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Paleoenvironmental study of the Sekada section based on palynology (western external rif, Northwestern Morocco)

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The Upper Cretaceous to Eocene sediments of the Sekada section, Western

External Rif (Northwest Morocco) are the subject of paleoenvironmental studies based on palynology. To this end, we formally identified 5575

palynomorphs in the Sekada samples. Biostratigraphy, based on dinoflagellate

cyst marker events, has provided detailed stage-level, Campanian- Ypresian

dating (Slimani et al., 2016). Quantitative analyses of dinoflagellate cysts and

other palynomorphs have allowed reconstructions of the paleoenvironments of

our section which evolved in a marine environment of external neritic type,

under a transgressive regime, followed by a cooling period and a regression at the end of the Maastrichtian. The remainder of the Paleogene is marked by a generalized transgression from the Danian to the Sélandien, then a regression at

the end of the Thanetian followed by a transgression in the Ypresian.

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1. Introduction

Morocco, considered rightly or wrongly as the paradise of geologists, is a country that is obviously rich in geological structures. One can observe both crystalline and sedimentary formations with all kinds of geological deformations. In the sedimentary layers, there is an important accumulation of fossils ranging from dinosaurs to microscopic fossils, including the famous trilobites and ammonites. All this has been studied a lot and has been visited by many researchers from all over the world. In spite of this, some geological maps lack some details, especially concerning the different ages of the geological layers observed in the field.

Thus, the Paleocene is unknown in the western outer Rif [1, 2, 3], the Senonian or Upper Cretaceous is followed directly by the Eocene. In this context, with the palynostratigraphic study of the Sekada section already published [4], we undertook the paleoenvironmental study of the same section to understand the emplacement of its sedimentary procession.

Abstract

The main objective of this study of the Cretaceous-Paleogene and Paleocene-Eocene passages is to reconstruct the depositional environments that prevailed during the emplacement of these sediments.

2. Geological and geographical setting

Conditioned by its position as a hinge between the African, European and American continents, Morocco has a long geological history that is marked by several successive orogenic cycles. Due to their magnitude and geodynamic context, these orogenic cycles have contributed to the shaping of three major structural domains in Morocco: from south to north, the Anti-Atlasic and Saharan domain, followed by the Atlas and Mesopotamian domain, and then the Rif domain.

Located in northern Morocco, the Rif range forms an arc-shaped mountain edifice open to the Mediterranean Sea that has its history spanning the Triassic to the late Miocene [1-2, 5-7]. The Rif constitutes the western termination of an alpine chain derived from the Tethys. It is part of a Betic-Rifo-Tellian structural ensemble around the western Mediterranean Sea and connects to the Apennines through Sicily [8]. The Rif is subdivided into three main areas: the Internal Areas, the Flysch Nappes and the External Areas (Figure 1).

The Sekada section is located in the Tanger Unit, in the western chain of the outer Rif (Figure 1) in northwestern Morocco.

The Sekada site (geographic coordinates: 35° 39′ 68″ North and 5° 87′ 76″ West) is located five kilometers south of Arba Ayacha village (Figure 2). This site is exposed along the road connecting Arba Ayacha to Souk Sebt Beni Garfett. In this section, Upper Cretaceous to Lower Eocene marly marl and limestone deposits, which have yet to be accurately dated, outcrop in sub-vertical north-south trending beds [4].

3. Material and method

The material used in this study consisted of 17 cuttings samples collected from the Sekada cut. Control samples from this section are kept at the Department of Earth Sciences of the Rabat Scientific Institute for possible future studies.

The methodological approach consisted of lithological and palynological analyses.

The determination of the lithological nature of the Sekada section was done in the field. The macroscopic description of the different samples consisted of identifying the color, coherence and nature of the rocks which allowed us to establish lithological logs [9].

The preparation of palynological slides in the laboratory is done in three steps as described by [10-11]: (1) sampling and physical treatment, (2) chemical attacks (HCl 10%, HF 40%) to dissolve the mineral matter and preserve the organic matter contained in the sediments, (3) mounting of the collected organic matter between slide and coverslip for microscopic study.

The determination of the paleoenvironment in this study is based on the relative proportions of dinocysts (marine organisms) to spores and pollen grains (continental organisms) in the palynological assemblage [12]. Thus, the S/D ratio indicates the continental influence on the depositional environment. It is also calculated with the formula of [13]: ratio sporomorphs (spores and pollens) / dinoflagellate cystes (dinoflagellate cystes and acritarchs) (S/D):

(S/D = nS/(nD + nS) with n= number.

Thus, we will qualify as a continental paleoenvironment, any environment whose sedimentary deposit contains a palynological assemblage consisting solely of spores, pollen grains and organic matter (wood debris).



Figure 1. Structural map of the Rif Mountains (modified by [14] after [15])

On the other hand, if the palynological assemblage contains dinoflagellate cystes and chitinous internal tests of microforaminifera in much higher proportions than the spores and pollen grains, with the presence of amorphous organic matter, we will say that this Paleoenvironment is marine.

When the proportions of dinoflagellate cystes (marine organisms), spores and pollen grains (continental organisms) are more or less equal, we speak of deposition in a lacustrine or estuarine environment. However, the slight dominance of one species in proportion shows a continental or marine influence.

The depositional environment can also be determined based on the relative proportions of certain intraspecific groups of dinoflagellate cystes that have a distribution preference along a neritic to oceanic transect.

The ratio of autotrophic to heterotrophic dinocysts or peridinioides/gonyaulacoides (P/G) ratio (P/G = nP/(nP + nG) sensu [13] provides information on the productivity of the sea surface.

The ratio between the number of dinocysts characterizing the internal neritic environments (IN) and the number of dinocysts characterizing the external neritic environments (ON) or IN/ON ratio is calculated according to the formula: IN/ON = nIN/(nIN + nON) [13, 16]. It provides information on the paleo-depth.

Other curves have been developed based on certain dinocysts groups that characterize a particular depositional environment, including:

- Areoligera Group: It includes dorsoventrally compressed gonyaulacoides skolochorates taxa, such as *Areoligera* spp. and *Glaphyrocysta* spp. It characterizes inland and coastal neritic depositional environments [9,16-20].

- The *Spiniferites* Group consists of proximochorate and cosmopolitan gonyaulacoid cysts including *Spiniferites* spp. and *Achomosphaera* spp. It characterizes an external neritic environment [9,16-29].



Figure 2. Geographic (A) and geological (B) location maps of the Sekada section (Arba Ayacha, Western External Rif, Northern Morocco); B, adapted from the 1/500,000 geological map of the Rif (Sutter, 1980; [4]).

- The *Senegalinium* Group includes cornucavate peridinioid cysts, such as *Cerodinium* spp., *Palaeocystodinium* spp., *Spinidinium* spp., *Senegalinium* spp., *Isabelidinium* spp. and *Deflandrea* spp. that are heterotrophic cysts marking a neritic to oceanic depositional environment. This group is associated with nutrient and high productivity levels [16-18,30-31,67].

- The *Fibrocysta* Group consists of fibrous, proximate, chorate gonyaulacoid cysts such as *Fibrocysta* spp., *Kenleyia* spp., *Cordosphaeridium* spp., *Operculodinium* spp., *Carpatella* spp, *Damassadinium californicum* and *Cribroperidinium* spp. This group generally characterizes an internal neritic depositional environment [16,19,24,32-34,67].

- The *Lejeunecysta* Group is composed of cornucavate proto-peridinoid cysts with proximate acavate and characterizes areas of high productivity [9; 16,23;35-38,67].

- *Impagidinium* spp. is instead composed of proximochorate gonyaulacoid cysts that are typical of oceanic marine environments [16-17,29,33,38-42,67].

- *Palaeohystrichophora* spp. consists of the peridinian cysts *Palaeohystrichophora infusorioides* and *Palaeohystrichophora palaeoinfusa*. It characterizes an external neritic environment [27,67].

- *Odontochitina* spp. consists of the *Odontochitina costata, Odontochitina operculata, Odontochitina porifera*, and *Odontochitina tabulata* cysts. It characterizes an external neritic environment [27,42].

4. Results and discussion

4.1. Lithostratigraphy

The lithology column of the Sekada section (Figure 3) was made on the basis of data from macroscopic observation of the sediments in the field. The lithologic cut was made from the base to the top [9,4].

The Sekada series (Figure 3) consists of gray to blackish marls (150 m thick) with intercalations of thin yellowish to brownish sandstone beds (5-10 cm thick), followed by a succession of greenish-gray marls (70 m thick) and brownish-gray marls (30 m thick). These deposits have previously been assigned to the Upper Cretaceous [1,3] in the Western External Rif Range. They are overlain by 50 m of marly limestone alternated with white marl, formerly dated to the Lower Eocene (Sutter, 1980a). The age of the deposits, Upper Cretaceous-Lower Eocene, of the Sekada section is refined to the stage level by Slimani *et al.* [4].

4.2. Palynolostratigraphy

The results of the palynolostratigraphic analysis of the Upper Cretaceous to Lower Eocene marly successions of the Sekada section, south of Arba Ayacha (Outer Rif, Northwest Morocco), are already known and published by Slimani et al. [4]. They revealed the presence of rich and wellpreserved assemblages of marine organic-walled microfossils formed mainly by dinoflagellate cysts. The dinoflagellate cyst biostratigraphy of this section allows the recognition of several important bioevents based on the lowest occurrence (LO), highest occurrence (HO), and global acme of dinoflagellate taxa. The most important dinoflagellate cyst bioevents recorded in this section are in ascending order and in alphabetical order: LOs of Exochosphaeridium? masureae, Senegalinium spp., LOs of Cerodinium spp, HOs of Cribroperidinium wilsonii subsp. wilsonii, E? masureae, HOs of Trithyrodinium suspectum, HOs of Odontochitina costata, Odontochitina operculata, Odontochitina porifera, Xenascus ceratioides, LCO of Alterbidinium varium, HOs of Alterbidinium acutulum, A. varium, Palaeohystrichophora infusorioides, LO of Disphaerogena carposphaeropsis, HO of Palynodinium grallator and Isabelidinium cooksoniae, LO of Manumiella seelandica, HOs of Dinogymnium spp, the acme of M. seelandica, LOs of Damassadinium californicum, Membranilarnacia? tenella, Senoniasphaera inornata, HOs of Cerodinium diebelii, M. seelandica, Senoniasphaera inornata, Carpatella cornuta, Damassadinium californicum, Disphaerogena carposphaeropsis, LO of Apectodinium spp, HOs of Cerodinium speciosum, Palaeocystodinium

australinum, LO of Homotryblium tenuispinosum, acme of Apectodinium spp. LOs of Adnatosphaeridium multispinosum, Deflandrea phosphoritica, and acme of Kenleyia spp. [4].

The most important stratigraphic results of Sekada's study are the identification of the Paleocene in the upper part of the said Upper Cretaceous succession and the famous Cretaceous-Paleogene and Paleocene-Eocene boundaries. These boundaries are not marked by mass extinctions of dinoflagellate cystes, but by significant changes in the relative abundance of heat-sensitive taxa. The most important changes in relative dinocyst abundances are the global acme of *Manumiella seelandica* and *Apectodinium* spp. suggesting, respectively, global cooling in the late Cretaceous and global warming (PETM) at the Paleocene-Eocene transition.

The ages assigned to the studied samples from the Sekada section are summarized as follows: The Sekada section is subdivided into Upper Campanian (Sk1-SK6), Lower Maastrichtian (Sk8), Upper Maastrichtian (Sk10), Danian (SK11-Sk12), Selandian (? between Sk12 and SK13), Thanetian (SK13-SK15) and Lower Ypresian (SK16-SK17).

4.3. Paleoenvironment

The palynological study of the Sekada section shows significant changes in the relative abundance of dinoflagellate cysts (Figure 3), reflecting changes in the paleoenvironment. To study the paleoenvironment, we have grouped the dinoflagellate taxa into groups that characterize particular depositional environments. The groups thus defined are: *Areoligera* Group, *Spiniferites* Group, *Senegalinium* Group, *Fibrocysta* Group, *Lejeunecysta* Group, *Impagidinium* spp., *Palaeohystrichophora* spp. and *Odontochitina* spp.

Upper Campanian deposits are dominated by *Palaeohystrichosphaera*, (40-70%) and the *Spiniferites* spp. group (0%-40%), *Trichodinium castanae* (10%) and *Odontochitina* spp. (<10%). These deposits are also marked by a high ratio of peridinioids to gonyaulakoids (P/G) that reaches 0.8.

Maastrichtian deposits are marked by the acme of *Manumiella seelandica* (up to 40%) at SK10 and by fairly high frequencies of the *Fibrocysta* (30%) and *Senegalinium* (less than 10%) groups.

The Paleocene (Danian) is marked at SK12 by the abundance of the *Senegalinium* group (~ 42%), which is predominantly composed of *Isabelidinium bakeri*, and the *Fibrocysta* (20%) and *Spiniferites* groups (up to 20%). There is a sharp decrease in dinoflagellate cysts in the late Paleocene (Selandian-Thanetian), the assemblage is dominated by the *Fibrocysta* group (~ 20%) and the *Spiniferites* group (up to 60%).

The Eocene is marked by a decrease in the number of dinoflagellate cyst species from 10 to 4 species at SK17. However, this assemblage is dominated by *Apectodinium* spp. (up to 90%) in sample SK16, *Deflandrea* spp. (up to 60%) and the *Senegalinium* group (up to 10%) in sample SK17.

Impagidinium spp., *Apectodinium* spp. and the *Areoligera*, *Fibrocysta*, *Lejeunecysta*, *Spiniferites* and *Senegalinium* groups show quantitative changes along the Sekada section. These changes in the proportions of dinokyst groups revealed nine (9) palynological intervals from A to I that follow each other from the bottom to the top of the Sekada section:

4.3.1 Interval A (SK1-SK6)

The A interval from SK1 to SK6 (Upper Campanian) is marked by the abundance of *Palaeohystrichosphaera* spp. which varies between 40% at SK1 and 70% at SK2 before dropping to 11% in SK5, then rising to 46% in the SK6 sample while, the *Spiniferites* group, a marker of external neritic environments [16,26-27,67] and inversely related to *Palaeohystrichosphaera* spp, fluctuates between 30% at SK1 and 37% at SK6. We also note in this interval, the presence in low proportion

(less than 10%) of *Odontochitina* spp. and *Trichodinium castanea* that characterize the external neritic environments [27]. The *Fibrocysta* group, a marker of internal neritic environments [16,33-34] is present in the A interval in a very low proportion (5% at SK4) as is *Impagidinium* spp. (3% at SK1, SK4 and SK5), which marks oceanic marine environments [16,29,33,40-42,67]).

The predominance of *Palaeohystrichosphaera* spp., *Odontochitina* spp, *Trichodinium castanea* and the *Spiniferites* group over the *Fibrocysta* and *Impagidinium* groups suggest an outer neritic depositional environment with high productivity or upwelling in the A interval (SK1 to SK6) [16-17,19,21-22,24-27,43-44].

Many authors have interpreted *P. infusorioides* as a cosmopolitan heterotrophic dinoflagellate species characterizing upwelling and high productivity sites [27,43-44,46], but it also characterizes an external neritic environment [27]. This is corroborated in the Sekada section by the high ratio of peridinioids to gonyaulakoids (P/G), which reaches 0.8 and reflects the presence of upwelling in the A interval.

4.3.2. Interval B (SK7)

Interval B (SK7) of Terminal Campanian age is unique in that it has no dinocyst or continental sporomorphs (non-saccate spores and pollen). Only five (5) bissacates were observed in this sample, making it difficult to determine the depositional environment.

4.3.3. Interval C (SK8)

This interval of the terminal Campanian is marked by a dominance of the *Spiniferites* group (16%) characterizing the external neritic environments. The *Fibrocysta* (1%) and *Aeroligera* (1%) groups, which characterize the internal neritic environments, are observed in very low proportions. The presence of the *Senegalinium* group in low proportion (6%) leads to a low P/G ratio (0.3) and thus a low productivity.

The preponderance of the *Spiniferites* group over the *Fibrocysta* and *Aeroligera* groups, associated with the low P/G ratio suggests an external neritic environment with low productivity.

4.3.4. Interval D (SK9)

No palynomorphs were observed in this interval. This could be due to a very agitated environment that would not have allowed the good conservation of palynomorphs.

4.3.5. Interval E (SK10-SK11)

The E interval (SK10-SK11), of Upper Maastrichtian age, is characterized by the dominance of marker species of internal neritic environments with the acme of *Manumiella seelandica* at sample SK10 (60%) and the average abundance of the *Fibrocysta* group (up to 30%) at SK10. In the same interval, the P/G ratio is high at SK10 (0.6), reflecting increased productivity. There is also a considerable decrease in species diversity in interval E from 38 species at Sk8 (interval D) to 10 species at SK10 (interval E), which could be explained by the major crisis of the late Cretaceous.

The acme of *M. seelandica* is considered to be an indicator of shallow depths and cold climatic conditions [20,29,47-50], but also of low salinity or even brackish conditions [49-51].

The low representativeness of the *Spiniferites* group (2%) and *Impagidinium* spp. (6%) in the E interval, as well as the abundance of *Manumiella seelandica* (60%) and the *Fibrocysta* group (30%) suggest an internal neritic environment during a regressive phase and under cold climatic conditions [4,9,20,29,38,42,47,49-50,52-53,67].

4.3.6. Interval F (SK12)

This interval, of Danian age, is marked by a dominance of the *Senegalinium* group (42%) which is associated with nutrient enrichment and high biological productivity ([17]; [20]). The *Spiniferites* group (23%) characterizes the external neritic environments; then, in small proportion, the *Fibrocysta* (19%) and *Impagidinium* spp. (2%) groups that characterize the internal neritic and oceanic environments, respectively. The non-negligible presence of the *Senegalinium* group (42%) results in an average P/G ratio (0.4), thus an average productivity. The preponderance of the *Spiniferites* group (23%) over the *Fibrocysta* (19%) and *Impagidinium* (2%) groups results in an IN/ON=0.44 ratio which associated with the average P/G ratio (0.4) suggests an external neritic environment with average productivity. This could be explained by a rise in sea level.

4.3.7. Interval G (SK13)

The G interval, dated Sélandien-Thanétien, is dominated by the *Fibrocysta* group (18%) which characterizes the internal neritic environments. The *Spiniferites* group falls to less than 1% (characterizing the external neritic environments) which, at the same time, leads to an increase in the IN/ON ratio (0.9). Present in low proportion, *Apectodinium* spp. (5%) and *Impagidinium* spp. (2%) characterize respectively warming conditions and oceanic environments. The low presence of peridinians (*Apectodinium* spp.) in this interval results in a low P/G ratio (0.05), thus no productivity. The preponderance of the *Fibrocysta* group (18%) over the *Spiniferites* (less than 1%) and *Impagidinium* (2%) groups associated with IN/ON (0.9) and P/G (0.05) ratios suggest an internal neritic environment with low productivity and declining sea level.

4.3.8. Interval H (SK14)

This interval is also dated Sélandien-Thanétien. It is marked by the explosion of the *Spiniferites* group (66%) characterizing the external neritic environments which generates a low IN/ON ratio (0.1). One observes there, in weak proportion, the groups characterizing the internal neritic environments like the groups of *Fibrocysta* (12%) and *Aeroligera* (1%). The scarcity of peridinoids in this interval leads to a very low P/G ratio (0.007), thus a low productivity. The preponderance of the *Spiniferites* group (66%) over the *Fibrocysta* (12%) and *Aeroligera* (1%) groups, associated with the low P/G ratio (0.007), suggests an external neritic marine environment and thus a rise in sea level.

4.3.9. Interval I (SK15-SK17)

Interval I (SK15-SK17) dated to the Terminal Thanetian to Basal Ypresian is dominated by the heterotrophic cysts *Apectodinium* spp. (97%) at SK15 and SK17 (indicating an internal neritic depositional environment and climatic warming) followed by *Deflandrea* spp. (67%) at SK16 (indicating a deeper internal neritic environment and a decrease in temperature compared to the last environment). In addition to these two groups of peridinoids dominating this interval, species of the *Fibrocysta* group (8%) at SK16 markers of internal neritic environments are observed in low proportions. In the same interval, the P/G ratio is high (0.9 at SK15 and SK16, then 1 at SK17), reflecting a very high productivity. The highest concentration of calcium carbonate CaCO₃ (5%) is also recorded in sample SK17. The overabundance of *Apectodinium* spp. suggests a heat event during the Paleocene-Eocene Thermal Maximum (PETM) interval [4,54-64,67]. Compared to the *Apectodinium* complex, the *Deflandrea* complex is indicative of a low sea surface temperature. Furthermore, the high abundance of the *Deflandrea* complex following the *Apectodinium* acme is consistent with previous studies suggesting cooled temperatures after the Paleocene PETM (e.g. [56,64-67].



Figure 3. Sekada section: Calcimetry curve; Sporomorph to Dinoflagellate ratio curve; Peridinoid to Gonyaulacoid ratio curve (productivity); relative abundances of morphologically and ecologically related dinoflagellate cysts; species diversity per sample; relative sea level change curve (IN/ON) and palynological intervals.

The preponderance of the *Fibrocysta* group (8% at SK16) over the *Spiniferites* group (less than 1%) and *Impagidinium* spp. (less than 1%) in interval I, associated with the abundance of *Apectodinium* spp. (97% at SK15 and SK17) and *Deflandrea* spp. (67% at SK16) suggests an inland neritic environment with high productivity, in a phase of marine regression, under warm climatic conditions, especially at SK15 and then cold at SK17.

Conclusion

This palynological study applied to the paleoenvironmental characterization of the marl and marllimestone successions of the Sekada Cup (Western External Rif, Northern Morocco) covers the period between the Upper Cretaceous (Upper Campanian) and the Paleogene (Lower Ypresian). Variations in the relative abundance of dinoflagellate cyst groups, S/D and P/G ratios revealed nine paleoenvironmental intervals from the bottom to the top of the Sekada section summarized as follows:

* The preponderance of the *Spiniferites* group characterizing an external neritic environment over the *Fibrocysta* and *Areoligera* groups characterizing internal neritic environments, with the corollary of high IN/ON ratios and the advent of an acme of the *Manumiella seelandica* species at the end of the Maastrichtian, imply that the Upper Cretaceous deposits of the Sekada section were deposited in a marine environment of external neritic type, in a transgressive regime, followed by a cooling period and a regression at the end of the Maastrichtian.

* The Maastrichtian to Danian transition is marked by marker species of internal neritic environments with a drop in the IN/ON ratio leading to a marine regression.

* The remainder of the Paleogene is marked by a generalized transgression from the Danian to the Sélandian, then a regression at the end of the Thanetian followed by a transgression in the Ypresian.

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