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1 **The Moroccan High Atlas phosphate-rich sediments:**
2 **unraveling the accumulation and differentiation processes**

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11

12 **Abstract**

13 The phosphate series of the Moroccan High Atlas accumulated during the Upper
14 Cretaceous-Paleogene phosphogenic period, on a biologically-productive shallow-water
15 platform. These phosphate-rich sediments were deposited during a relative sea-level
16 cycle generating major stratigraphic surfaces. Five different types of phosphate
17 lithofacies are recognized, based on their petrographic and sedimentologic features. The
18 *pristine phosphate* lithofacies corresponds to phosphatic marls formed by francolite
19 authigenesis within the outer platform domain below the storm wave-base (primary
20 phosphogenesis zone). This primary phosphate lithofacies can be differentiated as a
21 result of the interaction between hydrodynamic autocyclic processes and allocyclic
22 forcing. Accordingly, the *granular phosphate* lithofacies was formed by in-situ storm and
23 bottom currents that winnowed the pristine phosphate. This winnowed lithofacies,
24 composed of densely-packed peloids, shows relatively high P₂O₅ concentrations. The
25 *turbiditic phosphate* resulted from the basinward transport and deposition of other
26 phosphate types by gravity flows leading to normally-graded phosphate sediment. The
27 *phosphatic lags* were formed by wave reworking and transporting of pristine and
28 associated granular facies within the inner platform. The *karst-filling phosphate*
29 corresponds to former phosphate types transported by early transgressive currents and
30 trapped within karstic pockets as microconglomeratic phosphate. The distribution of the
31 different phosphate types across the margin and within the depositional sequences is
32 controlled by the effects of relative sea-level changes. The pristine phosphate and
33 associated winnowed facies are found above the major maximum flooding surface, which
34 is dated by nanoflora to the Selandian-Thanetian transition. The phosphatic turbidites
35 occurred during periods of high sea-level. The karst-related phosphatic facies

36 accumulated during early transgressive stages. The phosphatic lags accumulated mainly
37 during the regressive phases of third and fourth order sequences. The accumulation
38 processes of the different phosphate lithofacies control the ore grade of the phosphatic
39 sediments: repeated storm-induced winnowing of pristine phosphate contributes to
40 enrichment of the phosphate ore grade.

41 **Keywords**

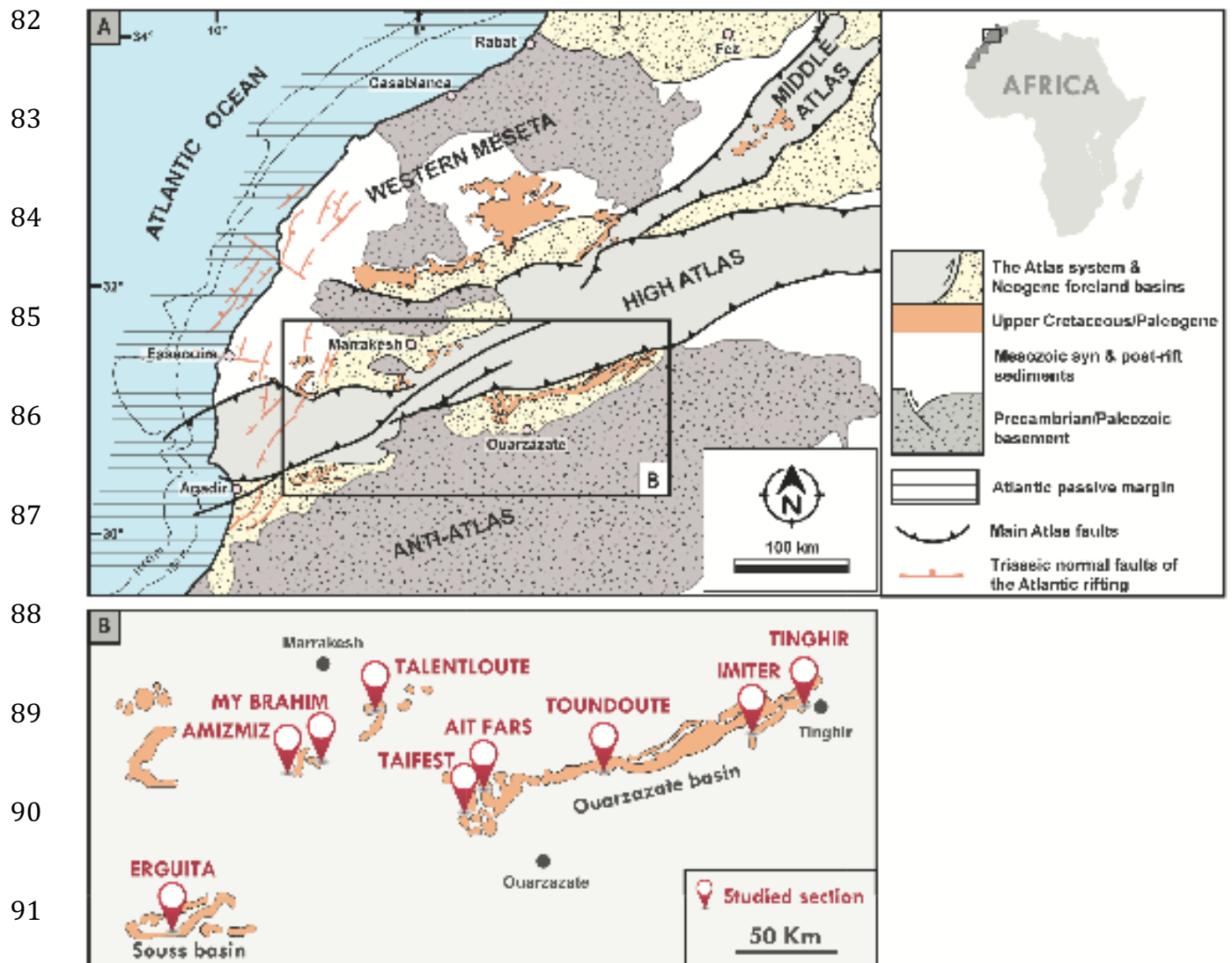
42 Phosphate accumulation, winnowing, reworking, High Atlas, Morocco, Upper Cretaceous-
43 Paleogene

44 **1. Introduction**

45 Sedimentary phosphate is a strategic phosphorus (P) resource, essential for agriculture
46 and industry (Glenn et al., 1994). The processes controlling phosphogenesis (the
47 authigenic precipitation of P-bearing minerals, mainly francolite which is a carbonate
48 fluorapatite; Föllmi et al., 1993; Jarvis et al., 1994) have stimulated considerable
49 discussion, giving rise to multiple theories (e.g., inorganic vs. organic precipitation of
50 apatite; Trappe, 1998, and references therein). Major advances in phosphate
51 geochemistry have led to a consensus on phosphogenesis involving biochemical
52 processes (Glenn et al., 1994; Jarvis et al., 1994; Krajewski et al., 1994). Consequently, it
53 has been demonstrated that phosphogenesis can occur in a large array of sedimentary
54 environments, from deep basin areas to anoxic marginal basins (Filippelli, 2011). The
55 diversity of sedimentary environments where phosphogenesis has been documented
56 argues for diverse geochemical, hydrodynamic, and paleoenvironmental controls. Thus,
57 phosphogenesis is not a unique process and it cannot lead by itself to phosphate-rich

58 sediments, without the intervention of post-phosphogenesis agents which facilitate ore
59 accumulation, concentration, and enrichment (Baturin, 1982). Despite their critical role
60 in the phosphate accumulation, these post-phosphogenesis agents remained
61 understudied. Phosphate-rich sediments are traditionally subdivided into primary and
62 reworked facies (e.g., Trappe, 1998, Föllmi 1996, 2016; Glenn et al., 1994; Pufahl et al.,
63 2003; Soudry et al., 2013; Pufahl and Groat 2017). Primary or pristine phosphate refers
64 to phosphatic fine sediments preserved in their initial state without undergoing
65 transport or reworking. It is generally of low P₂O₅ content within the host sediment.
66 Reworked phosphate is regarded as typically granular facies deposited by hydrodynamic
67 reworking agents. It is of economic interest due to the concentration of phosphatic grains.
68 When concentration reaches 18%wt P₂O₅, it is named phosphorite (Slansky, 1986).
69 Phosphate accumulations occur preferentially on continental shelves and epeiric seas,
70 where the water depth allows permanent, periodic or occasional reworking of the water-
71 sediment interface (Baturin, 1982; Glenn et al., 1994; Föllmi, 1996; Pufahl and Groat,
72 2017).

73 The Upper Cretaceous-Eocene interval is among the significant phosphogenic periods
74 known in the geological record (Pufahl and Groat, 2017). During this period, the Tethyan
75 province saw the formation of large sedimentary phosphate deposits which are now
76 exploited (Notholt 1985); e.g., in Algeria (Kechiched et al., 2018), Tunisia (Ounis et al.,
77 2008), and Egypt (Baioumy et al., 2007). Contemporaneous phosphate deposits of
78 Morocco correspond to the largest sedimentary phosphate reserve (70% of world-known
79 reserves; Jasinski, 2018). These deposits are currently mined in the central part of
80 Morocco (Meseta domain) and in the south, yet other occurrences exist along the High
81 Atlas (Fig. 1A).



92 Fig. 1. (A) Simplified structural map of Morocco illustrating the spatial distribution of the
 93 Upper Cretaceous-Paleogene phosphate-rich sediments and highlighting the main
 94 structural and geodynamic features of the Moroccan Atlas system. Modified after Hafid et
 95 al. (2006). (B) Location of the investigated sections along the northern and southern
 96 borders of the High Atlas system.

97 The exploited phosphate deposits of the Meseta have been extensively and repeatedly
 98 studied since first discoveries of phosphate in Morocco by Brives (1905). Previous work
 99 focused on phosphate petrography and granulometry (Salvan, 1986; Mouflih, 2015), and
 100 geochemistry (Belfkira, 1980; Prévôt, 1988). Basin-scale studies were conducted for

101 mining purposes (Boujo, 1976; Belfkira, 1980; Salvan, 1986; Gharbi, 1998). The
102 phosphate series of Morocco has attracted paleontologists for its extraordinary and well-
103 preserved vertebrate fauna (see Bardet et al., 2017, for review).

104 In spite of these numerous studies on the Moroccan phosphate series, accumulation and
105 preservation processes are poorly known. The relationship between sedimentary
106 processes and phosphate accumulation is still not well constrained. The exploited
107 phosphorites correspond to extensive, thin, tabular beds accumulated by reworking
108 (Belfkira, 1980; Boujo, 1976). However, there is this far, no record of the original pristine
109 phosphate sediments. Consequently, the succession of events between primary
110 phosphogenesis and final phosphorite accumulation and preservation remains unknown.

111 The presently exploited phosphorites basins of the Moroccan Meseta are flat-lying, often
112 covered by Pliocene to Recent sediment. Sections are only visible along the active
113 excavations of the open-cast mines, which are difficult to access for scientific
114 investigations. For these reasons, we targeted the contemporaneous phosphate-bearing
115 series along the High Atlas margins offering excellent section exposures of the folded
116 Cretaceous to Eocene sequences, which allows stratigraphic correlation. The purpose of
117 this study is to unravel the different processes behind the concentration and
118 accumulation of phosphate-rich sediments of the Moroccan High Atlas, using
119 sedimentologic and sequence stratigraphic tools. We present a detailed facies and facies
120 association analysis, describe and interpret the different accumulation modes of
121 phosphate, and establish the sequence stratigraphic framework of the studied series. This
122 requires a well-defined stratigraphic framework. In this study, we trace the post-genesis
123 pathways of phosphatic grains and the interaction between sea-level variations and
124 phosphate deposition. We analyze the lateral evolution of phosphate types across the

125 basin, and propose an integrated model for the phosphate accumulation within the High
126 Atlas of Morocco.

127 **2. Geological setting**

128 The investigated Upper Cretaceous-Paleogene sedimentary successions are located along
129 the northern and southern borders of the NE-striking High Atlas belt of Morocco, in the
130 Marrakech - Ouarzazate area ([Fig. 1A](#)). This orogen corresponds to a Mesozoic-Paleogene
131 intracontinental basin (Atlasic Basin), which was inverted during the Neogene ([Michard
132 et al., 2008](#); [Frizon de Lamotte et al., 2009](#)). The mountain range exhibits double verging
133 thrusts, resulting in high tabular plateaus in the axial part ([Fekkak et al., 2018](#)).

134 The evolution of the High Atlas started in the Triassic with the creation of the Atlasic
135 basins linked to the Central Atlantic rifting and the formation of the Atlantic passive
136 margin ([Tucholke et al., 2007](#); [Schettino and Turco, 2009](#); [Frizon De Lamotte et al., 2015](#)).

137 The basins have recorded important post-rift, thermally-enhanced subsidence of the
138 Atlantic margin ([Ellouz et al., 2003](#)), leading to the deposition of thick sequences of
139 Mesozoic sediments. The thermal cooling faded away with time and by the Upper
140 Cretaceous period, subsidence had drastically decreased ([Ellouz et al., 2003](#); [Tari et al.,
141 2012](#)). Consequently, relatively thin Paleogene successions, including the phosphate
142 series, accumulated in the Atlasic basin.

143 The major uplift and inversion event of the High Atlas was initiated during the Neogene,
144 i.e., postdating deposition of phosphate-rich sequences. The former syn-rift faults were
145 reactivated and inverted in response to the convergence between Africa and Eurasia
146 plates (e.g., [Beauchamp et al., 1999](#); [Frizon de Lamotte et al., 2009](#); [Frizon De Lamotte et](#)

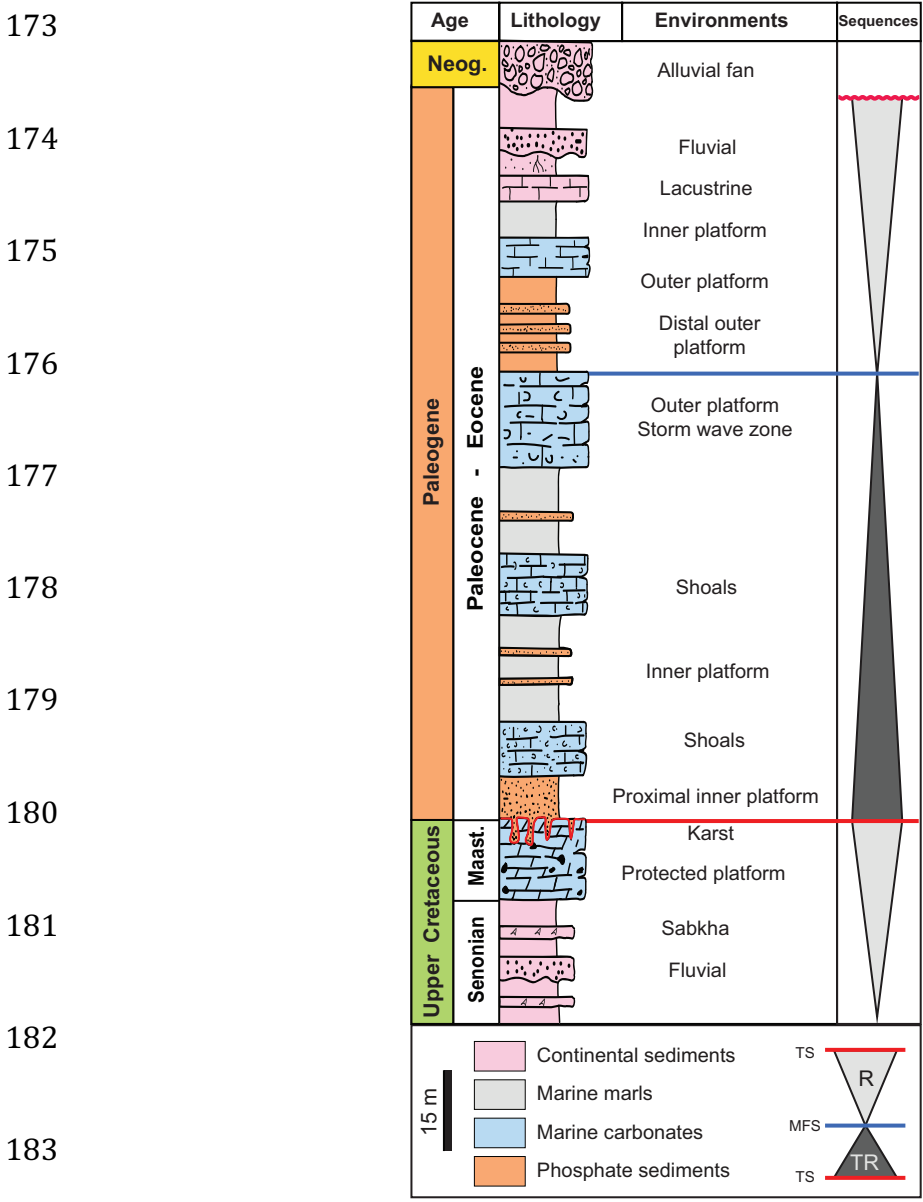
147 al., 2015). This ongoing uplift is also enhanced by deep thermal processes (Leprêtre et al.,
148 2015; Missenard et al., 2008; Teixell et al., 2005). Foreland basins were created north
149 (Marrakesh), and south (Ouarzazate and Souss) of the orogen and filled with continental
150 molassic sediments delivered by the erosion of the uprising belt (Görler et al., 1988;
151 Chellai and Perriaux, 1996; El Harfi et al., 2001; Michard et al., 2008).

152 The phosphate-rich sediments of the Moroccan High Atlas belong to the late Cretaceous-
153 Paleogene stratigraphic interval (Trappe, 1991; Chellaï et al., 1995; Marzoqi and Pascal,
154 2000). At that time, the Atlas phosphate basins were bordered to the south by the large
155 Paleozoic fold belt of the Anti-Atlas, constituting the southern hinterland area, and to the
156 north and east by the deformed Variscan basement of the Western Meseta (Herbig and
157 Trappe, 1994). These phosphate basins extended westwards to the Atlantic passive
158 margin and the westward thickening of the formations (Boujo, 1976) is related to the
159 increasing subsidence towards the passive margin. These phosphate accumulations are
160 hosted by a marine-dominated sedimentary succession displaying shallow-water
161 platform environments (Fig. 2). They are bounded by under- and overlying continental
162 sediments. The phosphate series of the High Atlas is subdivided into two sedimentary
163 systems separated by a regional-scale discontinuity formed during a second-order
164 transgressive-regressive cycle (Chellaï et al., 1995; Marzoqi and Pascal, 2000).

165 **3. Methodology**

166 This work is based on nine sections, measured along the margins of the Moroccan High
167 Atlas (Fig. 1B). They extend over 300 km from northeast to southwest and over 100 km
168 from the southeast, close to the Anti-Atlas Precambrian basement, to the northwest in the
169 Marrakesh area. Detailed field measurements were carried out, based on bed-by-bed

170 description. We sampled the studied series in multiple locations for petrographic and
 171 biostratigraphic purposes. We defined facies and facies associations based on field and
 172 petrographic observations, which allowed to interpret the sedimentary processes and



184 Fig. 2. Synthetic log of the Moroccan High Atlas phosphate-bearing series showing the
 185 marine dominated character of the studied sedimentary successions. Depositional
 186 sequences are from Chellai et al. (1995). TR: Transgressive hemicycle; R: Regressive
 187 hemicycle; TS: Transgressive surface; MFS: Maximum flooding surface.

188 visualize the evolution of the depositional environments. Biostratigraphic dating was
189 based on nannofossil analysis. The sediments collected have been studied in the fraction
190 of 2-30 μm , separated by the decantation method using 7% solution of H_2O_2 . Smear-slides
191 have been mounted with Canada balsam and analyzed at an Olympus transmitting light
192 microscope, with 1200x magnification. The preservation was estimated by using the
193 criteria proposed by [Roth and Thierstein \(1972\)](#), as follows: P = poor, severe dissolution,
194 fragmentation and/or overgrowth; the specific identification is hindered up to 75%; M =
195 moderate dissolution and/or overgrowth; the specific identification is hindered up to
196 25%; and G=good, little dissolution and/or overgrowth; diagnostic characteristics are
197 preserved, the specimens could be identified to species level (up to 95%). Calcareous
198 nannoplankton taxonomic identification follows [Perch-Nielsen \(1985\)](#) and [Burnett](#)
199 [\(1998\)](#). Biostratigraphic zones NP are from [Martini \(1971\)](#).

200 **4. Age of the series**

201 The phosphate series of Morocco ranges from the Upper Cretaceous to Paleogene.
202 However, the precise limits of the different stratigraphic intervals are still unclear. The
203 correlations and sequence stratigraphic interpretations we develop in this study require
204 a critical review of the biostratigraphy. The currently acknowledged age framework is
205 mainly based on early biostratigraphic works in the 20th century (e.g., [Moret, 1938](#);
206 [Arambourg, 1952](#)). The leading paleontological works were carried out within the
207 exploited phosphate basins (Ouled Abdoun and Ganntour), which contain remarkably
208 rich vertebrates and invertebrates' faunas. Selachian fauna is the most studied
209 [\(Arambourg, 1952; Cappetta, 1981, 1986, 1993; Noubhani and Cappetta, 1994;](#)
210 [Noubhani, 2010; Cappetta et al., 2014\)](#). Other biostratigraphic studies were carried out

211 including, invertebrates (Salvan, 1954), dinoflagellates (Rauscher and Doubinger, 1982;
212 Rauscher, 1985; Soncini, 1992), and pollens (Ollivier-Pierre, 1982). Hundreds of species
213 have been discovered and compared to their European and North African equivalents.
214 Following his pioneering paleontological study of vertebrates, Arambourg (1952)
215 assumed that the phosphate series of Morocco extended from Maastrichtian to Lutetian
216 and he defined three bio-units: Upper Cretaceous (Maastrichtian), Paleocene (Danian and
217 Thanetian), and Eocene (Ypresian and Lutetian). Most of the subsequent studies focused
218 more on the paleontological rather than stratigraphical consequences, and do not change
219 significantly the bio-units defined by Arambourg (1952). More recently a
220 chemostratigraphic approach, based on organic carbon isotopes, has been conducted
221 within the Ouled Abdoun basin (Yans et al., 2014). The $\delta^{13}\text{C}_{\text{org}}$ data indicates the
222 presence of the Selandian, a possible gap of the upper Thanetian, and supports the
223 absence of Lutetian occurrence within the phosphate series of Ouled Abdoun.

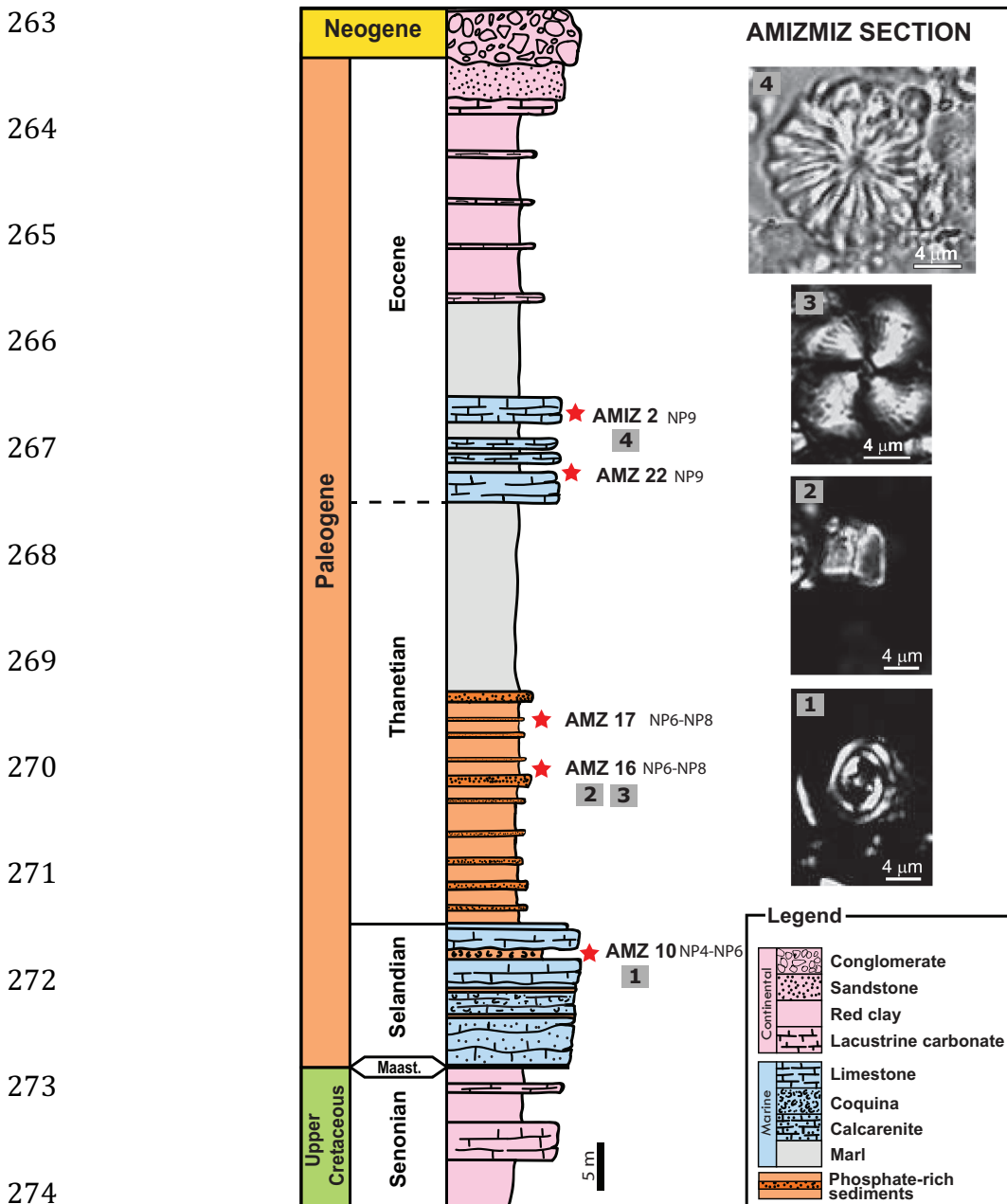
224 The phosphate series of the High Atlas is by far less studied when compared to the
225 exploited basins. The stratigraphic framework is based mainly on older works (Moret,
226 1938) and the identification of three mollusk fauna horizons within the Ouarzazate basin:
227 Fauna A (Maastrichtian-Danian), Fauna C (Thanetian-Ypresian), and Fauna B (Ypresian-
228 Lutetian). It can be noted that the inconsistent labeling of horizons has been a source of
229 later misinterpretations. This work was completed by Roch (1939) and Gauthier (1960),
230 who contributed to the recognition of the lower parts of the series (Maastrichtian and
231 Danian) Arambourg (1937) defined the Lutetian in the upper parts of the series as he
232 discovered *Carolia placunoïdes* within phosphatic marls. Selachian fauna was locally
233 studied within the eastern part of the Ouarzazate basin and compared to its equivalent
234 within the exploited basins (Cappetta et al., 1987; Gheerbrant et al., 1993; Tabuce et al.,

235 2005). Pollen and microplankton were also studied within the Upper Ypresian-Lower
236 Lutetian (Mohr and Fechner, 1986). A magnetostratigraphic approach has been
237 attempted in the eastern part of the Ouarzazate basin, suggesting much younger ages for
238 the series and attributing the lower red-beds, classically known as Senonian, to the
239 Thanetian-Danian (Gheerbrant et al., 1998).

240 The reliability of these biostratigraphic age determinations is questionable since facies
241 are frequently diachronous and the study of Selachian fauna was mostly interested in the
242 evolutionary trends of the species. The magnetostratigraphic results are not relevant
243 since the interpretation of magnetic reversal profiles was performed assuming two
244 different scenarios with constant sedimentation rates for the entire series.

245 As seen above, the age control of the studied sequence is poorly constrained in the
246 Maastrichtian to Eocene outcrops along the borders of the High Atlas. No
247 biostratigraphically significant macrofossils nor foraminifera were found in the marine
248 intervals so, we sampled Amizmiz and My Brahim sections for calcareous nannofossils.
249 Only some of the Amizmiz section samples yielded nannoflora (Fig. 3). Some of the
250 analyzed samples yielded more diversified and poorly to moderately preserved
251 nannofossils; the assemblages contain typical Paleocene to Lower Eocene nannofossils,
252 such as *Zygrhablithus kerabyi*, *Discoaster multiradiatus*, *Sphenolithus primus*, *S.*
253 *anarrhopus*, *Fasciculithus tympaniformis*, *F. hayii*, *Coccolithus pelagicus*, *Braarudosphaera*
254 *bigelowii*, *Heliolithus kleinPELLI*, *Bomolithus bramlettei*, *Zeugrhabdotus sigmoides*, and
255 *Toweius* spp. No reworked nannofossils from older deposits have been encountered in
256 the identified assemblages.

257 The sample AMZ 10 contains rare specimens of *Fasciculithus tympaniformis*, *Coccolithus*
 258 *pelagicus*, *Zeugrhabdotus sigmoides*, *Toweius pertusus*, *Biscutum* sp. and *Thoracosphaera*
 259 *saxea*. The FO of *Toweius pertusus* (NP4 biozone) took place in the late Danian. In the
 260 assemblages, *Fasciculithus tympaniformis* is also present; the FO of the aforementioned
 261 species is placed towards the top of NP5 in the Selandian ([Agnini et al., 2007](#)). Hence, a
 262 late Danian to Selandian age may be assumed for this sample.



275 Fig. 3. Sedimentary log of the Amizmiz section with biostratigraphic samples containing
276 nannofossils plotted in red stars. All the presented nannofossils are LM (light
277 microscope) photomicrographs in N+ (crossed-nicols), except the nannofossil 4 observed
278 in NII (polarized light). 1 – *Zeugrhabdous sigmoides* (Bramlette and Martini, 1964; Bown
279 and Young, 1997); Sample AMZ 10. 2 – *Fasciculithus tympaniformis* (Hay and Mohler in
280 Hay et al., 1967); Sample AMZ 16. 3 – *Heliolithus kleinpellii*; Sample AMZ 16. 4 –
281 *Discoaster multiradiatus* (Bramlette and Riedel, 1954); Sample AMIZ 2.

282 An assemblage with *Heliolithus kleinpellii*, *Fasciculithus tympaniformis*, *Sphenolithus*
283 *primus*, *Coccolithus pelagicus*, *Braarudosphaera bigelowii*, *Zeugrhabdotus sigmoides*,
284 *Toweius* spp. and *Ellipsolithus macellus* was found in the sample AMZ 16. *Heliolithus*
285 *kleinpellii* firstly occur towards the top of the NP6 biozone (Agnini et al., 2007). This bio-
286 event, along with the presence of *Toweius* taxa, including *Toweius tovae*, are indicative of
287 a late Selandian to Thanetian age (NP6-NP8 biozones). A similar age was recorded in the
288 sample AMZ 17. The occurrence of *Discoaster multiradiatus* in the samples AMZ 22 and
289 AMIZ 2 indicates the presence of NP9 biozone (Agnini et al., 2007), late Thanetian in age.
290 Our new biostratigraphic data suggest an older age than previously established for the
291 phosphate accumulation in the High Atlas area. The upper phosphate-rich interval spans
292 the entire Paleocene, over a 10 My period.

293 **5. Facies analysis**

294 The studied sections consist of carbonate-dominated sediments containing significant
295 phosphate accumulations. Detailed field and microscopic observations of the
296 investigated sedimentary successions allowed the identification 26 facies, interpreted in

297 terms of sedimentary processes and depositional environments, providing clues about
 298 paleobathymetry and helping to trace the relative sea-level variations curve. Genetically-
 299 related facies were grouped into six facies associations (FA) defining depositional
 300 environments. Facies associations are summarized in [table 1](#).

Facies association	Description	Interpretation
FA1	Coarsening upward successions; medium-grained sandstone with steep cross-bedding sets; thick evaporitic red-beds; parallel horizontally-laminated chalky limestones with <i>Charophyta</i> and <i>Ostracods</i> ; carbonate concretions and glaebules with roots traces; planar cross-stratified fine-grained sandstone; matrix-supported polygenic conglomerates (Fig. 4A-F).	Alluvial plain environment Debris flow Fluvial unidirectional currents Aeolian dune migration Lakes and evaporitic sabkha
FA2	Thick successions of interbedded grey marls and carbonates; mudstone to wackstone textures, horizontal parallel laminations, <i>Thalassinoides</i> bioturbation, poorly diversified fauna with relatively well-preserved thin shells of bivalves and gastropods (Fig. 4G-M).	Protected platform Suspension fallout
FA3	Geometrically irregular and discontinuous sedimentary bodies; coquina beds with fragmented shells of oysters and gastropods; cross-bedded calcarenites and phosphatic sandstones (Fig. 4N-P).	Open inner platform Shoal, wave reworking
FA4	Carbonate and sandy material; packstone to grainstone textures; diversified fauna including <i>Nautiloids</i> , echinoids, oysters, and scarce foraminifera; <i>Thalassinoides</i> bioturbation; bed amalgamation and hummocky cross stratifications (Fig. 5A-F).	Outer platform between fair-weather wave-base and storm wave-base
FA5	Muddy carbonate; parallel thinly-laminated phosphatic marls; granular phosphate beds with densely packed peloids; climbing ripples; micro-hummocky cross stratification; <i>Nautiloids</i> ; <i>Thalassinoides</i> burrows (Fig. 5G-J).	Around the storm wave base, storm winnowing of phosphate
FA6	Fine dark muddy organic-rich levels intercalated with normally graded sandstones to conglomerates, composed of a mixture of phosphatic and detrital particles (Fig. 5K-L).	Offshore suspension fallout episodically interrupted by gravity flows.

301 Table 1: Summary of facies associations in the Upper Cretaceous-Paleogene phosphate
 302 series of the Moroccan High Atlas.

303

304 **FA1. Alluvial plain**

305 *Description:*

306 This facies association is well exposed across the investigated zones. It systematically
307 bounds the carbonate intervals of the sections. FA1 is organized in coarsening and
308 thickening-upward succession in the uppermost parts of the sections, while it shows
309 finning-upward trend in the lower parts. FA1 includes cross-laminated sandstones (F1),
310 matrix-supported conglomerates (F2), evaporitic red-beds (F3), planar cross-stratified
311 sandstones (F4), ostracod and charophyta chalky limestones (F5), and carbonate
312 concretions and glaebules (F6).

313 F1 is preserved locally within Ouarzazate basin. It corresponds to m-scale intervals of
314 medium-grained, very well-sorted yellow sandstone composed of round and mat grains
315 of quartz. This poorly consolidated facies is azoic and shows m-scale cross-bedding sets,
316 where cm-sized steep foreset laminae are curved and become tangential to the basal
317 surface of the dunes (Fig. 4A). F2 consists of m-scale (up to 10 m) bars of matrix-
318 supported conglomerate composed of very poorly-sorted, weakly organized, pebble to
319 cobble-grade sub-angular to sub-rounded polygenic clasts within reddish mud to sand
320 matrix (Fig. 4B-C). F3 is composed of m-scale banks of fine-grained, very well-sorted,
321 azoic, red-colored sandstone showing planar cross-stratification. F4 corresponds to
322 poorly consolidated, structureless, azoic red clay and silt, interbedded with slightly
323 deformed gypsum beds (Fig. 4D). The bedding planes are rarely visible, and are mostly
324 highlighted by gypsum levels (Fig. 4D). In this facies, no root traces or concretions were
325 found. F5 comprises cm to m-thick beds of thinly-laminated, white spongy limestone with
326 sharp planar lower and upper contacts, containing ostracods, charophyta, and few thin-
327 shells of bivalves. F6 consists of m-scale horizons of yellow/white, cm-sized,

328 structureless carbonate concretions and glaebules (Fig. 4E), with root traces and
329 brecciated aspect. Observed glaebules consist of spherical carbonate peloids (<2 cm)
330 surrounded by circumgranular cracks (Wright, 1994)(Fig. 4F).

331 *Interpretation*

332 In F1, the rounded morphology of quartz grains and their mat aspect suggest an
333 important abrasion by grain collision during wind transport (Krinsley and Trusty, 1985;
334 Pye and Tsoar, 2009). The steep geometry of the foreset laminae indicates sedimentation
335 by aeolian dune migration (Hunter, 1977; Kocurek, 1991; Posamentier and Walker, 2006;
336 Pye and Tsoar, 2009). In F2, the matrix-supported conglomerates with their chaotic
337 character and randomly-oriented clasts indicate cohesive subaerial debris-flow
338 sedimentation (Nemec and Steel, 1984; Major, 2003), taking place in an alluvial fan
339 setting, at the border of the alluvial plain (Blair and McPhe, 1994). In F3, the oxidation
340 color, planar cross-stratification, and fine-grained aspect argue for a fluvial origin of this
341 facies, interpreted to form under lower-flow regime by unidirectional currents (Miall,
342 1996). In F4, the interbedding pattern of red clay and gypsum, as well as the absence of
343 pedogenesis evidence in this facies suggest formation under evaporitic conditions of
344 sabkha (Glennie, 1970), developed under hot and arid climate (Algouti et al., 1999). In F5,
345 the muddy depositional texture and fine parallel laminations indicate deposition under
346 low-energy conditions. The presence of ostracods and charophyta allows to assign this
347 facies to the lacustrine/palustrine domain (Murphy and Wilkinson, 1980; Platt and
348 Wright, 1991). In F6, carbonate concretions and glaebules with root traces and brecciated
349 aspect are distinctive features of paleosol horizons developed on a carbonate host rock
350 (Freytet and Plaziat, 1982; Freytet and Verrecchia, 1989; Wright, 1994). The observed

351 circumgranular cracks result from desiccation of the host rock, and confirm the
352 pedogenic origin of these horizons (Wright, 1994).

353 **FA2. Restricted inner platform**

354 *Description:*

355 This facies association is represented in all sections by carbonate sediments, organized
356 in marl-limestone alternations. FA2 includes grey laminated marls (F7), horizontally-
357 laminated dolo-mudstones (F8), *Turritella* and bivalves wackestones/packstones (F9),
358 and bioturbated phospharudites (F10).

359 F7 corresponds to poorly consolidated m-scale intervals of horizontally to wavy-
360 laminated grey marls (Fig. 4G), lacking macrofossils and bioturbation activity, it may
361 contain chert nodules. This facies is interbedded with mudstone and wackestone beds.
362 F8 is composed of cm to m-thick beds of horizontally-laminated yellow/white dolomitic
363 mudstones to wackestones (Fig. 4H), containing preserved thin shells of gastropods and
364 bivalves, scattered small sub-angular quartz grains, and rhombohedral dolomite crystals.
365 The lower surface of this facies shows occasionally *Thalassinoides* burrows network (Fig.
366 4I). F8 is sometimes affected by strong pervasive silicification and karstification filled
367 with red silt material (Fig. 4J). F9 includes m-thick bars of white-colored bioclastic
368 limestones with wackestone to packstone textures. It contains relatively well-preserved,
369 small-sized *Turritella* gastropods and bivalves. This facies exhibits low angle cross-beds
370 (Fig. 4K), and locally shows few scattered nautiloids (Fig. 4L), as well as intense pholad
371 borings at its upper surface (Fig. 4M). F10 consists of m-scale intervals of friable,
372 moderately-sorted phospharudite, containing yellow/brown color fragmented and
373 agglomerated peloids (up to 5 mm), fish teeth, and lithoclasts in a carbonate matrix. This

374 facies infills and overlays karstic cavities, and exhibits at its upper part, *Thalassinoides*
375 burrows infilled by gravel-sized phosphate grains.

376 *Interpretation*

377 The observed laminations in F7 suggest sedimentation by suspension fallout from
378 relatively quiet shallow-water (Flügel, 2010). Locally observed wavy-laminations are
379 generated by the wind-driven motion of the water column. In F8, horizontal laminations,
380 fine texture, and preserved poorly diversified fossil shells suggest formation in low-
381 energy environment within the inner platform (Flügel, 2010). The bioturbation style in
382 this facies is indicative of a shallow water environment (Ekdale and Bromley, 1984) and
383 a low sedimentation rate (Ekdale and Bromley, 2003). The small-sized and poorly
384 diversified fauna in F9 indicate deposition in the inner parts of the platform. Nautiloids
385 are indicative of open marine environments (Frey, 1987), their presence in this facies can
386 be explained by storm wash-over transport to the inner platform, which is also supported
387 by the presence of low-angle cross-beds. Nevertheless, this facies can also form within an
388 open shelf lagoon. In F10, the fragmented and agglomerated character of phosphatic
389 grains suggest significant transport and reworking. The presence of this facies within
390 karstic cavities allows to interpret it as allochthonous phosphate transported landward
391 during early transgression. This facies continued to accumulate above karsts in a shallow
392 water environment, where trace fossils were present.

393 **FA3. Inner platform (shoreface)**

394 *Description:*

395 This facies association is exposed discontinuously within the studied zone. It consists
396 predominantly of granular carbonates and shell beds organized in alternations and

397 exhibiting geometrically irregular bodies (Fig. 4N). To the west, in the Erguita section,
398 this association contains more sandy material. FA3 comprises calcarenites (F11), coquina
399 beds (F12), phosphatic sandstones (F13), and wavy-laminated sandstones (F14).

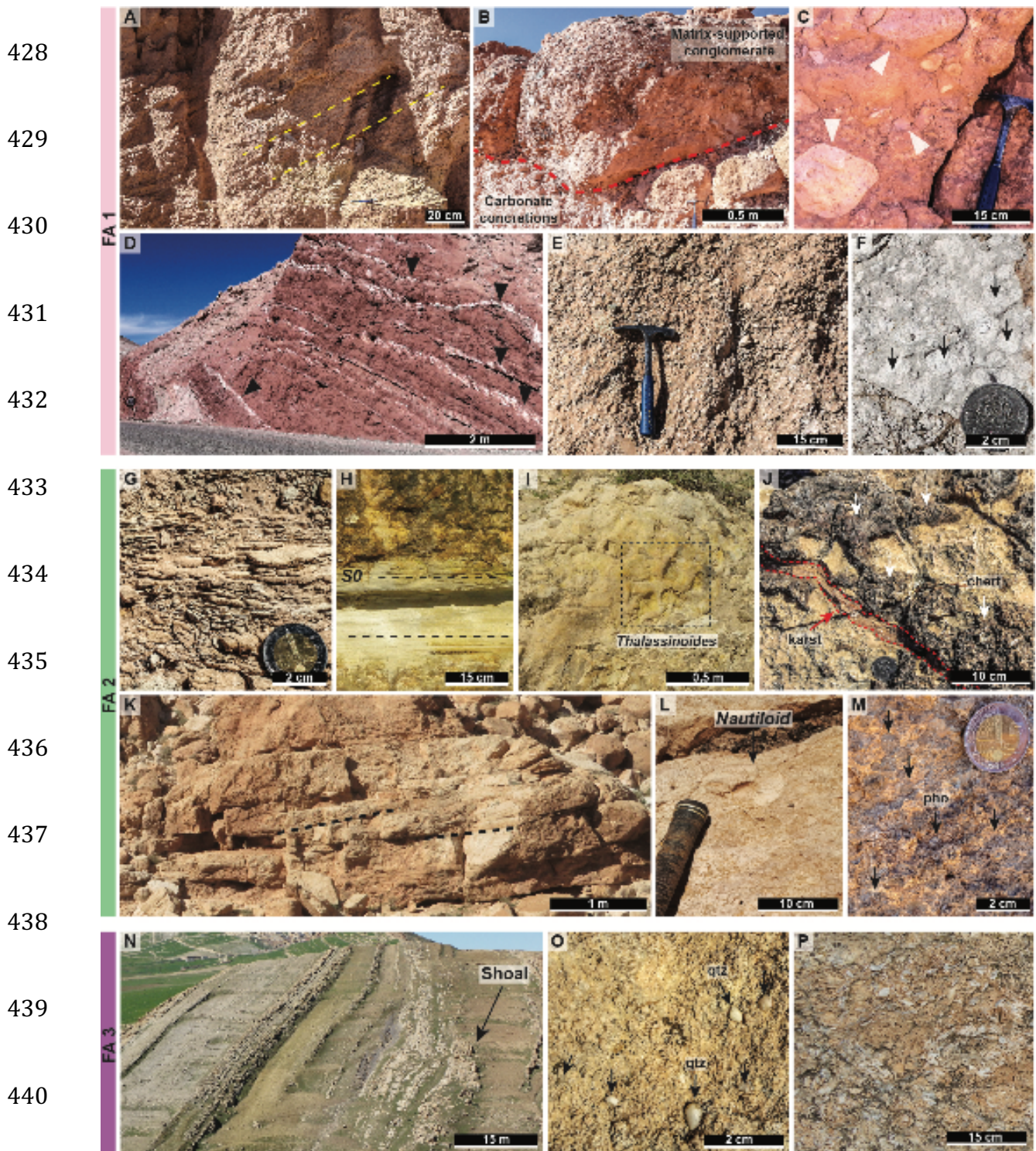
400 F11 consists of m-thick geometrically irregular levels of well-sorted granular limestones,
401 containing well-rounded quartz grains (Fig. 4O), cm-sized lithoclasts and bioclastic
402 debris (mostly fragmented oysters), and occasionally exhibiting trochoidal ripples and
403 cross-bedding. F12 corresponds to massive bars with scoured bases of bioclastic
404 limestone, showing a massive shell concentration, including disarticulated bivalves and
405 fragmented gastropod shells (Fig. 4P). In some cases, oyster fragments dominate the shell
406 content. F13 consists of indurated beds (<1.5 m) of relatively well-sorted, medium-
407 grained, locally cross-bedded grey phosphatic sandstone. This facies contains diversified
408 phosphatic particles (peloids, coprolites, fish teeth, and bone and vertebrate fragments)
409 and detrital grains dominated by sub-angular quartz. F14 consists of well-sorted, fine-
410 grained, wave-rippled calcareous sandstone, containing significant amount of detrital
411 quartz grains and few phosphatic particles.

412 *Interpretation:*

413 The nature and grain size of F11 bears evidence of reworking of an unlithified carbonate
414 material leading to the formation of a calcarenite. The rounded aspect of quartz grains
415 suggests an important wave-reworking of the sediment, which is also supported by the
416 presence wave ripples. The irregular geometry of these sediments, as well as the high-
417 energy character they display allows to interpret this facies as shoal accumulation. In F12,
418 the fragmented fossil shells indicate accumulation within high-energy domain, where
419 winnowing and reworking dynamics concentrate shells by the removal of the siliciclastic

420 fine detritus ([Kidwell, 1986](#); [Fürsich and Oschmann, 1993](#); [Jahnert et al., 2012](#); [Fick et al.,](#)
421 [2018](#)). The significant presence of sub-angular quartz grains in F13 reflects the vicinity
422 of detrital source. We interpret this facies to have accumulated within the inner platform
423 zones subjected to wave action, which explains the presence of cross-bedding. In F14, the
424 grain size and sorting, along with the presence of wave ripples indicate that this facies
425 accumulated within the inner platform above the fair-weather wave-base ([Burchette and](#)
426 [Wright, 1992](#)).

427



441 Fig. 4. Facies and facies associations (FA1-FA3). (A) Cross-bedded sandstone. (B, C)
 442 Matrix-supported conglomerate with randomly organized clasts (white triangles). (D)
 443 Red-beds and gypsum alternations (black triangles). (E) Carbonate paleosol. (F) Light-
 444 colored glaebules (black arrows) surrounded by grey-colored circumgranular cracks. (G)
 445 Grey marls. (H) Horizontally-laminated dolomitic mudstones. (I) Lower surface of a

446 dolomudstone bed showing *Thalassinoides* burrows. (J) Silicified and karstified
447 dolomitic mudstone. (K) Packstone showing low-angle cross-beds. (L) *Turritella* and
448 bivalves packstone containing nautiloids. (M) Intense pholad borings (black arrows) at
449 the upper surface of F9. (N) Panoramic view of the My Brahim section. (O) Granular
450 limestone with quartz grains (black arrows). (P) Fragmented fossil shells *coquina*. pho:
451 pholad; qtz: quartz.

452 **FA4. Outer platform (lower shoreface)**

453 *Description:*

454 This facies association is well-developed in the surveyed zones, except in the far east of
455 the Ouarzazate basin. FA4 is mainly composed of carbonate successions turning into
456 sandy facies towards the Erguita section. FA4 is made up of carbonate-matrix
457 conglomerates (F15), oyster marls (F16), *Cardita* grainstones (F17), *Thersitae* limestones
458 (F18), echinoid bioturbated limestones (F19), and hummocky cross-stratified calcareous
459 sandstones (F20).

460 F15 consists of sharp-based beds of poorly sorted conglomerate with carbonate matrix,
461 supporting dark-brown sub-rounded siliceous pebbles, cm-sized carbonate lithoclasts,
462 oyster and gastropod fragments, and few dark brown phosphate grains (Fig. 5A). F16
463 corresponds to m-scale intervals of structureless grey marls containing massive
464 accumulation of well-preserved uniform cm-sized oysters and showing no signs of
465 bioturbation. F17 consists of 1 m-thick grainstone beds containing moderately preserved
466 *Cardita*, oysters, recrystallized thick-shell gastropods, siliceous pebbles, and phosphate
467 peloids. F18 is made up of m-scale packstone bars containing disarticulated bivalves,
468 recrystallized thick-shell gastropods (*Hemithersitae marocana*) (Fig. 5B), nautiloids,

469 scarce benthic foraminifera, echinoids, quartz grains (Fig. 5C), and carbonate lithoclasts.
470 F19 comprises 3 to 5 m-thick recrystallized, bioturbated, and amalgamated bioclastic
471 packstone beds containing uniform cm-sized echinoids (Fig. 5D), bivalves, scarce
472 foraminifera, carbonate lithoclasts and phosphate particles (Fig. 5E). F20 consists of well-
473 sorted, fine to medium-grained calcareous sandstone, exhibiting hummocky cross-
474 stratification (Fig. 5F).

475 *Interpretation:*

476 The nature and organization of clasts indicate that F15 corresponds to an
477 intraformational conglomerate formed by storm reworking of semi-consolidated
478 sediments in the outer platform zone (Dott Jr, 1974). F16 is interpreted to form by in-situ
479 growth and accumulation of monospecific fauna on open muddy shelf. In F17, the
480 grainstone texture and the predominance of thick fossil shells suggest sedimentation
481 within agitated environment of the outer platform. The presence of nautiloids and
482 echinoids in F18 argues for an open marine environment (Frey, 1987; Bachmann and
483 Hirsch, 2006), which is subjected to storm reworking, as suggested by the fragmentation
484 of the thick fossil shells. In F19, the ubiquity of echinoids indicates sedimentation under
485 open marine conditions (Bachmann and Hirsch, 2006), where bed amalgamation is
486 interpreted to form by storms (Cheel and Leckie, 1993). F20 exhibits characteristics of
487 storm-generated deposits as evidenced by the presence of hummocky cross-stratification
488 (Cheel and Leckie, 1993). It is interpreted to form within the outer platform between the
489 fair-weather wave-base and the storm wave-base (Burchette and Wright, 1992).

490 **FA5. Outer platform (offshore transition)**

491 *Description:*

492 This facies association overlies FA4 and consists of carbonate and phosphate-dominated
493 sediments organized in alternations. FA5 comprises micro-HCS sandstones (F21),
494 nautiloids bioturbated mudstones (F22), granular phosphates (F23), and phosphatic
495 marls (F24). As the previous facies association, FA5 shows more sandy material within
496 the Erguita section.

497 F21 consists of cm to m-thick beds of fine to medium-grained, well-sorted calcareous
498 sandstone composed mainly of quartz grains and few phosphatic particles, including
499 peloids, lithoclasts, and bone fragments. This facies exhibits micro-hummocky cross-
500 stratification overlying well preserved centimetric climbing ripples (Fig. 5G). F22 is
501 composed of cm to m-thick beds of moderately bioturbated mudstones to wackestones
502 (Fig. 5H), with sharp upper and lower contacts. This facies contains large well-preserved
503 nautiloids (Fig. 5I), some bivalves, phosphate grains, bone fragments, and fish teeth. F23
504 is made up of m-thick (up to 1 m) semi-consolidated beds of granular phosphate,
505 interbedded with phosphatic marls, and composed predominantly of well-sorted,
506 homogeneous, brown-honey, phosphatic peloids cemented by calcite and phosphate.
507 This facies contains also fish teeth and bone fragments. F24 corresponds to parallel
508 thinly-laminated, unconsolidated grey phosphatic marls (Fig. 5J), containing floating
509 peloids in a micritic matrix. This facies shows no evidence of bioturbation, and lacks
510 quartz and other detrital grains.

511 *Interpretation:*

512 In F21, the fine-grained character and the good sorting of the sediment suggest
513 deposition under low to moderate-energy. The presence of climbing ripples and micro-
514 hummocky cross-stratification indicates sedimentation within the offshore transition

515 under storm and temporary wave reworking (Dott and Bourgeois, 1982). The fine texture
516 and *Thalassinoides* bioturbation of F22 indicate deposition under low-energy conditions
517 from mud settling. Given the presence of large nautiloids, we interpret this facies to form
518 in the outer platform below the storm wave-base (Frey, 1987). The granular feature of
519 F23 and its presence, sandwiched within phosphatic marls suggest hydrodynamic
520 accumulation around the storm wave-base from previously pristine phosphate facies
521 (Pufahl and Groat, 2017). In F24, the parallel lamination and the fine texture suggest
522 sedimentation under low-energy conditions from the fallout of particles in suspension.
523 The absence of coarse-grained detritals indicates deposition in distal parts of the
524 platform below the storm wave-base, where phosphatic peloids formed by authigenesis
525 (Föllmi, 1996).

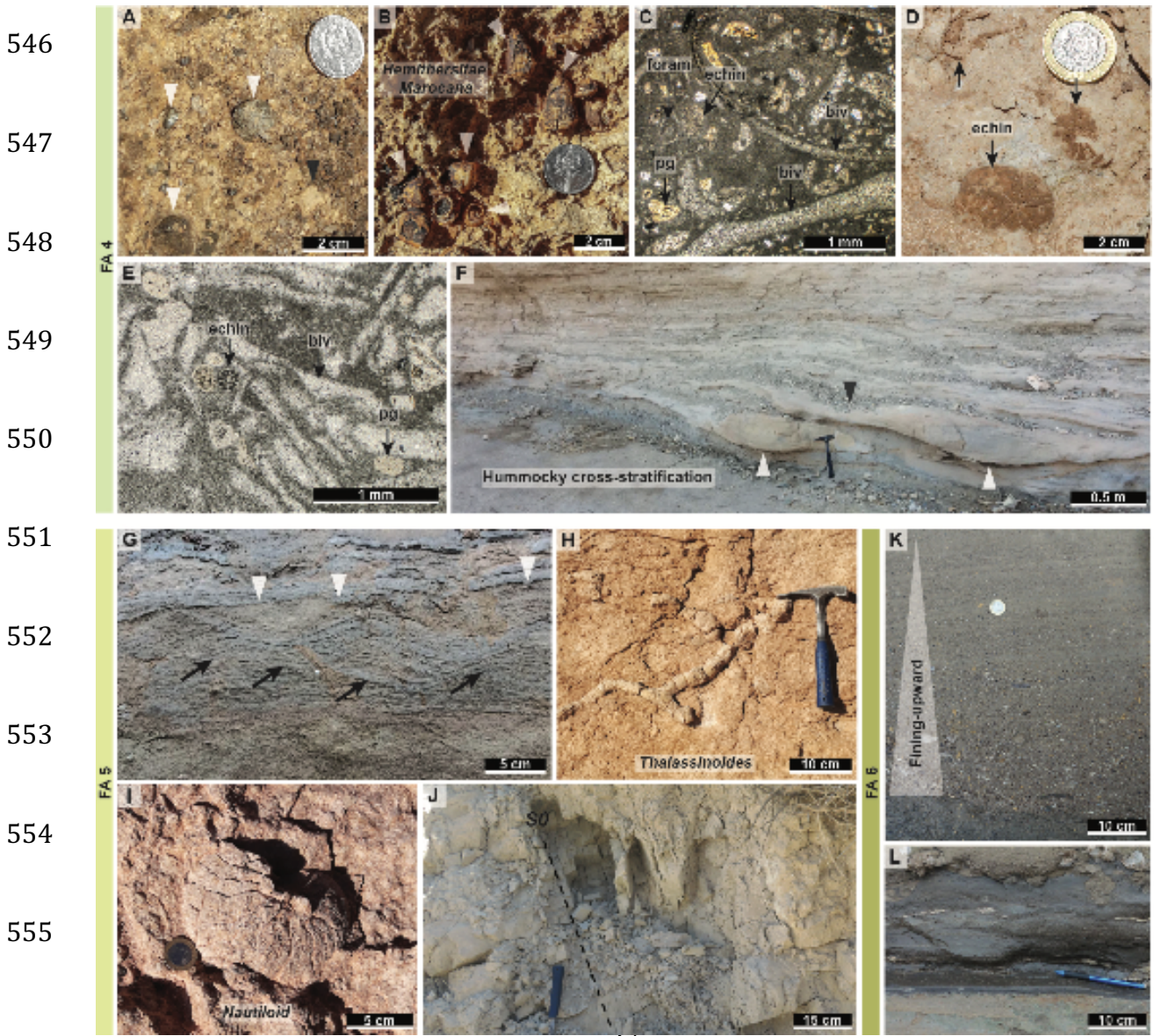
526 **FA6. Basin (offshore)**

527 *Description:*

528 This facies association exclusively occurs within the Erguita region. It is organized in
529 alternations between normally-graded microconglomerates (F25) and organic-rich
530 muds (F26). FA6 constitutes the ultimate part of a fining upward sequence. F25
531 comprises cm to m-thick sharp-based beds of normally graded sandstone to micro-
532 conglomerate (Fig. 5K). This facies contains detrital grains, phosphate particles, fish
533 teeth, bone fragments. F26 consists of thin layers (20 cm) of dark-colored muddy fine
534 sediment showing no internal structure and lacking bioturbation (Fig. 5L). This facies
535 occur by progressive an continuous transition from upper offshore sediments.

536 *Interpretation:*

537 The normally-graded sandstones and microconglomerates, occurring in association with
 538 organic-rich beds, are interpreted as disruption episodes caused by gravity-driven
 539 currents transferring detrital material and phosphate particles from shallow to deeper
 540 water environment (Pickering et al., 1986). The accumulation of this facies occurs by
 541 rapid grain by grain deposition (Pickering et al., 1986). The absence of hydrodynamic
 542 structures and the fine-grained aspect of the organic-rich facies indicate deposition under
 543 a low-energy regime, from the settling of suspension particles in a distal offshore
 544 environment (Stow et al., 2001). In this setting, anoxia conditions favor the preservation
 545 of the organic matter.



556 Fig. 5. Facies and facies associations (FA4-FA6). (A) Carbonate matrix-supported
557 conglomerate, containing siliceous pebbles and carbonate lithoclasts (white triangles).
558 (B) Thersitae limestone. (C) Transmitted light photomicrograph of a Thersitae limestone.
559 (D) Echinoid limestone. (E) Transmitted light photomicrograph of an echinoid limestone.
560 (F) Calcareous sandstones showing hummocky cross-stratification. (G) Slightly
561 phosphatic sandstone, showing climbing ripples (black arrows), and micro-hummocky
562 cross-stratification (erosion surface highlighted with white triangles). (H, I) Nautiloids
563 mudstone showing *Thalassinoides* burrows. (J) Parallel thinly-laminated phosphatic
564 marls. (K) Normally graded sandstone. (L) Muddy organic-rich fine sediment. biv:
565 bivalve; echin: echinoid; foram: foraminifera; pg: phosphatic grain; qtz: quartz.

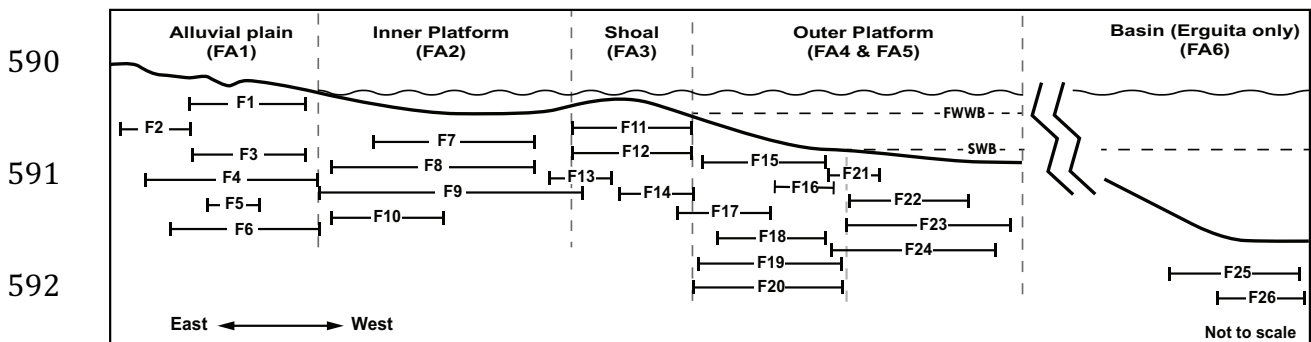
566 **6. Depositional model**

567 The aforescribed facies associations are genetically related and show continuous
568 lateral shifting, during the studied Late Cretaceous to Paleocene interval. The overall
569 dominance of carbonate, the fossil content, sedimentary structures, and facies
570 distribution, suggest a depositional model of a shallow-water carbonate platform,
571 characterized by tectonic quiescence and unequally distributed clastic inputs ([Wilson,](#)
572 [1975; Burchette and Wright, 1992](#)) ([Fig. 6](#)). Proximal facies are located in the east and
573 they change westward to more distal facies. This is mirrored by westward thickening of
574 the sedimentary sequences. In addition, a distinct orthogonal (southwards) facies
575 evolution trend is documented. The sedimentary configuration changes from shallow
576 water carbonate platform in the proximal area to mixed carbonate and siliciclastic storm-
577 dominated platform, in the Souss basin (Erguita section, [Fig. 6](#)). Similarly, this is

578 accompanied by an important southward thickening of the sequences and the presence
579 of more siliciclastic inputs, including gravity flows.

580 In this general setting, the proximal continental parts correspond to an array of alluvial
581 plain sub-environments, ranging from aeolian to lacustrine. The inner platform zone
582 shows low-energy muddy carbonates, locally interrupted by storm events. Shoal bodies,
583 acting as local and discontinuous barriers, exhibit high-energy granular and shelly
584 carbonate facies developed under wave reworking conditions. The outer platform
585 comprises various facies recording different energy degrees as a function of the storm
586 wave-base position and exhibits typical storm-derived structures, mainly hummocky
587 cross-stratification. Distal parts correspond to the basin zone with typically low-energy
588 organic-rich sediments disrupted by turbiditic events.

589



593 Fig. 6. 2D facies substitution diagram of the studied sedimentary series highlighting the
594 distribution of the defined facies within a shallow-marine platform profile. FWWB: fair-
595 weather wave-base; SWB: storm wave-base.

596 **7. The different types of the phosphate-rich sediments of the High**
597 **Atlas**

598 The petrography of the phosphatic sediments was extensively studied due to their
599 economic importance. Consequently, many classifications have been proposed to explain
600 the diversity of phosphate lithofacies. The most common nomenclature is based on the
601 modified Dunham/Embry and Klovan classifications ([Trappe, 2001](#)) by studying the
602 relative proportions between phosphatic and non-phosphatic allochems, and matrix
603 ([Slansky, 1986; Trappe, 2001](#)). In the Moroccan phosphate series, the petrography of the
604 phosphatic sediments is well established. The phosphatic allochems were studied based
605 on grain shape, size, internal structure, and origin ([Mouflih, 2015](#)). In this study, we
606 describe the different phosphate lithofacies with respect to the sedimentary processes
607 involved in their formation and accumulation. Correspondingly, five different phosphate
608 types are described and categorized into transported and non-transported facies with
609 respect to the primary phosphogenesis zone ([Table 2](#)).

Key Features	Pristine phosphate	Winnowed and reworked phosphate			
		In-situ	Transported		
			Platform	Basin	Karst 610
Lithology	Phosphatic marls	Granular peloidal phosphates	Phosphatic sandstones & coquina	Phosphatic sandstones and microconglomerates	Microconglomerates and phospharudites
Bedding	Thin	Thick	Thick	Thin to thick	undefined
Thickness	5-30 m	0.1-1 m	0.1-1 m	0.1-2 m	2-10 m
Petrographic composition	Yellow-brown peloids Traces of organic matter Calcite	Densely-packed peloids, coprolites, vertebrate debris, fish teeth Calcite & phosphate cement	Peloids, coprolites, vertebrate debris, fish teeth, composite grains, quartz grains	Peloids, coprolites, vertebrate debris, fish teeth, composite grains, quartz grains	Agglomerated peloids Fish teeth Copolites Quartz grains
Coarse detrital fraction	Absent or rare	Absent or rare	Very frequent	Frequent	Frequent
Sedimentary structures & depositional features	Horizontally laminated	Well-sorted Poorly consolidated	Well-consolidated Well sorted Cross-stratified	Normally graded	Unconsolidated Wavy laminated
Biological activity	Unbioturbated	Rarely bioturbated	Moderately bioturbated	Rarely bioturbated	Bioturbated <i>Thalassinoides</i> burrows
Process	Particles settling and francolite authigenesis	Storm and bottom currents winnowing	Transport and wave reworking	Gravity-driven transport	Wave currents transport and reworking
Phosphorus content	Low	High	Low to Medium	Medium	Medium to High
Sequence stratigraphic position	The base of the regressive system of a T-R sequence	The base of the regressive system of a T-R sequence	Occur in both stages of a T- R sequence	Around the distal maximum flooding zone	The base of the transgressive hemicycle
Spatial distribution	Northern border of the Marrakesh High Atlas	Northern border of the Marrakesh High Atlas	Abundant in the northern border of the Marrakesh High Atlas	Souss basin	Ouarzazate basin

Table 2: The main characteristics of the different phosphate lithofacies of the High Atlas.

6.1. Pristine phosphate

Description:

This phosphatic lithofacies is geographically restricted to the northern border of the Marrakesh High Atlas, and systematically occurs above FA4, which is capped by a hardground surface. Pristine phosphate facies consists of m-scale intervals of grey thinly parallel-laminated, poorly-consolidated phosphatic marls (Fig. 7A1), which prevents preparation of sample thin sections. It is composed of mm-sized homogeneous and structureless phosphatic grains scattered within a micritic matrix (Fig. 7A2). It is of interest to note that all the phosphatic allochems in this facies correspond to peloids (Fig. 7A2). This phosphate type shows no signs of bioturbation and a distinctive lack of detrital quartz grains.

Interpretation:

The fine depositional texture and the horizontal laminations fabric indicate deposition under a low-energy setting from the fallout of particles in suspension. The presence of phosphate peloids and the scarcity of detrital particles suggest the formation in relatively distal parts of the platform away from terrigenous inputs. Hence, we interpret these phosphatic marls to have formed pristinely in the outer platform, below the storm wave-base, where phosphatic peloids were precipitated authigenically in pore water microsystems at the water-sediment interface (Föllmi, 1996; Glenn et al., 1994; Pufahl et al., 2003; Pufahl and Groat, 2017; Soudry et al., 2013; Zhang et al., 2019). This phosphogenesis process requires the conjunction of many biochemical conditions to occur, including: i) the availability of phosphorus and its release from the organic matter

to pore water by bacterial mediation (Diaz et al., 2008; Krajewski et al., 1994), ii) the availability of fluorine (F), and iii) the pumping of Mg from pore water in order to precipitate the francolite by supersaturation of P (Jarvis et al., 1994, Glenn 1994).

6.2. Winnowed phosphate

Description:

This phosphatic facies only occurs along the northern border of the Marrakesh High Atlas, in close association with the previously described phosphatic marls, with which it is interbedded at a 0.1 to 1 m frequency (Fig. 7B1) over intervals that can reach a thickness of 30 m. This granular phosphate corresponds to a greyish, well-sorted, medium-grained, consolidated to semi-consolidated phosphate beds (Fig. 7B1). The cm to m-thick beds are almost entirely composed of densely-packed mm-sized rounded and structureless honey-brown peloids (Fig. 7B2-3). Beds also contain few vertebrate fragments and fish teeth showing generally elongated shapes. These particles are cemented by calcite and phosphate (Fig. 7B3). The morphology of grains is similar to pristine grains and show no signs of transport or grain overgrowth. This phosphatic facies has yielded the highest phosphorus concentrations (up to 25% P₂O₅) with respect to the other phosphate types in the studied sections.

Interpretation:

The composition, granular texture, and the very good sorting indicate a high-energy setting of this lithofacies. The interbedding pattern between granular phosphate and phosphatic marls suggests their genetic link. Similar interbedding pattern was described within the Campanian phosphorite of Jordan (Pufahl et al., 2003). We interpret the

granular phosphate to form around the storm wave-base where bottom water currents sweep the pristine phosphate sediment to remove the fine muddy fraction and concentrate peloids (Pufahl and Groat, 2017). This concentration process by winnowing is enhanced by the specific gravity of francolite, which is higher (2.9 g/cm³) than other sediment particles (1.5 to 2.5 g/cm³; Föllmi, 1996; Pufahl and Grimm, 2003). The peloids in this facies are cemented by phosphate, which indicates that a second phosphatization phase occurred, as the winnowed phosphate is reburied into the phosphogenesis zone (Glenn et al., 1994). The winnowing process therefore plays a critical role in the enrichment of the primary phosphate accumulation. The replication of this process over wide areas is thought to be responsible for the world's major economic phosphate deposits (Glenn et al., 1994; Föllmi, 1996; Pufahl and Grimm, 2003; Pufahl and Groat, 2017).

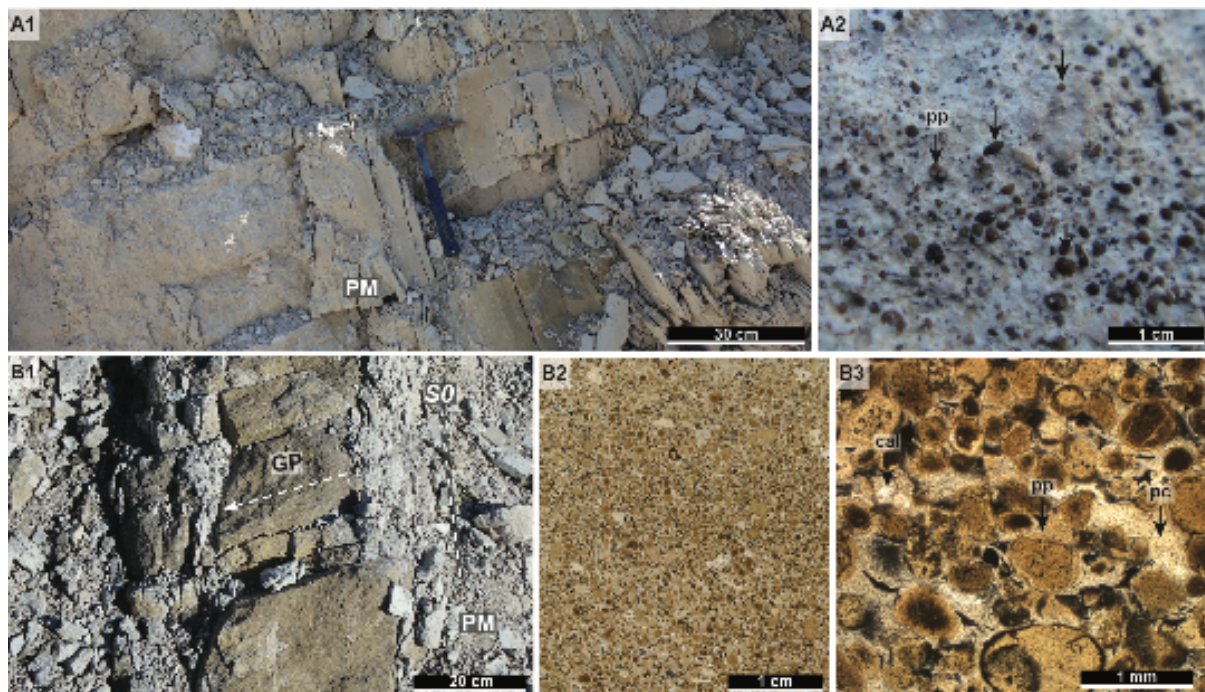


Fig. 7. In-situ formed phosphate lithofacies of the High Atlas. (A1) Pristine thinly parallel-laminated phosphatic marls. (A2) Limestone marl containing pristine phosphatic peloids.

(B1) Granular phosphate bed intercalated within phosphatic marls. (B2) Densely-packed peloids in granular phosphate. (B3) Transmitted light photomicrograph showing the composition of granular phosphate lithofacies. PM: phosphatic marls; GP: granular phosphate S0: stratification plane, pp: peloid; pc: phosphatic cement; cal: calcite.

6.3. Phosphatic lags

Description:

This phosphatic lithofacies is identified in different sections and at different stratigraphic positions. It occurs as phosphatic sandstones, with sharp upper and lower contacts (Fig. 8A1), or as cross-bedded phosphatic coquina. This facies is associated with the FA3. Phosphatic lags are made up of a mixture of relatively well-sorted phosphatic and non-phosphatic grains (Fig. 8A2). The phosphatic grains consist of yellow-brown well-rounded mostly structureless peloids, rod-shaped coprolites, fish teeth, bone fragments, and bioclasts (Fig. 8A2-3). Unlike the previous types, these phosphate sediments contain a significant amount of sub-angular quartz grains (Fig. 8A2) and other terrigenous components, including cm-sized pebbles.

Interpretation:

The lithology, the composition and the sedimentary structures recorded within this phosphate type suggest a formation under high-energy conditions enhancing the reworking and sorting of sediments. The ubiquity of sub-angular to sub-rounded quartz grains suggests the vicinity of proximal detrital supply. These conditions are common to the shoal zone within the wave action zone of a shallow-water platform. Storm and wave currents transport the phosphate grains, initially formed in situ, to the inner parts of the

platform, where they are mixed with a significant proportion of detrital components, and reworked by waves (Trappe, 1998). The accumulation of this phosphate type in a close association with shoal bodies suggests that these bodies play a role in trapping the reworked phosphate particles within the sheltered back-shoal depressions.

6.4. Karst-filling phosphate

Description

This phosphate facies occurs locally, within the Ouarzazate basin. It consists of up to 5 m thick phosphate sediment filling and covering karstic pockets (Fig. 8B1-2). This phosphate lithofacies exhibits a fining-upward trend above the karstic surface, within the cavities. It passes upward to beds displaying *Thalassinoides* burrows filled with granule-sized phosphatic grains (Fig. 8B3), and calcic geodes. These karstic pockets consist of several cm-wide cavities developed on carbonate rocks and can reach a depth of several meters. This phosphatic lithofacies corresponds to an unconsolidated phospharudite composed of very-coarse to granule-grained, medium sorted phosphatic grains contained in a grey carbonate matrix (Fig. 8B4). Petrographically, phosphate grains consist of agglomerated peloids (Fig. 8B4). A single peloid corresponds to a rounded yellow to dark brown grain. Phosphatic grains are mostly structureless and show evidence of corrosion (Fig. 8B4-5). They are frequently very fractured and altered (Fig. 8B5). The non-phosphatic grains consist of lithoclasts and few detrital particles.

Interpretation:

The lithology and the composition suggest a marine origin of this lithofacies. This phosphate lithofacies is interpreted as an allochthonous sediment, whose accumulation

onset corresponds to an early stage of a transgression above an emerged and karstified carbonate platform, where previous phosphate lithofacies were transported landwards. The agglomeration, corrosion, fragmentation, and alteration of phosphatic grains indicate significant transport and reworking of sediments. We interpret this accumulation to occur in two steps: i) landwards currents transport previously pristine and winnowed phosphate to inner parts of the platform; ii) during transgressive events, as the shoreline shifts landward, reworked phosphate sediments are eroded and further transported landward to cover previously exposed karstified sediment. This process occurs in the absence of significant detrital inputs, which explains the relatively good ore-grade of this phosphate type. This type of accumulation has been reported from the Upper Cretaceous phosphorite of Eshidiyya in Jordan containing friable phosphorite accumulations within a karstic depression ([Abed et al., 2007](#)).

6.5. Turbiditic phosphate

Description

This phosphate type occurs locally within the Erguita section, in the southwest of the study area, where it is associated with deeper environments facies represented by organic-rich layers (F26). It corresponds to coarse-grained to very coarse-grained and normally graded beds ([Fig. 8C1](#)) containing a wide variety of phosphatic particles including peloids, bone fragments, fish teeth, and non-phosphatic particles comprising carbonate lithoclasts and detrital grains ([Fig. 8C2](#)).

Interpretation:

The normal grading pattern and the association with offshore sediments suggest deposition in distal environments under turbidity conditions. We interpret this phosphate lithofacies as a gravity-flow deposit, with rapid accumulation of sediments enhancing the normal grading pattern. The phosphatic particles were derived from the other phosphate lithofacies, which have been transported basinwards. This interpretation corroborates with previous studies where this phosphate accumulation mode of phosphate was reported from many world-class phosphate deposits such as in Baja California in Mexico ([Galli-Olivier et al., 1990](#)), in the Upper Cretaceous of Colombia, ([Föllmi et al., 1992](#)), or in the Miocene of Salento in Italy ([Föllmi et al., 2015](#)).

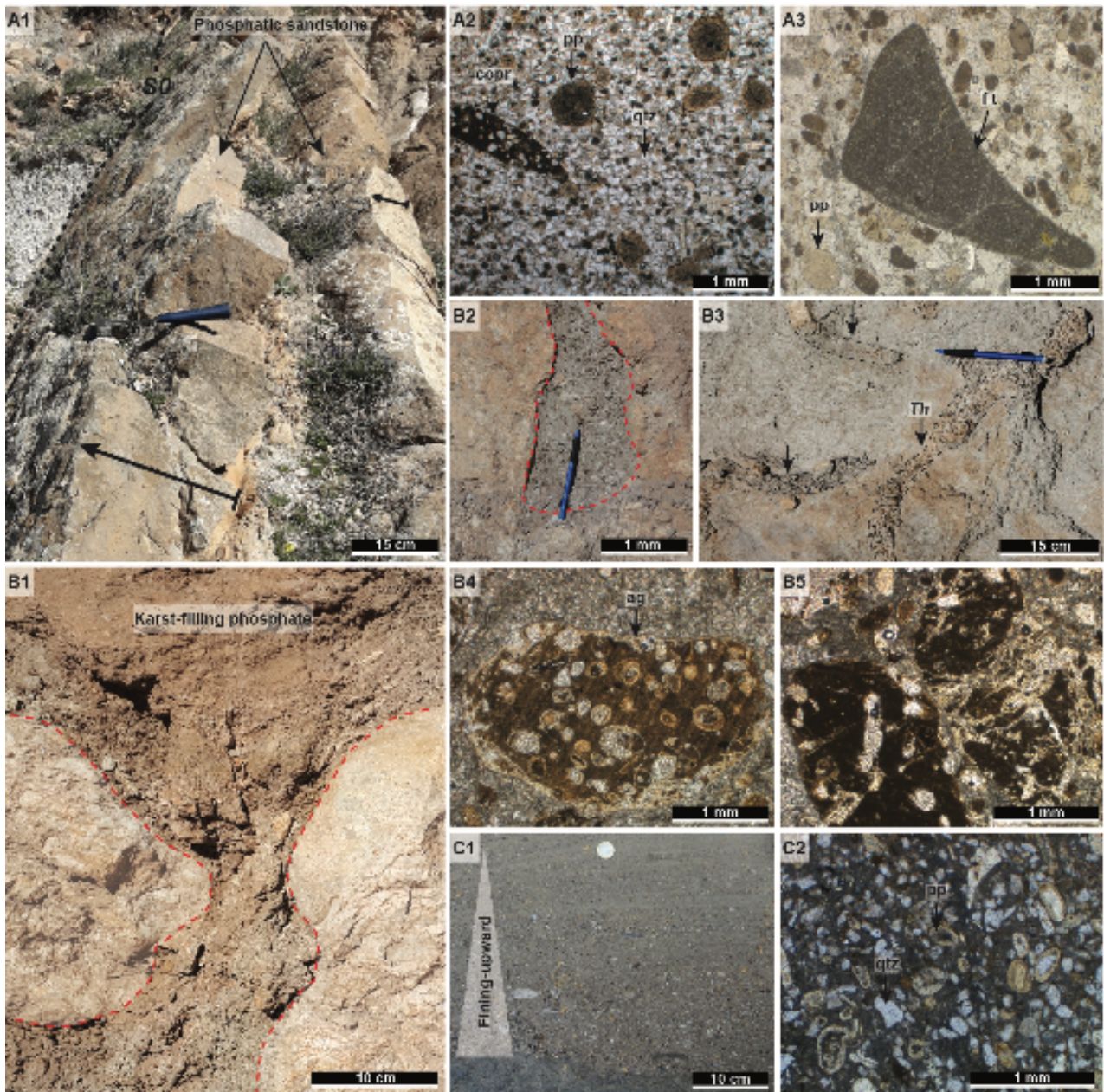


Fig. 8. Transported and reworked phosphate lithofacies (Allochthonous). (A1) Field photograph showing phosphatic sandstones. (A2-3) Transmitted light photomicrograph illustrating the petrographic composition of a phosphatic sandstone. (B1) Field photograph showing karst-filling phosphate. (B2) Granule-sized phosphate fill of karst. Dotted red line underlines the cavity. (B3) *Thalassinoides* burrows filled with granule-sized phosphate. (B4-5) Transmitted light photomicrograph of karst-filling facies. (C1) Field photograph exhibiting the normal grading features within the gravity-driven phosphate sediments. (C2) Transmitted light photomicrograph illustrating the

petrographic composition of turbiditic phosphate. **S0**: stratification plane; **pp**: peloid; **copr**: coprolite; **ft**: fish tooth; **ag**: agglomerated grains; **qtz**: quartz; **Th**: *Thalassinoides*.

8. Sequence stratigraphy

Sequence stratigraphy is used to visualize the organization of the phosphate-rich sediments and their position regarding the different stages of the relative sea-level variations (Fig. 9). The sequence stratigraphic framing, used in this study, is based on regional correlations of major key stratigraphic surfaces and facies changes. These regionally traceable surfaces reflect stratigraphic breaks and sedimentologic turnarounds, which thereby constitute reliable correlation datums. In this carbonate-dominated context, we adopted a transgressive-regressive sequence model (Embry, 1993, 1995; Embry and Johannessen, 1993) corresponding to sedimentary stacks embedded between two transgressive surfaces. These surfaces are used as sequence boundaries and then define depositional sequences. Two major stratigraphic datums have been identified (Fig. 9).

7.1. Major stratigraphic surfaces

The karstic surface (basal transgressive surface)

Located at the lower parts of the studied sections, this surface corresponds to the top of a karstic system affecting limestone and dolomite wackestones and packstones. The karst is developed as cm-wide interconnected dissolution fractures or as larger, m-scale cavities. The karstification process can act over 10 m depth. The karst infill varies from red silts to coarse-grained phosphate particles. The karstified lapiaz is filled and covered by transgressive sediments, including breccia and phospharudites. This karst system

formed in response to weathering processes when the carbonate layers were subaerially exposed due to sea-level fall. This extensively distributed key surface has been documented in the High Atlas areas as the D1 discontinuity, dated to the Upper Maastrichtian (Chellai et al., 1995; Marzouq et al., 1996; Marzouq, 2001). It has also been recognized within the exploited basins of Gantour and Ouled Abdoun in central Morocco (Mouflih, 2015). It constitutes a sequence boundary and set as the lower datum for regional-scale correlations in this study.

The major maximum flooding surface/zone (MFS/MFZ)

Regionally, this surface bounds the outer platform carbonate sediments (FA5). In the northern margin of the Marrakesh High Atlas, this stratigraphic marker corresponds to a hardground surface, highlighted by massive accumulation of encrusting organisms, silicifications, iron-oxides crusts, and frequent bioturbation burrows filled with phosphate grains. Along the southern margin of the High Atlas, we defined maximum flooding zones (MFZ) relying on sedimentological criteria as the deepest facies within the whole vertical succession (Wilmsen, 2003). In the Ouarzazate basin, this maximum flooding zone is represented by nautiloids mudstones, while it consists of thin organic-rich layers in the Souss basin (Fig. 5K). This maximum flooding surface/zone is characterized by the low sedimentation rates and the scarcity of detrital particles. This typical stratigraphic marker reflects the transition from fining-upward to coarsening-upward cycle, highlighting the turnaround from transgressive to regressive phase. It is set as the upper datum for regional correlations.

Our nannoflora determinations (Fig. 3) indicate that the major MFS, which we correlate across the study area, is dated to the NP6 biozone i.e. at the transition between the Selandian and Thanetian, at around 59 Ma (Gradstein et al., 2012). The overlying

regressive hemicycle extends at least until the NP9 biozone (end-Thanetian). However, the top of this section is truncated by syntectonic Neogene alluvial fans, and it is likely that in other more complete sections, the regressive hemicycle lasts until the Eocene (Marzoqi, 2001). Consequently, our correlation across the studied area indicates that the interval between the karst surface and the major MFS is Danian-Selandian in age, assuming a Maastrichtian age for the formations affected by the karst (see review in Marzoqi, 2001).

7.2. Depositional sequence organization

The studied sedimentary succession was deposited during a relative sea-level cycle as defined by the major stratigraphic surfaces and facies evolution (Fig. 9). Higher-order sequences (third or fourth-order?) were identified below the major MFS (Fig. 9). These depositional sequences are bounded by minor stratigraphic surfaces and show facies shifts mirroring the relative sea-level changes. Four sequences were defined from the base to the top (Fig. 9):

Sequence (S1)

This sequence consists of carbonate material corresponding to the first recorded marine incursion within the studied series. S1 mantles the Senonian red continental sediments. S1 consists of dolomitic wackestones and packstones with bivalve dominance (Fig. 4J-L). It is bounded to the top by the major karstic surface and constitutes the regressive phase of a second-order transgressive/regressive cycle. It is very reduced or even absent within the eastern parts of the Ouarzazate basin. The upper parts of the sequence are probably absent due to karstification and erosion. No record of this sequence, interpreted of a Maastrichtian age (Marzoqi et al., 1996), was found around the Amizmiz area, where it is

considered as an erosional gap of the upper parts of the Maastrichtian (Chellai et al., 1995).

Sequence (S2)

This sequence, coincides with the earliest recorded Cenozoic sediments (Chellai et al., 1995; Marzouqi et al., 1996). It develops above the major karstic surface (Fig. 9). S2 varies in thickness from 10 m to up to 40 m. The transgressive part of the sequence begins with dolomudstone breccia and phospharudites. S2 evolves in a shallow-marine inner platform setting producing carbonates. Within the Ouarzazate basin, the MFS can be placed within wackestone to packstone carbonates, while it corresponds within the other regions to phosphatic hardgrounds. Within the Marrakesh High Atlas basin, this sequence exhibits the accumulations of phosphatic sandstones and the development of shoal bodies. The regressive part shows a distinct facies transition from shallow-water carbonates to thin continental red sediments and local karsts, emphasizing the shoreline seaward shifting. The presence of significant phosphate accumulations at the early transgressive parts of S2 is a distinctive feature of the sections from the Ouarzazate basin. To the north of the High Atlas, the phosphate accumulation corresponds to isolated phosphatic sandstones. This S2 sequence is lacking in the Amizmiz region, which suggests a probable paleogeographic high, preventing the deposition of this sequence.

Sequence (S3)

This sequence shows a similar transgressive-regressive evolution. The first transgressive sediments are represented by high-energy shallow-water carbonate facies, mainly calcarenites and coquina beds, being shallower eastwards, showing more terrigenous content (Fig. 40-P). The MFS within the Marrakesh High Atlas and Souss basins,

corresponds to burrowed firm-grounds filled with phosphatic sediment, while it is represented by muddy carbonate sediments in the Ouarzazate basin. The regressive hemi-sequence marks an evolution from shoal and platform carbonates to continental red sediments, including red clay and silt. This interval is thicker in the easternmost part of the Ouarzazate basin.

Sequence (S4)

This sequence is the thickest in the whole succession, in every studied section (Fig. 9). It is characterized by lateral facies changes and significant phosphate accumulations. The transgressive system within S4 exhibits muddy carbonates and marls passing to packstone and grainstone carbonates with typical distal fauna, which characterizes a deepening upward trend with a facies transition from inner platform to outer platform, and finally to basin facies. The turnaround to the regressive part is marked by MFS, laterally changing to MFZ. In the northern border of the Marrakesh High Atlas, the MFS corresponds to a hardground surface showing echinoid accumulation (Fig. 5D), silicification, bioturbation, and phosphate grains on the hardground and filling the burrows. In the Souss basin, the MFZ corresponds to a thin layer (10 cm-thick) of organic-rich sediments while it is represented by nautiloids mudstone carbonate in the Ouarzazate basin (Fig. 5I). This correlative surface represents the most distal conditions within each measured section, in the whole studied area. The onset of the regressive system corresponds mostly to outer platform facies. Within the northern border of the Marrakesh High Atlas, these facies correspond to phosphatic marl intervals. These pristine phosphatic marls are restricted to this part of the sequence and are found only along the northern border of the High Atlas. Upwards, the regressive trend is marked by a progressive facies transition from marine carbonates to continental red beds, lacustrine

carbonate, paleosols horizons, and debris-flow conglomerate, respectively. Finally, Sequence 4 is truncated by Neogene molassic sediments derived from the erosion of the uprising High Atlas (Fig. 4B) (El Harfi et al., 2001; Görler et al., 1988).

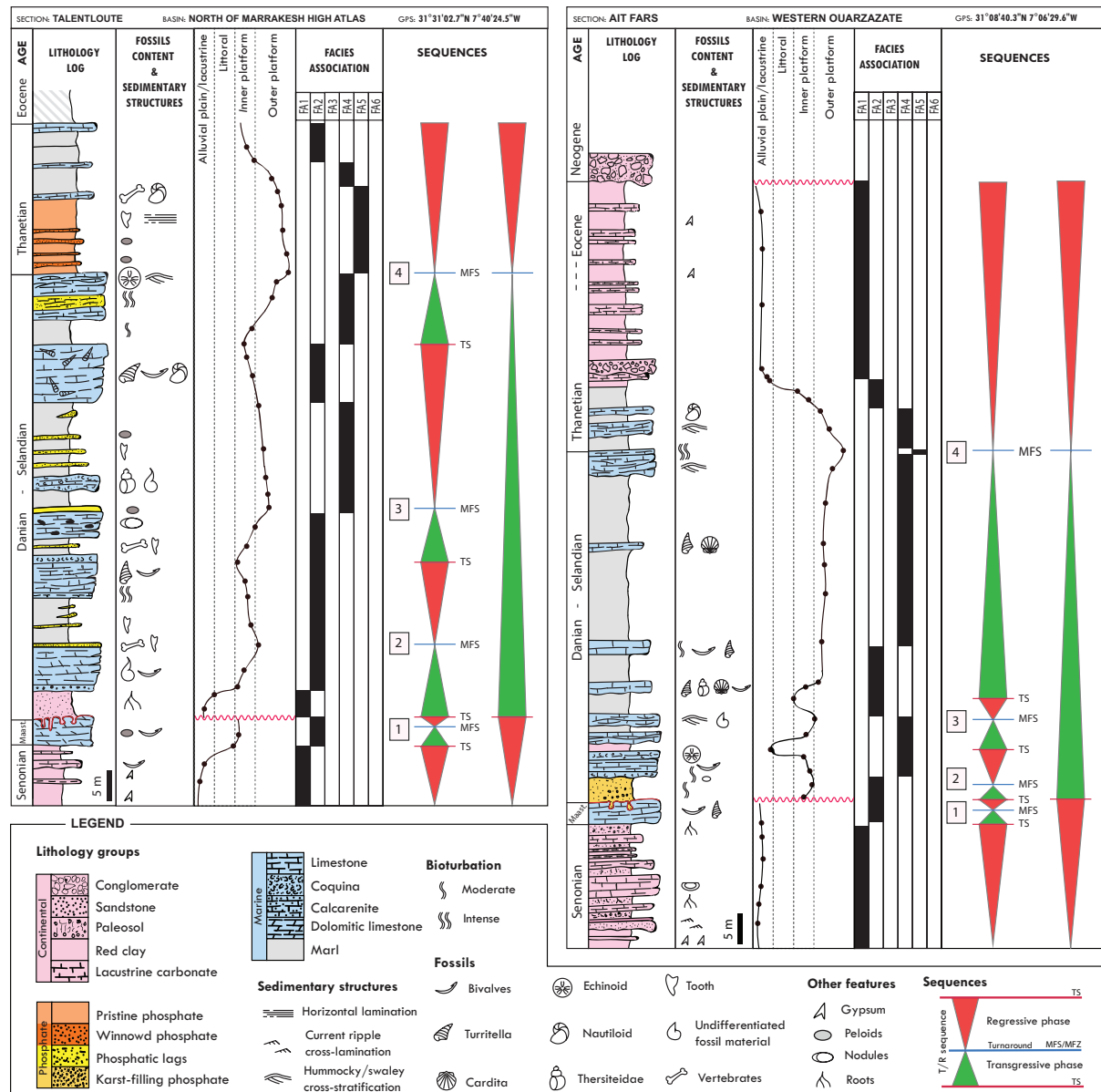


Fig. 9. Detailed logs (Talentloute and Ait Fars sections) showing the sedimentary evolution of the series and highlighting the sequence stratigraphic organization of the defined depositional sequences. The sequences are bounded by major and minor stratigraphic surfaces and are emphasized by facies shifts.

9. Discussion

The diversity of phosphate lithofacies within the Upper Cretaceous-Paleogene series of the High Atlas emphasizes the effects and interplay of different processes and controls over the phosphate sedimentation, within the studied marine platform system (Fig. 10). The fine laminated phosphatic marls deposited by settling suggest that pristine phosphate formed within the outer parts of the marine platform under low-energy conditions, below the storm wave-base. The formation of the primary phosphate grains (peloids) is believed to take place within closed and reduced pore water microsystems (Jarvis et al., 1994), in the unlithified sediment, which allows peloid growth up to mm-size diameter. Phosphorus is released to pore water from organic matter, Fe-oxhydroxides, and clay minerals, mainly by microbial mediation (Jarvis et al., 1994; Krajewski et al., 1994; Hiatt et al., 2015; Pufahl and Groat, 2017), and then precipitates along with other chemical elements (F and Ca) as authigenic francolite. The latter corresponds to peloids scattered within a muddy matrix. Such primary phosphate sediment may undergo several sedimentary differentiation processes, leading to the formation of different phosphate lithofacies (Fig. 10). This differentiation is controlled by autocyclic and allocyclic processes. Firstly, autocyclic physical processes include hydrodynamic winnowing, reworking, and transporting. Storm and bottom currents sweep the pristine phosphate at the water-sediment interface to winnow the fine-grained material which is consequently removed, resuspended, laterally transported and redeposited away when the energy decreases. This hydrodynamic process causes the in-situ enrichment in phosphatic peloids, forming the so-called winnowed phosphate. When winnowing is repeated, it can lead to the formation of granular phosphate. This natural beneficiation process significantly enriches the phosphate grade and leads to economic

accumulations (Zhang et al., 2019). Transport and wave reworking of previously pristine and associated winnowed phosphate, produce phosphatic lags. This occurs in the proximal parts of the platform, at the vicinity of shoal complexes which act as morphologic traps for this phosphate lithofacies. Reworking eliminates the fine-grained portion of the sediments but integrates coarser detrital grains instead, including quartz, lithoclasts, and bone fragments, which counteracts the enrichment process of the phosphate grade. Gravity flows are responsible for the basinward redistribution of all previously described phosphate lithofacies. In the slope and basin, transported phosphates are redeposited with other terrigenous components in the form of turbiditic beds, showing normal grading patterns, and their association with thin black shales indicates deep depositional environment, below storm wave-base.

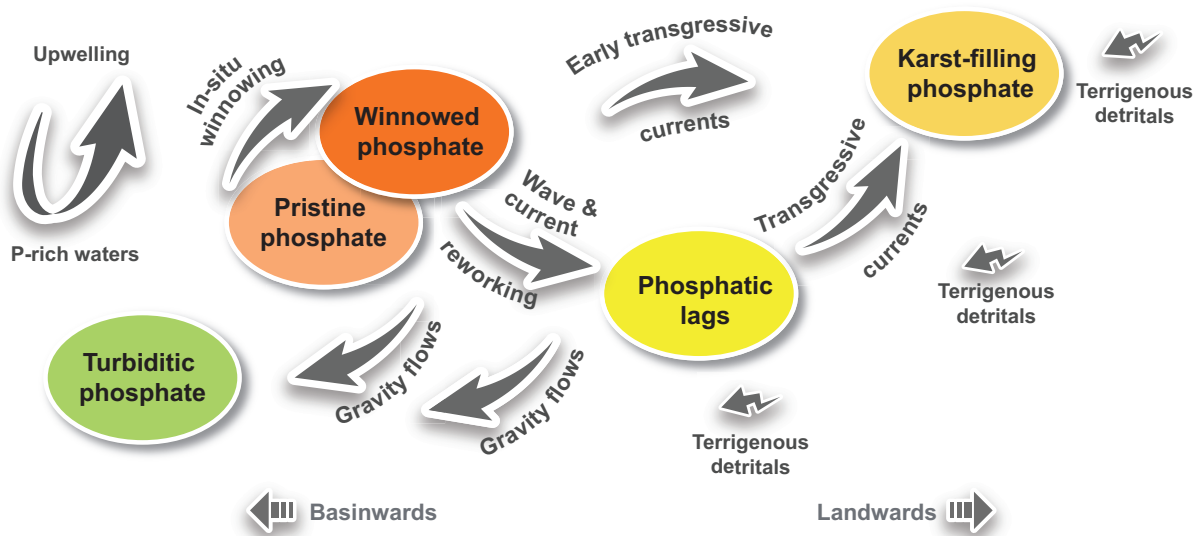


Fig. 10. Flow diagram showing the genetic links between the different types of phosphate identified in this study and highlighting the possible scenarios of sedimentary differentiation, as well as the sedimentary processes involved.

In addition to the aforementioned processes, the sedimentary differentiation of phosphate is further enhanced by allocyclic processes acting at the scale of the whole margin. Correspondingly, allocyclic (tectono-eustatic) relative sea-level variations generate correlative stratigraphic surfaces with which the main phosphate accumulation events are associated. Relative sea-level rise creates deepening upward sequences until reaching the maximum flooding surface (or zone). The pristine and associated winnowed phosphates are found preferentially above this surface (Fig. 11), which reflects relatively high bathymetric conditions, suitable for phosphogenesis (Föllmi, 1990). This pristine phosphate accumulation can be preserved in-situ or completely redistributed. Relative sea-level fall induces the fair-weather wave-base and storm wave-base to intercept the seafloor, which allows the previously deposited pristine phosphate to be reworked and transported. Accordingly, phosphatic lags are found in the regressive interval of the sequences (Fig. 11). Relative sea-level fall also causes the subaerial exposure of the proximal inner shelf, with the development of widespread karstification of carbonates. During subsequent sea-level rise, early transgressive landwards currents, erode, rework, and transport sediments accumulated on the inner shelf (Cattaneo and Steel, 2003). In the study area, karst-filling phosphates, showing evidence of landward transport and redeposition from older phosphate accumulations (agglomerated and fragmented phosphate grains) indicate that phosphatic lags and/or granular phosphate previously accumulated on the shelf have been redeposited within and above the karstic pockets. Moreover, the deposition of such phosphate grains above a subaerial karst surface is an evidence for its allochthonous character.

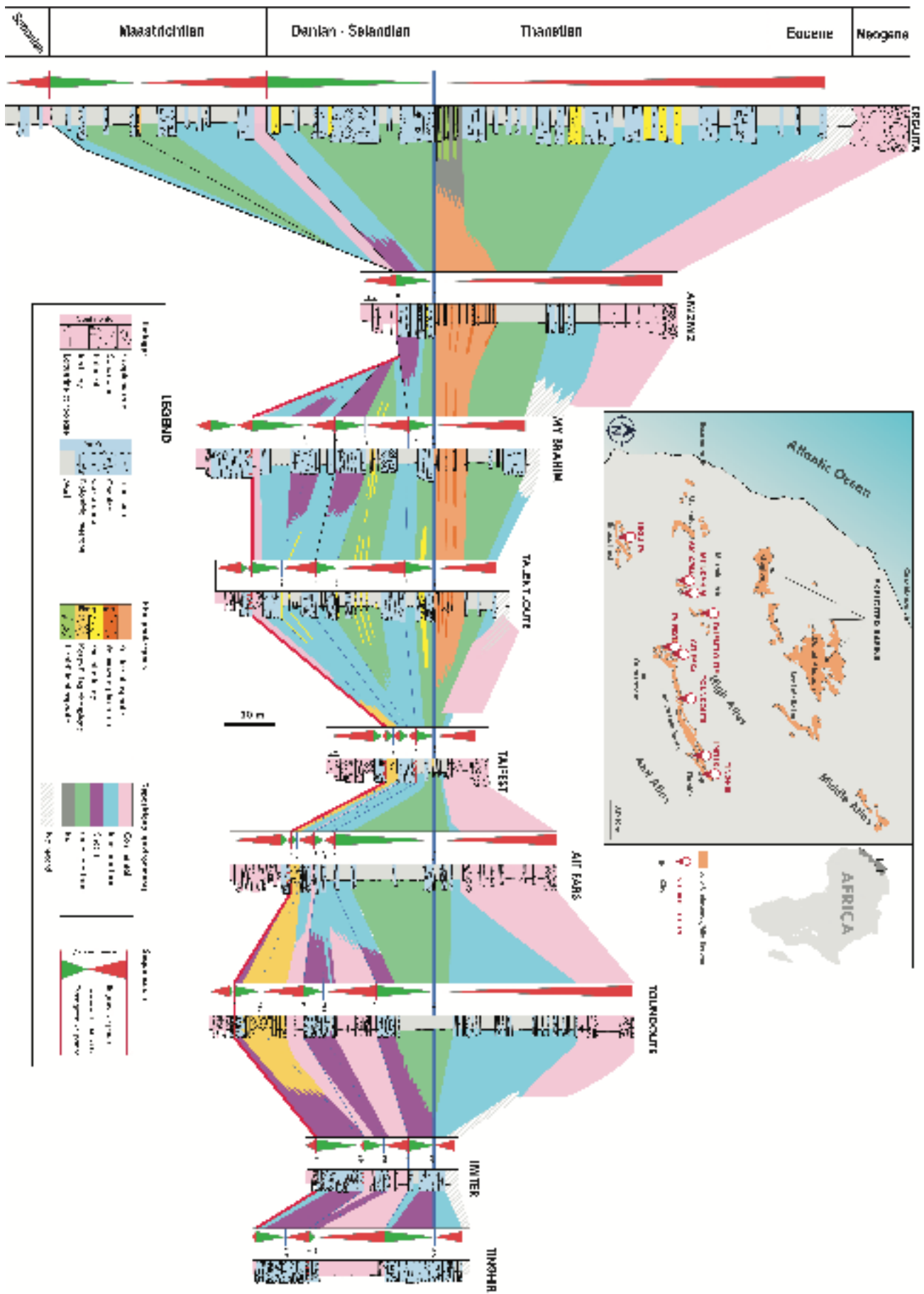


Fig. 11. Fence diagram showing the lateral correlation of the studied sections in the High Atlas. The major MFS is set as the reference datum for horizontalization. The lateral and vertical distribution of the different phosphate types is highlighted with respect to the different stages of the sea-level variations.

The sedimentary record of the High Atlas phosphate series reflects the interaction of allocyclic controls and autocyclic processes through lateral shifts induced by relative sea-level variations. Hence, the spatial distribution of the different phosphate types is eustatically and paleogeographically controlled. Our results indicate that the late Cretaceous-Paleogene series of the High Atlas were deposited in a single shallow platform passing to basin deepening northwestward, which is consistent with the views of [Herbig and Trappe, \(1994\)](#). During the studied interval, central Morocco was flooded over a wide area reaching the emerged Anti-Atlas ([Herbig and Trappe, 1994](#)). At that time, the Atlantic margin was characterized by an active upwelling system ([Holbourn et al., 1999](#)) bringing in deeper P-rich waters ([Lucas and Prévôt, 1975](#)) to the platform margin, where the primary phosphogenesis was stimulated in the phosphogenic window ([Trappe, 1998](#)).

At the end of the Maastrichtian, a general regression caused the subaerial exposure of the whole Atlasic basin resulting in a westward shift of the phosphogenic window, the creation of extensive karstification, and development paleosol horizons. As relative sea-level rose again during the Danian and Selandian ([Fig. 12A](#)), the phosphate previously formed in the margin and reworked on the shelf were transported landward by early transgressive currents, and trapped within karst pockets in the Ouarzazate basin. In the same time, phosphogenesis was still active in the phosphogenic window and hydrodynamics was reworking phosphate sediments in the inner platform,

corresponding to the present-day Marrakesh High Atlas, where phosphatic lags are found.

Relative sea-level rise during the Selandian progressively moved the phosphogenic window towards the southeast. During the Selandian-Thanetian transition ([Fig. 12B](#)), the maximum bathymetry was reached and the phosphogenic window was active within the outer platform (Marrakesh High Atlas basin). Interbedded pristine and winnowed phosphates were formed, preserved, and buried under subsequent carbonate and marl sequences. Storm and wave currents episodically reworked part of the winnowed phosphate and transported it landward up to the Ouarzazate basin, where only few phosphatic lags are described. The absence of pristine and associated winnowed phosphate within the Ouarzazate basin implies that paleoenvironments in this part of the system were never deep enough to form and preserve this facies. During this time, the Souss basin presented relatively deep environments where offshore organic-rich sediments and turbiditic phosphate beds were preserved. During the late Cretaceous-Paleogene interval, the detrital inputs were more expressed within the east of the Ouarzazate basin (close to the Anti-Atlas terrigenous sources) and Souss basin (gravity flows, maybe connected to a deltaic system), while only minor amounts of coarse clastic sediments were delivered to the Marrakesh High Atlas basin. Such small detrital input contributed to the observed low sedimentation rate in this part of the basin. This sediment starvation is important for the productivity of the phosphate factory as it drastically reduces the dilution of the phosphatic particles within the ambient sedimentation ([Filippelli, 1997](#)).

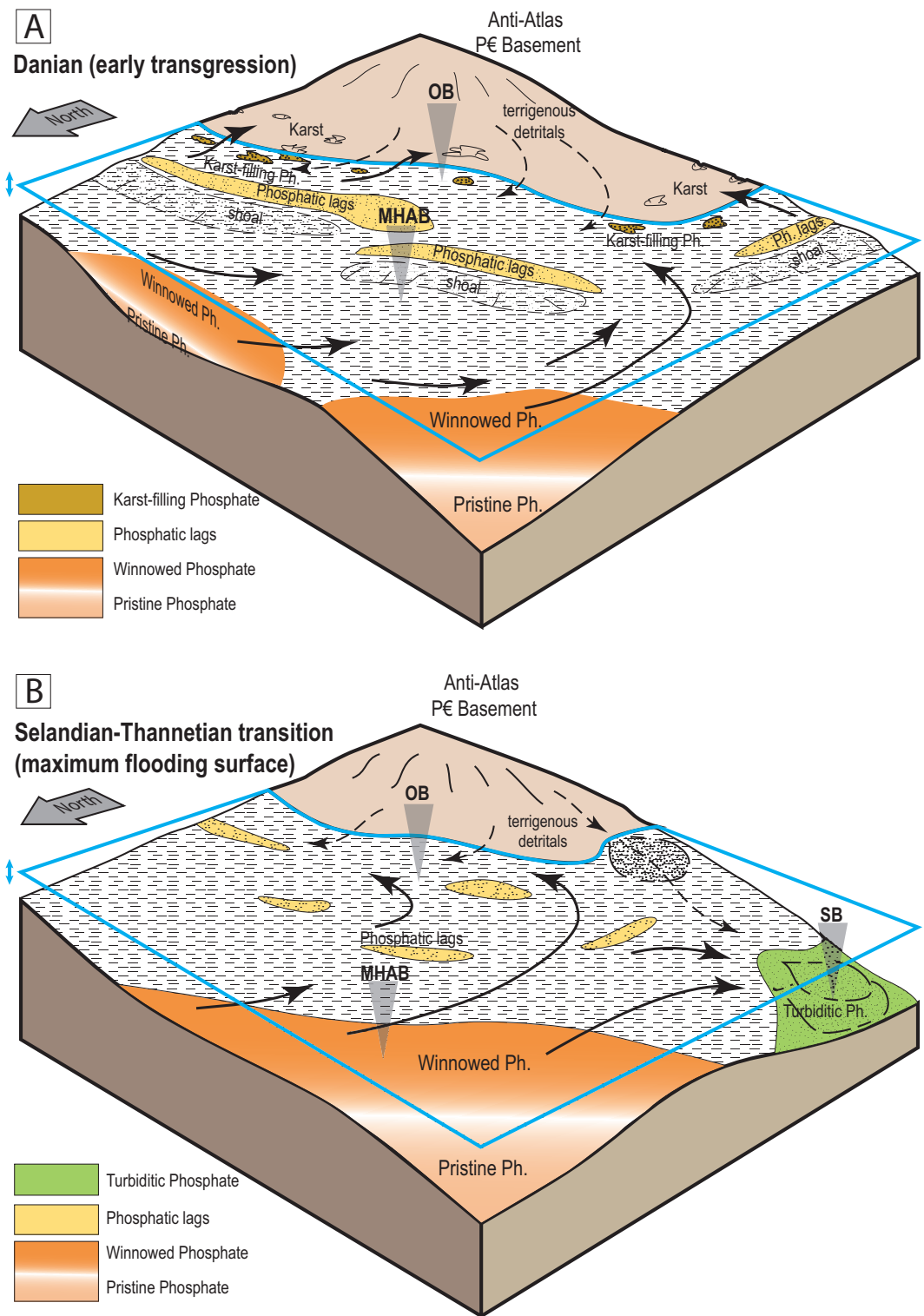


Fig. 12. 3D paleogeographic model for the accumulation of phosphate within the High Atlas of Morocco illustrating the different accumulation modes of phosphate and highlighting the shifting of the primary phosphogenesis window in two successive periods of the evolution of the studied series. OB: Ouarzazate basin; MHAB: Marrakesh High Atlas basin; SB: Souss basin.

10. Conclusions

Our study of the phosphate sequences of the Moroccan High Atlas brings new understanding on the sedimentological controls on their accumulation and preservation in the Maastrichtian to Paleocene sedimentary record. In particular, the markedly varying types of phosphate sediments, and the diversity of sedimentary environments where they were found, do not result from different phosphogenesis processes in a range of paleoenvironmental settings. Lithofacies analyses, combined with basin-scale correlations allowed to identify the genetic links between five type of phosphate-rich sediments. Primary phosphogenesis leads to the formation of pristine phosphate, in the phosphogenesis window, offshore of a carbonate platform, and under the control of upwelling currents. All other types of phosphate-rich sediments, known as reworked phosphates (Glenn et al., 1994; Pufahl and Groat, 2017), derive from sedimentary differentiation of this authigenically-formed pristine phosphate. On one hand, the sedimentary differentiation is controlled by the interaction of hydrodynamic autocyclic processes, such as wave and storm winnowing, currents across the platform, as shown by the spatial distribution of the five types of phosphate across the basin. On the other hand, tectono-eustatic allocyclic forcing modifies the position of the phosphogenesis window, in response to relative sea-level variations. As a result, the whole phosphogenic system is shifting landward or basinward during relative sea-level rise and fall, respectively. The main phosphate interval in the Marrakesh High Atlas corresponds to alternations of pristine and granular phosphates, that accumulated and were preserved above a major maximum flooding surface, which we date to the lower Thanetian.

On a global scale, we show that upwelling-controlled, primary phosphogenesis, allows the formation of pristine phosphate, which typically results in low-grade phosphatic sediments, as phosphate grains are scattered within the host marls. The phosphate enrichment, leading to economic-grade ore, requires hydrodynamic processes. Repeated storm and currents winnowing is an effective enrichment mode of the phosphate ore grade. Winnowed granular phosphate accumulations represent the richest phosphate type, which is accumulated on the outer platforms, close to the storm wave-base, away from the main terrigenous sources, and which is preserved during the early regressive hemi-sequence. These new insights on the controlling parameters of phosphate accumulation will help the exploration and exploitation of this non-renewable resource.

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