of methane hydrates, which are present in pore spaces of deep marine sediments, could be the source for the negative excursion during the thermal maximum.

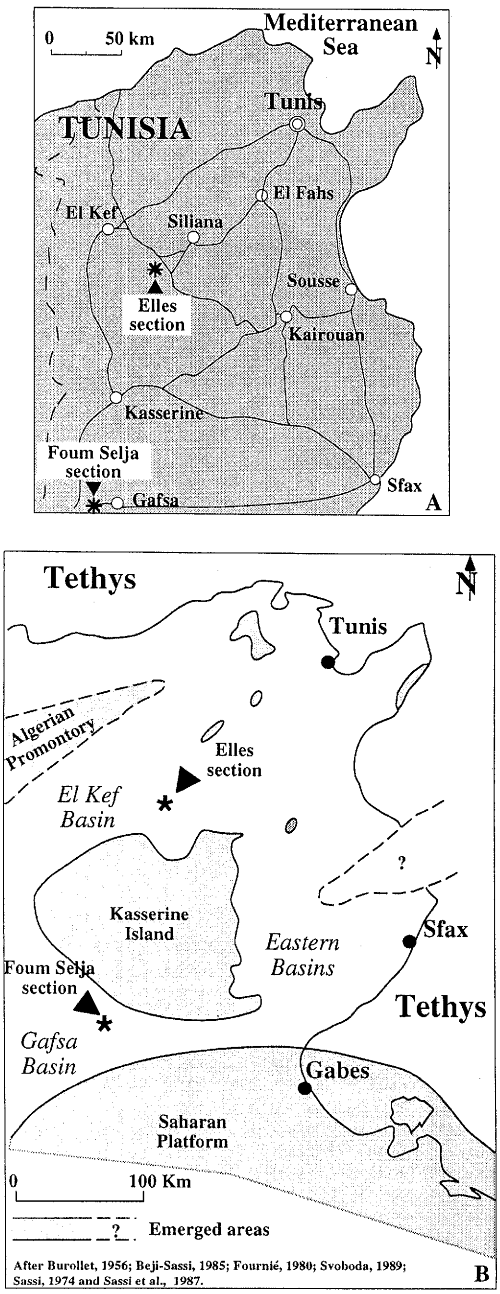
During the Paleocene-Eocene, the Tethys was a semi-restricted basin surrounded by vast shallow epicontinental seas and was undergoing intense tectonic activity [Oberhänsli and Hsü, 1986; Klootwijk *et al.*, 1992; Oberhänsli, 1992]. The geographic and tectonic features suggest that the Tethys is a key region for the investigation of global climatic and oceanic changes during the Paleocene-Eocene [Kennett and Stott, 1990, 1991; Lu *et al.*, 1996].

This study evaluates the Paleocene-Eocene transition in central and southern Tunisia based on two sections, Foum Selja, and Elles, and is an integrated multidisciplinary approach that includes micropalaeontology, sedimentology, mineralogy and geochemistry (stable isotopes). The palaeogeographic location of these sections provides an important new database that aids our understanding of the climatic and environmental changes across the Paleocene-Eocene transition, in shallow marginal seas of the Tethys as well as their potential influence in contributing to global environmental changes.

LOCATION AND PALAEOGEOGRAPHICAL SETTING

The Elles section is located in the El Kef Basin and can be reached by the road from Siliana to El Kef. The Foum Selja section is located in a gorge about 10 km west of the city of Metlaoui and is reached by following the road from Metlaoui to Tozeur (fig. 1A).

During the Palaeogene, Tunisia was located at the southern margin of the Tethys and was the site of major phosphate deposition. The phosphate deposition occurred mainly in the shallow Gafsa Basin of southern Tunisia during the late Paleocene to early Eocene and to a lesser extent in the El Kef Basin (Tunisian Trough) of west-central Tunisia (fig. 1B) [Berthon, 1928; Visse, 1952, 1973; Burollet, 1956, 1967; Sassi, 1974, 1980; Fournié, 1980; Svoboda, 1983, 1985, 1989; Beji-Sassi, 1985]. In the Foum Selja section in the Gafsa Basin we analyzed a sequence comprising the Thelja, Chouabine and Kef Eddour Formations [Regaya



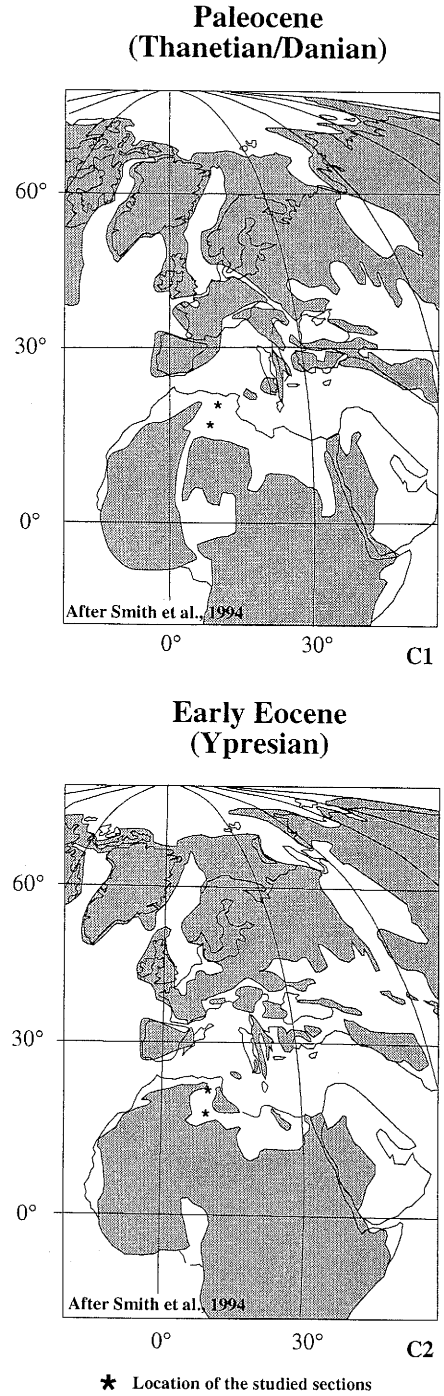


FIG. 1
A – Geographic location of the Elles and Foum Selja sections in Tunisia.
A – *Localisation géographique des profils d'Elles et de Foum Selja, Tunisie.*
B – Palaeogeography during the Paleocene and early Eocene in Tunisia.
B – *Paléogéographie de la Tunisie du Paléocène à l'Eocène inférieur.*
C1 – Palaeocoastline map during the Paleocene at 60 Ma (Thanetian-Danian).
C1 – *Carte des paléocôtes au Paléocène (60 Ma).*
C2 – Palaeocoastline map during the early Eocene at 53 Ma (Ypresian).
C2 – *Carte des paléocôtes à l'Eocène inférieur (53 Ma).*

et al., 1991] in order to observe the global environmental changes across the Paleocene/Eocene transition (fig. 2). These three formations are equivalent to the Lower, Middle and Upper Metlaoui Formations previously defined by Lucas *et al.* [1979]. Another P/E transition, the Elles section in the El Kef Basin was analyzed. The studied sequence comprises one part of the El Haria Formation [Said, 1978].

Palaeogeographic reconstructions for the Paleocene and early Eocene reveal several tectonic events that may have affected climate and ocean circulation (fig. 1B and C). These events include the closing of the north-south seaway between the southern Tethys and the South Atlantic, and the onset of the opening of the North Atlantic, between Greenland and Great Britain (fig. 1, C1 and C2). In Tunisia, the closure of the seaway to the south is accompanied by the re-emergence of Kasserine Island. At the time of the Paleocene-Eocene transition, Tunisia was divided into three emerged areas, the Saharan Platform, Kasserine Island and the Algerian Promontory separated by the Gafsa, the El Kef and the Eastern Basins (fig. 1B).

The palaeogeography of the region significantly influenced the nature of sediment deposition. At Foum Selja, in the Gafsa Basin, sedimentation was primarily influenced by the adjacent land areas, the Saharan Platform and Kasserine Island, whereas at Elles in the El Kef Basin, sedimentation was primarily influenced by Kasserine Island and the Tethys ocean.

LITHOLOGY

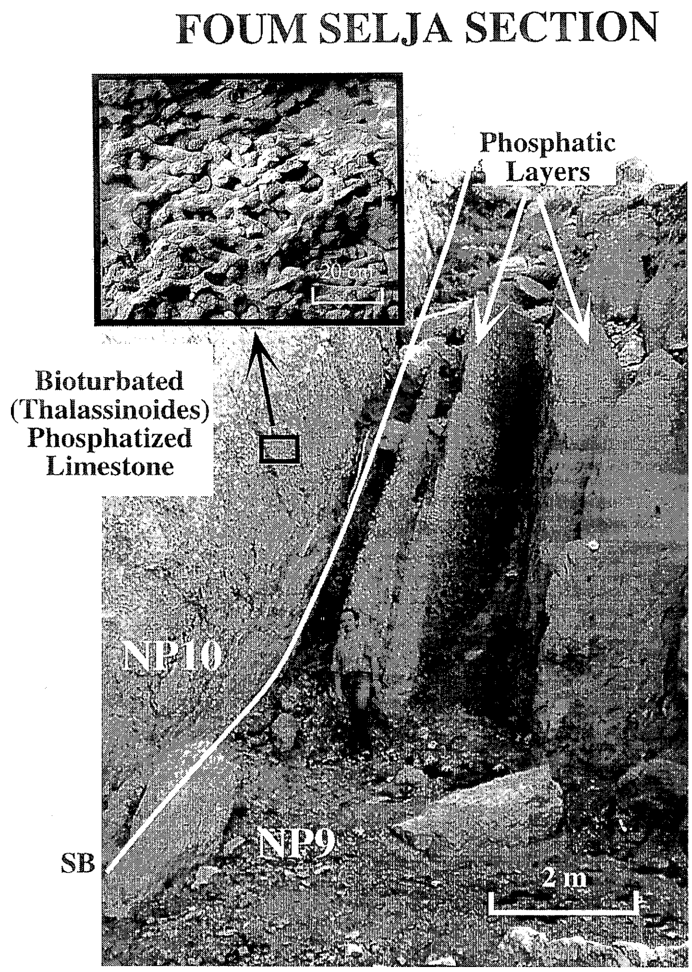
Foum Selja

The part of the section studied is about 135 m thick and spans at least nannofossil Zones NP4-5 to NP10 (fig. 2). The Thelja Formation [Lower Metlaoui after Lucas *et al.*, 1979] consists of a 56 m thick, evaporitic sequence that contains three massive evaporite beds, each several metres thick. These evaporite beds are interbedded with grey shales and thin calcareous beds enriched in shells and gastropods. The top of this interval is marked by a phosphatic hard ground (Hg, in fig. 2). The Chouabine Formation [Middle Metlaoui after Lucas *et al.*, 1979] consists of a 44 m thick phosphatic sequence (56 to 100 m, fig. 2). The lower 20 metres consist of grey shales alternating with thin calcareous layers enriched in oysters and gastropods. Upsection, sediments are increasingly more massive and more phosphatic. The Kef Eddour Formation [Upper Metlaoui after Lucas *et al.*, 1979] is 60 m thick with the basal 2 metres composed of discontinuous, lenticular, and highly bioturbated (Thalassinoides) phosphatized limestones [Sassi *et al.*, 1987] (ph. 1). Visse [1952] designated this facies as "conglomerate layer". The top of the studied section consists of two thick shelly limestones separated by alternating phosphates, marls and limestones containing cherts.

Thin sections of the phosphatic sequence in the Chouabine Formation show rounded phosphatic particles, phosphate-coated grains, phosphatized shells of gastropods, oysters, fish and vertebrate debris and a few detrital quartz grains. The phosphatic grains, phosphatized shells and the non-phosphatized micritic matrix indicate the absence of in situ phosphatogenesis and a probable allochthonous reworking. Nevertheless the absence of extraclasts produced by erosion of older sediments in these phosphatic layers could suggest that phosphate formation is nearly contemporaneous with the deposits (Föllmi, oral comm., 1998).

Elles

This section is about 55 m thick and spans the upper Paleocene to lower Eocene nannofossil Zones NP7 to NP10 and foraminiferal Zones P4a to P6a (fig. 2). Three coarse glauconitic layers are present. The basal glauconitic bed is

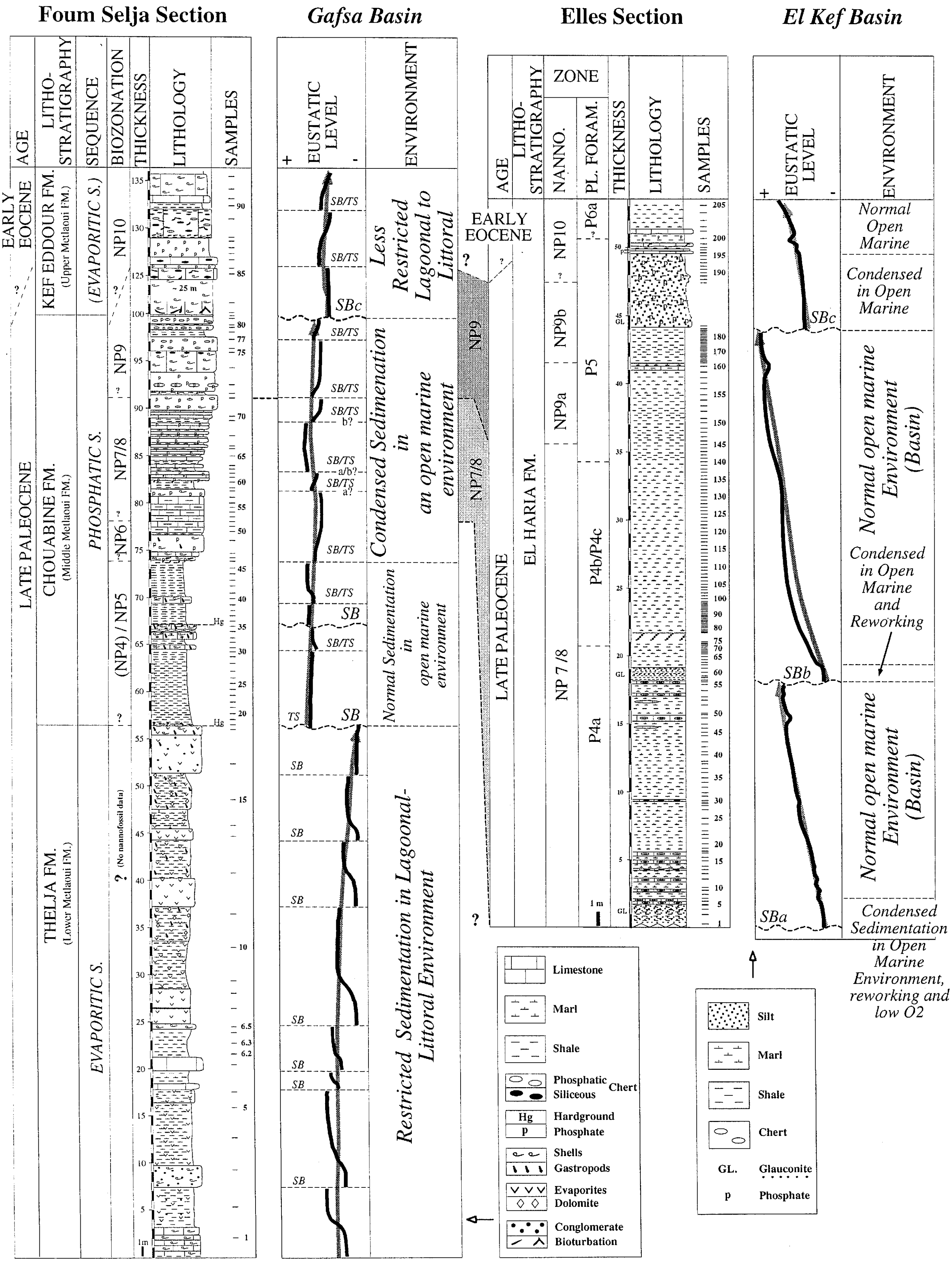


PH. 1. – Upper part of the phosphatic sequence at Foum Selja (SB = sequence boundary).

PH. 1. – *Partie supérieure de la séquence phosphatique à Foum Selja (SB = limite de séquence).*

FIG. 2. – Lithologic description of the Foum Selja and the Elles sections with sample locations. Planktic foraminiferal and nannofossil biozonations used in this study are from Berggren *et al.* [1995] and Martini [1971]. Sea level fluctuations and sequence boundaries (SB) are estimated by lithologic changes, abrupt change in faunal assemblages, variations in terrigenous and phosphatic influx, and by sedimentological criteria such as reworking, hard grounds and condensed or eroded surfaces.

FIG. 2. – *Description lithologique des profils de Foum Selja et Elles avec la position des échantillons. Les biozonations de foraminifères planctoniques et de nannofossiles utilisées dans cette étude sont celles de Berggren* et al. *[1995] et Martini [1971]. Les changements abrupts dans les assemblages faunistiques, les variations des apports détritiques et phosphatés ainsi que les critères sédimentologiques tels que surfaces érodées, condensées ou remaniement permettent d'évaluer les variations du niveau marin et les limites de séquence.*

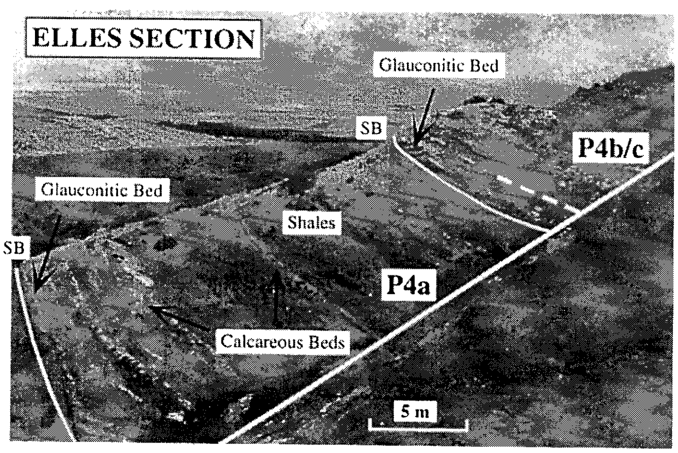

Foum Selja Section
Gafsa Basin
Elles Section
El Kef Basin
AGE
LITHO-STRATIGRAPHY
SEQUENCE
BIOZONATION
THICKNESS
LITHOLOGY
SAMPLES
EARLY EOCENE
LATE PALEOCENE
KEF EDDOUR FM. (Upper Metlaoui FM.)
CHOUABINE FM. (Middle Metlaoui FM.)
THELJA FM. (Lower Metlaoui FM.)
(EVAPORITIC S.)
PHOSPHATIC S.
EVAPORITIC S.
NP10
NP9
NP7/8
NP6
(NP4) / NP5
(No nannofossil data)
EUSTATIC LEVEL
ENVIRONMENT
Less Restricted Lagoonal to Littoral
Condensed Sedimentation in an open marine environment
Normal Sedimentation in open marine environment
Restricted Sedimentation in Lagoonal-Littoral Environment
SB/TS
SBc
SB
TS
EL HARIA FM.
ZONE
NANNO.
PL. FORAM.
NP9b
NP9a
NP 7/8
P6a
P5
P4b/P4c
P4a
Normal Open Marine
Condensed in Open Marine
Normal open marine Environment (Basin)
Condensed in Open Marine and Reworking
Condensed Sedimentation in Open Marine Environment, reworking and low O2
SBb
SBa
Limestone
Marl
Shale
Phosphatic Siliceous Chert
Hardground
Phosphate
Shells
Gastropods
Evaporites
Dolomite
Conglomerate
Bioturbation
Silt
Chert
GL. Glauconite
p Phosphate

1.8 m thick and is overlain by 17 m of alternating grey marls and thin calcareous beds with chert nodules. The second glauconitic layer is overlain by 15 m of marls followed by 10 m of shales and shaly marls (fig. 2 and ph. 2). The third glauconitic layer is 6 m thick and contains phosphatic grains. This glauconitic layer is overlain by alternating phosphate and marl layers.

Thin sections show that the first two coarse glauconitic beds consist predominantly of glauconitic particles. The presence of this authigenic mineral suggests condensed sedimentation in an open marine environment, reworking and low oxygen conditions. The third glauconite layer contains in addition to phosphatic and glauconitic particles, small benthic and planktic foraminifera and detrital quartz. The phosphatic particles are irregular in size, but generally well-rounded. The co-existence of phosphate which indicates high nutrients and oxic or suboxic conditions and glauconite implies formation of these mineral grains in two different open marine environments and subsequent reworking. Reworking in these sediments is also suggested by the presence of detrital quartz and the absence of a phosphatized matrix (no *in situ* phosphatogenesis, Föllmi, oral comm., 1998).

METHODS

In the field, the sections were measured and samples collected from all lithologic units. More closely spaced samples were collected from marls, shales and clays (Elles) than from the evaporites (Foum Selja). A total of 93 samples were collected from the Foum Selja section and 205 samples from the Elles section. Analyses of planktic foraminifera for identification and biostratigraphic determinations were based on the size fraction greater than 106 µm. For calcareous nannofossil studies, simple smearslides were studied with the light microscope at a magnification of 1000x. Oxygen and carbon stable isotopes analyses were based on powdered samples. Analyses were conducted at the stable isotope laboratory of the University of Berne, Switzerland, using a VG Prism II ratio mass spectrometer equipped with a common acid bath (H_3PO_4). The results were calibrated to the PDB scale with the standard errors of 0.1‰ for $\delta^{18}O$ and 0.05‰ for $\delta^{13}C$. X-Ray Diffraction (XRD) analyses of whole rock and clay mineral studies were conducted at the Geological Institute of the University of Neuchâtel, Switzerland using a SCINTAG XRD 2000 Diffractometer. Whole rock compositions were determined by XRD based on methods described by Ferrero (unpublished) and Kübler [1983]. This method for semi-quantitative analysis of the bulk rock mineralogy used external standards. Clay mineral analyses followed the analytical method of Kübler [1987] described in Adatte *et al.* [1996]. We present here data from the 2µm fraction. Clay minerals are given in relative percent abundance and the clay mineral ratios are calculated from XRD mineral peak data in counts per minute.



PH. 2. – Alternance of shales, marls and thin calcareous beds in P4a and P4b/c intervals at Elles (SB = sequence boundary).

PH. 2. – *Alternance de shales, marnes et minces bancs calcaires des intervalles P4a et P4b/c à Elles (SB = limite de séquence).*

RESULTS

Biostratigraphy

Foraminifera

Samples from the Foum Selja section lack planktic foraminifera and frequently also benthic foraminifera. At Elles, preservation of planktic foraminifera is variable with a relatively well preserved fauna in carbonate-rich intervals and strong dissolution in phosphate-rich intervals. In addition, there is considerable reworking of Cretaceous and Danian faunas which may reach up to 30 % of the total assemblage in the lower part of the section (Zone P4a), though reworking is relatively minor upsection. The planktic foraminiferal zonation used in this study is that of Berggren *et al.* [1995]. For the Paleocene interval this zonation differs from other zonal schemes in that the original Zone P5 has been eliminated, or effectively included in Zone P6a. Thus, the name "Zone P5" includes the interval formerly encompassed by Zones P5 and P6a. In the new zonation, the ^{13}C shift and benthic extinction event which characterize the P/E boundary interval (and Subzone P6a in previous studies) are now within Zone P5.

Zone P4

The base of the Elles section (up to 20.7 m) contains planktic foraminiferal assemblages characteristic of Subzone P4a, which include the concurrent ranges of the marker species *Globanomalina pseudomenardii* and *Acarinina subsphaerica* (fig. 3). Other characteristic species within this interval include *Acarinina mckannai*, *A. nitida*, *Morozovella velascoensis*, *M. apanthesma*, *Subbotina triangularis* and *S. velascoensis* (fig. 3). Subzones P4b and P4c mark the interval between 20.7 m and 34.3 m and are characterized by the last appearance of *A. subsphaerica* at the base of P4b and the last appearance of *G. pseudomenardii* at the top of P4c. The two subzones could not be differentiated because the marker species for the b/c boundary, *A. soldadoensis*, is already present at the top of Subzone P4a. This suggests a range overlap of *A. subsphaerica* and *A. soldadoensis* and possibly condensation or a hiatus with part of P4b missing. An abrupt change in the faunal assemblage at 20.7 m, maximum reworking between 19-20.7 m, plus a lithological change across this interval all point towards a sea level fall and erosion, followed by a sea level rise (fig. 2).

Zone P5

Zone P5 marks the interval from the last appearance of *G. pseudomenardii* to the last appearance of *M. velascoensis* and at Elles spans the interval between 35 m and 51.5 m (fig. 3). In the lower part of this zone (from 34.3 m to 41.5 m) planktic foraminifera are rare and poorly preserved. Between 41.5 m and 44.2 m, samples are barren due to dissolution. The upper part of Zone P5 contains increasingly abundant and well preserved planktic foraminifera. Characteristic assemblages in Zone P5 include abundant morozovellids (*M. velascoensis*, *M. subbotina*, *M. apanthesma*, *M.*

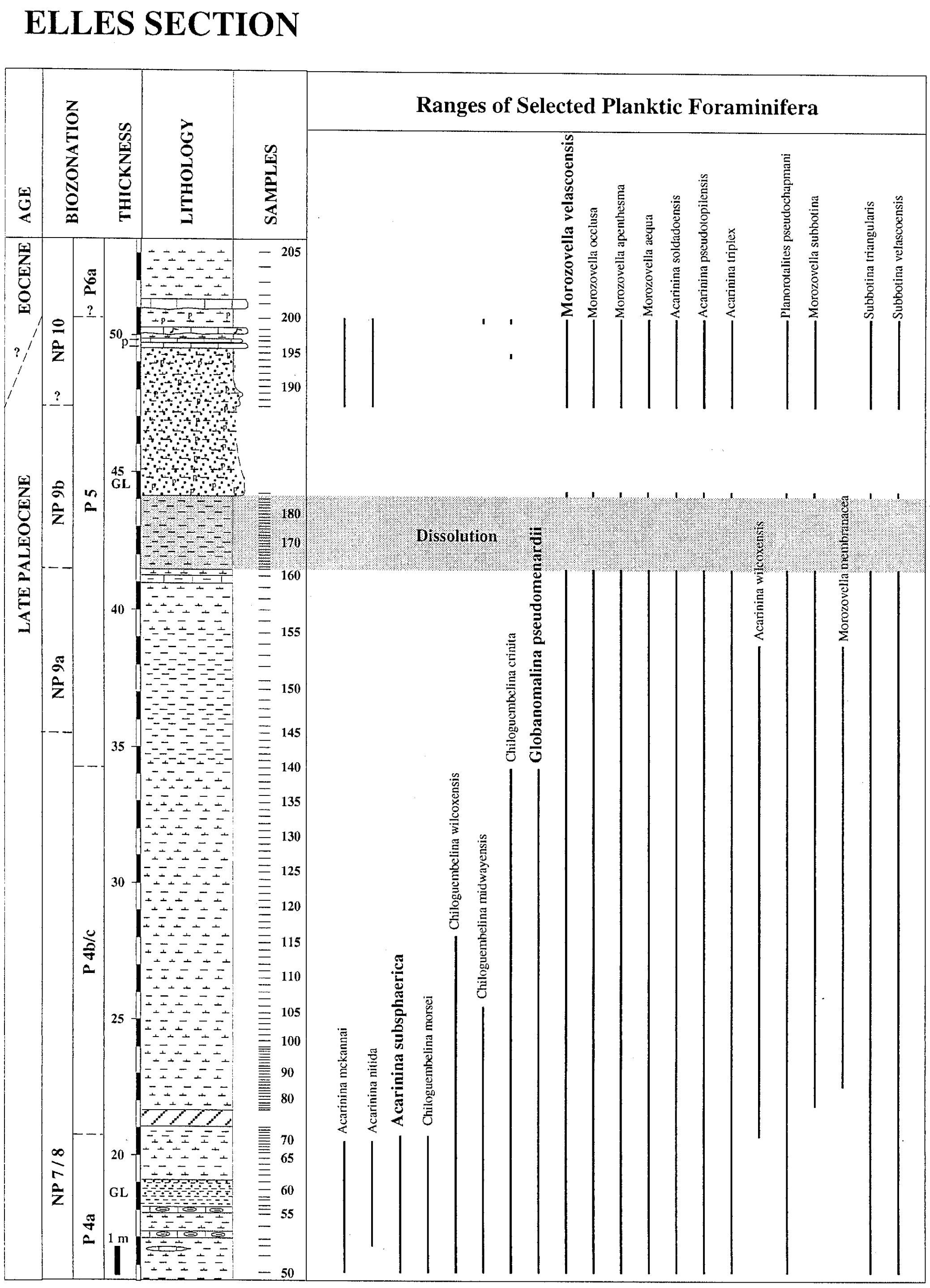


FIG. 3. – Range chart of critical planktic foraminifera at Elles.
FIG. 3. – *Charte de répartition des espèces critiques de foraminifères planctoniques à Elles.*

aequa, *M. occlusa*), large acarininids (*A. soldadoensis*, *A. pseudotopilensis*), and common biserial taxa (*Chiloguembelina crinita*) (fig. 3). High abundance of these taxa is characteristic of the generally warm climate following the ^{13}C shift and benthic extinction event [Pardo *et al.*, 1997], suggesting that the P/E event is likely within the dissolution interval below. In many sections, the P/E event is marked by strong carbonate dissolution, reduction of primary productivity and/or dilution by detrital minerals [Lu *et al.*, 1996; Bolle *et al.*, 1998].

Zone P6a

This zone is defined by the stratigraphic interval from the last appearance of *M.velascoensis* to the first occurrence of *M. formosa* and/or *M. lensiformis*.

Calcareous nannofossils

With the exception of rare, small and not identifiable reticulofenestrids in the uppermost thick bed, no calcareous nannofossils were found in the Thelja Formation of the

TABLE I. – Distribution chart of calcareous nannofossils identified at Elles and Foum Selja.

TABL. I. – *Charte de distribution des nannofossiles calcaires identifiés à Elles et Foum Selja.*

Calcareous nanno-fossils at Foum Selja and Elles	Abundance	Preservation	Biantholithus sp.	Biscutum sp.	Braarudosphaera bigelowii	**Campylosphaera (eo)dela**	Chiasmolithus cf. C. bidens	Chiasmolithus sp.	Chiasmolithus solitus	Coccolithus eopelagicus	Coccolithus pelagicus	Cruciplacolithus latipons	Cruciplacolithus sp. 10µ	Discoaster anartios	Discoaster binodosus	Discoaster bramlettei	Discoaster delicatus (4-8µ)	Discoaster diastypus	Discoaster falcatus	Discoaster lenticularis	Discoaster mediosus	Discoaster megastypus	**Discoaster mohleri**	**Discoaster multiradiatus**
FS 86	vR	P						X			X				?									X
FS 79	R	P																						?
FS 71	+	vP									X													?
FS 52	+	vP									?												?	
FS 48	F	M					X	X			X												X	
FS 46	R	P									X													
FS 31	F	P	X	X							X	X												
FS 28	+	vP									X													
EL195	R	Pm																						
EL194	F	Pm				X		X		X	X													X
EL187	F	P								X	X		X					X						
EL183	+	P									X													
EL181	+	P									X													
EL179	+	P								X	X													X
EL177	R	P									X													X
EL175	vR	P									X								X					X
EL173	vR	P									X													X
EL171	R	P									X													X
EL169	R	P									X													X
EL167	Fc	Pm	?						X	X	X		X											X
EL163	F	Pm								X	X			?						X		X		X
EL161	Cf	Mp				X		X		X	X	?								X				X
EL156	FC	M					X			X	X													X
EL151	C	M					X	X	X	X	X	X	X				X							X
EL145	Fc	M							X	X	X	X				X			X	X			X	X
EL139	A	Gm					X	X	X	X	X	X	X			?	X					?		
EL129	Fc	M									X		X										X	
EL122	C	M						X		X	X		X										X	
EL105	A	Gm						X		X	X	X	X							?	?		X	
EL101	A	G						X		X	X	X	X	?									X	
EL32	C	M			X			X		X	X	X	X		?								X	

Calcareous nanno-fossils at Foum Selja and Elles	Discoaster s. 6 arms	Discoaster sp. 8 arms	Discoaste rsp. 9 arms	Ellipsolithus distichus	Ellipsolithus macellus	Ericsonia robusta	Ericsonia subpertusa/formosa	Fasciculithus magnicordis	Fasciculithus involutus	Fasciculithus? sp.	Fasciculithus schaubii	Fasciculithus sidereus	**Fasciculithus tympaniformis**	Fasciculithus sp.	Fasciculithus/Heliolithus? sp.	**Heliolithus kleinpellii**	Hornibrookina sp.	Markalius variabilis	Markalius sp.	Micrantolithus sp.	Neochiastozygus distentus	Neochiastozygus sp.	Neochiastozygus junctus	Neochiastozygus c.f N. perfectus	Neococcolithes protenus	Neocrepidolithus sp.	Placozygus sigmoides
FS 86																											
FS 79																											
FS 71																											
FS 52					?																						
FS 48							X	X					X			?	?						?	X	X	X	X
FS 46							X									X								X			
FS 31							X										X									X	X
FS 28							X			X																	
EL195																											
EL194					X		X														X		X				
EL187																X						X					
EL183													X														
EL181									X				X														
EL179									X	X			X														
EL177											X																
EL175									X				X														
EL173													X														
EL171																											
EL169		X											X														
EL167			X	X					X				X														X
EL163	X										X	X	X						?								
EL161							X		X				X														
EL156													X														X
EL151				X	X	X	X		X				X	X					X			X	X	X			X
EL145				X	X				X				X									X	X				
EL139				X	X	X	X		X	X			X	X	X				X		X	X	X	X			X
EL129							X						X														
EL122						X	X		X				X				X		X		X	X		X		X	
EL105				X	X	X	X		X				X	X	X	X	X	X			X	X		X	X	X	
EL101				X	X	X	X		X				X	X	X		X					X		X		X	
EL32				X		X	X		X				X	X			X			X	X	X		X			X

Calcareous nanno-fossils at Foum Selja and Elles	Pontosphaera rimosa	Pontosphaera sp.	Prinsius bisulcus	Prinsius martinii	**Rhomboaster cuspis**	Scampanella sp.	Scapholithus fossilis	Scapholithus rhombicus	Semihololithus biskayae	Sphenolithus anarrhopus	Sphenolithus sp.	Sphenolithus cf. S. radians	Sullivania consueta	Sullivania "maxi" >15µ	Sullivania sp. MINI	Thoracosphaera sp.	Toweius craticulus	Toweius eminens	Toweius occultatus	Toweius sp.	Zygodiscus bramlettei	Zygodiscus herlyinii	Zygrhablithus bijugatus	Zygodiscus adamas	NP, Martini, 1971
FS 86																				X					10
FS 79																									?
FS 71																									9
FS 52											X														
FS 48				X							X		X		X	X	X	X		X					7/8
FS 46				X												X	?			X					6
FS 31			X	X														X		X					4/5
FS 28																									
EL195																									
EL194		X		X												X				X			X		10
EL187				X							X					X	X	X							
EL183																									
EL181																									
EL179																									
EL177											X							X					X		
EL175											X		X						X						
EL173											X														
EL171											X							X		X					9b
EL169																				X					
EL167											X					X		X		X			X		
EL163				X							X														
EL161				X	?				X		X						X			X		X			
EL156											X							X							
EL151				X				X			X		X		X	X	X	X		X	X	X		X	9a
EL145								X			X		X			X		X				X			
EL139				X				X			X		X		X	X	X	X		X		X			
EL129		X		X									X												
EL122				X							X	X	X		X	X	X	X		X		X		X	
EL105	X			X			X	X		?	X		X		X	X	X	X		X		X		X	7/8
EL101	X	X		X		X	X	X			X		X	X		X	X	X		X		X	X	X	
EL32			X	X				X			X		X	X	X	X	X	X		X		X	X		

Reworked Calcareous nanno-fossils at Foum Selja and Elles	Arkhangelskiella cymbiformis	Biscutum sp.	Cretarhabdus crenulatus	Cribrosphaera ehrenbergii	Eiffellithus turriseiffelii	Lithastrinus grillii	Lucianorhabdus cayeuxii	Microrhabdulus attenuatus	Micula decussata	Micula prinsii	Micula swastica	Quadrum sp.	Prediscosphaera cretaceae	Watznaueria barnesae
FS 86														
FS 79									X		X	X		X
FS 71														
FS 52														
FS 48														X
FS 46					X			X						
FS 31			X			?			X				X	
FS 28														
EL195														
EL194														X
EL187														
EL183														
EL181														
EL179									X					
EL177														
EL175														
EL173									X					
EL171									X					
EL169														
EL167									X					
EL163									X					
EL161														
EL156									X					
EL151	X													
EL145														
EL139														
EL129														
EL122														
EL105														
EL101														
EL32					X									X

Abundance
A = abundant
C = common
F = few
R = rare
X = present
X = marker species

Preservation
G = good
M = moderate
P = poor

Foum Selja section. In samples 6.2 and 6.3, however, reddish spherules with a diametre of about 5 μ are quite common. Such spherules are not unusual in sediments where no coccoliths are found. The spherules could represent pseudomorphs after coccospheres of very small coccoliths such as *Neobiscutum* or *Prinsius* (Lower Danian), *Prinsius dimorphosus* (Lower Danian) or other, younger very small coccospheres. The first, very rare and poorly preserved calcareous nannofossils appear towards the top of the lowermost marly interval of the Chouabine Formation (fig. 2 and table I). The presence, in sample 28, of *Coccolithus pelagicus*, *C.* cf. *C. robustus* and *Fasciculithus* sp. indicates an age not older than the upper part of Zone NP4, more likely Zone NP5 of Martini [1971]. The presence of *Heliolithus cantabriae* and specimens between *H. cantabriae* and *H. kleinpellii* suggest the upper part of Zone NP5 in sample 31, which also contains an unusually high abundance of *Hornibrookina* cf. *H. teuriensis*. The very poor assemblage of sample 52 contains the first specimen of the genus *Discoaster*, possibly *D. mohleri*, and thus can tentatively be assigned to Zone NP7 or younger. In samples 71 and 79, poorly preserved parts of what are probably *Discoaster multiradiatus* were found. This suggests that the upper part of the Chouabine Formation belongs to Zone NP9 (or Zone NP10). No classical markers of calcareous nannofossil zones younger than Zone NP9 were found in sample 86 which includes very rare *Discoaster multiradiatus*, *D. binodosus*, *Chiasmolithus* cf. *C. solitus* and *Toweius* sp. (tab. I). The number of rays in *D. multiradiatus* is around 18, the size about 13 μ. Such small forms with few rays usually occur in Zone NP10 rather than Zone NP9 [Wei, 1992].

At Elles, calcareous nannofossils are rare to common and poorly to moderately-well preserved. *Discoaster mohleri* was found from the lowermost samples studied, thus Zone NP7 includes the base of the section. The marker for the base of Zone NP8, *Heliolithus riedelii*, was not found – a not uncommon situation, which has led to the combining of the two zones in many regions of the world. At the base of Zone NP9, the first occurrence (FO) of *Discoaster multiradiatus*, was observed in sample 145 and the presence of the upper part of Zone NP9 (NP9b) is indicated by *Campylosphaera eodela* in sample 161 (tab. I). Above this level, one would expect the successive appearances of the genera *Rhomboaster* and *Tribrachiatus*, which usually serve to subdivide Zone NP10. Neither genus was found and thus Zone NP10 could not be recognized with the original marker. On the other hand, the FO of *Discoaster diastypus* is often used to approximate the lower boundary of Zone NP10, and its lowermost occurrence is in sample 187. At this level, no more species of the genus *Fasciculithus* were found (tab. I). The genus usually becomes extinct in the lower part of Zone NP10. At Elles, the stratigraphically highest specimens were encountered in the shales which represent the P/E boundary interval. These are the very rare calcareous nannofossils which resisted dissolution, in addition to *Discoaster multiradiatus*.

Reworked flora from the upper Cretaceous were found in several samples from both Foum Selja and Elles (tab. I). Reworking from sediments of this age thus occurred repeatedly during the deposition of the Chouabine Formation. At Elles, reworking seems to have been most common before and after the P/E event. At Foum Selja, reworking is especially evident in sample 79, where the reworked Upper Cretaceous calcareous nannofossils *Micula decussata*, *M. swastica*, *Quadrum* sp. and *Watznaueria barnesae* are more abundant than the very rare, probably in situ, forms.

The abundance relationship between the families of the *Coccolithaceae* and *Prinsiaceae* changes across the P/E boundary interval both in the northern and southern Tethys and in the Pacific [Von Salis *et al.*, 1998]. From a predominance of small and middle sized forms of *Prinsiaceae* below the P/E boundary interval a near total disappearance of the *Prinsiaceae* can be observed and their return occurs well after the P/E boundary interval. At Elles, this shift can be observed in NP9b, below the barren interval. Upsection where coccolith assemblages are again preserved (sample 187), the *Prinsiaceae* are again dominant over the *Coccolithaceae*. The *Prinsiaceae* are coccolithophorids which today take advantage of high nutrient supply whereas other families are more abundant at lower nutrient levels. This relationship may suggest that nutrients were relatively scarce at the P/E boundary at this locality.

Mineralogy

Bulk rock

Bulk rock variations reflect changes in sediment source that reflect variable intensity of weathering and erosion under arid and humid climates and the variable influx of terrigenous sediments into the oceans during sea level fluctuations. Bulk rock compositions were analyzed in the marine sediments of the Elles and Foum Selja sections to evaluate sediment sources, proximity to terrigenous sediments and intensity of erosion and transport associated with sea level changes.

Foum Selja

In this section, bulk rock analysis shows variable mineralogy (fig. 4). In the first 25 metres of the Thelja Formation, dolomite averages 50 % in shaly beds and alternates with calcite-rich shelly beds (60-90 %), with the remaining constituents phyllosilicates. From 25 m to 56.5m, dolomite predominates, averaging 75 % though decreasing near the top to 55 % (fig. 4), with phyllosilicates increase. The presence of gypsum and halite reflects enhanced evaporation. The low detritus/carbonate ratio in the Thelja Formation suggests reduced terrigenous input into the shallow restricted Gafsa Basin during the formation of evaporites. In the Chouabine Formation phyllosilicates dominate (71 %) in the lower part. In this interval, first phosphate deposits appear and calcite is highly variable from bed to bed ranging from near 0 to 80 %. The phosphatic layer consists of a carbonate fluoroapatite, francolite [Lucas *et al.*, 1979]. Phosphate can reach a maximum of 93 %. This enrichment is interpreted to be a result of the low sedimentation rate leading to episodes of phosphatogenesis [Sassi, 1974]. In the Kef Eddour Formation, carbonates (calcite and dolomite) are dominant, varying between 10 % and 80 %. In this interval, francolite and phyllosilicates decrease to a mean value of 10 % and 36 % respectively (fig. 4). Minor components of this section include detritus (the combination of quartz, K-feldspar and plagioclase). The low detritus/carbonate ratio and high francolite content indicate decreased detrital input during periods of phosphate deposition.

Elles

The major components of the bulk rock are phyllosilicates, which average 68 % in the first 45 metres of the section and decrease to 20 % in the last 9 metres (fig. 5). Calcite content is variable and reaches 70 % in calcareous beds of the lower and top parts of the section, but generally averages less than 25 %. Phosphate reaches 16 % in the upper part of the section and coincides with a decrease in phyllosilicates to 25 %. Detrital minerals are less common and include primarily quartz, some plagioclase and K-feldspar. Quartz averages 5 % throughout the section.

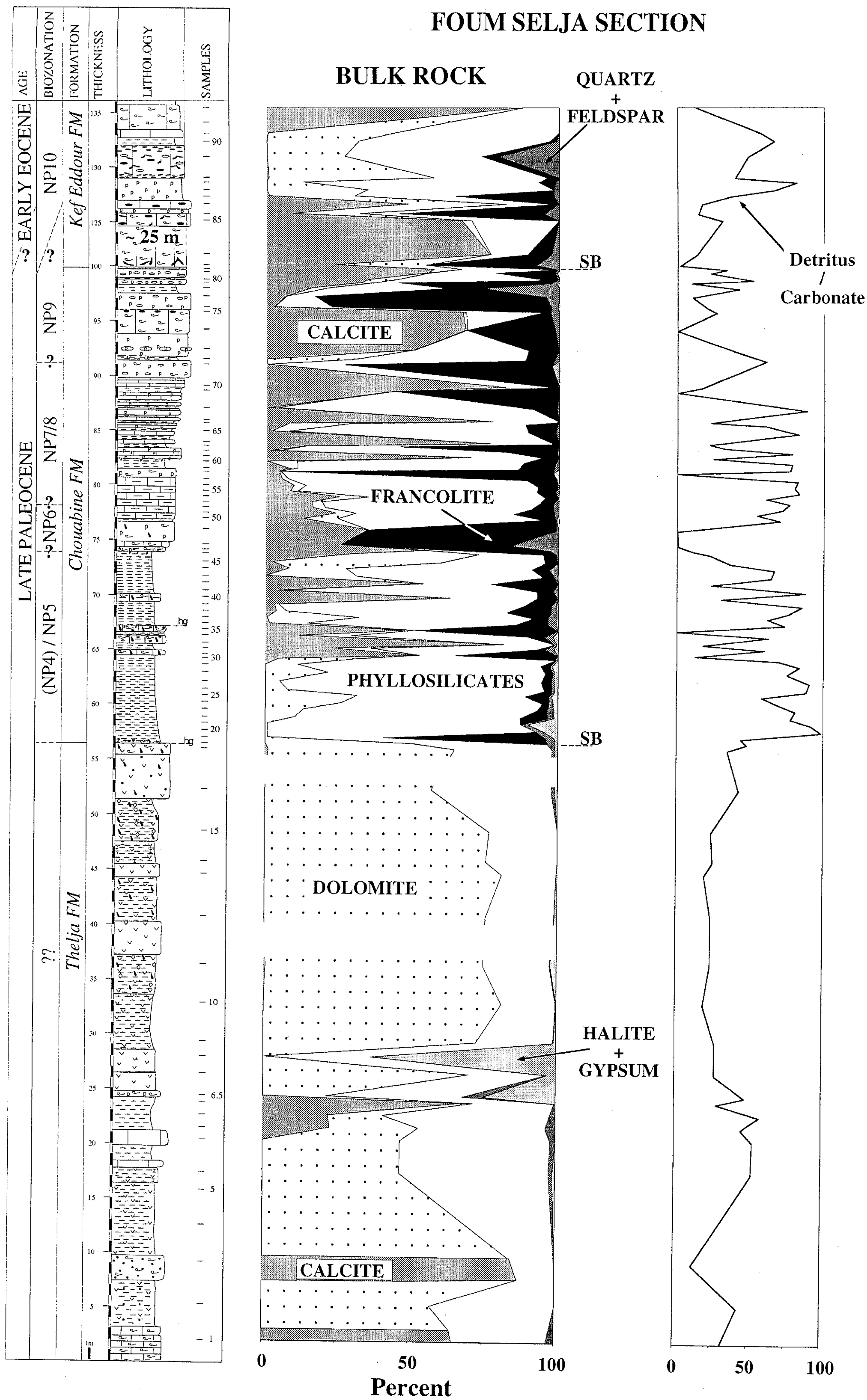


FIG. 4. – Bulk rock mineral compositions and the detritus/carbonate ratio at Foum Selja. The label detritus includes quartz, plagioclase, K-feldspar and phyllosilicates. The ratio is calculated from XRD mineral peak data in counts per minute.

FIG. 4. – *Composition minéralogique de la roche totale et rapport détritique/carbonate à Foum Selja. Le label détritique inclus le quartz, le plagioclase, le feldspath potassique et les phyllosilicates. Le rapport est exprimé en intensités brutes (coups par minute).*

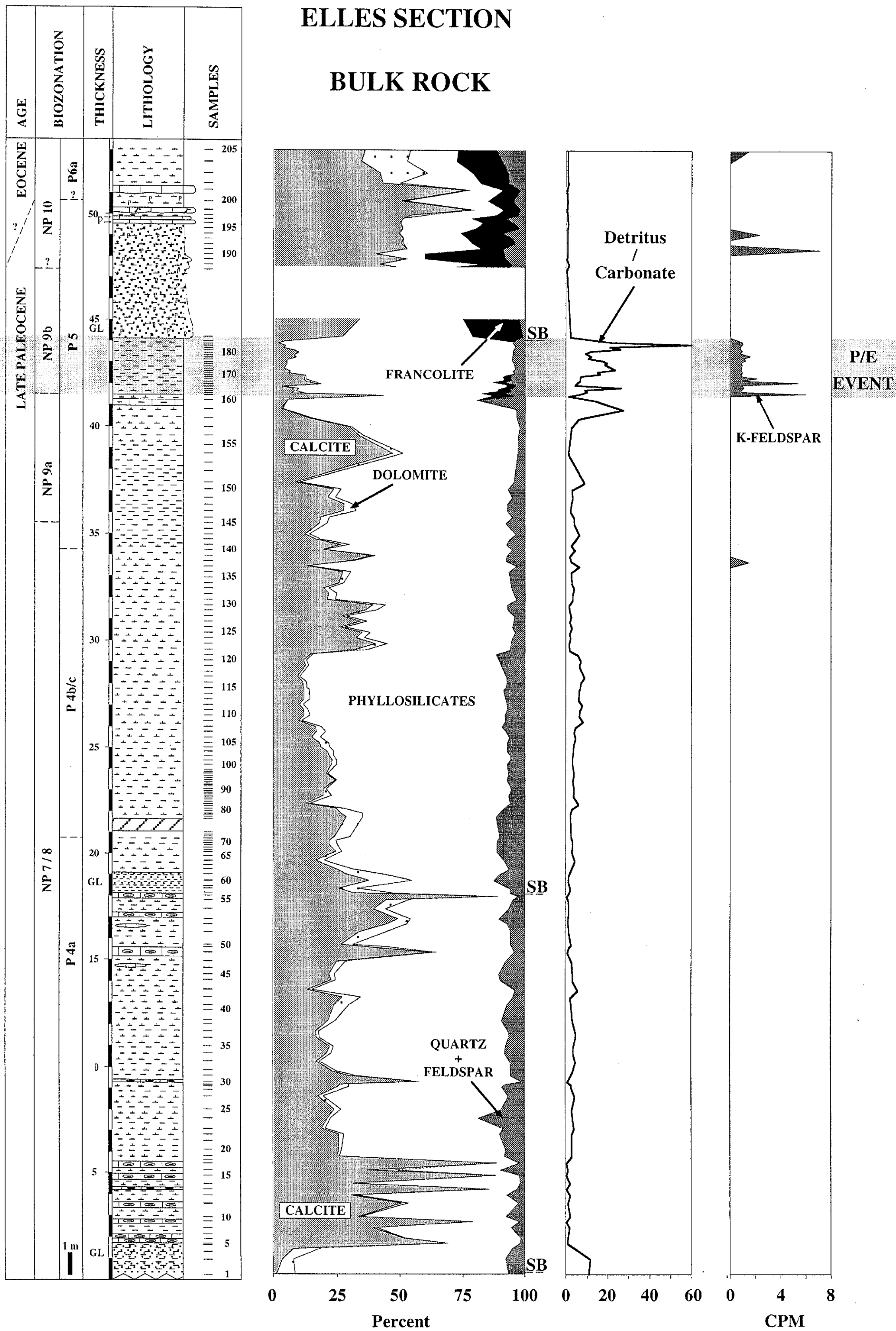


FIG. 5. – Bulk rock mineral compositions and the detritus/carbonate ratio at Elles. Ratio is calculated from XRD mineral peak data in counts per minute.

FIG. 5. – *Composition minéralogique de la roche totale et rapport détritique/carbonate à Elles. Le rapport est exprimé en intensités brutes (coups par minute).*

The clay interval (P/E transition event) is marked by a drastic decrease in calcite from 30 % to 7 %, an increase in phyllosilicates to 85 %, the occurrence of K-feldspar (1 to 6 %). The restricted presence of K-feldspar and the high detritus/carbonate ratio in this interval suggest an increase in terrigenous influx at this time. These mineralogical changes may reflect decreased primary productivity and/or dissolution and increased erosion.

The main mineralogical differences between the Foum Selja and the Elles sections include the higher quartz content at Elles (5 %) as compared with Foum Selja (1.5 %) and the dominance of phyllosilicates at Elles versus calcite and dolomite at Foum Selja. In addition, glauconite is abundant at Elles whereas francolite is abundant at Foum Selja. The onset of phosphate deposition is diachronous in the two sections. At Elles, phosphatic minerals first appear in Zone NP9 at the base of the P/E event and increase strongly above it, whereas at Foum Selja, francolite is already present in Zone NP4 or NP5.

In the two sections, sequence boundaries (SB) and transgressive surfaces (TS) are marked by bulk rock composition changes. In a sequence-stratigraphic context, phosphate deposits preferentially occur along transgressive and maximum flooding surfaces [Föllmi, 1996]. Thus at Foum Selja, high francolite contents underline the transgressive surfaces and consequently the sequence boundaries below (fig. 2). At Elles, sequences boundaries are essentially marked by the presence of glauconite. Nevertheless in this section, bulk rock composition changes characterize mainly the P/E interval, reflecting processes other than erosion, reduced sedimentation or reworking (fig. 5).

Clay-minerals

Foum Selja

In this section, the clay mineral content (< 2 µm fraction) is highly variable (fig. 6). Kaolinite is the major component in the first 23 metres (11 to 77 %). The dramatic decrease in kaolinite coincides with an increase in smectite (34 to 75 %) and increased mica (20 to 50 %) in the uppermost 22 metres of the Thelja Formation. The Chouabine Formation is characterized by high amounts of smectite (37 to 95 %), the presence of mica (1 to 25 %) and the occurrence of palygorskite and sepiolite (2 to 40 %). Kaolinite is only present (1 to 30 %) in the basal 5 metres of the Chouabine Fm. The mineralogical composition of the Kef Eddour Formation is very similar to that of the Chouabine Fm, though palygorskite reached peak abundance of 60 % and smectite decreased.

Elles

Smectite is the major component in Zone P4a with an average of 74 %. Kaolinite (9 %), mica and chlorite are minor components and average respectively 11 % and 6 % (fig. 7). The Zone P4b/c interval is marked by increased smectite (78 %), kaolinite (12 %) and decreased mica (8 %) and chlorite (3 %). The lower part of Zone P5 is characterized by increased kaolinite, with maximum values (16-48 %) coinciding with decreased smectite from 78 to 58 % across the P/E transition. The upper part of Zone P5 (45 m to 52 m) and lower part of Zone P6a lack kaolinite. Its absence corresponds with an increase in smectite to 92 % and an increase in mica from 4 % to 7 %.

Stable Isotopes

Elles

Below the 2.7 metres thick clay layer which biostratigraphically corresponds to the P/E transition, $\delta^{13}C$ values gradually decrease from 1.25 to – 0.4 ‰ (fig. 8 and table II). Within the clay layer, $\delta^{13}C$ values decrease by 1.3 ‰ and reach minimum values (– 1.7‰) between 42.8 and 44.6 m. Above the P/E interval, in the glauconite enriched-phosphate sandstone, $\delta^{13}C$ values drop to a minimum of – 2.5‰. In this sandstone $\delta^{18}O$ values are also very negative (– 3.8 to – 2.95‰). High carbonate fluorapatite (francolite) content generally coincides with the negative $\delta^{13}C$ and $\delta^{18}O$ values measured above the P/E interval (fig. 8 and tab. II).

TABLE. II. – Elles section : analyses of stable isotopes ($\delta^{13}C$ and $\delta^{18}O$) and francolite content.

TABL. II. – *Profil d'Elles : analyses isotopiques ($\delta^{13}C$ and $\delta^{18}O$) et minéralogiques.*

Elles section

Samples	δ 13 C	δ 18 O	Apatite
	(‰)		(%)
86	1.25	-2.97	0
102	0.69	-1.49	0
115	-0.44	-1.05	0
122	0.32	-1.38	0
130	0.16	-2.43	0
137	0.10	-1.44	0
143	-0.16	-1.11	0
149	-0.93	-1.26	0
153	-0.12	-0.97	0
156	-0.86	-2.03	0
160	-0.41	-1.34	0
162	-0.71	-1.51	8.45
164	-0.55	-1.50	7.39
166	-1.25	-1.51	3.3
168	-1.05	-1.52	2.83
170	-1.71	-1.69	2.19
172	-0.67	-1.29	0
175	-0.78	-1.11	0
178	-0.86	-1.50	0
180	-1.31	-1.68	0
183	-1.34	-1.28	0
185	-0.90	-1.45	0
186	-2.63	-3.82	19.92
189	-1.85	-3.14	31.95
193	-1.46	-2.95	18.08
198	-0.99	-2.74	8.59
202	-1.17	-2.47	11.1
205	-1.56	-2.24	15.42

Foum Selja

The very negative $\delta^{13}C$ (between –2 and –12‰) and $\delta^{18}O$ (between –0.7 and –5.5‰) values coincide generally as in the Elles section with high francolite content (fig. 8 and table III).

The presence of francolite, formed during early diagenesis and characterized by very "light" $\delta^{13}C$ (– 12‰) and $\delta^{18}O$ (– 11‰) values [Kastner *et al.*, 1984; Mertz, 1984] probably obscurs or overprints the original marine isotopic signals in both sections.

TABLE III. – Foum Selja section : analyses of stable isotopes ($\delta^{13}C$ and $\delta^{18}O$) and francolite content.

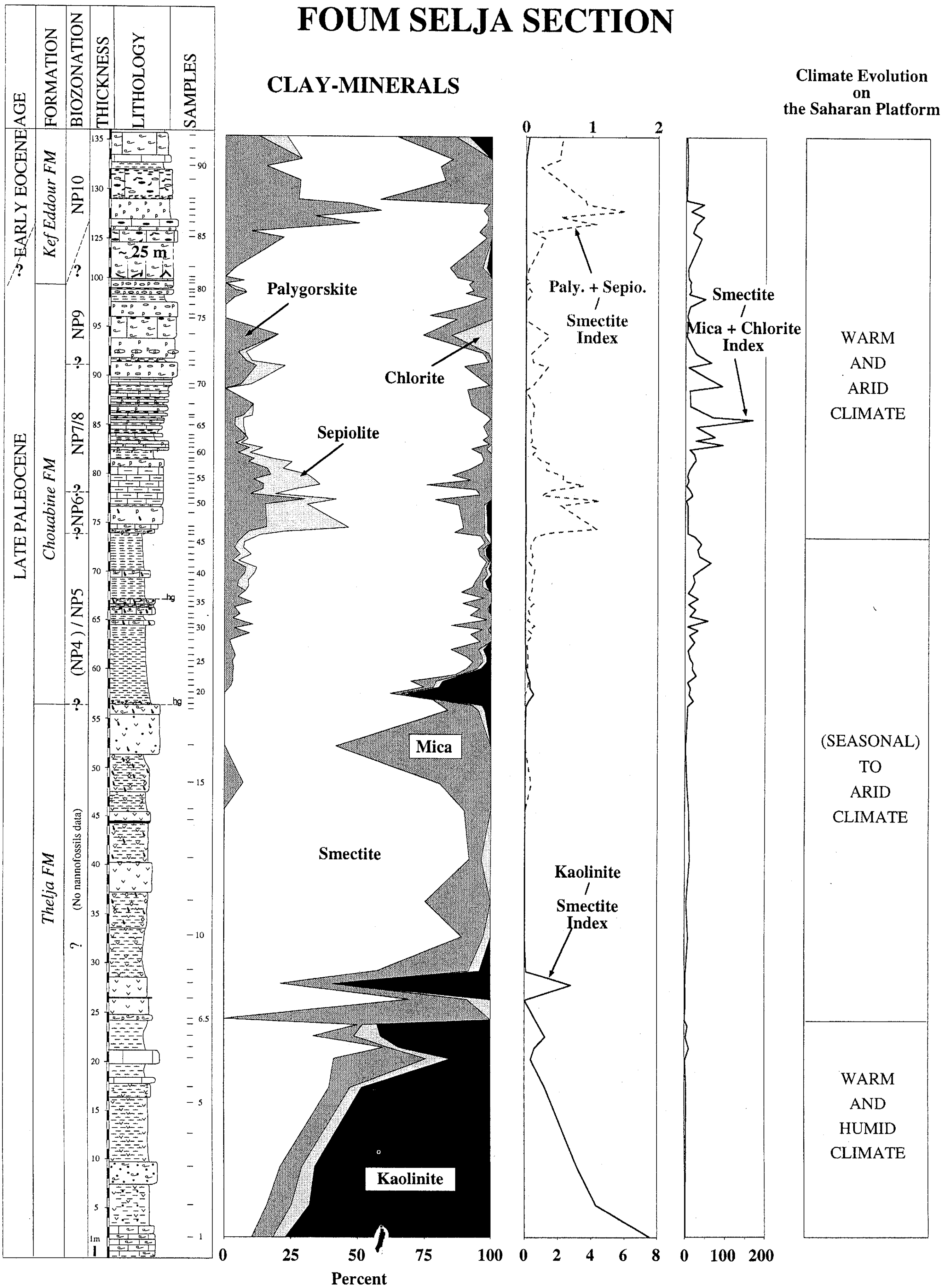
TABL. III. – *Profil de Foum Selja : analyses isotopiques ($\delta^{13}C$ and $\delta^{18}O$) et minéralogiques.*

Foum Selja Section

Samples	δ 13 C	δ 18 O	Apatite
	(‰)		(%)
60	-5.55	-0.70	10.99
65	-4.98	-1.31	9.35
69	-10.57	-5.37	56.74
70	-12.77	-1.48	1.84
72	-8.45	-1.02	9.93
73	-9.55	-3.34	10.29
74	-2.64	-3.36	30.57
75	-1.96	-3.51	2.60
78	-6.69	-2.84	12.23
80	-8.44	-3.38	4.33
82	-8.70	-3.50	0
84	-2.21	-4.89	8.30

FIG. 6. – Clay mineral composition, smectite/mica + chlorite ratio and inferred climatic conditions at Foum Selja. Ratio is calculated from XRD mineral peak data in counts per minute.

FIG. 6. – *Nature des minéraux argileux, rapport smectite/mica + chlorite et évolution climatique à Foum Selja. Le rapport est exprimé en intensités brutes (coups par minute).*


FOUM SELJA SECTION
CLAY-MINERALS
Climate Evolution on the Saharan Platform
AGE
FORMATION
BIOZONATION
THICKNESS
LITHOLOGY
SAMPLES
EARLY EOCENE
LATE PALEOCENE
Kef Eddour FM
Chouabine FM
Thelja FM
NP10
NP9
NP7/8
NP6
(NP4) / NP5
(No nannofossils data)
~25 m
Palygorskite
Sepiolite
Chlorite
Mica
Smectite
Kaolinite
Percent
Paly. + Sepio. / Smectite Index
Kaolinite / Smectite Index
Smectite / Mica + Chlorite Index
WARM AND ARID CLIMATE
(SEASONAL) TO ARID CLIMATE
WARM AND HUMID CLIMATE

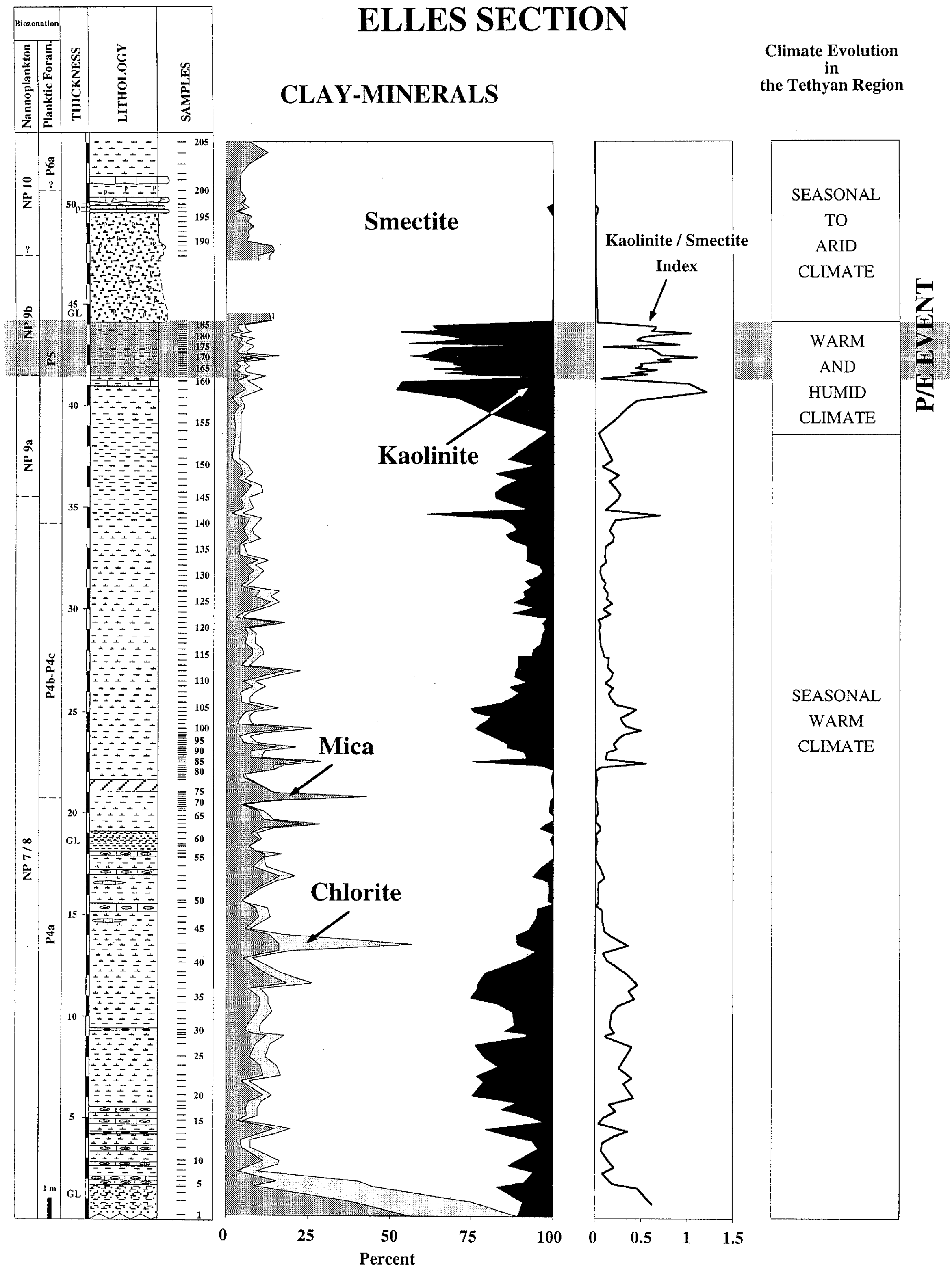


FIG. 7. – Clay mineral composition, kaolinite/smectite ratio and inferred climatic conditions at Elles. Ratio is calculated from XRD mineral peak data in counts per minute.

FIG. 7. – *Nature des minéraux argileux, rapport kaolinite/smectite et évolution climatique à Elles. Le rapport est exprimé en intensités brutes (coups par minute).*

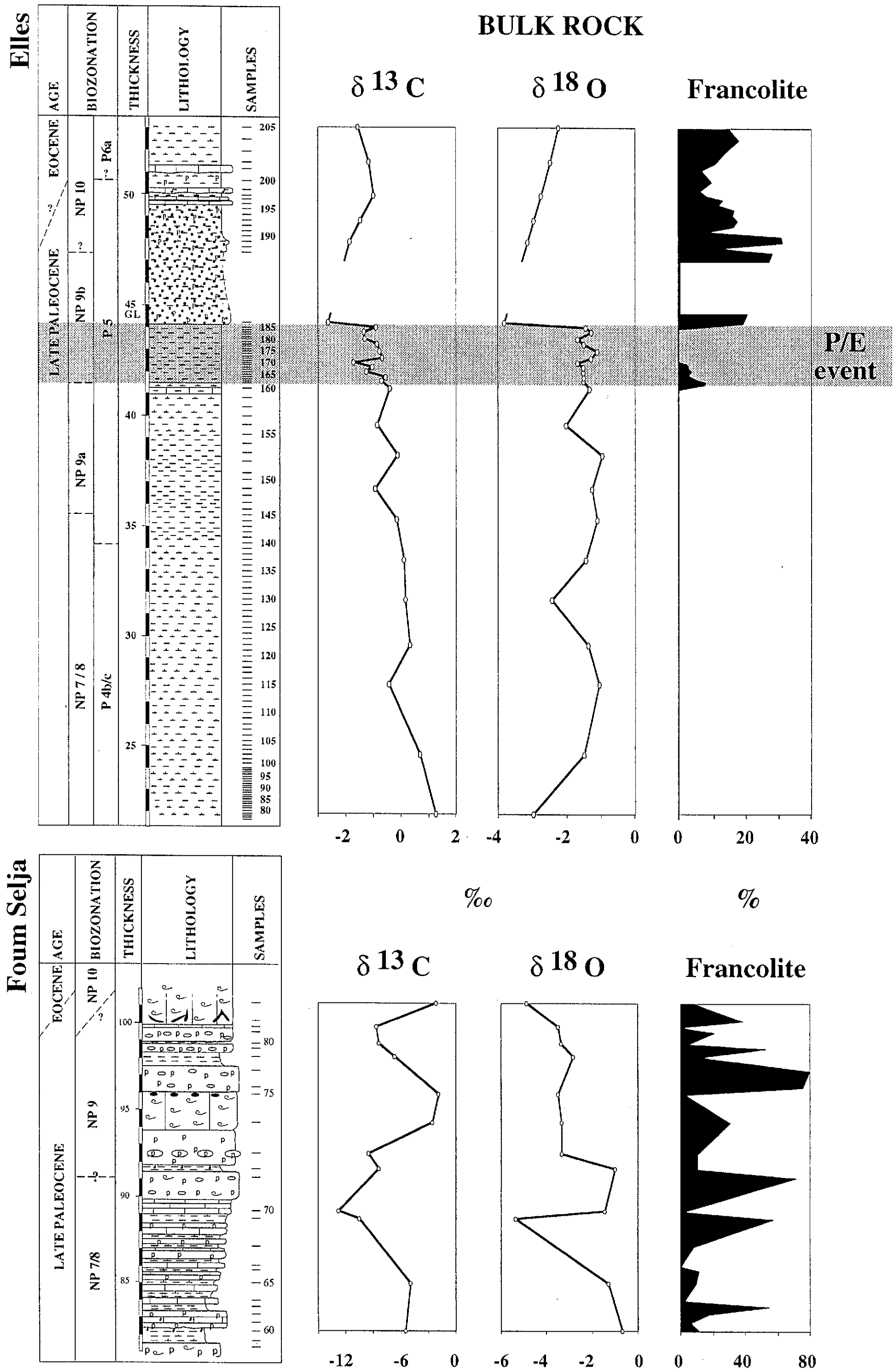


FIG. 8. – Stable isotopic bulk rock analysis ($\delta^{13}C$ and $\delta^{18}O$) correlated with francolite across the Paleocene-Eocene transition at Elles and Foum Selja.

FIG. 8. – *Variations des valeurs des isotopes stables ($\delta^{13}C$ and $\delta^{18}O$) mesurés sur la roche totale corrélées avec la teneur en francolite à Elles et à Foum Selja.*

DISCUSSION

Paleocene-Eocene transition

The P/E transition is globally characterized by a mass extinction in benthic foraminifera, turnover in planktic foraminifera and calcareous nannoplankton, an abrupt negative $\delta^{13}C$ excursion, decreased calcite and increased detrital minerals. At Elles, the P/E transition identified by fauna, mineralogical bulk rock and isotopic analyses corresponds to a 2.70 m thick clay layer as also observed at Zumaya and Trabakua [Canudo *et al.*, 1995; Bolle *et al.*, 1998] in northern Spain (Atlantic Realm) and at Alamedilla [Lu *et al.*, 1998] and Caravaca [Canudo *et al.*, 1995] in southern Spain (Tethyan Realm). These characteristic trends cannot be identified at Foum Selja where sediments were deposited in the shallow restricted Gafsa Basin which bordered the Saharan Platform to the south.

Phosphate deposits which obliterate the original isotopic signal, strong dissolution of the planktic fauna and flora in these phosphatic layers, and the presence of a condensed interval just after this event, all are criteria that prevent the choice of the Elles section as a potential GSSP candidate for the P/E boundary.

Clay minerals : Climatic signal ?

Clay minerals and their relative abundance may record informations on climate, eustasy, burial diagenesis, or reworking. The constant but variable presence of smectite and the high kaolinite content observed at the base of Foum Selja and during the P/E interval at Elles suggest that the sediments of the two sections did not suffer a deep burial diagenesis. This implies that clay minerals may come from detrital or authigenic sources. Authigenic smectite, palygorksite and sepiolite can form locally in deep-sea environments during hydrothermal weathering of volcanic rocks [Karpoff *et al.*, 1989; Chamley, 1998] or through the alteration of clay minerals at the water/sediment interface [Thiry and Jacquin, 1993; Pletsch, 1998]. However, from the Paleocene to early Eocene the southern Tethyan margin corresponded to a relatively stable period, with no hydrothermal and submarine volcanic activity [Oberhänsli, 1992] suggesting a detrital origin for these minerals which can thus be used as markers of past continental climates. Smectite reflects generally a warm climate, with seasonally alternating wet and dry conditions whereas palygorksite and sepiolite form mainly on warm but arid land masses associated with enhanced evaporation [Robert and Chamley, 1991].

Kaolinite results either from increased runoff, which could be caused by sea level lowering, or by increased rainfall. This mineral may develop in tropical soils characterized by warm, humid climate, well-drained areas with high rainfall and accelerated leaching of parent rocks [Robert and Chamley, 1991; Robert and Kennett, 1994]. Nevertheless, kaolinite may be introduced in significant amounts into oceanic sediments through the erosion of older sediments and soils during sea level transgressions [Thiry, 1989; Chamley, 1998].

The P/E interval is marked in South Atlantic and Antarctica [Robert and Chamley, 1991; Robert and Kennett, 1992, 1994], in North Atlantic [Gibson *et al.*, 1993; Knox, 1996; Gawenda *et al.*, 1999] and in some Tethyan sections [Adatte and Lu, 1995; Lu *et al.*, 1998] by the appearance or a strong increase in kaolinite. This high kaolinite content has been interpreted as marker of humidity. Even if at Elles, kaolinite is partly reworked, the general trend of this mineral is in agreement with those observed in many P/E sections. In this section, the strong increase of kaolinite may be related to the humid climatic episode which affected many regions during the P/E transition. At Foum Selja, the disappearance of kaolinite before Zone NP4-5, during a relatively stable high sea level, its absence during the P/E transgression [Haq *et al.*, 1988] and the appearance of different minerals such as palygorskite and sepiolite confirm that the detrital clay mineral distribution record minors regional qualitative climatic changes. Thus, the kaolinite/smectite index reflects climate variations from humid/warm to more seasonal conditions. The increase of the palygorskite-sepiolite/smectite index indicates changes from seasonal to warm and arid climatic conditions. However, at Foum Selja, the reappearance in few amounts of kaolinite, restricted to the first 3 metres of the Chouabine Formation (fig. 6) is probably rather due to reworking accelerated during the sea level rise which marks the base of the phosphatic sequence than to a brief warm and humid pulse (fig. 2).

Climatic Evolution

Clay mineral variations in the sediments of Foum Selja and Elles reveal the climatic and environmental evolution of the Gafsa and El Kef Basins during late Paleocene to early Eocene. The two sections are located in two different palaeogeographic areas separated by Kasserine Island and their mineral composition suggests different climatic conditions. At Foum Selja, sediment deposition occurred in the shallow restricted Gafsa Basin which was generally cut-off from the open marine environment to the north during low sea level intervals. The principal sediment source for the Gafsa Basin was the adjacent Saharan Platform. The high kaolinite/smectite ratio observed before Zone NP4-5 indicates a warm and humid climate on the Saharan Platform (fig. 6). This climatic trend is in agreement with the generally humid and warm climate that marked the end of the Cretaceous and the early Danian (P1a to P1c) in this region [Keller *et al.*, 1998]. The disappearance of kaolinite and high amount of smectite suggest a seasonal to arid climate with enhanced evaporation on the adjacent coastal areas, as indicated by the presence of evaporites. Arid climatic conditions developed on the Saharan Platform in nannofossil Zone NP6, reaching maximum aridity in Zone NP 10 indicated by the high ratio of palygorskite-sepiolite/smectite. Similar climatic conditions have been observed in the coastal basins and peri-marine environments of West Africa, from Morocco to Benin, where palygorskite deposition increased during the late Paleocene, indicating that low-latitudes and especially their coastal areas, were subjected to intensive dryness and evaporation [Robert and Chamley, 1991].

Sediment deposition at Elles occurred in an open marine environment connected to the Tethys. The sediment source was primarily from the Tethyan region. The low kaolinite content and the abundance of smectite suggest a seasonal warm climate in the late Paleocene (Zones P4, NP7-8) whereas the very high kaolinite/smectite ratio implies a warm and humid climate across the P/E transition (Zones P5, NP9). The development of arid to seasonal climatic conditions in the Tethyan region after the P/E event is suggested by the disappearance of kaolinite and the increase of mica and smectite (fig. 7).

Similar climatic variations have been observed in the Atlantic and the northern part of the Tethyan Realms. At Zumaya in northern Spain, kaolinite was deposited during the early Paleocene (Zones NP1 to NP4), and just before the P/E interval (Zone NP9) reaching a maximum of 45 % within this interval [Gawenda *et al.*, 1999]. The early Eocene (Zone NP10-11) is marked by decreased kaolinite and corresponding increase in smectite. Gawenda *et al.* [1999] interpreted the re-appearance of kaolinite as indicating a climatic change from warm, seasonally wet conditions to very warm, perennially humid conditions during the P/E transition. Seasonal conditions dominated again in the NP11 zonal interval. In the central North Sea, the P/E transition was marked by the influx of kaolinite, which persisted into Zone NP10 [Knox, 1996] indicating increased warm and humid conditions in the source areas in the northwestern part of Europe. Kaolinite increases several metres below the P/E transition at Alamedilla and Caravaca, in southern Spain [Adatte and Lu, 1995; Lu *et al.*, 1998] and at Elles (Tethyan Realm, fig. 9). The abundance of smectite observed above the P/E event in these sections indicates increased aridity in the Tethyan region at the end of Zone NP9. Except the southern Tethyan margin where very arid climatic conditions prevailed during the P/E transition, both Tethys and Atlantic Realms were marked by increased precipitation. This humid climate was recorded several metres below the P/E interval, reaching a paroxysm within it. During the early Eocene (end of Zones NP9-NP10), seasonal to arid climatic conditions developped in the Tethys whereas the Atlantic Realm was always submitted to humid conditions. From Africa to northern Europe kaolinite disappeared diachronously, before Zone NP4-5 at Foum Selja (southern marginal Tethys), in Zone NP9 at Elles (Zone P5) and Caravaca (early part of Zone P6a) and in Zone NP11 (later part of Zone P6a) at Zumaya (fig. 9). At Alamedilla, very low kaolinite contents persisted into the early Eocene. This diachronous disappearance of kaolinite suggests a latitudinal shift in the source area of kaolinite and consequently in the climatic zones, from lower to higher latitudes (fig. 9).

Environmental changes

At Elles, sea level changes are suggested by two glauconitic sandstones (Zones NP7-8) and a more phosphatic sandstone (Zone NP9b). In an open marine environment the presence of glauconite indicates condensed sedimentation and reworking. Allochthonous reworking is also suggested by the coexistence of phosphatic grains and glauconite, two minerals which form in different open marine environments. An abrupt change in the faunal assemblage above the second glauconitic bed (20 m) and maximum reworking between 19 m and 20 m, all point towards a sea level fall and erosion probably below this glauconitic level, followed by a sea level rise. The Elles section shows three sequence boundaries (SBa,b,c) associated with unconformities and some minor fluctuations (fig. 2). The two lower sequence boundaries identified in the NP7-8 zonal interval and the third one at the top of Zone NP9 appear to represent major sequences with probably tectonic enhancement. The smaller sequence boundaries related to minor sea level fluctuations are difficult to identify in this relatively deep water section because no major facies changes occurred.

The shallower Foum Selja section should record facies changes at essentially all sea level fluctuations but since the deposits very shallow, the section must be expected to be incomplete. Local tectonic activity (e.g the uplift of Kasserine Island) associated with an alkaline explosive volcanism of which traces have been observed in the phosphate deposits of the Upper Paleocene [Beji Sassi *et al.*, 1996] could be one of the major mechanisms behind the sea level fluctuations observed at Elles and more particularly at Foum Selja.

The Thelja Formation corresponds to a period of relatively low sea level marked by reduced terrigenous input, during which the seaway between the Gafsa Basin and the open sea to the north was nearly closed. This restricted marine setting (littoral-lagoonal) under warm and arid climatic conditions favoured the formation of primary evaporites (gypsum and halite) (figs. 2 and 4). Upsection (Chouabine Formation) a change to phosphate-rich sedimentation suggests a sea level rise and hence a more open seaway to the north. During time of climate warming, rising sea levels and increased nutrient-rich oceanic water influx, phosphate deposition accelerated, taking place preferentially along the transgressive surfaces [Föllmi *et al.*, 1992; Föllmi, 1996]. Reworked floras from the upper Cretaceous seem to be at a maximum (e.g. sample 79, see p. 9) near the transgressive surfaces (TS) defined by the high apatite content. It has also been shown that maximum amounts of smectite frequently coincide with long-term or short-term high sea levels [Adatte and Rumley, 1989; Chamley *et al.*, 1990; Debrabant *et al.*, 1992; Deconinck, 1992]. The high smectite/mica and chlorite ratio from the upper part of Zone NP4-5 confirms that the Chouabine Formation corresponds to a period of relatively high sea level with probably a maximum of rise in Zone NP7-8 where the ratio is highest (fig. 2 and 4). The base of this interval is marked by a major lithological change from evaporite to phosphate deposits and the presence of a phosphatized hard ground (Hg, fig. 2) which indicates a period of non-deposition and/or erosion. A second phosphatized hard ground is observed in the NP4-5 zonal interval (fig. 2). The base of the Kef Eddour Formation shows a lithological change from phosphate deposits to shelly limestones with the two basal metres highly bioturbated (Thalassinoides) and phosphatized. The nature of the facies indicates in this uppermost interval a return to more restricted environmental conditions. Based on these observations, the Foum Selja section appears to have three sequence boundaries associated with unconformities and some sea level changes without unconformities. Smaller sequence boundaries related to minor sea level fluctuations were identified because major facies changes occurred (fig. 2).

Without more appropriate investigations we can only attempt to correlate the relatively deep sequences of Elles with the shallower sequences of Foum Selja. Based only on the biostratigraphic data, the two lower sequence boundaries (SBa and SBb) observed at Elles should correlate with the Zone NP7-8 of the Chouabine Formation of Foum Selja. However because of the condensation of this interval, their identification is difficult and we cannot determine with precision the correspondance between SBa and SBb observed at Elles and the small sequence boundaries of Foum Selja. At least the sequence boundary (SBc) identified above the P/E event at Elles could correspond with the boundary between the Chouabine and the Kef Eddour Formations of Foum Selja (fig. 2).

Intermittent upwelling episodes which is one of the best known and most efficient ways of supplying nutrients [Lucas and Prévôt-Lucas, 1997] must have affected the southern Tethyan margin particularly from the late Paleocene to the early Eocene (Zones NP5 to NP10), a period of time marked by repeated occurrences of phosphate deposits linked to rising sea level. However, in addition to high organic productivity, some conditions such as no or very few detrital input, a shelf fringing an arid continent and the dominance of organisms without carbonate shells in an environment which does not favour the precipitation of biogenic carbonate are required to favour the accumulation of phosphates [Lucas and Prévôt-Lucas, 1997]. At Foum Selja, phosphate deposition coincides with arid climatic conditions onto the Saharan Platform and subsequent reduced detrital sediment supply into the Gafsa Basin (figs. 4 and 6). The episodes of phosphate accumulation reflect probably the invasion of nutrient-rich upwelling waters into this shallower basin. At Elles, the increase of the aridity in the Tethyan region and subsequent very low detrital input into the El Kef Basin only after the P/E event (figs. 5 and 7) could be the main causes for the late accumulation of phosphates (in Zone NP9) compared to Foum Selja (in Zone NP4-5).

The occurrence of phosphate deposits related to climate change and consequently reduced detrital influx suggests a change in palaeoceanic and/or palaeoatmospheric circulation on the southern Tethyan margin from the upper Paleocene (Foum Selja) through the Paleocene-Eocene transition (Elles).

CONCLUSIONS

During the early Paleocene, the Saharan Platform experienced a warm and humid climate that changed to warm and

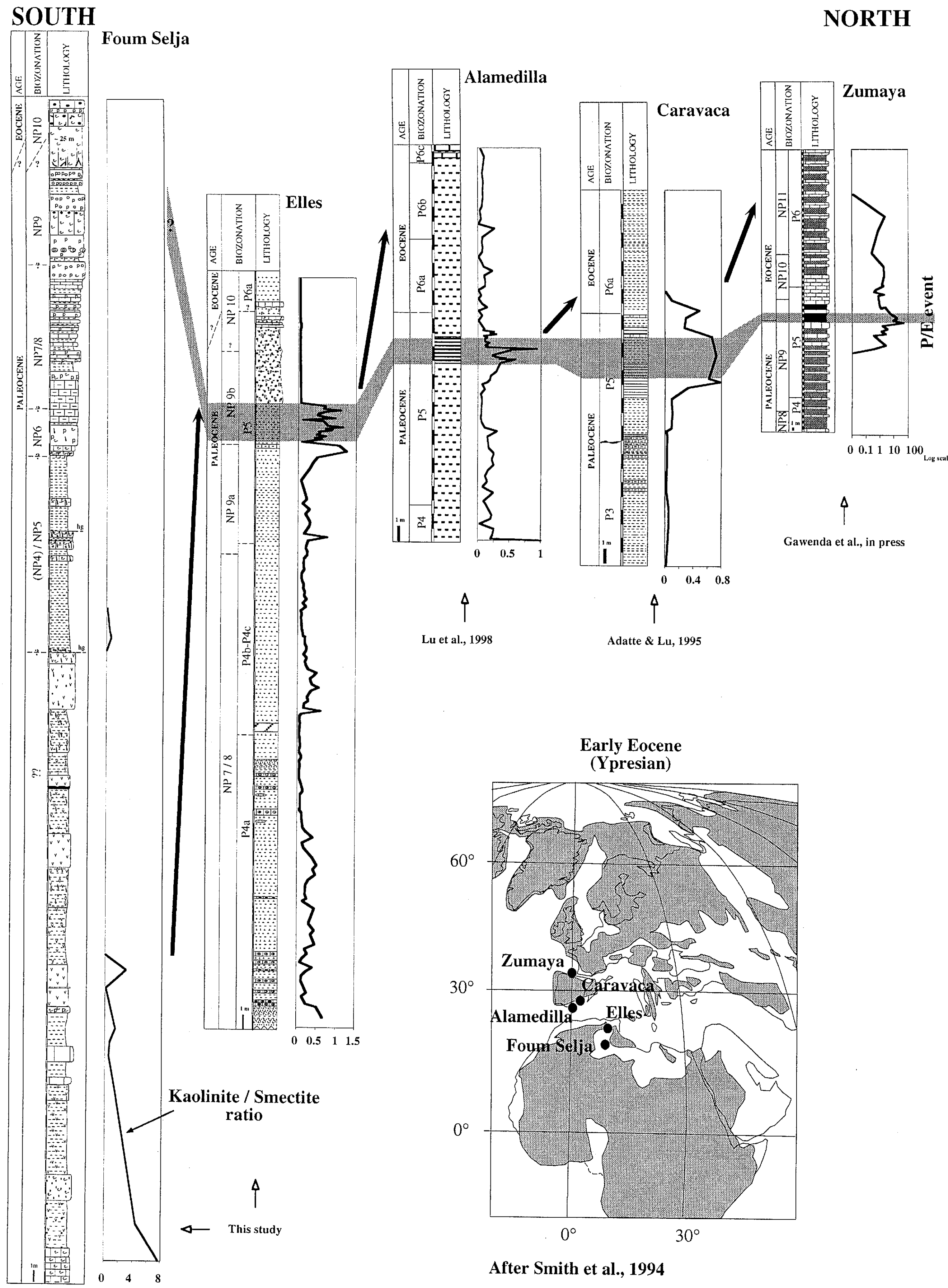


FIG. 9. – Variations in the kaolinite/smectite ratios with the palaeogeographical location of the studied sections. Ratios are calculated from XRD mineral peak data in counts per minute.

FIG. 9. – *Variations des rapports kaolinite/smectite et situation paléogéographique des profils étudiés. Les rapports sont exprimés en intensités brutes (coups par minute).*

very arid climatic conditions during the late Paleocene to early Eocene. In contrast, the Tethyan region was marked by a seasonal warm climate in the late Paleocene changing to a warm and humid climate across the P/E transition and to arid/seasonal conditions in the early Eocene. From south to north, the disappearance of kaolinite is diachronous suggesting a latitudinal shift in the kaolinite source and consequently in the climatic zones, from lower to higher latitudes.

The Elles section shows three major sequence boundaries associated with unconformities. The two lower identified in the NP7-8 zonal interval should correlate into the Chouabine Formation of Foum Selja. However, because of the condensation in this interval, their identification is difficult. The third sequence boundary identified above the P/E interval at Elles corresponds to the boundary between the Chouabine and Kef Eddour Formations at Foum Selja.

Arid climatic conditions and consequently reduced detrital influx are consistent with phosphate deposits which are associated with intermittent upwelling episodes, suggesting palaeoceanic and/or palaeoatmospheric circulation changes in the southern Tethys from the upper Paleocene to the early Eocene.

At Elles, fauna, bulk rock mineralogic and isotopic analyses identified the P/E event interval which corresponds to a 2.7 m thick clay layer. These characteristic trends cannot be identified at Foum Selja where sediments were deposited in the shallow restricted Gafsa Basin which bordered the evaporite Saharan Platform to the south.

Phosphate deposits which obliterate the original isotopic signal, strong dissolution of the planktic fauna and flora in these phosphatic layers and the presence of a condensed interval just after this event, all are criteria that prevent the choice of the Elles section as a potential GSSP candidate for the P/E boundary.

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