

# Aptian – Early Albian Sedimentation In The Essaouira-Agadir Basin, Western Morocco

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# APTIAN - LOWER ALBIAN SEDIMENTATION IN THE ESSAOUIRA-AGADIR BASIN, WESTERN MOROCCO

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Etienne Jaillard<sup>1</sup>, Walid Hassanein Kassab<sup>2</sup>, Fabienne Giraud<sup>1</sup>, Emmanuel Robert<sup>3</sup>, Moussa Masrour<sup>4</sup>, Lhoussaine Bouchaou<sup>4</sup>, Khadija El Hariri<sup>5</sup>, Mohamed S. Hammed<sup>2</sup>, Mohamed F.

- 6 Al $y^2$ .
- 7
- 8 1 : Université Grenoble Alpes, ISTerre, IRD, CNRS, IFSTTAR, CS 40700, 38058 Grenoble
   9 Cedex 9, France. <u>Etienne.Jaillard@univ-Grenoble-Alpes.fr</u>
- 10 2 : Earth Science Department, Cairo University, Gizah, Egypt.
- 11 3 : Université Lyon 1, ENS Lyon, CNRS, UMR 5276 LGLTPE, 69622 Villeurbanne, France.
- 4 : Université Ibn Zohr, Faculté des Sciences, Département de Géologie, Laboratoire LAGAGE,
   BP 8106, Cité Dakhla, Agadir, Morocco.
- 5 : Université Cadi Ayyad, Faculté des Sciences et Techniques-Guéliz, Département Sciences
   de la Terre, Avenue Abdelkrim el Khattabi, BP 549, 40000 Marrakech, Morocco.
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# 18 ABSTRACT

19 Aptian to early Albian times are marked by various geodynamic and paleoenvironmental events such as

- 20 large igneous province volcanism, perturbations of climate and the carbon cycle, and sea-level changes.
- The Essaouira-Agadir basin (EAB), located on the Atlantic passive margin of Morocco, offers good and fossiliferous exposures of the Aptian-Albian sedimentary series. A detailed analysis of this succession
- made it possible to establish a biostratigraphic framework. The identification of discontinuities allowed
- to define eight depositional sequences. As most of them are correlatable with depositional sequences of
- other Tethyan areas, they suggest that eustacy was the main parameter controlling sedimentation. The
- analysis of sedimentary facies and nannofossil assemblages provides information on
   paleoenvironmental changes.
- 28 Sedimentation in the EAB evolved from a very low energy, carbonate ramp in the early Aptian to a low
- energy, slightly deeper, mixed carbonate-clastic ramp in the early Albian. This change occurred alongwith an increase of clastic input, a change from oligotrophic to mesotrophic faunal assemblages, and a
- 30 with an increase of clastic input, a change from oligotrophic to mesotrophic faunal assemblages, and a 31 decrease of sea-surface temperatures. The occurrence of current sedimentary features, sporadic
- 32 dysaerobic deposits and local phosphatic and glauconitic crusts suggests that upwelling currents were
- 33 significant during this period.
- Paleogeographic and isopach maps support a transgressive trend in the late Aptian and early Albian, and
   unravel subsidence anomalies suggesting mild halokinetic movements during Aptian–early Albian times.
- 36
- 37 Keywords: Early Cretaceous, sedimentology, sequence stratigraphy, paleoenvironment,38 paleogeography
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# 40 I. INTRODUCTION

The Aptian to early Albian time is a period of important oceanographic, climatic and geodynamic changes. In fact, this period recorded the earliest significant Oceanic Anoxic Event (OAE) of the Cretaceous crises in the biological and/or carbon cycles, resulting in deposition

- 44 of organic-rich "black shales" (e.g. Schlanger and Jenkyns, 1976; Giorgioni et al., 2015). The
- rifting and opening of the Atlantic ocean at equatorial latitudes (e.g. Moulin et al., 2010;
  Klingelhoefer et al., 2016) opened new N-S oceanic connections, whereas the former Tethyan

system was dominated by E-W oceanic circulations. A warm climate, related to the greenhouse 47 effect (Föllmi, 2012) was followed by significant cooling of the global ocean and climate in the 48 49 late Aptian (Bottini et al., 2015). The emplacement of large igneous provinces influenced global climate (Kuroda et al., 2011). Noticeable, widespread lower Aptian carbonate shelves 50 developed during the early Aptian (e.g. Skelton and Gili, 2012), and a significant sea-level fall 51 in the early Aptian was followed by a marked late Aptian-early Albian sea-level rise recorded 52 in most areas around the world (Haq, 2014). Therefore, Aptian-early Albian times have been 53 54 extensively studied in the North-Tethyan margin, but remain relatively poorly studied elsewhere. The sedimentary record of Aptian-early Albian is poorly known in northern Africa, 55 likely because it consists either of carbonate shelf, or of sand-rich deposits poor in ammonites 56 (e.g. Burollet, 1956; Vila, 1980), or of shelf marls rich in endemic ammonite fauna (e.g. Latil, 57 2011; Robert in Peybernès et al., 2013; Luber et al., 2017). The Western Atlas of Morocco 58 offers a good opportunity for studying the Aptian-early Albian period, since good exposures 59 of fossiliferous successions are easily accessible. 60

We did a stratigraphic and sedimentological study of the Aptian-lower Albian deposits of the 61 Essaouira-Agadir Basin (EAB), which constitutes the Western end of the Atlas chain (Fig. 1). 62 Here, we present a preliminary biostratigraphic scheme, a detailed sedimentological analysis 63 mainly based on field observations along thirteen sections distributed in the central and southern 64 parts of the EAB, a sequence stratigraphic interpretation of this succession and a 65 paleogeographic synthesis of the sedimentary evolution of the basin. In order to better constrain 66 paleoenvironments, we provide additional data on calcium carbonate content, total organic 67 carbon (TOC) and calcareous nannofossils. These data are compared to sedimentary facies to 68 better understand the temporal and spatial relationships between carbonate production, primary 69 productivity, oxygenation of the water column, and organic carbon burial during changes in 70 both sea-surface temperature and sea level. 71

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#### 73 II. GEOLOGICAL BACKGROUND

The EAB (Fig. 1) belongs to the Atlantic passive margin. Its Mesozoic sedimentary history 74 began with the Tethyan rifting, which eventually provoked the opening of the Central Atlantic 75 (Zühlke et al., 2004; Hafid et al., 2008; Schettino et al., 2009). Therefore, it has been marked 76 by strong extensional tectonics from Late Permian to early Liassic times, coeval with deposition 77 of thick red beds, overlain by shales and evaporites interbedded with basaltic flows, and sealed 78 79 by a pre-Pliensbachian unconformity (Hafid, 2000). An extensional regime prevailed until the Late Cretaceous, and favoured the deposition of shallow marine deposits in the EAB. Shelf 80 carbonates deposition prevailed during the Jurassic and was interrupted by regressions in 81 Middle and latest Jurassic times (Stets, 1992), due to the general uplift of the High Atlas (Frizon 82 de Lamotte et al., 2008). The Early Cretaceous is marked by the deposition of thick, mainly 83 marly marine deposits, sporadically interrupted by clastic deposits deriving from the East (late 84 Hauterivian, late Barremian; Canérot et al., 1985; Rey et al., 1988; Masrour et al., 2004; Witam, 85 1998; Al Yacoubi et al., 2017). Aptian to Turonian times are represented by marine, marly and 86 87 calcareous strata (Ambroggi, 1963; Bourgeoini et al., 2002; Ettachfini et al., 2005; Jati et al., 2010; Peybernès et al., 2013). The Upper Cretaceous mainly calcareous sedimentation (Andreu, 88 1989) was then disturbed by a first Santonian-Campanian compressional deformation (Guiraud 89 and Bosworth, 1997) and became mostly clastic (Algouti et al., 1999). The Tertiary Alpine 90 91 compression (mainly middle-late Eocene to Pleistocene) then inverted the Lower Jurassic normal and transcurrent faults, and folded the EAB (Hafid, 2000; Frizon de Lamotte et al., 2000, 92 2008, 2011). Offshore in the EAB, salt tectonics are well documented to have been active in 93 Middle Jurassic and Late Cretaceous-Eocene times, with local activity in the Early Cretaceous 94 (Hafid, 2000; Davison et al., 2010; Tari and Jabour, 2013). Brautigam et al. (2009) and Bertotti 95

and Gouiza (2012) mentioned Upper Jurassic-Lower Cretaceous synsedimentary tectonics,
which they hypothetically related to compressional strain in part of the EAB.



Figure 1. Location of the study area. A. Location of the Essaouira-Agadir basin. B. Geological sketch
 of the EAB, and location of the studied sections.

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102 The EAB is presently bounded to the North by the Jebilet High, and to the East and South by the High Atlas (Hafid, 2000) (Fig. 1). The Mesozoic sedimentary strata of the EAB dip gently 103 towards the West. The western part of the EAB is divided into three parts by two major E-W 104 trending anticlines, the Amsittene and Imouzzer anticlines, the western tips of which form the 105 Cap Tafelney and the Cap Rhir, respectively (Fig. 1). Between these two major folds, a minor, 106 smooth, E-W trending anticline separates two gentle synclines where Aptian-Albian deposits 107 crop out (Fig. 1B). In the western part of the EAB, uplifted Pliocene marine terraces truncate, 108 and unconformably overlie, the Mesozoic series, and are presently at 50 to 100 m above sea 109 level. 110

Most of our present knowledge on the Aptian–Albian stratigraphy is due to Gentil (1905) and 111 Roch (1930), who first described ammonites from this area, to Ambroggi (1963), who proposed 112 113 an exhaustive stratigraphic scheme for the EAB, based on detailed lithostratigraphic descriptions and associated fossil determination, to Duffaud et al. (1966), who published a 114 synthesis of the area and defined formations in the Cretaceous series, and to Rev et al. (1988). 115 Witam (1998) and Bourgeoini et al. (2002), who conducted micropaleontological studies on the 116 Lower Cretaceous succession. More recently, Peybernès et al. (2013) and Luber et al. (2017; 117 118 2019) proposed preliminary stratigraphic, sedimentological and paleoenvironmental analysis of the upper Aptian-lower Albian series of the EAB. According to these authors, the Aptian-119 lower Albian sedimentary rocks rest on red beds and massive sandstones of the Bouzergoun 120 Formation (Fm) of late Barremian age, and encompasses (i) the Tamzergout Fm, made of 121 122 marlstone and limestone of early Aptian age, (ii) the alternating marlstone and limestone of the Tadhart Fm of early late Aptian age, (iii) the thin, marly Lemgo Fm of latest Aptian age, and 123 (iv) the mainly marly Oued Tidzi Fm, of early to late Albian age (Fig. 2). 124



Figure 2. The Lower Cretaceous deposits in the northern part of the Essaouira-Agadir basin, part of the Atlantic passive margin, from Rey et al. (1988), modified.

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129 In this work, we shall use the biostratigraphic scheme based on ammonites by one of us (E.R.), which has been published in Peybernès et al. (2013). The study area encompasses the area 130 comprised between the city of Agadir, and the northern major anticline (jebel Amsittene). 131 Thirteen sections of the Aptian-lower Albian series have been studied: five are located south 132 of the Imouzzer anticline, five to the north of the latter, and three at the Amsittene anticline 133 latitude (Fig. 1B, Table 1). 134

Section	Base	Тор
Addar	30°36'04''N – 9°43'31''W	30°35'54"N – 9°43'04"W
Alma	30°31'47''N – 9°35'45''W	30°31'54"N – 9°35'46"W
Anzate	30°32'18''N – 9°35'08''W	30°32'23"N – 9°35'10"W
Aoulkjdad	30°45'47''N – 9°35'31''W	30°46'17"N – 9°35'58"W
lda w Shayq	31°03'35''N – 9°36'04''W	31°03'31"N – 9°36'01"W
Imsouane	30°50'33''N – 9°48'54''W	
Smimou	31°11'39''N – 9°39'56''W	31°11'42"N – 9°39'56"W
Takoucht	31°09'52''N – 9°24'17''W	31°09'56"N – 9°24'37"W
Tamri	30°45'49''N – 9°48'40''W	30°45'47"N – 9°48'38"W
Tamzergout	30°32'47''N – 9°34'01''W	30°32'40"N – 9°34'12"W
Taounerine	30°48'35''N – 9°44'27''W	30°48'45"N – 9°44'19"W
Tinfoul	30°32'27"N – 9°24'53"W	30°32'24"N – 9°24'58"W
Tiskatine	30°45'43''N – 9°39'14''W	30°46'06''N – 9°39'23''W

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Table 1. Geographical coordinates of the studied sections (see Fig. 1B).

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#### **III. MATERIAL AND METHOD** 138

#### 139 **III.1.** Sedimentology and biostratigraphy

Twelve sections have been studied in the central and southern parts of the EAB (Fig. 1B), which 140 are 30 to 120 m thick, except for the Tamri and Imsouane condensed sections, whose 141

thicknesses do not exceed 20 m. All sections have been measured, studied and sampled bed by
bed for paleontological study. Most sedimentological observations have been made in the field,
where the lithology, sedimentary features (texture, bioturbation, current figures, dissolution or
erosion features etc.), mineral concentrations and faunal assemblages have been carefully noted.
Particular attention was paid to the lower and upper bed surfaces, as they bear important
information on sedimentary discontinuities.

When present, ammonites were extensively collected bed by bed, and precisely located along the studied section. Ammonites consist of pyritic, phospatic or calcareous molds, the latter being less well preserved. After transport to France, these thousands of ammonites were cleaned and studied by one of us (E.R.), through comparisons with specimens or casts preserved in museum and university collections, and thanks to the large paleontological collection and library available at the University of Lyon.

# 154 III.2. Calcimetry and rock-eval pyrolysis

155 The calcium carbonate content was measured in 195 samples from five sections (Takoucht, Ida

- w Shayq, Tiskatine, Anzate and Tinfoul) and in 49 new samples from the Addar, Tamzergoutand Alma sections, for which previous results have been published (Peybernes et al., 2013).
- The calcium carbonate content was determined using the carbonate bomb technique (Müller
- and Gastner 1971), which measures  $CO_2$  pressure during a hydrochloric acid attack. For the
- 160 calculation of the calcium carbonate percentage, see Appendix A in Peybernes et al. (2013).
- 161 Twenty-five dark shaly marlstone samples from the Takoucht section were selected for organic matter analysis. Total organic carbon content (TOC), and the nature and thermal maturation of 162 organic matter were estimated using a Rock-Eval 6 Turbo apparatus (Vinci Technologies) at 163 164 UPMC–University of Paris 6. The method, described in detail by Behar et al. (2001), consists of a two steps analysis with programmed temperature: a pyrolysis between 300 and 650°C 165 (25°/min), under an inert atmosphere (He), followed by oxidation between 300 and 850°C 166 (20°/min). All those parameters allow the calculation of the TOC, which is expressed as wt% 167 of bulk rock samples. The hydrogen index (HI), corresponds to the quantity of hydrocarbon 168 compounds released during the pyrolysis relative to the TOC (S2/TOC) in mg of HC per g of 169 TOC, and the Oxygen Index (OI, in mg CO<sub>2</sub>/g TOC) is related to the amount of oxygen in the 170 kerogen and is normalized to the S3 value (S3/TOC). Although the source of organic matter is 171 usually defined by the mean of elemental analysis, the HI and OI parameters approximate 172 respectively the H/C and O/C atomic ratios, which are the determining factor for organic matter 173 174 characterization. The production index (PI) shows the level of thermal maturation. Tmax (°C) is defined as the pyrolysis temperature at which the maximum amount of hydrocarbons is 175 yielded by kerogen. Tmax increases linearly with the natural maturation degree of the organic 176 177 matter, thus giving a rapid estimate of the thermal maturity of sedimentary basins (Espitalié et al, 1985-1986; Dellisanti et al., 2010). The measurement accuracy is of  $\pm 0.05\%$  for TOC,  $\pm 2^{\circ}$ C 178 for Tmax, and  $\pm 10$  for HI and OI. Values are reported in the Appendix. 179

# 180 III.3. Calcareous nannofossils

181 Calcareous nannofossils were studied in 139 samples from Ida w Shayq, Tiskatine, Anzate and 182 Tinfoul sections. Samples were prepared using the random settling technique of Geisen et al. 183 (1999), adapted from Beaufort (1991), which allows the calculation of absolute abundances 184 (number of specimens per gram of rock). Nannofossils were observed at 1560 x magnification 185 using a polarizing light microscope,. At least 300 specimens per sample, both coccoliths and 186 nannoliths, were generally counted in a variable number of fields of view (a mean of 446, 369, 187 402, and 497 for the Anzate, Ida w Shayq, Tinfoul and Tiskatine sections, respectively). An

188 amount of 300 counted specimens is generally considered to be sufficient to have a good 189 estimation of species richness in one sample; in addition, the number of fields of view required

to count 300 specimens allows an estimation of the nannofossil abundance (Bown and Young, 190 1998). In 20 samples (9, 5, 3, and 3 samples from Anzate, Ida w Shayq, Tinfoul and Tiskatine, 191 192 respectively), less than 300 nannofossils (from 1 up to 208 specimens) were counted, due to the paucity and poor preservation of nannofossils. All nannofossils with at least more than half of 193 the specimen preserved were counted. Both nannofossil total absolute abundance and relative 194 abundances of some key taxa were calculated for each sample. In these calculations, 195 Nannoconus spp. were excluded from the total sum of nannofossils because of their uncertain 196 biological affinity (Aubry et al., 2005). The taxonomic frameworks of Perch-Nielsen (1985) 197 and Burnett et al. (in Bown, 1998) were followed. The nannofossil preservation was evaluated 198 following the classes defined by Roth (1983). 199

200 Calcareous nannofossils are used in this study to better constrain the paleoenvironmental conditions, in particular, trophic levels in the water column, pelagic carbonate production and 201 sea-surface temperatures. Calcareous nannofossil primary productivity is an indicator of trophic 202 levels in the water column; it is estimated here both with total absolute abundance and relative 203 abundances of fertility indicators such as Biscutum spp., Discorhabdus rotatorius, 204 Lithraphidites carniolensis and small Zeugrhabdotus spp. (Table 2; Peybernes et al., 2013). 205 206 The relative abundances of both Nannoconus spp., which constitute the biggest nannofossil carbonate calcifiers and of calcareous nannofossil sea-surface temperature indicators were 207 calculated. Calcareous nannofossils considered as high latitude taxa (Crucibiscutum spp., 208 209 Repagulum parvidentatum, Rhagodiscus angustus and Seribiscutum spp.; Table 2) were considered in this study. 210

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# 212 IV. RESULTS

#### 213 IV.1. Ammonite biostratigraphy

In the EAB, Aptian and Albian ammonites have been first reported by Brives (1905), Lemoine 214 (1905), Gentil (1905), Kilian and Gentil (1906, 1907) and Roch (1930). While carrying out a 215 regional stratigraphic synthesis of the EAB, Ambroggi (1963) listed Cretaceous ammonite 216 specimens, collected unit by unit and identified by Breistroffer (e.g., Ambroggi and Breistroffer, 217 1959). Later, Wiedmann et al. (1978, 1982), Rey et al. (1986, 1988), Andreu (1989) and Witam 218 (1998) brought new precisions on ammonite occurrences. Since then, E. Robert (in Peybernès 219 et al., 2013) and L. Bulot (in Luber et al., 2017; 2019) refined the ammonite biostratigraphy of 220 the Aptian-lower Albian succession of the EAB. 221

In this work, since many new species and genus have been identified, and the lower part of the 222 successions is locally highly condensed, the presented biozones are accurate but preliminary, 223 pending on careful taxonomic revision (Giraud, Robert et al., in progress). In spite of the 224 absence in our collected samples of many of the zonal markers, we were able to correlate the 225 ammonite successions of the EAB with those of the Mediterranean and Tethyan regions, and 226 thus with the standard biostratigraphic ammonite zones (Reboulet et al., 2018). Although latest 227 Barremian ammonites are present (Jaillard et al., 2019), earliest Aptian specimens from the 228 Deshayesites oglanlensis Zone have not been found in the recently studied Aoulkidad and 229 Takoucht sections, confirming a hiatus of this interval (Peybernes et al., 2013, Luber et al. 2017). 230

Early Aptian times are poorly represented, and were best studied in the northern sections. There,
the *Deshayesites forbesi* Zone has been tentatively identified by the presence of *Deshayesites consobrinus*, associated with *Ancyloceras* sp. and first cheloniceratids (Procheloniceras sp. and
Cheloniceras sp.). The *Deshayesites deshayesi* Zone is marked by the occurrence of *Deshayesites deshayesi*, *D. consobrinoides*, *D. cf. grandis*, *Pseudohaploceras* sp., numerous
cheloniceratids specimens (among which *Procheloniceras* spp., *Cheloniceras cornuelianum*, *C. meyendorfi*) and the *Ancyloceras* genus, among which *A. cf. matheronianum*. The subsequent

- 238 Dufrenoyia furcata Zone is identified because of the presence of Dufrenoyia furcata,
   239 Australiceras sp. and Toxoceratoides emericianum.
- 240 Late Aptian times are well represented in almost all sections. The *Epicheloniceras martini* Zone
- is identified by the appearance of numerous specimens of the *Epicheloniceras* genus (*E. martini*,
- 242 E. tschernyschewi), together with Colombiceras crassicostatum and other species of the genera

Vectisites, Neodufrenoyia gen. nov. and Colombiceras. The upper part of the E. martini Zone
is marked by a well correlatable horizon bearing abundant Australiceras and

- 245 *Pseudoaustraliceras* ("Tropaeum beds" of the literature).
- The *Parahoplites melchioris* Zone is poorly represented in the EAB. The association of *Acanthohoplites* sp., *Colombiceras discoidales* and *Valdedorsella akuschaense* is tentatively ascribed to this zone. In overlying strata, the *Acanthohoplites nolani* Zone and subsequent zones present a fairly high faunal diversity.
- The Acanthohoplites nolani Zone is represented in all sections and the historical, long 250 recognized "nolani bed" represents a good correlation level. Bulot and Latil (2014) called into 251 question the use of A. nolani as a zone index, and Luber et al. (2017) pointed out the 252 253 misidentification of this species for the Moroccan representatives, and introduced the species Esaisabellia tiskatinensis. Nevertheless, we will follow the current standard zonation, awaiting 254 for next discussions of this purpose by the Kilian Group. In the "A. nolani" zone, the associated 255 fauna consists of Epicheloniceras clansayense, Aconeceras aptiana, Pseudohaploceras sp., 256 Diadochoceras sp., Zuercherella sp. and speciments of the Neodufrenoyia gen. nov. and 257 Acanthohoplites genera (among which A. bergeroni, A. Bigoureti anthulai). 258
- The Hypacanthoplites jacobi Zone is mainly represented by pyritous ammonites, and is defined by the first occurrence of Hypacanthoplites spp. (H. nolaniformis, H. elegans, H. clavatus). They are associated with Epicheloniceras clansayense, Pseudorbulites convergens, Phylloceras (Phylloceras) aptiense, Diadochoceras migneni, Parasilesites kilianiformis, and representatives of the genera Eogaudryoceras, Fallotermiericeras gen. nov., Neodufrenoyia, first Phyllopachyceras and Eogaudryceras (Eotetragonites).
- Earliest Albian times are well represented, although the corresponding fauna is poorly 265 preserved. The Leymeriella tardefurcata Zone is characterized by the occurrence of various 266 specimens of Silesitoidinae and of the genera Phylloceras, Phyllopachyceras, 267 268 Hypacanthoplites, Mellegueiceras, Parengonoceras, Uhligella, Pusozia, Eogaudryceras (*Eotetragonites*) together with Douvilleiceras leightonense, *Oxytropidoceras* 269 (Oxytropidoceras) sp., O. (Mirapelia) mirapelianum, Neosilesites palmensis, Ptychoceras 270 271 laeve, Parabrancoceras sp. and other less representative or endemic specimens. Mainly because of poor outcrops in a chiefly argillaceous series, the Douvilleiceras mammillatum 272 Superzone is less represented. However, the occurrence, among others, of Douvilleiceras 273 mammillatum aequinodum, Prolyelliceras gevreyi, Beudanticeras dupinianum africana, B. 274 revoili, Uhligella rebouli, Parengonoceras bussoni and P. hachourii characterizes this time 275 span. The "Beudanticeras beds" (Roch, 1930; Ambroggi, 1963) mostly belong to this interval. 276
- Toward the West (Tamri, Imsouane), the Aptian–lower Albian series is condensed in a phosphate- and glauconite-rich, conglomeratic level, which contains ammonites of early Aptian to earliest Albian age (Robert, *in* Peybernès et al., 2013).

# 280 IV.2. Sedimentary facies

- Aptian facies differ from those of the uppermost Aptian–lower Albian series, in their lithologyand detrital quartz content, as well as in their faunal content.
- 283 **IV.2.1. Aptian facies** (Fig. 3)

Facies 1 (F 1): Facies 1 is made of shales or shaly marlstone, containing mainly belemnites and
 some ammonites. Sandstone or marl beds are almost absent (less than 5% in thickness). Scarce
 thin-shelled bivalves, annelids (serpulids) and small-sized gastropods may occur. Because of
 the shaly nature of the deposits, bioturbation is hardly visible. Ammonites may be pyritous.

*Interpretation*: The lack or scarcity of carbonate suggests that sedimentation took place far from
 the "carbonate factory" (Tucker and Wright, 1990; Schlager, 2003) located in the nearshore
 euphotic zone, where photosynthesis favours the organic activity of carbonate generating
 organisms (from bacterias to algae and molluscs). The strong predominance of pelagic
 organisms and the scarcity of benthic fauna suggests a deposition below the euphotic zone.
 Therefore, facies F1 is interpreted as characterizing distal outer shelf deposits.

Facies 2 (F 2): Facies 2 consists of shales or shaly marlstone, with some marly beds (about 20-30% of total thickness). The faunal content is dominated by belemnites, ammonites, irregular sea urchins, brachiopods (terebratulids) and plicatulids, associated with some gastropods, bivalves (mostly thin-shelled), annelids and scarce nautiloids. Isolated corals locally occur. Bioturbation consists of track molds, small sized curved burrows and digging traces (sediment feeders), mainly visible in the marlstone beds.

*Interpretation*: The occurrence of benthic, relatively deep water organisms (e.g. echinoids, brachiopods), together with planktonic fauna (cephalopods) suggests a hemipelagic environment. The lithological association (prevailing marl, subordinate limestone) also points to an outer shelf setting. Bioturbations are dominated by the activity of sediment feeders, suggesting an outer shelf environment and moderately oxygenated conditions.



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Figure 3. Sedimentary facies of the Aptian (A) and uppermost Aptian–Lower Albian (B) along the ramp of the Essaouira-Agadir basin.

- **Facies 3 (F 3)**: Facies 3 is made of marly limestones (about 30-50% of total thickness) with marly interbeds. The faunal content is dominated by benthic organisms, such as brachiopods, annelids and bivalves, among which oysters, plicatulids, pectinids and thick-shelled large bivalves. Ammonites occur commonly. Bioturbation dominantly consists of burrows (curved and straight) and track molds.
- *Interpretation*: The predominance of a diversified benthic fauna indicates a shallow, open marine environment, while the abundance of limestone suggest the proximity of the "carbonate factory" and hence, of a carbonate platform. However, the lack of algae and of very shallow organisms or features (e.g. oncolites, rudistids, corals) precludes a very shallow environment. The dominance of burrows and surficial track molds supports the interpretation of a shallow
- 319 (proximal) open shelf environment.
- Facies 4 (F 4): This facies is lithologically marked by thick, massive limestone beds, containing
   shallow marine benthic bivalves, such as abundant oysters, some trigonids and scarce rudistids.
   Bioclasts are common and belemnites may occur at the top of these beds. Bioturbation is
- 323 represented by burrows. The top of these beds is locally karstified (see surface S1, below).
- *Interpretation*: The predominance of a shallow marine benthic fauna indicates a shallow carbonate shelf environment. Evidence of frequent emergence at the top of these deposits support this interpretation. The presence of bioclasts suggests a moderate energy environment, which is supported by the predominance of suspension feeders. F4 sediments are thus interpreted as deposited in a well oxygenated, shallow to very shallow carbonate shelf environment, with moderate energy.
- 330 IV.2.2. Uppermost Aptian–Albian Facies (Fig. 3)
- Facies I (F I): Facies I is made up of monotonous, dark-coloured, almost azoic shales or shaly
   marlstones. Long searches on these outcrops allowed only to find scarce ammonite casts.
- *Interpretation*: The lack of fauna and sedimentary structures makes any reliable interpretation difficult. However, as this facies usually overlies or underlies the FII facies, is devoid of benthic fauna, and occurs at the top of the studied sections, it is interpreted as a pelagic, deep water marine deposit.
- Facies II (F II): Facies II is very comparable to the F 1 facies, and consists of silty shales or
  silty shaly marlstone, containing mainly belemnites and some ammonites. Sandstone beds are
  virtually absent (less than 5 % of the total thickness). Scarce thin-shelled bivalves, annelids,
  plicatulids, small sized gastropods and brachiopods (mostly rynchonellids) occur sporadically.
  Because of the shaly nature of the deposits, bioturbation seems to be absent, except in the
- 342 sandstone or marlstone beds, where digging tracks dominate.
- *Interpretation*: The lack, or scarcity, of carbonate suggests that sedimentation took place far
  from the carbonate factory, i.e. in a distal place, if the carbonate content is due to export from
  shallow water deposits. The strong predominance of pelagic organisms and the scarcity of
  benthic fauna support a deposition depth below or near the lower limit of the euphotic zone.
  Therefore, facies F II is interpreted as a hemipelagic deposit, in a distal outer shelf environment,
- 348 and is thought to be roughly equivalent to the F 1 facies.
- Facies III (F III): Facies III is made of shales or shaly marls, with thin beds of sandstone or
  sandy marl (about 30 % of the total thickness). The faunal content is dominated by belemnites,
  ammonites and brachiopods (mostly terebratulids), associated with some gastropods,
  plicatulids, and thin-shelled bivalves. Bioturbation in the sandstone beds consists of small sized
  curved burrows and digging traces (sediment feeders).

*Interpretation*: The occurrence of benthic, relatively deep water organisms (e.g. brachiopods, plicatulids), together with planktonic fauna (cephalopods) suggests a hemipelagic environment. The lithological association (prevailing silty to sandy marlstone) also points to an outer shelf setting, comparable to that of Facies F 2. However, the presence of sediment feeders, even in the sandstone beds, suggests that sea bottom waters were less oxygenated than in Facies 2.

Facies IV (F IV): F IV consists of yellow, dolomitic, well-sorted sandstone beds, usually 359 separated by silty to marly interbeds. The faunal content is dominated by benthic organisms, 360 such as brachiopods (terebratulids) and bivalves, among which gastropods, oysters, plicatulids, 361 pectinids and other bivalve fragments. Ammonites and belemnite fragments are common. 362 Sedimentary structures such as current ripples and cross-bedding are also common. The lower 363 part of the dolomitic sandstone beds is commonly rich in varied reworked elements: phosphatic 364 fragments, internal molds of gastropods or ammonites, brachiopods, lithoclasts and belemnite 365 rostra. Bioturbation consists of burrows (curved and straight), track molds and digging traces. 366 367 F IV commonly overlies erosional surfaces, below described as S 4.

Interpretation: The predominance of a diversified benthic fauna indicates an open marine 368 environment. The occurrence of current-related structures indicates a moderate to high energy 369 during deposition, which is supported by the good sorting of sandstone grains. The abundance 370 and diversity of bioturbation, as well as the energetic conditions, support the interpretation of a 371 shallow (proximal) outer shelf environment, probably above the fearweather wave base. When 372 F IV deposits overly S 4 surfaces, they are interpreted as resulting from the decreasing intensity 373 374 of submarine currents responsible for the erosional surface. As these currents decrease, they allow deposition of sandstones, mixed with reworked elements, both brought out from the 375 underlying, eroded strata. When F IV does not overly S 4 surfaces, it may be interpreted as 376 storm deposits, resulting from an abrupt detrital supply derived from littoral areas, possibly 377 related to river floods, or resulting from high frequency relative sea-level drops. 378

Facies D (F D): Facies F D is characterized by a poor faunal diversity, together with the high
abundance of one type of organism, usually annelids (serpulids) or buchidae bivalves (e.g. *Aucellina* sp.). F D is usually associated with monotonous shales or shaly marlstones, or with
alternating marlstone /silty marlstone and marlstone /sandstone, with predominance of
marlstones or silty marlstones (lithologies of F 1, F 2, F II or F III). Bioturbation is sparse, but
this may be due to the shaly lithology. Pyrite is commonly abundant.

Interpretation: The poor faunal diversity, the presence of pyrite and the predominance of 385 386 organisms tolerating oxygene-depleted environments (buchidae, serpulids, De la Mora et al., 2000; Henderson, 2004) point to dysaerobic conditions. However, the occurrence of scarce 387 bioturbation indicates that benthic life was still possible, and therefore, that conditions were not 388 389 anoxic. Because of the scarcity of other fauna, the depositional environment is difficult to assess precisely, and it will be interpreted based on the lithology. For this reason, the dysaerobic facies 390 (F D) will be nammed based on their lithology, for instance F 2D or F IID. In all cases, in the 391 studied sections, F D is of restricted to outer shelf environments. 392

393

# 394 IV.3. Peculiar sedimentary surfaces

**Surface 1 (S 1)**: The first type of surface is usually found on top of a massive limestone bed. It is an uneven, corroded surface, the cavities of which are filled by the overlying highly glauconitic deposits, or by iron oxydes (see below) (Fig. 4A, 4B). The centimeter-scale cavities may penetrate in the limestone beds as much as several tens of centimeters deep. In the upper surface of the bed, the calcite of bioclasts has been locally dissolved and is replaced by iron oxydes, iron-rich dolomite or by glauconitic-rich sediments.



401

Figure 4. Types of sedimentary surfaces in the Essaouira-Agadir basin. A. Karsted surface S1 (D1,
Takoucht section). B. Glauconitic infilling of a karstic cavity on a S1 surface (D1, Addar section). C.
Bored rounded clast in a phosphatic conglomerate (S2 surface, Tamri section). D. Iron oxide rich
crust (S3 surface, D3, Addar section). E. Concentration of belemnites and plicatulids and gastropod
shells at the base of a dolomitic sandstone bed (S4B surface) (D4, Taounerine section). F. S4A surface
marked by a concentration of brachiopods and plicatulids shells in a marly succession (D4, Ida w
Shayq section).

410 *Interpretation*: S1 is interpreted as a karstified surface, which indicates a period of subaerial 411 exposure and explains the dissolution by meteoric water. S1 is, therefore, interpreted as a 412 sequence boundary (SB). It is only found at the base of the studied sections (i.e. in lower Aptian 413 deposits), and mainly in the southern part of the basin, where several S1 surfaces may be 414 amalgamated. In the latter case, reworked ammonites of different ages suggest large time gaps

- amalgamated. In the latter case, reworked ammonites of different ages suggest large time gaps.
- 415 Surface 2 (S 2): The second type of surface is represented by a thin layer of highly glauconitic,
- 416 sometimes phosphatic deposits that commonly form a crust. It commonly contains lithoclasts,
- 417 fossils and bioclasts (oysters, brachiopods, gastropods, belemnites, ammonites) of various

nature and origin. It may fill the karstic cavities and depressions of S1, or form a distinct layer.
In some cases, large lithoclasts are bored (Fig. 4C).



421 Figure 5. North-South correlations of some Aptian–lower Albian sections of the Essaouira-Agadir
 422 basin.

420

- Interpretation: S 2 is thought to represent a condensed deposit, resulting from a submarine 423 hiatus. The occurrence of a variety of organisms living in shallow to moderately deep 424 425 environments suggests that condensation partly occurred in a shallow marine environment. This is supported by the local presence of bored clasts, boring being restricted to shallow marine 426 environments and being common in tidal environments. However, the presence of glauconite 427 428 and phosphate suggests that at least part of the condensation occurred in an outer shelf environment, likely related to mineralised, deep water currents. S 2 is, therefore, interpreted as 429 related to a transgressive episode. S 2 is usually found at the base or at the top of the studied 430 sections, and only in the western part of the basin. 431
- 432 Surface 3 (S 3): Surface 3 is marked by a thin, discontinuous, iron-rich crust, which covers the
  433 upper surface of marly or calcareous beds (Fig. 4D). It is locally associated with some small434 sized lithoclasts, and concentrations of pelagic fauna (cephalopods). It is mainly recorded in the
  435 upper Aptian deposits.
- 436 Interpretation: S 3 is interpreted as a hard ground representing a submarine hiatus, likely related 437 to marine currents. In upper Aptian deposits, S 3 commonly laterally evolves to S 4 surface 438 (submarine erosion, see below). In this case, S 3 is interpreted as resulting from the 439 mineralization by submarine currents of a hard bed (calcareous marlstone or limestone) that 440 resisted to the submarine erosion, the latter having removed the underlying shales and being 441 still active elsewhere. In the western, condensed sections, S 3 may be merged with S 1 or S 2 442 surfaces.
- Surface 4 (S 4): An other type of surface is found at the base of high concentrations of 443 444 belemnites rostra associated with lithoclasts, flat pebbles, phospatized white internal molds of fossils (commonly gastropods and ammonites) and scarce other bioclasts (Fig. 4E and 4F). 445 These elements can be found, either as coquina layers within a marly shale succession (S 4A), 446 447 or reworked at the base of, or within, limestone or calcareous sandstone beds (S 4B) (see Fig. 5). In the first case (S 4A; Fig. 4F, and D4 in Ida w Shayq section on Fig. 5), these coquinas are 448 frequently lenticular in shape, since they overlie a slightly uneven surface, and may be 449 associated with fine-grained sand. Where the coquina is lacking, S 4 may be only marked by a 450 slight lithological change, associated with an upward change in the faunal content, from pelagic 451 organisms to assemblages including benthic species. In the second case (S 4B; Fig. 4E), clasts, 452 bioclasts and molds are concentrated at the base of the overlying bed, and rapidly disappear 453 upward. S 4 occurs in the uppermost Aptian and lower Albian succession. 454
- 455 Interpretation: S 4 may be interpreted in two distinct ways. In the most common case, the reworked faunal assemblage, as well as the overlying one, contain pelagic organisms. Such an 456 erosional surface is interpreted as representing a submarine hiatus, associated with erosion of 457 the underlying marlstone or shale, related to relatively strong submarine currents. In this 458 interpretation, the submarine erosion would have removed the small-sized sedimentary 459 particles (shale, marlstone), thus bringing out and concentrating their detrital and pelagic faunal 460 content. The frequent occurrence of phosphatic internal molds of organisms suggests that 461 upwelling currents played a role in this erosion and allowed phosphatisation of carbonate 462 463 elements during the erosional hiatus. However, since the S 4 surface is always found at the top of shaly or marly series, the occurrence of emersion periods cannot be ruled out for some of 464 these surfaces. As a matter of fact, on one hand, the overlying bed may contain shallow water 465 fauna (oysters, trigonids, corals), and on the other hand, shale or marlstone cannot be karstified, 466 467 and possible evidences of subaerial erosion (e.g. paleosoils, fluvial or eolian sands, etc.) may have been eroded, and removed or reworked by the overlying, transgressive high-energy 468 469 deposits.

#### 471 IV.4. Calcimetry and rock-eval pyrolysis

For all successions, calcium carbonate values are higher in the Aptian than in the Albian deposits, with values generally comprised between 40% and 90% up to the end of the *A. nolani* ammonite Zone. Close to the Aptian–Albian boundary, the calcium carbonate content sharply decreases, and remains low or slightly decreases through early Albian times (Fig. 6).



476

477 Figure 6. Stratigraphic changes in calcium carbonate content and relative abundances of Nannoconus
478 spp. for the different sections. For the Takoucht section, the TOC is added. The sedimentary
479 discontinuities (D0 to D7) are indicated.

In the Takoucht section, the 25 analyzed samples contain between 0.2 and 1.5% TOC, with an 480 average of 0.7%. There is no clear relationship between TOC% and CaCO<sub>3</sub>% (Fig. 6), which 481 suggests that the percentage of organic matter does not result from its dilution by carbonate 482 input. Hydrogen indices are comprised between 128 and 198 mg/g of rock, Oxygen indices 483 from 159 to 311 mg/g, S1 from 0.01-0.05 mg/g, and S2 from 0.12 to 3.01 mg/g. The PI is 484 always very low with values in the range of 0.01 to 0.16. Temperatures of maximum pyrolytic 485 yield (Tmax) are in average of 438°C (Appendix), indicating that the organic matter did not 486 experience high temperature during burial. Thus, organic matter in the Takoucht section was 487 still immature with respect to petroleum generation. The very low free hydrocarbon content (S1 488 = 0.01-0.05 mg/g rock) confirms this immaturity. Such low maturation allowed the use of the 489 hydrogen index (HI) as an indicator of the origin and composition of the organic matter 490 (Espitalié et al., 1985-1986). According to the low range of the HI values, the organic matter 491 of the Takoucht section could be attributed to Type III, related to terrestrial higher plants debris 492 or to altered Type II, derived mainly from algae and/or bacteria, but highly oxidized. 493

494

# 495 IV.5. Calcareous nannofossils

Calcareous nannofossil total absolute abundance, relative abundances of calcareous nannofossil 496 fertility (meso-eutrophic taxa), sea-surface temperature indicators (cold taxa) and Nannoconus 497 spp. are plotted with the ammonite biostratigraphic information for each section. Calcareous 498 nannofossil data obtained from the present study (Ida w Shayq, Tiskatine, Anzate and Tinfoul) 499 are compared to those published from Addar, Tamzergout and Alma (Pevbernès et al., 2013) 500 501 (Figs. 6 and 7). The lower part of the Alma succession contains many barren samples due to dolomitization. This section is not shown in Figure 7, because the few scattered data do no 502 allow to comment any trend. 503

In the studied sections, preservation of calcareous nannofossils is poor to good and fluctuates 504 505 all along the successions (Fig. 7); some samples of both Tiskatine and Anzate sections are barren of nannofossils and/or contain very rare nannofossils (Fig. 7). The means of the 506 nannofossil total absolute abundance are higher in the distal sections of Addar (0.57 x  $10^9$ 507 specimens per gram of rock) Ida w Shayq  $(0.43 \times 10^9)$ , Tiskatine  $(0.35 \times 10^9)$  and Tamzergout 508  $(0.33 \times 10^9)$ , with respect to the more proximal sections of Anzate  $(0.18 \times 10^9)$  and Tinfoul 509  $(0.13 \times 10^9)$ . A progressive decrease in the nannofossil total absolute abundance is recorded 510 through the Aptian-early Albian interval, except for the Ida w Shayq section, which shows a 511 sharp decrease around the Aptian-Albian boundary (Fig. 7). The mean relative abundance of 512 meso-eutrophic taxa is comprised between 17.8 (Ida w Shayq) and 28.6% (Addar), which 513 represent relatively high values. The relative abundance of meso-eutrophic taxa follows an 514 515 opposite trend with respect to the nannofossil total absolute abundance, since it generally increases in the latest Aptian and earliest Albian (between D3 and D5); in both Tamzergout and 516 Anzate the absence of data below this interval does not allow to observe this trend (Fig. 7). 517 Above D5 (D. mammillatum Superzone), the relative abundance of meso-eutrophic taxa 518 decreases (Fig. 7). In all sections except Tinfoul, an increase in the relative abundance of cold 519 520 taxa is recorded from the late Aptian to the early Albian, and the Anzate section shows higher percentages than the other ones (Fig. 7). The relative abundance of the largest nannofossil 521 calcifier, Nannoconus spp., decreases from the late Aptian to the early Albian (Fig. 7). The 522 proximal Tinfoul section presents both the lowest Nannoconus spp. percentages and calcium 523 524 carbonate contents (Fig. 6).

525

# 526 V. INTERPRETATIONS

# 527 V.1. Aptian–lower Albian depositional sequences

528 The identification of facies and discontinuity surfaces allowed us to define seven depositional 529 sequences in the Aptian–early Albian interval ( $\approx 15$  Ma).





532 533

Figure 7. Stratigraphic changes in calcareous nannofossil total absolute abundance and relative abundances of both meso-eutrophic and cold taxa. The sedimentary discontinuities (D0 to D7) are indicated.

The **first sequence** (< 10 m) is only developed in the northern part of the EAB. In Ida w Shayq and Smimou, its lower part yielded latest Barremian ammonites (*M. sarasini* ammonite Zone,

- Jaillard et al., 2019), whereas the upper part contains ammonites from the D. deshayesi Zone at
- 537 Smimou, Ida w Shayq and Aoulkjedad. Its lower limit (D 0, Figs. 5, and 8 to 10) is an S 1-type,

538 karstified surface.



539
540 Figure 8. East-West correlations of the Aptian–lower Albian sections in the southern part of the
541 Essaouira-Agadir basin. D: dysaerobic facies. See Fig. 10 for caption, and Fig. 3 for explanation of 1
542 to 4, and I to IV.

At Ida w Shayq, parts of the section are covered, and it is possible that this sequence includes an additional, unobserved discontinuity. The lower, transgressive part of the sequence is dominated by marlstone and sandstone beds rich in oysters, with subordinate pectinids and trigonids. The middle part contains irregular urchins, associated with ammonites, oysters and serpulids, while the marly to calcareous upper part yielded mainly ammonites and brachipods. Its top is usually represented by a remarkable accumulation of cheloniceratids (*« Cheloniceras* bed *»*), locally exhibiting karstic dissolution (Ida w Shayq). These features indicate an overall transgressive trend for the sequence. In the southern sections, this sequence may be represented
by the undated infilling of karstic cavities related to amalgamated emersion surfaces. This
sequence seems to roughly coincide with the Tamzergout Fm of Rey et al. (1988) and Witam
(1998).

The second sequence (< 11 m) is mainly observed in the northern part of the basin. In the Ida 554 w Shayq section, it yielded late early to early late Aptian ammonites (D. deshayesi? to E. 555 martini zones). Its lower boundary (D 1, Figs. 5, and 8 to 10) is an S 1 surface in Takoucht, Ida 556 w Shayq and Aoulkjdad. There, it is marked by a thinning upward succession of limestone beds. 557 Whereas the lower part is dominated by ammonites and brachiopods, the shaly upper part 558 mainly contains plicatulids and scarce ammonites. This evolution is interpreted as a mainly 559 transgressive succession, the regressive part of the second sequence being eroded below the 560 upper discontinuity surface. In the Tiskatine and Aoulkidad sections, it is represented by a 561 monotonous marlstone-limestone alternation, rich in plicatulids, belemnites and ammonites. 562 This sequence commonly ends with a limestone bed rich in large ammonites (« 'Tropaeum' 563 bed »). In the southern sections, the second sequence is usually represented by a massive 564 limestone bed intercalated between two emersion surfaces (S 1), whereas it is lacking in the 565 566 easternmost section (Tinfoul, Fig. 8).

567 The third sequence (< 14 m) is recorded in all sections. It yielded early late Aptian ammonites (E. martini, to base of A. nolani zones). Its base (D 2, Figs. 5, and 8 to 10) is locally a S 4B 568 surface, consisting of a limestone bed rich in phosphatized fossils (Addar, Ida w Shayq). 569 Elsewhere, the base of the sequence is placed at the top of the "Tropaeum bed" (S 3 surface). 570 This sequence comprises a first thinning-upward, then thickening upward alternation of shaly 571 and calcareous marl beds. The fauna is dominated by belemnites, ammonites and plicatulids, 572 which are associated with oysters at the base, irregular urchins in the middle part, and 573 brachiopods at the top of the sequence. This faunal evolution supports a deepening-, then 574 shallowing-upward trend. In all sections, its top is clearly marked by a noticeable marly 575 limestone bed extremely rich in «Nolaniceras» spp. (« Nolani bed »). The second and third 576 sequences appear to correspond to the Tadhart Fm (Rey et al., 1988; Witam, 1998). 577

The **fourth sequence** (< 5 to 30 m) crops out in all sections. It is well dated by latest Aptian 578 ammonites (A. nolani to H. jacobi zones). Its base (D 3, Figs. 5, and 8 to 10) is locally marked 579 by a slightly erosional sandy bed (Anzate Alma, Tamzergout, Takoucht). At Aoulkidad, it 580 consists at the base (S 4B) of a bed rich in phosphatized ammonites and bioclasts. Elsewhere, 581 it is marked by the oxydized top of the « Nolani bed » (S 3). In Takoucht, a low angular 582 unconformity can be seen between the sandstone bed (S 4 surface) and the « Nolani bed » (S 3 583 584 surface), thus evidencing submarine erosion, which took place during the hiatus causing the sequence boundary (Fig. 10). The fourth sequence is usually a thinning-upward, mainly marly 585 succession, rich in ammonites, belemnites and plicatulids. According to the sections, thin 586 587 sandstone beds are present (Addar, Anzate, Taounerine), some ammonites are pyritous (Anzate, Taounerine), and calcareous beds appear in the upper part of the sequence (Ida w Shayq), 588 illustrating a progradational trend. The presence of numerous Aucellina sp. and of abundant 589 pyrite suggests reducing conditions, which represent the equivalent of one of the upper Aptian 590 anoxic events known in southeastern France (Kennedy et al., 2014 and references therein). This 591 sequence is correlated with the Lemgo Fm of Rey et al. (1988) and Witam (1998). 592

In Tamzergout, the Aptian-lower Albian succession is thicker than elsewhere, and the more complete ammonite succession suggests that an additional sequence (12 m) is preserved below the major discontinuity of the Aptian-Albian boundary (D 4', Fig. 8). If so, this would imply on one hand that subsidence was higher in this area than in other areas, and on the other hand that the overlying unconformity surface is strongly erosive, as this sequence is not recorded elsewhere.



Figure 9. East-West correlations of the Aptian-lower Albian sections in the central part of the
Essaouira-Agadir Basin. D: dysaerobic facies. See Fig. 10 for caption, and Fig. 3 for explanation of 1
to 4, and I to IV.

The **fifth sequence** (< 35 m) is well represented in all studied sections. It yielded numerous 603 604 ammonites, which ensure an earliest Albian age (L. tardefurcata Zone). The lower sequence boundary (D 4, Figs. 5, and 8 to 10) is a typical S 4B surface at the base of a reworked bed, 605 reflecting strong erosion. Among the reworked bioclasts in the basal sandy bed, the presence 606 607 of corals (Addar), pectinids (Tamzergout), oysters (Tiskatine, Takoucht) or regular urchins (Ida w Shayq) suggests a shallow marine environment. Therefore, the occurrence of subaerial 608 erosion related to a significant sea-level drop cannot be ruled out for this sequence boundary. 609 which encompasses the Aptian–Albian boundary time-span. An emersion period during D 4 is 610 supported by the fact that sequence 4 is locally deeply eroded, with its thickness varying 611 between 30 m (Tamzergout) and 5 m (Anzate) in the South (Fig. 8), and between 4 m 612 613 (Aoulkidad) and 11 m (Taounerine) in the center of the basin (Fig. 9). The fifth sequence is mainly made of shaly marlstone, containing belemnites, ammonites and plicatulids, although 614 oysters, brachiopods, pectinids and annelids may occur as well. This sequence is locally rich in 615 616 buchidae bivalves (Aucellina sp.) (Takoucht, Aoulkjdad), especially in its upper part (Tinfoul, 617 Tiskatine), suggesting dysaerobic conditions (e.g. Henderson, 2004).

618 Due to poor outcrop conditions, the identification of the sixth and seventh sequences are still 619 preliminary. The ammonite content of the **sixth sequence** (< 20 m) indicates an early Albian 620 age (late *L. tardefurcata* Zone and *D. mammillatum* Superzone p.p.). In all sections, the lower

sequence boundary (D 5, Figs. 5, and 8 to 10) is a S 4B surface. Beside pelagic fauna, the strata
 overlying D 5 contains a molluscan fauna (brachiopods, pectinids, plicatulids) not as shallow

as those overlying D 4, and frequent phosphatized internal molds. Therefore, D 5 may 623 correspond to a submarine erosion period. The fauna is dominated by belemnites, serpulids and 624 plicatulids; some flat ammonites ("Beudanticeras beds") are present in the lower part, and 625 Aucellina sp. and serpulids are quite abundant in some sections (Tiskatine, Aoulkidad, 626 Takoucht, Tamzergout). The latter indicate a clear dysaerobic environment, which may be an 627 equivalent of the organic-rich deposits of the coeval "Niveau Paquier" of southeastern France 628 (Kennedy et al., 2000). The top of the sequence is marked by the increase of sandy beds, 629 suggesting the progradation of a coastal clastic system. 630



631

Figure 10. East-West correlations of the Aptian-lower Albian sections in the northern part of the
Essaouira-Agadir Basin. D: dysaerobic facies. See Fig. 3 for explanation of 1 to 4, and I to IV.

634

The seventh sequence (< 30 m) has been identified only in the Tamzergout, Tiskatine, 635 Aoulkidad and Takoucht sections. Its poor ammonite content indicates an early Albian age (D. 636 mammillatum Superzone p.p.). The lower discontinuity (D 6, Fig. 8 and 9) is an erosional 637 638 surface (S 4B) overlain by a sandstone bed containing phosphate clasts. Sequence 7 consists of sandy/silty marls with abundant sandy limestone and sandstone beds. The fauna is similar to 639 that of the sixth sequence (plicatulids, serpulids, belemnites, Aucellina sp., scarce large 640 bivalves). In Tinfoul and Anzate, this sequence is probably present but has not been 641 differentiated from the sixth sequence (Fig. 8). The thickness of the sequence and the amount 642 of detrital quartz and sandstone beds seem to increase toward the North and East (Tinfoul, 643 Aoulkidad, Takoucht). 644

An **eighth sequence** is locally partly visible (Addar, Tiskatine, Aoulkjdad, Tamzergout). Its lower boundary (D 7, Figs. 5 and 7) is an S 4B surface. The sandstone bed overlying D 7 contains wood remains, ostreids, frequent lithoclasts, and locally presents parallel laminae and Hummocky Cross Stratification, which suggest a very shallow depositional environment. These features suggest that D 7 may correspond to a subaerial erosion period. This interpretation is substantiated by common plant remains in the abundant sandstone beds of the underlying sequence 7, which suggest the proximity of emergent land. Scarce and little diversified ammonites indicate an early Albian age. The rare faunal content comprises ammonites, belemnites, plicatulids and serpulids in the sandstone beds, and *Aucellina* sp. in the sandy, marly shales. Together with the apparent scarcity of bioturbation, this suggests ongoing dysoxic conditions. The overlying shales are frequently covered. The fifth to eighth sequences constitute the lower part of the Oued Tidzi Fm (Duffaud et al., 1966).

#### 657 V.2. Comparison with other areas

Although the Aptian period has been extensively studied for paleoenvironmental and 658 paleooceanographic conditions (e.g. Sabatino et al., 2015, and references therein), relatively 659 few works are available on the sequence stratigraphy of this stage. A SB of latest Barremian 660 age (within the Martellites sarrasini Zone) has been identified in southern (Ruiz-Ortiz and 661 Castro, 1998) and northern Spain (Bover-Arnal et al., 2009), and in the Urgonian platform of 662 the Swiss and French Prealps (Arnaud et al., 1998; Clavel et al., 2013; Tendil et al., 2018), 663 which correlates with our D0. Some authors mentioned a first lower Aptian SB around the limit 664 665 between the Deshayesites oglanlensis and D. forbesi ammonite zones (Bover-Arnal et al., 2009; Martín-Martín et al., 2013; Tendil et al., 2018), and a second one between the *D. forbesi* and *D.* 666 deshayesi zones (Ruiz-Ortiz and Castro, 1998; Arnaud et al., 1998; Raddadi, 2004; see also 667 Embry et al., 2010). Because of common condensation and poor sedimentary record, none of 668 669 these discontinuities has been recognized confidently in the EAB, most probably due to the low sea level globally recorded in earliest Aptian times (e.g. Haq, 2014). A third lower Aptian SB 670 has been dated as close to the D. deshayesi-Dufrenoyia furcata ammonite zones boundary 671 (Martín-Martín et al., 2013; H. Arnaud, pers. comm., 2014), which may be correlated with D1. 672 D2, dated as close to the early-late Aptian boundary (D. furcata-Epicheloniceras martini zones) 673 is probably coeval with the SB identified in Spain (Bover-Arnal et al., 2009; Martín-Martín et 674 al., 2013; Embry et al., 2010) and in south-eastern France (H. Arnaud, pers. comm., 2014; Pictet 675 et al., 2015). The SB identified in Spain within the E. martini and Parahoplites melchioris zones 676 (Ruiz-Ortiz and Castro, 1998; Bover-Arnal et al., 2009; Martín-Martín et al., 2013) has been 677 recognized neither in the EAB, nor in southern France (Raddadi, 2004; Clavel et al., 2013). The 678 D3 identified in the EAB is located within the Acanthohoplites nolani Zone, and therefore, is 679 correlatable with the SB identified in southern Spain (Ruiz-Ortiz and Castro, 1998), while D4' 680 seems to be correlatable with the SB identified in the late Hypacanthoplites jacobi Zone in 681 Spain (Ruiz-Ortiz and Castro, 1998; Bover-Arnal et al., 2009; Martín-Martín et al., 2013) and 682 Tunisia (Chihaoui et al., 2010; Latil, 2011; Hfaied et al., 2013). D4 of the EAB, the erosional 683 surface of which contains the Aptian-Albian boundary, is easily correlated with the base of the 684 Hameima Fm in Central Tunisia (Chiahoui et al., 2010; Latil, 2011) and with the base of the 685 Alb 1 sequence of Hfaied et al. (2014) in southern Tunisia, both marked by a sedimentary hiatus. 686 In Spain, it probably correlates with the Aptian–Albian boundary of Martin-Martin et al. (2013) 687 and with Sb7 of Ruiz and Castro (1998). As a consequence, and taking into account that poor 688 sedimentary record may have locally limited SB identification in the EAB, the good 689 chronological correlations with other regions of the Tethys suggest that sea-level variations 690 were the main factor controlling the sedimentary discontinuities in the EAB during Aptian-691 early Albian times. 692

# 693 V.3. Calcareous nannofossil primary productivity and carbonate production

The nannofossil total absolute abundance depends on primary productivity in the water column, preservation, and sedimentation rate. Significantly lower nannofossil total absolute abundances are observed in Albian than in Aptian strata in samples with different preservation states (poor to good; Fig. 7) and thus do not result from a poor preservation. The decrease in nannofossil total abundance is associated with an increase in the relative abundance of high-fertility nannofossils indicators, which seems condradictory. Indeed, both high nannofossil total abundances and relative abundances of high-fertility taxa can be related to a high primary 701 productivity in marine surface waters. The Aptian lower parts of the sections are more 702 condensed with respect to the lower Albian upper parts, and the change to higher sedimentation 703 rates occurs above D4. Thus, the decrease in nannofossil total absolute abundances recorded in 704 all sections through early Albian times may be explained by an increase in the sedimentation 705 rate, with a dilution effect by the siliciclastic fraction. During the early Albian, enhanced 706 relative abundances of high-fertility taxa suggest an increase in the nannofossil primary 707 productivity.



708

Figure 11. Bivariate plot showing the relationship between CaCO<sub>3</sub> content and calcareous
 nannofossil absolute abundance for different time intervals, recognized in the Essaouira-Agadir basin.
 176 measurements from the Addar, Alma, Anzate, Ida w Shava, Tinfoul and Tiskatine sections.

1	170 measurements	jrom ine Aaaar,	Aima, Anzaie,	Iaa w	snayq, 11njo	oui ana Tiskaii

Таха	Surface-water fertility	Paleoceanography		
Biscutum constans	high1.2.3.4.5.6.7.8.9			
	high, but lower than Z. erectus <sup>10,11,12</sup>			
B. ellipticum*	high <sup>2</sup>			
	moderate to high13			
Biscutum spp.**	moderate <sup>14</sup>			
Crucibiscutum salebrosum		high latitude15,16,17		
Discorhabdus rotatorius	high <sup>4,5,18</sup>	-		
	moderate <sup>13</sup>			
Lithraphidites carniolensis	moderate <sup>4,5</sup>			
Nannoconus spp.	low <sup>9,18,19,20,21</sup>			
· · ·	low to moderate <sup>22</sup> , moderate <sup>23</sup>	warm waters9.24, deep-dweller21		
Repagulum parvidentatum		high latitude17,25,26,27,28		
Rhagodiscus angustus		high latitude27		
Seribiscutum gaultensis		high latitude29		
S. primitivum		high latitude <sup>1,2,3,16,17,27,28</sup>		
Zeugrhabdotus erectus	high <sup>1,2,3,6,7,10</sup>			
small Zeugrhabdotus (with major axis $\leq 5 \ \mu m$ )	high <sup>7,8,11</sup>			

\**B. ellipticum* is considered as a morphotype of *B. constans* (Bornemann and Mutterlose, 2006) \*\**Biscutum* spp.: *B. constans* (abundant), *B. ellipticum* (common) (Linnert et al., 2010)

712

- 713 Table 2. Paleoecological significance of selected calcareous nannofossil taxa. 1. Roth (1981); 2. Roth
- and Bowdler (1981); 3. Roth and Krumbach (1986); 4. Erba (1987); 5. Premoli Silva et al. (1989); 6.
  Roth (1989); 7. Watkins (1989); 8. Williams and Bralower (1995); 9. Mutterlose and Kessels (2000);
- 715 Roin (1989), 7. wakins (1989), 8. withans and Bralower (1999), 9. Multeriose and Ressets (2000),
   716 10. Erba (1992); 11. Erba et al. (1992); 12. Eleson and Bralower (2005); 13. Giraud et al. (2003); 14.
- 717
   Linnert et al. (2010); 15. Mutterlose (1992a); 16. Mutterlose (1992b); 17. Street and Bown (2000);
- 718 18. Coccioni et al. (1992); 19. Tappan (1980); 20. Busson and Noël (1991); 21. Erba (1994); 22.
- Pauly et al. (2012); 23. Scarparo Cunha and Shimabukuro (1997); 24. Mutterlose (1989); 25. Wise
  (1988); 26. Erba et al. (1989); 27. Crux (1991); 28. Watkins et al. (1996); 29. Lees (2002).

721 In a carbonate ramp setting such as the EAB, carbonate production may result from benthic 722 fauna and/or from pelagic organisms, such as calcareous nannofossils. We have investigated 723 more in detail the relationship between nannofossil total abundance and calcium carbonate content. When all data from the different sections are plotted, a correlation exists between these two variables, but remains unclear, especially for high values of calcium carbonate content (> 70%) corresponding to Aptian samples (Fig. 11). If the latter values are not taken into account, a low positive correlation (r = 0.343, with 162 values and p < 0.0001) is observed. This suggests that on the EAB ramp, the carbonate fraction was partly produced by calcareous nannofossils,

especially in sediments with values of calcium carbonate content lower than 70%.

The carbonate production was lower for the early Albian deposits in comparison to the Aptian deposits in the EAB. This is shown by a decrease in the carbonate content starting around D4 (Fig. 6), by a decrease in both semi-quantitative abundance and diversity of shallow marine benthic fauna, and by a decrease in the relative abundances of the bigger calcareous nannofossil calcifier such as *Nannoconus* spp (Fig. 6). The latter is considered as a deep dweller, which is more abundant in marine paleoenvironments with prevailing oligotrophic sea-surface conditions (Table 2).

737 In carbonate oligotrophic environments, the photic zone is supposed to be thicker than in siliciclastic environments, leading deep dweller to develop. This explains that nannoconids 1) 738 are less present in the proximal, more siliciclastic section of Tinfoul with respect to the other 739 sections, and 2) are much more abundant in the upper Aptian carbonate-rich deposits 740 corresponding to low fertility surface waters, with respect to the more siliciclastic deposits that 741 prevailed during the early Albian. Nannoconids are also associated with warm marine 742 paleoenvironments (Table 2). Decrease in their relative abundance in the latest Aptian-early 743 744 Albian interval may indicate cooler sea-surface temperatures. As a matter of fact, the significant increase in the relative abundance of cold water nannofossil taxa in the latest Aptian, and overall 745 in the earliest Albian, suggests that cooling occurred, but may be also due to connections with 746 747 higher latitudes, linked to the recorded sea-level rise. However, connections with higher latitudes cannot explain the decrease in the relative abundance of warm water nannofossil taxa, 748 such as nannoconids. In most of the studied sections the maximum relative abundance of cold 749 water taxa is reached in the early D. mammillatum ammonite Superzone. Such sea-water 750 temperature cooling in the late Aptian and earliest Albian is consistent with previous studies in 751 other Tethyan areas (e.g. Bottini et al., 2015; Bodin et al., 2015), although other authors 752 advocated for an ongoing warm climate in parts of the Tethyan realm (see discussion in Föllmi, 753 754 2012).

755

# 756 V.4. Dynamics of the EAB in Aptian–early Albian times

# 757 V.4.1. General statement

Deposition during the Aptian–early Albian is marked in the EAB by an overall low energy 758 environment, as documented by the lack of oolites, coral reefs or grainstone textures. 759 Additionnally, the abundance of pyrite in marls, together with the abundant buchidae, suggests 760 that bottom waters were little oxygenated in the middle to distal areas. Facies successions are 761 monotonous and lateral changes are quite gradual. These observations call for a very low-sloped, 762 even ramp topography. The lack of high-energy deposits is probably favoured by the 763 764 geographic location of the EAB on the western side of a continent. As a matter of fact, in the northern hemisphere, storms are formed in intertropical latitudes and shift first toward the West, 765 due to the trade winds, and then to the North, because of the Coriolis deviation, thus affecting 766 the eastern or southern coasts of the continents. Since the EAB is located on the northwestern 767 margin of Africa, storms were probably scarce, thus favoring a low energy regime and possibly 768 water stratification. Coastal upwelling enhanced by the westward trade winds might have 769 favoured biological activity, resulting in little oxygenation of bottom water in the outer ramp 770 771 and organic-rich deposition shoreward.

On the other hand, during the late Aptian–early Albian interval, the faunal assemblages are dominated by brachiopods, oysters, plicatulids, pectinids and other bivalves, as well as serpulids, gastropods and irregular urchins. Conversely, they are almost devoid of oolites, oncolites, stromatolites, corals, rudistids and algae. This suggests that, in spite of its intertropical latitude (15 to 20° lat. N; e.g., Trabucho-Alexandre et al., 2011), the EAB behaved as a temperate platform, at least during late Aptian and early Albian times.

The occurrence of phosphate- and glauconite-rich crusts or clasts suggests that the EAB was 778 submitted to cold, upwelling currents, as documented by Leckie (1984), Herrle et al. (2004), 779 Haydon et al. (2008) and Hofmann et al. (2008) along the Moroccan margin. This interpretation 780 is supported, on one hand by the abundance of glauconite and phosphate clasts in upper Aptian 781 to lower Albian deposits. On the other hand, the westernmost areas (Tamri, Assaka, Imsouane; 782 783 Fig. 1 and 9) exhibit very condensed sections, where 50 cm-thick, glauconite- and phosphaterich conglomerates contain ammonites of early Aptian to earliest Albian age. Such a 784 condensation may be attributed to significant, continuous upwelling currents affecting the 785 western edge of the ramp during Aptian to earliest Albian times. 786

# 787 V.4.2. Comparison between Aptian and latest Aptian–early Albian environments

Albian facies differ from the Aptian ones by the abundance of clastic input. A high carbonate 788 production is favoured by a large photic zone, few terrigenous influx, warm sea-surface 789 790 conditions and slow rise of sea level. Albian facies differ from the Aptian ones by the abundance of detrital input. Aptian deposits comprise marls and limestones, with few, fine grained detrital 791 quartz. Conversely, Albian sedimentation is marked by silty marls and shales, and sandstones. 792 793 This provoked a change in the overall faunal content. As a matter of fact, pectinids and irregular sea urchins, common in the Aptian beds, are much scarcer in lower Albian deposits, whereas 794 oysters and plicatulids are much more abundant in the latter. In the same way, scarce corals are 795 796 present in the Aptian succession but are totally absent in the lower Albian series. Although the development of oysters from Albian times onward is a widespread feature that may be related 797 to a global sea-level rise (Dhondt et al., 1996), this suggests also that the lower Albian 798 799 environment is marked by more important terrigenous sediment supply (local occurrence of plant fragments), and associated nutrients input to the basin, which led to both a reduction of 800 the photic zone depth, and a change from oligotrophic to mesotrophic conditions, illustrated 801 both by increasing calcareous primary productivity and the faunal change. Increasing 802 terrigenous supply was probably caused by enhanced runoff from the emergent continents 803 during more humid climatic conditions. However, the highest nannofossil primary productivity 804 conditions are recorded above D4 (L. tardefurcata and early D. mammillatum ammonite Zones), 805 806 which corresponds to a period of sea-level rise. Therefore, increasing nutrient content could also be due to upwelling encroaching the platform during sea-level rise and high sea-level 807 808 periods.

The average deposition depth seems to have been higher in the early Albian than during the 809 Aptian. During the latter period, the deposition depth varied between 0 meters (S 1) and little 810 below the lower limit of the euphotic zone (F 1), whereas in the early Albian, deposition depth 811 812 varied from the fair weather wave base (F IV), to largely below the euphotic zone (lack of benthic macrofauna in F I). However, this qualitative assessment may be exaggerated, as the 813 more important detrital sediment supply during the early Albian might have reduced the 814 thickness of the photic zone because of repeated clay input into the basin. Therefore, we cannot 815 816 rule out that facies F II and F III may have been deposited in environments equivalent to, or slightly shallower than, facies F 1 and F 2, respectively. 817

818 The average energy level that prevailed during deposition of the lower Albian succession was819 higher that during the Aptian, as shown by the occurrence in the lower Albian succession of

erosional surfaces, dolomitic sandstone beds and current structures in the latter. Since many of
these beds overlie erosional surfaces and thus correspond to drops in sea level, this suggests
that these high energy deposits were sedimented in an environment shallower than the storm
wave base, or even shallower than the fair weather wave base. This supports the fact that the
average deposition depth remained moderate, even during the early Albian.

825 Finally, the F D facies are restricted to the lower Albian succession, which suggests that the EAB ramp was more oxygen-depleted at that time, than during the Aptian. Two causes may be 826 invoked. On one hand, the O<sub>2</sub> depleted zone may have been too deep to reach the Moroccan 827 ramp during the Aptian, whereas, the higher deposition depth during the early Albian allowed 828 the O<sub>2</sub> depleted zone to reach and impinge upon the EAB. On the other hand, the influence of 829 upwelling currents may have favoured the marine life in the outer zones of the ramp, consuming 830 a part of the available oxygen through biological activity and organic matter degradation, thus 831 favoring the extension of the O<sub>2</sub> depleted zone onto the EAB ramp (e.g. Erbacher et al., 1996; 832 Haydon et al., 2008). One of these O<sub>2</sub> depleted deposits may have been coeval with the OAE1b, 833 since it occurred in Tamzergout during the L. tardefurcata ammonite Zone (Peybernès et al., 834 2013), and has been recognized in Takoucht at the same level (Fig. 5 and 10). There, TOC 835 measurements indicate fluctuations around 1% TOC, but due to the lack of other TOC analysis 836 in other intervals, no comparison can be made. 837

838

# 839 V.5. Paleogeographic and tectonic evolution

During latest Barremian to earliest late Aptian times (Sequences 1 and 2, M. sarasini to E. 840 martini p.p. ammonite Zones), the western, southern and eastern areas of the basin are marked 841 842 by repeated emersions (numerous karstic and epikarstic cavities), which likely produced erosions of part of the previous deposits. As a consequence, S1 and S2 in these areas are absent 843 or extremely reduced. In many sections, however, the occurrence of ammonites shows that 844 marine sedimentation sporadically occurred. Significant carbonate sedimentation only took 845 place in the central part of the EAB (Fig. 12A). This pattern seems inherited from the latest 846 Barremian paleogeography, during which only in the central part of the EAB accumulated a 847 significant thickness of fine-grained marine sandstone ( $\approx 5$  m), while the western and southern 848 part of the area where submitted to subaerial to submarine condensation (Jaillard et al., 2019) 849 It suggests that the western and southern parts of the EAB were slightly uplifted with respect 850 to the central part around the Barremian-Aptian boundary. 851

During late Aptian and early Albian times (Sequences 3 to 5), an increase of the depositional 852 depth is recorded by the eastward retrogradation of the sedimentary facies. Shallow marine 853 carbonates were dominant during Sequence 3 and almost disappeared during Sequence 5, 854 whereas outer ramp deposits were absent during Sequence 3 and became predominant during 855 Sequence 5 (Figs. 12B to 12D). Meanwhile, the southern coastal part of the area (Asaka, Tamri) 856 recorded a submarine condensation (glauconites, phosphate) likely related to upwelling 857 currents, assumed to be active offshore the Moroccan margin in Aptian-Albian times (Herrle 858 et al., 2004; Haydon et al., 2008). Deposition resumed during earliest Albian times, since 859 Sequence 5 is recorded in all studied sections. Note that the Tamzergout area shows a quite 860 localized thickness anomaly, which suggests an anomalous subsidence regime. 861

B62 During the early Albian, the studied outcrops are unsufficient to allow detailed facies mapping. B63 However, Sequences 6 and 7 (late *L. tardefurcata* and early *D. mamillatum* Zones) are dominated by outer ramp facies in all areas, including in the southwestern part of the area where the long-lasting submarine condensation ended, and by more homogeneous thicknesses. The thickness anomaly of the Tamzergout area seems to have disappeared.



867 868 869 *E* 

Figure 12. Paleogeographic and isopach maps of the study area. A. Sequences 1 and 2 (latest Barremian-Early Aptian); B. Sequence 3 (Early Late Aptian); C. Sequence 4 (latest Aptian); D. Sequence 5 (earliest Albian).

872 As a whole, the paleotopography inherited from the Upper Barremian tectonic event (i.e. uplift of the southern and western areas; Jaillard et al., 2019) seems to be progressively leveled by the 873 lower Aptian accumulation. However, subsidence anomalies are recorded around the present-874 day Amsittene and Imouzzer anticlines, which are presently underlain by evaporitic diapirs 875 (Mrhidek et al., 2000; Tari and Jabour, 2013). To the north, the Amsittene anticline and its 876 surroundings are marked by a low subsidence regime (Aptian sequences are less than 10 m 877 thick), and to the south, the Imouzzer anticline is first uplifted (Sequences 1 and 2), and then 878 presents an anomalously high subsidence in the Tamzergout section. This localized subsidence 879 anomaly is most likely related to the presence of underlying evaporites, and may be due either 880 to the formation of a rim-syncline or mini-basin located in the vicinity of a rising diapir (e.g. 881 Gilles and Rowan, 2012; Brandes et al., 2012), or to a collapse structure above a karstic system 882 caved in evaporites (e.g. Belderson et al., 1978; Guttiérrez et al., 2008). In the latter 883 interpretation, the occurrence of repeated emersions may have favoured dissolution of evaporite, 884 885 but the radial or concentric normal faults, commonly associated with these structures (Stewart, 2006), were not observed in the field, neither at small-scale, nor at large-scale. In the former 886

interpretation, the absence of normal faults is frequent in rim-syncline structures, which show
locally a ring-shaped morphology or are surrounded by uplifted areas above the rising diapir.
These features seem consistent with our data, but more geological observations and surveying
are needed to choose between these two interpretations.

891

# 892 VI. CONCLUSIONS

893 Our detailed study of the Aptian–lower Albian succession of the EAB allowed to define a 894 biostratigraphic framework, correlated with the standard ammonite zonation of Europe. In this 895 scheme, lowermost Aptian deposits are lacking, lower Aptian strata are poorly represented, and 896 the Aptian–Albian boundary is included within a hiatus marked by a major sedimentary 897 diecontinuity.

898 Careful analysis of sedimentary facies and surfaces made possible to decipher the sedimentary 899 evolution of the EAB during Aptian–early Albian times, and to subdivide this interval into eight 900 depositional sequences. The latter can be correlated with coeval sequences identified in other 901 Tethyan areas, thus suggesting that they were mainly controlled by eustatic variations. In this 902 context, the lack of the lowermost Aptian sequences is most probably related to the significant 903 sea-level fall recorded at that time (Haq, 2014).

904 As a whole, Aptian-lower Albian sediments of the EAB were deposited on a low energy ramp that evolved from a carbonate to a mixed carbonate-clastic system. This evolution occurred 905 progressively in Late Aptian times and was associated with an increase of sandy and shaly 906 907 deposits, with a change from oligotrophic to mesotrophic faunal and nannofossil assemblages, and with and increase of cold water nannofossil taxa indicating a cooling of sea-surface 908 temperatures. Deposition depth seems to be slightly higher in the early Albian than during the 909 Aptian, consistent with the eustatic sea-level rise recorded at that time. The more energetic 910 environment displayed by lower Albian deposits, together with the occurrence of dysaerobic 911 deposits and the abundance of phosphate and glauconite, suggest that upwelling currents were 912 significant in Aptian to early Albian times. 913

914 The overall sea-level rise in the late Aptian and early Albian is illustrated by the evolving facies 915 distribution on paleogeographic reconstructions. Furthermore, the latter evidence subsidence 916 anomalies around the present-day anticlines cored by evaporites, thus suggesting the play of

917 mild halokinetic movements during Aptian–early Albian times.

918

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