Reconstruction of the last cretaceous anoxic event in the Tarfaya Laayoune basin (South of Morocco): Biostratigraphy and Paleoenvironment of the Oum Debaa Formation

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Abstract: The Tarfaya-Laayoune coastal basin developed in a stable passive margin, where sedimentation occurred in shallow bays. During the Late Cretaceous, bituminous and phosphatic series were deposited in the shallow depression such as Sebkha Oum Debaa. In this work, the age of these Cretaceous layers are refined using a palynological approach and their paleoenvironments are described using organic geochemistry. Based on quantitative and qualitative palynological analyses, the sediments revealed a rich and diverse dinoflagellate cyst assemblage (65 taxa); among them 9 important biostratigraphic markers: *Andalusiella inflata*, *Andalusiella ivoirensis*, *Andalusiella mauthei*, *Cerodinium diebelii*, *Cerodinium speciosum*, *Dinogymnium acuminatum*, *Odontochitina porifera*, *Trichodinium castanea*, and *Trithyrodinium evittii*. According to the reported stratigraphic dinoflagellate taxa distribution, an age range of late Campanian to early Maastrichtian is herein proposed for the Oum Debaa Formation. This biostratigraphy update has been correlated to the Tethyan and Sub-Boreal domains. On the paleoenvironmental level, geochemical proxies have displayed an anoxic lagoon depositional which is dominated by an intermediate climate between hot / humid and arid with an often low paleoproductivity regime which induces redox conditions.

Key words: Tarfaya-Laayoune Basin, Sebkha Oum Debaa, dinoflagellate cysts, upper Campanian, palynofacies.

Introduction

The Upper Cretaceous and Tertiary is generally characterized by a greenhouse climate, high atmospheric concentrations of CO₂, high global mean temperatures, and high sea level (Littler *et al.* 2011; Föllmi 2012), but some cooling episodes were also recognized (Price *et al.* 1999). These conditions favoured the formation of organic-rich rocks, often characterized by supra-regional occurrence, which originated during oceanic anoxic events (OAEs) and/or episodes of environmental changes (Föllmi 2012).

Bituminous sedimentary series rich in potential petroleum sources are known from the Silurian–Devonian, Domerian, and Cenomano–Turonian periods in the Atlantic, Atlas, and Tethyan basins in Morocco (El Albani *et al.* 1999; Aquit *et al.* 2013, 2017; Arthur & Natland 2011; Benalioulhaj 1991; Benalioulhaj & Trichet 1990; Le Heron *et al.* 2008; Keller *et al.* 2008; Kolonic *et al.* 2002; Kuhnt *et al.* 2001, 2005; Lebedel *et al.* 2013; Lüning *et al.* 2004; Nzoussi *et al.* 2005; Rachidi *et al.* 2009; Sachse *et al.* 2011, 2014).

In North Africa, the Upper Cretaceous formations are dominated by continental shelf deposits; among them black shales rich in organic matter, indicating the development of anoxic conditions (Robinson and Engel 1993). These continental shelf environments have also been characterized by high sedimentation rates (El Ayyat 2015; El-Shafeiy *et al.* 2014, 2017; Grosheny *et al.* 2008; Hartwig *et al.* 2012; Lüning *et al.* 2004; Meinhold *et al.* 2013; Pletsch *et al.* 2001; Tourtelot 1979).

The bituminous formation is contemporaneous with the appearance of the phosphatogen window in this basin. The pioneer works of J. La Vina (1961) and J. Rios (1972) have discovered phosphates comparable to those already discovered in the Moroccan meseta.

Fig 1: Lithostratigraphic synthesis of the Tarfaya-Laayoune basin according to Martinis and Visintin (1966), Choubert *et al.* (1960), Auxini (1969), Ratschiller (1970), Linder and Querol (1971), and petroleum exploration data (modified after Rjimati *et al.* 2009, 2011).

Its represents an important gulf quiet and independent from the other basins; it's known as "Tarfaya-Dakhla gulf". Recently, Nguidi *et al.* (2021) provide some answers and suggest that these deposits accumulated in a shallow oxygenated plateau environment initially formed in an anoxic environment during a Highstand system tract.

In this study, we focus on Cretaceous bituminous sedimentation of the Oum Debaa Formation in southern Morocco which is well-developed in the coastal basin of Tarfaya-Laayoune-Dakhla (Abioui *et al.* 2019; Ali *et al.* 2019; Beil *et al.* 2018; Benammi *et al.* 2019; Fabre *et al.* 2018; Ghassal *et al.* 2016; Lebedel *et al.* 2015; Meister *et al.* 2017; Prauss 2015; Zouhri *et al.* 2018, 2014).

Here our main objective is to date with biostratigraphy the bituminous sediments of the Oum Debaa Formation in the Laayoune basin located between Tarfaya and Laayoune. The present work aims to restudy the final stage of the sedimentation of organic-rich rocks from the Oum Debaa formation outcropped around the Laayoune region (southwest of Morocco) based on Dinoflagellate cysts. Other aims are to provide new data for the cartography of the region and to characterize the type of organic matter constituting the bituminous facies of the investigated section. In addition, based on the obtained results reconstruction of ancient depositional environments is attempted.

Geological setting

The Tarfaya-Laayoune-Dakhla Basin, a coastal basin that developed in a stable passive margin, is located in the NW region of the Archean–Proterozoic ridge of the Reguibate Domain /i.e., NW of the West African craton, see Rjimati *et al.* (2011). The basin is bordered by the Proterozoic Anti-Atlas Domain, the Paleozoic–Cenozoic Tindouf Basin to the N and NE, and the Archean and Proterozoic crystalline massifs of the Tiris Domain to the E. At the S-SE edge, the basin is linked to the Archean and Proterozoic crystalline massifs of the Oulad Dlim Domain, which were affected by the Hercynian orogenic phase.

The Precambrian and Paleozoic basement is composed of very complex structures divided into horsts and grabens. These structures are filled by Liassic syn-rift sequences which are essentially composed of red clastic sediments comprising conglomerates, sandstones, and shales. In the grabens, dolerite are interbedded within these deposits.

During the Cretaceous, sedimentation occurred only in shallow depressions, known as sebkhas. The studied region belongs to one such depression, called Sebkha Oum Debaa. Regarding the overall stratigraphy of the onshore portion of the Tarfaya-Laayoune Basin (Fig. 1), the Upper Cretaceous deposits display a complete succession attributed to different lithostratigraphic units, described as follows in chronological order from the bottom to the top:

- 1) The Turonian and Cenomanian deposits are attributed to the Marnes d'Oued Chbeika Formation (Choubert *et al.* 1966) and also to the Ankech Formation (Lindner & Querol, 1971).
- 2) The Campanian, Santonian, and Coniacian deposits belong to the Marnes d'Oued Khaoui Naam Formation (Choubert *et al.* 1966) and Gada Formation (Geological map of the Northern Spanish Sahara 1:200 000, sheet 15, Spanish Geological and Mining Institute).
- 3) The Campanian deposits are also partly associated with the Gada Formation (Lindner & Querol, 1971), with further parts belonging to the Oum Debaa Formation (Rjimati *et al.* 2002; Rjimati & Zemmouri 2009).
- 4) The Maastrichtian deposits are associated with the Lebtaina Formation (also known as the Tbeila Formation or Briber Formation) (Ratschiller 1970) and consist of marls intercalated with siliceous and/or phosphatic chalk.

Table 1: Correlations of Meso-Cenozoic lithostratigraphic units in the Tarfaya Laayoune basin (modified after Rjimati *et al.* 2011).

Period	Stage	Choubert (1966)	Lindner et Querol (1971)	Ratshiller (1971)	Martinis et Visintin (1966)	Lecointre (1962)	Ortlieb (1975)	Rjimati et al. (2011)	
Quaternary		Continental Facies Dunes (post-Moghrebian) Lumachelle with Pectinidae (Moghrebian)	Sands	Lacustrine crust		Continental Quaternary	Silt	Dunes and sand	
			Alluviums	Continental crust		Mellahian	Limestone crust with helicids Mellahian	Silts and evaporites	
			Fluvial conglomerate Old terraces Fossil dunes			Ouljian	Ouljian		
						Anfatian	"Aguerguer"	Hélix slab	
			Lumachelle and sandstone			Maarifian Messaoudian	Moghrebian slab	Amgriv Formation	
Pliocene		Hamada slab	Ugranat Formation	Izic Formation	Tarfaya Sandstone				
Miocene		Tah Formation	Laayoune Formation	Laayoune Formation				Mrissat Charout Formation/ Laayoune Formation	
Oligocene				Sumlat Formation	Morcha Member				
Eocene	Late		Aridal Formation, Wad Al Khat Formation		Gueran Member				
	Early		Itgui Formation		Itgui Member				
Cretaceous	Late	Maastrichtian		Lebtaina Formation				Oum Debaa Formation	
		Campanian	"Mames d'Oued Khaoui Naam" Formation	Gada Formation					
		Santonian							
		Coniacian							
		Turonian	"Mames d'Oued Chbeika" Formation	Ankech Formation					
		Cenomanian							
	Early	Albian			Agouitir Formation				
		Aptian							
		Barremian	"Tan Tan Sand"	Gor Tbeila Formation	Khrebichat Formation	Tan Tan Formation			
		Neocomian							

Table 1 outlines the debate that occurs in the assignment of lithostratigraphic units and formation names. A marked erosional truncation can be observed offshore in the northwestern part of the basin between the town Tarfaya at Cape Juby and Cape Boujdour (Daoura 1-1 borehole, site 397). At this location, part of the Early Cretaceous, Late Cretaceous, and Paleogene sediment covers have been eroded (Rad & Wissmann 1982).

The Sebkha Oum Debaa shallow depression (Fig. 3) is a morphological relief typical of arid regions. Typical sebkhas are closed depressions with impermeable bases and indicate arid conditions in which aeolian and evaporative processes mainly contribute to their formation. Arid regions are often located inland or centripetal to drainage areas, and globally tend to occur in deserts below sea level (Goudie 2013). Sebkha Oum Debaa is no exception, at 11 m below sea level, and is the smaller western extension of the larger Sebkha Tah (55 m below sea level). Sebkha Oum Debaa formed on a plain lying between land and sea. In our study, these characteristics are useful for studying the overlying formations in the outcrops, especially since the peneplain topography of the Sahara Desert makes such research difficult.

Fig 2: Geological Map of the Tarfaya-Laayoune basin (source: the geological map of Morocco 1:1000000) and the studied area has been surrounded by a black frame.

Materials and methods

Location of the studied section

The studied section is located in the NE edge of sebkha Oum Debaa (N 27°28'47.833'' / W 12° 59'22.969''). It is located 35 km north of the city of laayoune and 5 km from the center of Deroua (Fig. 3).

Palynology

Eight Cretaceous samples (samples 1–8, Tab. 2) were collected from the studied section and treated according to the standard palynological techniques (Wood *et al.* 1996; Traverse 2007).

All palynological slides are stored in the palynology laboratory, Ben M'sik Faculty of Sciences (Hassan II University of Casablanca-Morocco). In this work, the paleoenvironment reconstitution has been performed according to the Tyson's method (1993, 1995) which considers three parameters: phytoclasts, palynomorphs and amorphous organic matter (AOM). These parameters expressed in a ternary diagram subdivided into ten fields which decipher the environment deposit and the related kerogen type.

All dinocyst taxa identified in this study are listed in alphabetical order in the species list. The England Finder (EF) coordinates of the specimens shown are given in the legends on the plates (see pages 89-91).

Geochemistry

Concerning the major and trace element geochemistry of the sediments, the samples were analyzed with Inductively Coupled Plasma Mass Spectrometry ICP-MS (the sample preparation method complies with Standard BS EN 13346, which describes the method for extracting trace elements and phosphorus in sludge and solids with aqua regia), but only elements related to a proxy for depositional conditions are shown in this study.

Age	Samples	Litho-stratigraphy	Log	Lithology
Quaternary q5				Hamada slab: limestone slab with helix
Mio-Pliocene		Formation Laayoune 2		A whitish, marly facies with a cavernous appearance
			Limestone slab
			Whitish marly limestone facies
			Cavernous limestone, bioturbated with lenticular stratification with a marked porosity
			Lumachella with a massive appearance
			Whitish marls
			Gray sandstone limestone with detrital elements
Miocene		Formation Laayoune 1		Whitish sandstones, with darker bed intercalations
			Nodular facies, bedded limestones
			Dark gray sandstone facies with blackish oxides
			Gray sandstone, with horizontal stratification and diastems which are sometimes filled with level rich in salts
			Sandy facies with some sandstone concretions and nodules
Late Campanian-Early Maastrichtian	8 ●	Formation Oum Debaa		Blackish clay marls compact with foul smell and oily appearance
	7 ●			
	6 ●			
	5 ●			
	4 ●			
	3 ●			
	2 ●			
	1 ●			

Fig 3: Lithostratigraphy and lithology of the type section of Oum Debaa Formation in Sebkhata Oum Debaa and related overlying Cenozoic rocks.

Fig 4: **A** - Panoramic view of all formations in the Oum Debaa section; k5 = Oum Debaa Formation (Late Cretaceous), MLa1 = Laayoune 1 Formation (Miocene), MLa2 = Laayoune 2 Formation (Mio-Pliocene), q5 = Hammada slab; **B** - The erosional truncation between the Oum Debaa Formation and the sandstone and Cenozoic carbonate formations; **C** - Close-up on the bituminous facies. Note the blackish color and oily appearance; **D** - Location of collected samples; **E** - The passage between the Laayoune 1 Formation, which primarily presents sandstone facies and the Laayoune 2 Formation of the Mio-Pliocene age, which mainly shows carbonate or marly facies.

Table 2: Organic matter and palynofacies characterizations of the Campanian Bituminous marly facies from the Oum Debaa Formation. Note that the TOC content ranges between 0.51 and 4.67%.

Samples	Organic Matter	Description of organic matter	Preservation	Maturity	Kerogen type
OD8	AOM (30%) Phytoclasts (15%) Palynomorphs (55%), predominated by dinoflagellate cysts	Golden yellow amorphous organic matter in the form of granules. Phytoclasts are common and dinoflagellate cysts are very abundant and diverse. Some rare pollens and a very good representation of <i>Palambages</i> .	Good conservation	Post-mature	III
OD7	AOM (65%) Phytoclasts (5%) Palynomorphs (30%)	Amorphous organic matter is very abundant in the form of clumps and brown in color, masking the palynomorphs. Spores and pollens are	Good conservation	Immature	II
OD6	AOM (50%) Phytoclasts (5%) Palynomorphs (45%)	Sparse brown amorphous organic matter in the form of field or granules. Phytoclasts are rare, some spore/pollens, foraminifera and a very	Good conservation	Immature	II
OD5	AOM (64%), Phytoclasts (2%) Palynomorphs (34%)	Marine amorphous organic matter in the form of field or clumps, dominant (masking the palynomorphs). Dinoflagellate cysts are common and	Good conservation	Immature	II
OD4	AOM (60%) Phytoclasts (2.5%) Palynomorphs (37.5%)	Amorphous organic material of marine origin as clumps or field, uniform, and dark in color. Phytoclasts are rare. Cysts are abundant with rare pollens,	Good conservation	Immature	II
OD3	AOM (62%) Phytoclasts (5%) Palynomorphs (33%)	Sparse amorphous organic matter, in the form of a darkfield. Dinoflagellate cysts are common with a few foraminifera, pollens, and algae.	Good conservation	Immature	II
OD2	AOM (70%) Phytoclasts (0%) Palynomorphs (30%)	Very dark marine amorphous organic matter in the form of dark accumulation or clumps. Absence of Phytoclasts. Dinoflagellate cysts are masked by the dense AOM, and	Very Good conservation	Immature	II
OD1	AOM (60%) Phytoclasts (0%) Palynomorphs (40%)	Amorphous organic matter in the form of clumps or field, well-preserved dark brown color. Phytoclasts are absent. Dinoflagellate cysts	Very Good conservation	Immature	II

Results

Lithostratigraphy

The base of the section (Fig. 3) contains Late Cretaceous compacted marl that is generally grayish on the surface and appears greenish and dark when fresh; its color is dependent on the content of organic matter. Overall, the formation presents an oily appearance, generating a visibly bituminous, monotonous series along the length of the outcropped formation.

This study exclusively highlights the bituminous formation at the point where its maximum thickness does not exceed 10 m in the studied zone. In the outcrop, the contact between the Coniacian and Campanian deposits is not visible; further, the transition between the bituminous sedimentation and the overlying formations is marked by an angular discordance which has eroded all of the Paleogene formations in the northwestern part of the Tarfaya Laayoune Dakhla Basin.

Above the Oum Debaa Formation, the lithological succession displays in the following order from the base to the top (Fig. 4):

- 1) Sandy facies with some concretions and nodules of grayish brown sandstone;
- 2) Levels of meter-thick gray sandstone facies. This interval is horizontally stratified with diastems, which are sometimes filled with salt-rich layers;
- 3) A sedimentary Miocene–Pliocene cycle, essentially consisting of limestone alternating with whitish marls;
- 4) A limestone slab at the top containing terrestrial fossils (e.g., *Helix*) deposited during the Moghrebian time period (Quaternary - q5). It should be noted that, currently, discrepancies exist about the precise stratigraphic age, being considered either Pliocene (Lecointre 1949), or Quaternary (Choubert 1946). The Moghrebian sediments are calcareous sandstone, appearing as an erosion-resistant slab with an average thickness of ~20 m (Brebion & Ortlieb, 1976).

Geochemical characteriation

The main oxides identified in the samples are dominated mainly by CaO and SiO₂, followed by Al₂O₃, MgO, Na₂O, while the concentration of the other oxides is generally low (<1%). The CaO contents vary from 16.38 to 27.55 %, while the SiO₂ concentrations range between 12.21 and 21 %. The variation of these major oxides concur with sedimentological observation such as the bituminous shale has expected higher Si and Al content versus bituminous limestone with relatively higher Ca content. The generally low MgO may reflect only minute proportions of dolomite in the carbonate fraction.

In terms of trace elements, they yielded, in decreasing order, the following median values: Sr (354), V (141), Cr (134), Mo (37), U (22), Th (6). Except Sr, the analyzed trace elements are redox sensitive and hence can help tracing redox conditions in the depositional environment.

In the study series, TOC content mostly ranged from 2.85–4.67 wt.% Which indicates a medium to high organic matter content. on the other hand, the top of the series indicates lower values in TOC not exceeding 0.51 wt.%.

Biostratigraphy

The palynological material recovered after treating the samples shows exceptional richness in the palynomorphs comprising spores and pollen, acritarchs, primitive foraminifera, and algae including Palambages and dinoflagellate cysts, of which the latter predominates among the palynomorphs with a proportion ranging from 80–95%. The dinoflagellate cyst assemblages are highly rich, diverse, and in an excellent preservation state. A total of 65 taxa were identified from the eight samples. The distribution of the species along the studied section is illustrated in Fig. 5.

Samples from the studied section display an association dominated by the genera *Odontochitina* spp. and *Trichodinium* spp. in its lower part (between the base and location of sample 4). The genera *Spiniferites* spp. and *Alterbidinium* spp. Also show high rates along the section (over 50% in some samples). The genera *Andalusiella* spp., *Trithyrodinium* spp., and *Dinogymnium* spp. show good representativeness, particularly in the upper part of the section (between the locations of samples 4 and 8). Other taxa, listed in our associations, are rarely noted, such as *Thalassiphora pelagica* (single specimen, sample 8) and *Senoniasphaera inornata* (single specimen, sample 6).

Fig 5: Stratigraphic range chart of the dinoflagellate cysts species identified in the Oum Debaa section.

From the bottom of the section (sample 1), we identified the coexistence of two taxa that show stratigraphic significance, even at the genus level: *Areoligera* spp. and *Andalusiella* spp. The First Occurrence (FO) of *Areoligera* did not occur before the Campanian (Bujak and Williams 1985; Williams *et al.* 2004) but was recorded in the Campanian at sites in Gabon, West Africa (Boltenhagen 1977) and at Tercis les Bains (Global Standard-stratotype Section and Point for the Campanian-Maastrichtian boundary, Masure 1985), as well as in the Campanian strata of New Jersey in the United States (Aurisano 1989). The *Andalusiella* group is well-known in the Campanian strata of Gabon (Boltenhagen 1977) and Egypt (Schränk 1987).

In the strata of this study, these two taxa are common, starting at the base of the section (sample 1), together with the following species: *Andalusiella mauthei*, *Cerodinium speciosum*, *Odontochitina operculata*, *Odontochitina porifera*, and *Trichodinium castanea*. *Trichodinium castanea* has a wide stratigraphic distribution (Barremian–Campanian) (Pemaor *et al.* 2010), but its Last Occurrence (LO) is located in the early Maastrichtian throughout the Northern Hemisphere (Fensome & Williams 2004). Its association with *C. speciosum*, *O. operculata*, and *O. porifera* at the base (sample 1) indicates that this part of the section cannot be older than the late Campanian. Indeed, the *C. speciosum* FO is located in the late Campanian both at high latitudes, such as in strata of Canada (Kurita & McIntyre 1995; McIntyre 1999) and the Antarctic (Smith *et al.* 1992), as well as strata in the mid-latitudes (Beilstein 1994).

In most regions, the species *O. operculata* has as broad stratigraphic distribution as *T. castanea*; its LO is recorded in strata of the lower Campanian (Razmjooei *et al.* 2018); however, in France in the Tercis-les-Bains region its LO is in the late Campanian (Antonescu *et al.* 2001a; 2001b). This species has been even used to characterize strata of the Campanian in northern Egypt (Ela *et al.* 2019). The Tercis-les-Bains area is correlated with Zone II deposits in NW Egypt (Schränk & Mia, 1995), which belong to the Campanian–Maastrichtian age. However, in Morocco, *O. operculata* is detected until the early Maastrichtian (Rauscher & Doubinger, 1981).

Coupled with this species, we also identified the abundance and dominance of the species *O. porifera*, with a prevalence of 31.85% among the discovered dinoflagellate cysts. This species has a distribution from the Santonian to the Campanian (Pemaor *et al.* 2010), and its LO coincides with the early Maastrichtian (Williams *et al.* 2004) in both the Northern and Southern hemispheres. This evidence argues for a strata age which is no older than the late Campanian.

Between the samples 1 and 4, we found simultaneous or progressive occurrences of other taxa. In sample 2, we identified simultaneous FOs of several taxa, including *Exochosphaeridium multifurcatum* and several species of the genus *Spiniferites*, including *S. bejui*, *S. fluens*, *S. membranaceus*, *S. nodosus*, *S. ramosus*, and *S. septatus*.

The latter genus generally has a wide stratigraphic distribution, though its FO is in the Campanian (May, 1980). However, the presence and dominance of these species within the present studied section (51% of all dinoflagellate cysts) could have ecological significance. This is because all *Spiniferites* species have a wide stratigraphic distribution except *S. fluens*, which is of stratigraphic interest since it has never been recorded in sediments younger than the early Maastrichtian (Stover *et al.* 1987; Kirsch, 1991; Habib *et al.* 1994; Helenes, 1998; Masure *et al.* 1998; Oboh-Ikuenobe *et al.* 1998).

Other appearances are progressive; for example, the FO of *Trithyrodinium evittii* characterizes a biozone, corresponding to the late Campanian of Tercis-les-Bains (Antonescu *et al.* 2001a, 2001b). In sample 4, the LO of *Trichodinium castanea* occurs with the FOs of the following taxa: *Alterbidinium acutulum*, *Andalusiella inflata*, *Cannosphaeropsis utinensis*, *Cerodinium diebelii*, and *Xenascus ceratioides*. This evidence reinforces that the strata of the lower part of the section (between samples 1 and 4) belong to the late Campanian.

However, the LOs of *T. castanea* and the FOs of *C. diebelii* are in line with the world distribution maps of Williams and Bujak (1985), which suggest a Campanian age. However, *C. diebelii* is a better marker for the base of the Maastrichtian according to Antonescu *et al.* (2001b) but its optimal occurrence (OC) have been verified in the late Campanian (Antonescu *et al.* 2001a, 2001b; Slimani 2001a, 2001b; Slimani *et al.* 2011). In addition, *C. diebelii* is a cosmopolitan species; even at higher latitudes, it has been identified in the Campanian–Maastrichtian interval in Canada and Greenland deposits (Ionnides, 1986; Nøhr-Hansen, 1996), the mid-latitudes (Lentin & Williams 1985; Masure *et al.* 1998; Oboh-Ikuenobe *et al.* 1998), and Antarctica (Pirrie *et al.* 1997; Riding *et al.* 1992).

Between samples 4 and 8, the associations are enriched with Maastrichtian-affinity taxa, such as *Alterbidinium acutulum*, *Andalusiella inflata*, *Andalusiella ivoirensis*, *Cannosphaeropsis utinensis*, *Dinogymnium acuminatum*, and *Trithyrodinium quinqueangulare*. The taxon *C. utinensis* can be distributed from the late Santonian to the late Maastrichtian (Begouën *et al.* 1990; Williams *et al.* 2004; Radmacher *et al.* 2014), and is typically found in association with Maastrichtian-affinity taxa, such as the species *Alterbidinium acutulum* (early Maastrichtian) (Antonescu *et al.* 2001a, 2001b; Nøhr-Hansen 2012; Slimani 2001a, 2001b; Slimani *et al.* 2011), *Alterbidinium minus* (lower Maastrichtian) (Antonescu *et al.* 2001a, 2001b; Kjellström 1973; Slimani *et al.* 2011; Soncini and Rauscher 1988; Wilson 1971), *Alterbidinium varium* (early Maastrichtian) (Kirsch 1991; Slimani 1995, 2001b; Slimani *et al.* 2011), *Andalusiella inflata* (Lentin & Williams 1985; Masure *et al.* 1996; Soncini & Rauscher 1988), *Andalusiella ivoirensis* (Maastrichtian) (Masure *et al.* 1996, 1998), and *Trithyrodinium quinqueangulare* (early Maastrichtian) (Antonescu *et al.* 2001a, 2001b; Lentin 1993; Marheinecke 1992).

Within this association of highly rich and diverse dinoflagellate cysts, the top of the section is marked by the presence of two species: *Senoniasphaera inornata*, which is common in both the Northern and Southern hemispheres (Williams *et al.* 2004), and *Thalassiphora pelagica* (Habib *et al.* 1996; Stover *et al.* 1996; Roncaglia & Corradini, 1997; Oboh-Ikuenobe *et al.* 1998; Brinkhuis *et al.* 2003; Landman *et al.* 2004). Both species' FOs are in the Maastrichtian, but their LOs are in the Cenozoic. Thereby, we raise the question: does the presence of these species indicate an early appearance in Morocco or is it related to a reworking phenomenon associated with the nature of the sediment deposition?

Overall, the palynological analysis of the sediments in the Oum Debaa Formation shows enrichment of dinoflagellate cysts dominated by the genus *Spiniferites*, a phenomenon which has already been observed in upper Campanian sediments of Iran (Razmjooei *et al.* 2018). It should be noted that organisms in the Tethyan domain typically associated with this time interval, whether from Iran (Razmjooei *et al.* 2018) or Egypt (El Beialy *et al.* 2010; Ela *et al.* 2019; Schrank 1987; Tahoun *et al.* 2018; Tahoun & Ied 2019), are commonly not rich in dinoflagellate cysts. In Morocco, the wealth cysts (Rauscher & Doubinger 1981; Soncini & Rauscher 1988; and this work) is more similar to those observed in NW Europe (Antonescu *et al.* 2001a, 2001b; Radmacher *et al.* 2014; Slimani 2001a, 2001b; Slimani *et al.* 2011) and Latin America (Garzon, Warny & Bart 2012).

In correlation with other paleogeographic domains, *C. speciosum*, *T. castanea*, *O. porifera*, *D. acuminatum*, and *C. diebelii* characterize well the late Campanian–early Maastrichtian interval. In fact, *C. diebelii* identifies the Campanian–Maastrichtian passage (Antonescu *et al.* 2001; a, 2001b) and coincides with the presence of three genera *Alterbidinium*, *Isabilidinium*, and *Manumiella*, which collectively constitute an event of the Campanian–Maastrichtian transition in NW Europe (Antonescu *et al.* 2001a, 2001b). These genera are common along the studied section, and with notable frequencies.

The attribution of the late Campanian–early Maastrichtian age in the studied outcrop of the Oum Debaa Formation is also supported by the presence of the species *D. acuminatum*,

which constitutes a zone that is consistent with the Campanian–Maastrichtian interval in Egypt (El Beialy, 1995; Schrank & Mia, 1995). Further support is owing to the presence of *A. mauthei*, which is present along the section and is the dominant species, among other species of the same genus (i.e., *Andalusiella* spp.). The FO of this species is found within deposits of the Senonian (Riegel & Sarjeant, 1982; Masure *et al.* 1996), but its OC is in the Campanian–Maastrichtian interval (Masure *et al.* 1998; Tea-Yassi *et al.* 1999; Yepes 2001).

The taxa associations (*A. inflata*, *A. acutulum*, *A. varium*, *A. minus*, *A. ivoirensis*, and *T. quinqueangular*) and the markers of the early Maastrichtian in the studied sediments of the Oum Debaa Formation reinforces the late Campanian–early Maastrichtian age in this section.

Palynofacies

Using the Tyson method (1993, 1995), 300 particles of the main constituents of palynofacies (i.e., phytoclasts, palynomorphs, and AOM) were counted and an associated ternary diagram was produced (Fig. 6), illustrating the distribution of the samples according to their depositional environments, including the indication of redox conditions. In addition to determining the redox conditions in the basin, the three main constituents were evaluated for association with one of the four types of kerogens (type I, II, III, or IV) (Harwood 1977; Tissot & Welte 1984; Tyson 1995).

Fig 6: Tyson-type ternary diagrams showing distribution of principal palynological groups for the studied samples in the Oum Debaa section.

Counted phytoclasts included translucent phytoclasts (e.g., wood cuticles), referring to all plant particle structures of yellow to brown color, and opaque phytoclasts (equidimensional or elongated), referring to all plant particles that are oxidized or charred, of black to brownish color, and structured or derived from kerogen. Counted palynomorphs included all structured organic microfossils resistant to strong acids (e.g., spores, pollens, acritarchs, primitive foraminifera, and dinoflagellate cysts or other related compounds).

Discussion

Origin and maturation of organic matter

The interaction of the three palynofacies components in the Oum Debaa Formation sediments suggest two types of paleoenvironments based on the Tyson ternary diagram (Fig. 6):

First, Samples 1 to 7, which are located between fields VII and VIII on the ternary diagram, correspond to a distal platform with anoxic to dysoxic redox conditions (see Tyson, 1993, 1995), with AOM in the form of clumps or tufts or as well-structured, well-preserved resin. The palynomorphs are dominated by dinoflagellate cysts covered by AOM. The terrigenous fraction (i.e., spores, pollens, and phytoclasts) is rare. The abundance and dominance of this AOM, which occupied between 50–70% of the total palynofacies, is the consequence of a low energy environment, which is also an indicator of anoxic–dysoxic conditions (Tyson 1993, 1995) and is in agreement with similar findings by Koleif and Ibrahim (2010). In this interval, the dinoflagellate cysts associated are characterized by the presence and abundance of peridinooid cysts, which do not only tolerate fluctuations in salinity, but also seem to thrive in relatively nutrient-rich environments, such as shallow marine areas or upwelling regions (Bujak, 1984; Dale & Fjellså, 1994; Eshet *et al.* 1994; Lewis *et al.* 1990; Powell *et al.* 1990). The intense paleoproductivity indicated by the Oum Debaa Formation could be linked to the upwelling cell that has been active at the level of the Moroccan Atlantic margin since the upper Cenomanian (Einsele & Von Rad, 1979; Einsele & Wiedmann, 1982; Kuhnt & Moullade, 1991; Prauss, 2015). The same conditions have already been observed by Eshet *et al.* (1994), who pointed out an abundance of peridinooids in AOM-rich sediments in the Zin and Shfela basins under the influence of upwellings during the Late Cretaceous period (Campanian to Maastrichtian) (Almogi-Labin, Bein, and Sass 1993). For this type, the main organic source comes from phytoplankton, with subordinate zooplankton and occasional important contributions from benthic algae. A predominance of marine organic matter may also be provided by generalized transgressions creating shallow epicontinental seas with high biological productivity. This situation was probably more common during certain conducive geological periods, for example, as indicated by the Cretaceous black shales of the Atlantic basins (Tissot & Welte, 1984). Moreover, planktonic organic matter is generally found in areas of relatively high productivity where conservation of such organic matter was ensured by the anoxic or nearly anoxic depositional conditions. Overall, the associated potential for oil and gas is high.

A second paleoenvironment is revealed by sample 8 at the top of the studied section, which consists of light gray marls and plots in field V of the Tyson ternary diagram (Fig. 6) and reflect an oxic platform (unconfined basin) conditions (Tyson 1993, 1995). The AOM of sample 8 is moderate (30%) compared to that of the other samples and features a granulated texture. Palynomorphs (55%) are abundant with a predominance of dinoflagellate cysts. This indicates that the initial paleoenvironment have been transitioned to evolve towards more oxic conditions.

Paleoenvironment reconstruction

Quantitative and qualitative palynological analyses of the sediments yielded a rich and diverse association of dinoflagellate cysts (65 taxa) among the different strata and new datation have been assigned to this series: late Campanian-early Maastrichtian. This series records values from medium to high TOC values which leads us to propose that the depositional environment of this time could well be related to the ocean currents type Upwelling.

The binary diagram $\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O}$ vs SiO_2 (Suttner and Dutta, 1986) (Fig. 7), makes possible to trace the climatic conditions prevailing at the time of deposits of the studied sediments. All the sediments treated show a fluctuation between arid and semi-humid periods.

Fig 7: Discrimination diagrams SiO_2 vs. $(\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O})$ after Suttner and Dutta (1986)).

Regarding redox conditions, sediments formed in anoxic environments usually show enrichment of redox-sensitive trace metals such as U, Mo, Cr, Ni, Cu, As, Zn, Pb, Cd, Ag, and V (Rakociński *et al.* 2018). The signatures of sediments combined with mass balance calculations are commonly used to reconstruct changes in the past oceanic cycling of Mo and U and to estimate the extents of anoxia in the ancient ocean (Brüske *et al.* 2020). For this purpose, these two elements have been used or coupled with other proxies in several studies. In the present study, to get further insight about the redox conditions we used the Th/U ratio (Figure 5) that can be more efficient than other trace metal (Racka *et al.* 2010; Rakociński *et al.* 2018). The Th/U ratio of anoxic oil shales is less than 3, while in carbonates this ratio is generally less than 1 (Myers & Wignall 1987; Bond & Zatoń, 2003; Bond *et al.* 2004). In the studied section, most samples yielded Th/U values less than 3 (Fig. 8), indicating anoxic conditions, but a few samples reflect typical oxic conditions.

Molybdenum concentrations vary along the section without strong correlation. This may indicate decoupling redox behavior or possibly other sources for these elements in the sedimentary environment. Nevertheless, the overall concentration ranges could support anoxic conditions prevailed during sedimentation as it has been reported in other studies (Francois 1988; Wignall 1994; Brumsack 2006; Calvert & Pedersen 2007; Motzer 2016). Still, bottom water conditions could have been rather dysoxic as indicated by Th/U ratios. The studied sediments also formed in a low productivity regime, which is reflected by the high TOC values.

Fig 8: Composite plot of the section showing the thorium/uranium ratio, molybdenum contents and TOC contents in the studied section.

Conclusion

The present study was carried out to investigate biostratigraphy and organic geochemistry of an outcrop of the bituminous Sebkhia Oum Debaa Formation in the Tarfaya-Laayoune coastal basin of Morocco. Quantitative and qualitative palynological analyses of the sediments yielded a rich and diverse association of dinoflagellate cysts (65 taxa) among the different strata. We propose a late Campanian age for this section due to the presence of internationally recognized index fossils and their stratigraphic importance: *Andalusiella inflata*, *Andalusiella ivoirensis*, *Andalusiella mauthei*, *Cerodinium diebelii*, *Cerodinium speciosum*, *Dinogymnium acuminatum*, *Odontochitina porifera*, *Trichodinium castanea*, and *Trithyrodinium evittii*. The results show associations of dinoflagellate cysts typical of the late Campanian, although those of the lower Maastrichtian cannot be definitively excluded.

Palynofacies and organic geochemistry revealed the presence of two paleoenvironment types. The first (from samples 1 to 7) represents reducing, confined conditions, with TOC levels ranging from 2.85–4.67 wt.%, indicating a very high organic carbon content and good richness in the source rock (kerogen type II). Upwelling zones were highlighted by the dominance of peridinioids, which reflect intense paleoproductivity. These pulses of productivity are a major contributing factor for the accumulation of TOC during the Late Cretaceous, as have been demonstrated at previous locations (the Zin and Shfela basins and Tarfaya Basin). Through

cysts (ecological markers), this paleoenvironment corresponds to two intervals tracing its evolution: the first (the base of the section), would be an outer neritic environment (by the high rate of *Ondochitina* group) and which would evolve towards an inner neritic environment (by the abundance of *Andalusiella* group).

Plate 1: Dinoflagellate cysts in the Oum Debaa section, Tarfaya-Laayoune Basin, Morocco. Scale bar in all figures is 20µm. **A** - *Trichodinium castanea*, sample OD 1, slide 1, EF W40; **B** - *Acanthaulax wilsonii*, sample OD 1, slide 1, EF Y10; **C** - *Trichodinium castanea*, sample OD 1, slide 2, EF T28/4; **D** - *Dinogymnium elongatum*, sample OD 8, slide 1, EF Y42/1; **E** - *Xenascus ceratioides*, sample OD 6, slide 2, EF X29/4; **F** - *Trithyrodinium quinqueangulare*, sample OD 8, slide 4, EF Z25/2; **G** - *Dinogymnium* sp.2, sample OD 2, slide 2, EF T10; **H** - *Dinogymnium acuminatum*, sample OD 6, slide 1, EF E39/1; **I** - *Dinogymnium denticulatum*, sample OD 8 slide 1, EF N29/1.

The second contrasting paleoenvironment (from sample 8), corresponding to the top of the section despite the series being monotonous, reflects oxic, unconfined conditions, with the lowest TOC (0.51 wt.%) and the largest Tmax (608°C). The association of dominant cysts (the *Dinogymnium* and *Exochosphaeridium* groups) indicates a marginal environment which always remains under the influence of outer neritic environment.

In conclusion, the present results challenge all previous interpretations of this region, particularly regarding the bituminous and phosphatic sedimentation continuing until the Maastrichtian. Earlier studies in this basin have largely attributed this age to thick phosphate sedimentation in deeper depressions in the SE region of the basin. This disparity highlights the necessity of updating our knowledge about the age of the phosphatic series and related geology of this area.

Data Availability: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Appendix A

List of dinoflagellate cyst taxa observed in the Oum Debaa section. Dinocyst taxa are arranged in alphabetical order by genera and their nomenclature and references to their authors follow DINOFLAJ3 (Williams *et al.* 2017).

- *Alisogymnium euclaense* (Cookson and Eisenack, 1970a) Lentin and Vozzhennikova, 1990.
- *Alterbidinium acutulum* (Wilson, 1967b) Lentin and Williams, 1985.
- *Alterbidinium minus* (Alberti, 1959b) Lentin and Williams, 1985.
- *Alterbidinium* sp1.
- *Alterbidinium* spp.
- *Alterbidinium varium* Kirsch, 1991.
- *Andalusiella dubia* (Jain and Millepied, 1973) Lentin and Williams, 1980.
- *Andalusiella inflata* (Rauscher and Doubinger, 1982) Lentin and Williams, 1985.
- *Andalusiella ivoirensis* Masure *et al.* 1996.
- *Andalusiella mauthei* Riegel, 1974.
- *Andalusiella polymorpha* (Malloy, 1972) Lentin and Williams, 1977b.
- *Andalusiella* sp1.
- *Andalusiella* spp.
- *Areoligera* spp.
- *Biconidinium reductum* (May, 1980) Kirsch, 1991.
- *Biconidinium* spp.
- *Bosedinia* spp.
- *Cannosphaeropsis utinensis* Wetzel, 1933b.
- *Cerodinium diebelii* (Alberti, 1959b) Lentin and Williams, 1987.
- *Cerodinium pannuceum* (Stanley, 1965) Lentin and Williams, 1987.
- *Cerodinium speciosum* (Alberti, 1959b) Lentin and Williams, 1987.
- *Chatangiella* cf. *robusta* (Benson, 1976) Stover and Evitt, 1978.
- *Circulodinium distinctum* (Deflandre and Cookson, 1955) Jansonius, 1986.
- *Cleistosphaeridium* spp.
- *Coronifera oceanica* Cookson and Eisenack, 1958.
- *Cribroperidinium wilsonii* (Slimani, 1994) Schiøler *et al.* 1997.
- *Cyclonephelium/Circulodinium*.
- *Cyclonephelium* spp.
- *Deflandrea* spp.
- *Diphyes colligerum* (Deflandre and Cookson, 1955) Cookson, 1965.
- *Dinogymnium acuminatum* Evitt *et al.* 1967.
- *Dinogymnium denticulatum* (Alberti, 1961) Evitt *et al.* 1967.
- *Dinogymnium digitus* (Deflandre, 1936b) Evitt *et al.* 1967.
- *Dinogymnium heterocostatum* (Deflandre, 1936b) Evitt *et al.* 1967.
- *Dinogymnium* sp. Tahoun *et al.* 2018.
- *Dinogymnium* spp.
- *Dinogymnium westralium* (Cookson and Eisenack, 1958) Evitt *et al.*, 1967.
- *Downiesphaeridium aciculare* (Davey, 1969a) Islam, 1993.
- *Exochosphaeridium bifidum* (Clarke and Verdier, 1967) Clarke *et al.* 1968.
- *Exochosphaeridium multifurcatum* (Deflandre, 1937b) Masure in Fauconnier and Masure, 2004
- *Exochosphaeridium* sp1.
- *Exochosphaeridium* spp.
- *Fibrocysta axialis* (Eisenack, 1965b) Stover and Evitt, 1978.

- *Fibrocysta* spp.
- *Hafniasphaera fluens* Hansen, 1977.
- *Hafniasphaera septata* (Cookson and Eisenack, 1967) Hansen, 1977.
- *Odontochitina porifera* Cookson, 1956.
- *Odontochitina operculata* (Wetzel, 1933a) Deflandre and Cookson, 1955.
- *Oligosphaeridium* spp.
- *Pervosphaeridium* spp.
- *Pervosphaeridium tubuloaculeatum* Slimani, 1994.
- *Senoniasphaera inornata* (Drugg, 1970b) Stover and Evitt, 1978.
- *Spiniferites bejui* Masure *et al.* 1998.
- *Spiniferites membranaceus* (Rossignol, 1964) Sarjeant, 1970.
- *Spiniferites monilis* (Davey and Williams, 1966a) Sarjeant, 1970.
- *Spiniferites nodosus* (Wall, 1967) Sarjeant, 1970.
- *Spiniferites ramosus* (Ehrenberg, 1837b, pl.1, fig.15) Mantell, 1854.
- *Spiniferites/Achomosphaera*.
- *Spiniferites* spp.
- *Tanyosphaeridium regulare* Davey and Williams, 1966b.
- *Tanyosphaeridium variecalamum* Davey and Williams, 1966b.
- *Tanyosphaeridium xanthiopyxides* (Wetzel, 1933b) Stover and Evitt, 1978.
- *Thalassiphora pelagica* (Eisenack, 1954b) Eisenack and Gocht, 1960.
- *Trichodinium castanea* (Deflandre, 1935) Clarke and Verdier, 1967.
- *Trithyrodinium evittii* Drugg, 1967.
- *Trithyrodinium quinqueangulare* Marheinecke, 1992.
- *Trithyrodinium suspectum* (Manum and Cookson, 1964) Davey, 1969b.
- *Trithyrodinium* spp.
- *Xenascus ceratioides* (Deflandre, 1937b) Lentin and Williams, 1973.
- *Xenascus perforatus* (Vozzhennikova, 1967) Yun Hyesu, 1981.

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