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The Paleogene continental basins from SE France: new geographic and climatic insights from an integrated approach

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23 and stable isotope analyses. U-Pb dating on calcite, pollen-based climatostratigraphy and
24 strontium and sulfur isotope signatures of sulfates provided a robust chronostratigraphic
25 framework for the Upper Eocene and Oligocene succession from the Vistrenque, Alès and
26 Roussillon basins. The thick Priabonian- lower Rupelian lacustrine succession from the
27 Vistrenque Basin is interpreted to be deposited in a strike-slip basin associated with the latest
28 stages of pyrenean shortening. Floral assemblages are used to reconstruct the vegetation cover
29 in the lacustrine systems and their neighbouring lowlands and highlands. Composition of
30 saltwater inferred from strontium and sulfur isotope signatures of sulfates, the occurrence of
31 calcareous nannofossils, dinoflagellate cysts and pollen grains of mangrove-related plants
32 provided strong evidence for marine intrusions into the Alès Basin during the Priabonian and the
33 Vistrenque Basin during the Rupelian and Chattian. Paleogeographic reconstructions of
34 Southeast France during the Priabonian and late Rupelian strongly suggest marine incursions
35 from the Alpine Sea via two potential pathways: upper Rhône Valley via the Crest Sill and lower
36 Rhône Valley via the Haut-Var Pyrenean synclines. On the other hand, Upper Oligocene
37 evaporite basins in the Camargue area have been subjected to marine intrusions from the Western
38 Mediterranean Sea following the collapse of the eastern pyrenean relief during the Liguro-
39 Provençal rifting stage. Finally, pollen analysis and Climate Amplitude Method revealed a brief
40 but significant stage of cooling and aridification at the very base of the Rupelian which could
41 represent the regional and terrestrial expression of the global climate cooling following the
42 Eocene-Oligocene Transition.

43

44 **Keywords:** Priabonian, Rupelian, Eocene-Oligocene Transition, U/Pb dating, pollens,
45 strontium and sulfur isotopes, climatostratigraphy, marine intrusion.

46

47 1. Introduction

48 In Southeast France, several continental basins were formed during the Paleogene and are
49 located in Languedoc (e.g. Alès, Saint-Chaptes and Issirac (ASCI) basins, [Sanchis and Séranne,](#)
50 [2000](#); [Lettéron et al., 2022](#); [Séranne et al., 2021](#)), Rhone Valley (Mormoiron Basin, [Triat and](#)
51 [Truc, 1974](#)), Provence (e.g. Apt-Manosque-Forcalquier Basin, [Lesueur, 1991](#); Marseille Basin,
52 [Nury, 1990](#)), and Camargue (e.g. Vistrenque Basin, [Benedicto et al., 1996](#)). These basins are
53 characterized by thick siliciclastic, carbonate and evaporite sedimentation (e.g. [Rouchy, 1997](#)).
54 The formation and the filling of these basins initiated during the Late Eocene (Priabonian) and
55 lasted until the Late Oligocene (Chattian). These basins were interpreted as branches of the
56 European Cenozoic Rift System (ECRIS, [Fig 1A](#)) ([Ziegler, 1992](#)) or resulting exclusively from
57 the Oligocene to Aquitanian extension linked to the Liguria-Provence rifting (e.g., Vistrenque
58 Basin, [Benedicto et al., 1996](#)), and a few cases as polyphased extensional structures (e.g.
59 [Sanchis and Séranne, 2000](#)) ([Fig. 1B, 1C](#)). In their recent work, [Séranne et al. \(2021\)](#) reassessed
60 the origin of Priabonian continental basins located in Languedoc, between the Northeast
61 trending Cévennes and Nîmes major regional faults and found that those basins resulted from
62 left-lateral strike-slip movements of these faults which accommodated both the Western
63 European rift system extension (ECRIS) and the still active N-S shortening of the Central and
64 Western Pyrenees.

65 The origin of evaporites in the saline paleolakes within the Paleogene basins of Southeast
66 France is poorly understood and is still a matter of controversy that has lasted for decades
67 particularly on the origin of the salt water that may result from marine incursions and/or the
68 recycling of Triassic evaporites ([Giraud, 1902](#); [Fontes et al., 1996](#); [Bodergat et al., 1999](#);
69 [Sissingh, 2001, 2006](#); [Dèzes et al., 2004](#); [Ziegler and Dèzes, 2007](#); [Briot, 2008](#); [Lettéron et al.,](#)
70 [2017](#)). Questions also remain on the patterns of saline water masses connections and
71 diachronism of the evaporite intervals between the different basins but also on the role of

72 changing climate on evaporite deposition and continental depositional system evolution at the
73 key Eocene-Oligocene transition (e.g., [Sissingh, 2001](#); [Lettéron et al., 2022](#)) which represents
74 a crucial period for the Cenozoic global climate evolution. Until recently, assumptions have
75 been made about the role of the Camargue area as a saline water corridor into the Languedoc
76 and Rhône Valley continental basins (e.g., [Lettéron et al., 2018](#)).

77 Since the Camargue area is located in a pivotal position among these France south-eastern
78 basins, between the Languedoc basins to the west, the Provence basins to the east, and the
79 Valence and Bresse grabens to the north (see location in [Fig. 1A](#)), the Paleogene Vistrenque
80 Basin occupies a key geographic position for constraining the geodynamic and structural
81 evolution of southeast France and Gulf of Lion areas during the Late Eocene and Oligocene
82 times and provides new insights into these hitherto unresolved paleogeographic issues.

83 The Vistrenque Basin is considered as the deepest (~ 5 km) Cenozoic basin in southeast
84 France and in the Gulf of Lion margin ([Benedicto et al., 1996](#)). The Paleogene sequence, up to
85 3200 m-thick, is entirely buried beneath the Rhône Delta sediments ([Valette and Benedicto,](#)
86 [1995](#)) ([Fig 2](#)). The drill cores have yielded very scarce and poorly preserved biota thus
87 preventing the definition of a detailed and well-constrained chronostratigraphic framework. The
88 correlation of thick halite and anhydrite deposits ([Valette and Benedicto, 1995](#)) with the
89 Priabonian and Oligocene evaporites from the neighbouring Rhone and Languedoc basins is
90 not yet established, thus preventing the reconstruction of a well-constrained paleogeographic
91 map of these basins during the Paleogene and the elucidation of the question of their potential
92 connection with the marine realm.

93 Comprehensive and detailed analyses of subsurface data from the Paleogene sedimentary
94 record of the Vistrenque Basin (cores, cuttings, well logs) as well as from the neighbouring
95 Alès Basin were undertaken to resolve these tectonic and paleogeographic issues ([Fig. 3](#), [Fig.](#)
96 [4](#)). Based on the integration of different dating methods such as U-Pb absolute dating on

97 carbonates, pollen-based climatostratigraphy, the interpretation of strontium and sulfur isotopes
98 measurements, and additional micropaleontological analyses (dinoflagellate cysts, calcareous
99 nanofossils), the present work aims at: (1) constraining the lithostratigraphic and
100 chronostratigraphic framework of the Paleogene sedimentary succession from the Vistrenque
101 Basin; (2) bringing new insights into the pending issue of the origin of salts in the Paleogene
102 saline lakes of Southeast France and the occurrence of marine incursions, and (3) refining the
103 paleogeographic and paleoclimatic reconstructions of Southeast France during the Late Eocene
104 and Oligocene times. In order to complement the overview in time and space of the regional
105 vegetation and climate evolution during the Oligocene, pollen data from the Canet 1 borehole
106 from the Roussillon Basin (Eastern Pyrenees) (location in [Fig. 1B](#)) have been integrated in this
107 study.

108

109 **2. Geological setting**

110 **2.1 Regional tectonic setting and stratigraphy**

111 Following the development of Upper Cretaceous carbonate platforms in Southeast France,
112 the Mesozoic to Eocene cover has been folded and thrustured during the Pyrenean shortening
113 which resulted from the convergence and collision of the Iberia-Corsica-Sardinia block with
114 the European plate (e.g. [Arthaud and Laurent, 1995](#); [Séranne et al., 1995](#); [Bestani et al., 2015](#)).
115 In Languedoc, the Nîmes and Cévennes faults have been shown to accommodate sinistral strike-
116 slip movements as early as the Priabonian in response to both the Pyrenean shortening and
117 Western European Rift extension ([Séranne et al., 2021](#)). As a consequence, within a 50 km wide
118 wrenching zone located between the Cévennes and Nîmes faults, fluvial and lacustrine
119 sedimentation occurred during Priabonian times, in releasing bends and oversteps of left-lateral
120 strike-slip faults, ([Séranne et al., 2021](#)). The pyrenean orogen and associated syn- and tardi-

121 orogenic basins have been It was later dismantled from the late Rupelian to the Aquitanian to
122 form the Gulf of Lion rifted margin (Arthaud et al., 1981; Arthaud and Séguret, 1981; Gorini
123 et al.,1994; Séranne et al., 1995; Mauffret and Gorini, 1996; Mascle and Vially, 1999; Séranne,
124 1999; Guennoc et al., 2000; Lacombe and Jolivet, 2005). The Oligocene-Aquitainian Gulf of
125 Lion rifting phase accompanied the retreat of slab and is followed by the Burdigalian break-up.
126 Paleogeographic reconstructions made by Benedicto et al., 1996 suggest a high relief, more
127 than 1 km of elevation, at the southern margin while the total extension across the Vistrenque
128 Basin is estimated to range from 9 to 9.5 km. The break-up event was dated to the early to
129 middle Burdigalian (Oudet et al., 2010a) and corresponds to the onset of the spreading of the
130 Liguro-Provençal Basin which led to the south-eastward drift of the Corsica-Sardinia Block
131 (Gorini et al., 1993; Séranne et al., 1995). During the Burdigalian, a marine transgression
132 followed the break-up and Burdigalian to Tortonian post-rift marine sediments were deposited
133 (Fig. 2B-C-D). By the end of the Miocene, the Messinian Salinity Crisis resulted in valley
134 incision into the Miocene deposits and affected the Oligocene deposits in places. The resulting
135 canyons are overlain by Pliocene and Quaternary sediments (Beaufort, 1954; Benedicto et al.,
136 1996; Leroux et al., 2017).

137

138 **2.2 The Paleogene Vistrenque Basin**

139 The Camargue region is constituted of two main Cenozoic basins separated by the Mesozoic
140 Albaron High (Fig. 2A-C): the Vistrenque Basin to the West and the Vaccarès Basin (=Petit-
141 Rhône Basin) to the East. The Vistrenque Basin is oriented NE-SW and extends over 50*30
142 Km²s This basin is linked to the northeast with the Pujaut Through (Fig. 2A) along the bounding
143 NNE-SSW trending major Nîmes Fault that separates the basin from the Mesozoic hills of the
144 Garrigues region (Fig. 2C; Semmani et al., 2022). The Vistrenque Basin is bounded to the south
145 by the Highs of Grau-du-Roi and Saintes-Maries-de-la-Mer (Fig. 2A). The basin is structured

146 by a set of syn-rift faults mostly parallel to the Nîmes Fault (**Fig. 1C**, **Fig. 2B-C**) that determine
147 tilted blocks within the basin but also by transfer faults that separate different sectors with
148 specific structural styles (e.g., **Fig. 2B**; [Benedicto et al., 1996](#) and their figures).

149 The maximum thickness of the Cenozoic sedimentary succession of the Vistrenque Basin is
150 known from the Pierrefeu 1 well (4920 m) where it rests on a Lower Cretaceous marine
151 carbonate basement (**Fig. 2B**). The Cenozoic infill of the Vistrenque Basin is subdivided into
152 poorly defined pre-rift series, syn-rift series attributed to the Oligocene-Aquitainian extension,
153 and post-rift series of Burdigalian to Pliocene and Quaternary age (**Fig. 2B-C-D**; [Valette and](#)
154 [Benedicto, 1995](#); [Benedicto et al., 1996](#)). Below the Aquitainian deposits, the Paleogene strata
155 have been subdivided classically into three main lithological units of hundreds to thousands of
156 metres thick: from top to bottom: *Série Calcaréo-salifère* Formation, *Série Rouge* Formation
157 and *Série Grise* Formation (**Fig. 2D**). These subdivisions have been adopted by [Cavelier et al.](#)
158 (1984) in their synthesis on the Paleogene of Southeast France and these authors suggested an
159 Eocene age for the lowermost parts of the *Série Grise* Formation based on the observed
160 similarities in the sedimentary trends with the neighbouring basins.

161 The compartmentalization of the Vistrenque Basin by transfer faults results in different
162 stratigraphic successions between the northern Pierrefeu sector and the southern Gallician
163 sector (**Fig. 3A-C**). The depositional setting and stratigraphic architecture of the Vistrenque
164 Basin has been recently reassessed by [Semmani \(2022\)](#). The Paleogene lithological succession
165 at the reference well (Gallician 9) from the Gallician sector is composed of five distinct
166 formations (**Fig. 3A**). 1) The lowermost *Série Grise* Formation is several hundred metres thick
167 (the base of the Paleogene is not reached in this sector) and is made of a monotonous succession
168 of sandstones (calcarenites), conglomerates, marlstones and less frequent evaporites deposited
169 in lacustrine settings. 2) The overlying *Série Calcaire* Formation is around 250 m thick and is
170 made essentially of sandstones (calcarenites) and calcisiltites (siltstones), and a few monomictic

171 conglomerates at the base. These lithologies become scarce upward while variegated calcareous
172 claystones and vacuolar limestones become more frequent, and the unit is capped by a major
173 subaerial exposure surface. 3) The *Série Mixte* Formation is 42 m thick and characterized by
174 alternation of dominantly polymictic conglomerates, siliciclastic sandstones, variegated
175 calcareous claystones and limestones. 4) The *Série Rouge* Formation is made of alternations of
176 siliciclastic-dominated sandstones and marlstones with frequent conglomerates at the base. 5)
177 The *Série Calcaréo-salifère* Formation is around 300 m thick in the Gallician sector and
178 constituted mainly of limestones and papyraceous marlstones at the base. The upper part of the
179 unit is made of two sequences made of alternations of sandstones, marlstones, limestones,
180 anhydrite and halite.

181 In Pierrefeu 1 well ([Fig. 3A](#)), the nomenclature is slightly different and the *Série Calcaire*
182 and *Série Mixte* formations have not been recognized probably because of lateral variations of
183 facies. The top of the *Série Grise* from the Pierrefeu 1 well likely corresponds to the *Série*
184 *Calcaire* defined in the Gallician sector. Compared to the Gallician sector, the considerable
185 thickness of the evaporite-rich *Série Calcaréo-salifère* Formation (~900 m) from the Pierrefeu
186 sector results from the abnormal overlay of evaporite intervals caused by halotectonic gravity
187 slides on top of the NW-dipping roll-over of the Nimes Fault, linked to the Oligocene-
188 Aquitanian extension ([Valette and Benedicto, 1995](#)).

189

190 **2.3 The Paleogene Alès and Saint-Chaptes basins**

191 Located between the Nîmes and Cévennes faults, the Alès and Saint-Chaptes basins
192 are characterized by a thick Priabonian fluvial and lacustrine succession (up to 900m)
193 deposited during the latest stages of pyrenean compression ([Séranne et al., 2021](#)). The
194 Priabonian succession is unconformably overlain by Chattian continental deposits
195 accumulated in extensional setting related to the Gulf of Lion rifting ([Sanchis and Séranne,](#)

196 2000). The Alès Basin is located along the Cévennes fault with a NE-SW direction (25 km
197 long, 5 km large), while the Saint-Chaptes Basin occupied by a saline lake (ASCI lake
198 system) whose mixed carbonate, siliciclastic and evaporitic sedimentation has been
199 exhaustively studied by [Letteron et al. \(2018; 2022\)](#). These authors subdivided the
200 Priabonian deposits in six unconformity-bounded parasequences from SP_r1 to SP_r6 defined
201 as transgressive-regressive (T-R) cycles ([Fig. 4](#)). The chronostratigraphy of the Priabonian
202 deposits is well-constrained and based on mammalian ([Rémy, 1985, 1994; Rémy and](#)
203 [Fournier, 2003; Rémy and Lesage, 2005](#)) and charophyte biostratigraphy ([Feist-Castel,](#)
204 [1971; Lettéron et al., 2017](#)) coupled with magnetostratigraphic analyses ([Lettéron et al.,](#)
205 [2022](#)).

206

207 **2.4 The Roussillon Basin: Canet 1 borehole**

208 The Canet 1 well, located in the Roussillon Basin (location: [Fig. 1B, Table S1](#)), cuts through
209 a 1785 m thick sequence of Quaternary to Permo-Triassic deposits overlying the Hercynian
210 basement ([Gottis, 1958](#)). The lithostratigraphic succession and chronostratigraphic framework
211 of well Canet 1 are summarized in [Figure S1](#). This section displays around 700 m of sandy-
212 clayey-lignitic deposits (1015–1716 m depth) which may correlate the Late Oligocene to the
213 Early Miocene interval ([Gottis, 1958](#)) and thus has been ascribed to the rifting episode of the
214 Gulf of Lion evolution ([Mauffret et al., 2001; Séranne, 1999; Romagny et al., 2020](#)).

215

216 **3. Material and methods**

217

218 This work is based on the analysis of cores, well cuttings and well logs from boreholes drilled
219 in the Gallician and Parrapon sectors of the Vistrenque Basin, boreholes and exposed sections
220 from the ASCI system and cuttings from Canet 1 well located in the Roussillon Basin (see
221 locations in [Fig. 1B](#), [Fig. 3](#) and [Fig. 4](#); [Supplementary data, Table S1](#)).

222

223 **3.1 Chronostratigraphic framework construction**

224 The chronostratigraphic framework of the studied basins (Vistrenque, Alès, Saint-Chaptes
225 and Roussillon basins) has been defined or improved by using U-Pb dating on carbonates,
226 pollen-based climatostratigraphy and calcareous nannofossil biostratigraphy.

227

228 **3.1.1 U-Pb geochronology**

229 *Sampling*

230 The *Série Grise* Formation being almost entirely detrital, the U-Pb method has been used
231 exclusively for calcite veins. In contrast, the overlying formations are carbonate-rich and
232 display various carbonate mineral phases (cements, pedogenic carbonates, root calcifications,
233 molluscan shells *-neomorphs*) making the dating method possible. The dating of these calcite
234 phases, and therefore the corresponding geological events (e.g. subaerial exposure) helps to
235 approximate the depositional age of the sedimentary intervals. Events post-dating the
236 deposition give younger ages whereas events pre-dating the following depositional unit give
237 maximum ages.

238

239 *Analytical method*

240 In order to carry out U-Pb dating on calcite, 30 samples containing a calcite mineral phase
241 were selected for the confection of thin sections. For each sample, a 30 μm -thick and a 100 μm -
242 thick thin section have been prepared respectively for petrographic observations and for the
243 sampling by laser ablation for spectrometric analyses.

244 Prior to the analyses, sedimentological and diagenetic observations were carried thoroughly
245 in order to identify the relevant mineral phases that should be dated and to avoid sampling from
246 two different mineral phases, since sampling from different calcite generations would result in
247 misinterpretations of ages. Diagenetic analysis and carbonate phase selection were performed
248 by coupling cathodoluminescence and fluorescence microscopy. Confocal microscopy
249 observations have been performed at the PRATIM (Aix-Marseille University) using an Axio-
250 observer Z1 inverted confocal microscope with single or two-photon laser scanning comprising
251 04 visible lasers (Argon multi-ray laser: 458, 488 and 514 nm, DPSS 561 nm, He-Ne 594 nm,
252 and He-Ne 633 nm) and a Chaméleon Vision II IR laser with pre-compensation system coupled
253 with a ZEN 2010 software. Cathodoluminescence observations have been made at the CEREGE
254 (Marseille, France) using a Cathodyne cold-cathodoluminescence from NewTec [®] operating at
255 16 to 18 Kv and 160 to 200 μA coupled to an Olympus BH-2 microscope and Olympus-
256 UPMTVC camera.

257 Once a carbonate phase has been individualized, the next step consists of the screening on
258 this area for U and Pb content on thin section in order to estimate the variability of U/Pb ratios.
259 For this purpose, elemental mapping of U, Pb, Fe and Sr was performed on the area of interest
260 of the thin section. U-Pb dating on calcite used *in situ* Laser Ablation Inductively Coupled
261 Plasma Mass Spectrometry (LA-ICP-MS) method which requires scattered U/Pb ratios in order
262 to make robust statistical calculations thus allowing a reliable age, with the least uncertainty, to
263 be obtained. Analyses were performed at the DatCarb A*midex platform (CEREGE, Aix-
264 Marseille university).

265 Where the screening shows suitable U and Pb concentrations variability, about 30 circular
266 spots of 100 μm diameter are picked within the mineral phase to perform the Laser Ablation.
267 Calcite ablation on thick sections was performed using an ESI (Electro Scientific Industries)
268 laser (193nm ArF Excimer laser) the resolution of which is 100 μm . Reference standards were
269 used to correct the inter-elemental fractionation. The raw data were processed with the Lolite
270 $\text{\textcircled{R}}$ software designed for laser ablation analyses. An Excel macro, inhouse to the CEREGE, is
271 used to handle the U-Pb data. Finally, the U-Pb age is calculated by using the Tera-Wasserburg
272 diagram with add-on isoplot 4.15 (Excel). The obtained absolute ages have been calibrated on
273 the Geological Time Scale of [Gradstein *et al.* \(2012\)](#). Further details on the methodology and
274 the analytic parameters are given in [Godeau *et al.* \(2018\)](#) and their online supporting data
275 section.

276 **3.1.2 Pollen-based climatostratigraphy**

277 Pollen grains have been extracted at the GeoBioStratData.Consulting laboratory (Rillieux-
278 la-Pape, France) and the results have been integrated within a regional climatostratigraphic
279 chart (e.g., [Suc, 1984](#); [Suc *et al.*, 2018, 2020](#)). 52 samples of about 20-30 grams weight have
280 been processed in order to obtain pollen floras using the classical method (acid digestions with
281 hydrochloric acid (HCl) and hydrofluoric acid (HF), concentration in ZnCl_2 at density 2, and
282 sieving at 10 μm). Only 18 samples yielded pollen grains in enough quantities (their geographic
283 distribution is shown in [Figure 1B](#) and specified in [Supplementary data, Table S3](#)). The
284 residues are mounted within glycerol between the slide and coverslip that allows to slightly
285 move each pollen grain for observation purposes under various sides. Some pollen records,
286 from the wells (Gallician 1, 4 and 9, Maruéjols 1) and the exposed Monteils section (Saint-
287 Chaptes Basin, ASCI system), display a number of taxa that is lower than 25 (= systematic
288 entities equivalent to families or genera). This value is the diversity threshold to assess the

289 representativeness of a pollen flora sample. These non-representative samples should be
290 interpreted with caution.

291 The main advantage of this new pollen analysis approach based on a detailed taxonomic
292 investigation is that it aims to reconstruct the botanical flora and is therefore a peculiar approach
293 for the Paleogene times. The accurate examination of the morphological characters of fossil
294 pollen grains and their comparison with modern pollen grains of rich and varied collections
295 (ISEM mainly, GeoBioStratData.Consulting) and iconographic databases allow to confidently
296 identify fossil pollen grains at least at the family level and very often at the genus level. A
297 powerful ecological interpretation of pollen floras results from such botanical identifications.
298 These botanical identifications are robust as it has been demonstrated that almost all the modern
299 genera of plants already existed since the Early Paleogene and were altitudinally-latitudeally
300 distributed similarly to the present time ([Suan et al., 2017](#); [Salpin et al., 2019](#); [Suc et al., 2020](#)).
301 The significance of our pollen records in terms of ecological-climatological changes are also
302 enhanced thanks to pollen countings. To date, pollen counting approach has been a routine
303 investigation for the Pliocene and Quaternary and less used for ancient series.

304 High-quality in botanical pollen identification and pollen countings have allowed to
305 successfully apply on these pollen floras the ‘Climatic Amplitude Method’ ([Fauquette et al.,](#)
306 [1998](#)) in order to quantify the Paleogene paleoclimatic conditions ([Suan et al., 2017](#); [Salpin et](#)
307 [al., 2019](#); [Suc et al., 2020](#)). The analyses have been performed on a AX10 Zeiss light
308 microscope at X250 magnification, each pollen grain being observed at X1000 magnification
309 for its identification.

310 A minimum of 150 pollen grains were counted per sample extra those of *Pinus* (a
311 cosmopolitan genus), those of meso-microthermal trees, inhabiting mid-altitudes (*Cathaya*,
312 *Podocarpus*, *Fagus*, *Cedrus*, *Tsuga*), and those of microthermal trees, inhabiting higher
313 altitudes (*Abies* and *Picea*). The detailed pollen analyses are provided in [Supplementary data](#)

314 (Table S3). Taxa are grouped according to the climatic and/or ecological significance of their
315 modern representatives (Table S3), resulting in two types of synthetic pollen diagrams. The
316 first type includes all the pollen grains excepted those of *Pinus* and provides a local and regional
317 image of the vegetation (including that growing on reliefs); the second type excludes the mid-
318 and high-altitude plants and provides a perception of the local vegetation (i.e., that of low
319 altitudes). In such diagrams, plants are grouped mainly according to the classification of Nix
320 (1982) based on the mean annual temperature (MAT), the concerned taxa usually requiring
321 relatively elevated to high precipitation: megatherms ($\text{MAT} > 24\text{ }^{\circ}\text{C}$), mega-mesotherms (20
322 $^{\circ}\text{C} < \text{MAT} < 24\text{ }^{\circ}\text{C}$), mesotherms ($14\text{ }^{\circ}\text{C} < \text{MAT} < 20\text{ }^{\circ}\text{C}$), meso-microtherms ($12\text{ }^{\circ}\text{C} < \text{MAT}$
323 $< 14\text{ }^{\circ}\text{C}$), and microtherms ($\text{MAT} < 12\text{ }^{\circ}\text{C}$). The other groups have various significations:
324 environmental for the herbaceous plants (more often not-identifiable at the infra-family level),
325 ecological for the water plants, indicative of some dryness (Mediterranean sclerophyllous
326 plants, steppe plants and subdesertic plants), insignificant (for example, the Cupressaceae with
327 a *Cupressus-Juniperus* like pollen unidentifiable at the genus level). Details about taxa
328 composing the groups are provided in Table S3. Reworked palynomorphs from older periods
329 are not very abundant except in few samples (Canet 1 1100 and 1701 m; Gallician 1 1648 m;
330 Gallician 9 2530 m; Table S3). They are easily recognizable by their morphology and/or their
331 darker colour and/or their altered preservation.

332 The varying content of successive pollen locations is mostly considered as markedly driven
333 by global climate changes which was affected by major and secondary fluctuations during the
334 time interval 38–23 Ma as illustrated by the global oxygen reference isotope curve (Westerhold
335 et al., 2020). Accordingly, pollen floras are hypothesized to correlate with the global climatic
336 evolution, which constitutes the principle of climatostratigraphy (Suc, 1984; Suc et al., 1995,
337 2018, 2020; Popescu et al., 2010). Factually, we propose to correlate each pollen assemblage
338 with the oxygen isotope stage that corresponds the best to its climatic significance, still within

339 the established stratigraphic succession and/or within the chronologic range separately
340 indicated by mammal fauna or calcareous nannofossils when available.

341 This approach contrasts with the traditional palynostratigraphy based on the direct attribution
342 of a chronological value to some pollen grains (Sittler *et al.*, 1975; Châteauneuf, 1980;
343 Châteauneuf *et al.*, 2019) that may lead to serious misinterpretations (see the **Supplementary**
344 **Data**).

345

346 **3.1.3 Calcareous nannofossils**

347 The analysis of calcareous nannofossils has been performed for refining the
348 chronostratigraphic framework and evidencing potential marine incursions. Calcareous
349 nannofossils have been studied in the fraction of 2–30 µm and separated by decantation method
350 using a 7% solution of H₂O₂. Smear-slides were mounted with Canada balsam and analyzed
351 with an Olympus transmitting light microscope at x 1200 magnification. Nannofossil
352 identifications follows the taxonomic classification of Perch-Nielsen (1985) and Raffi *et al.*
353 (2006). Nannofossil zones are after Martini (1971). Further calibration follows Raffi *et al.*
354 (2006) and Gradstein *et al.* (2012).

355

356 **3.2 Climatic Amplitude Method**

357 The endeavour in pollen identification and counting implies the possibility to use the Climatic
358 Amplitude Method to reconstruct climate conditions during the deposition of the sediments.
359 This method allows estimating past climate variables by transposing the climatic requirements
360 of the maximum of modern taxa to the fossil records. This approach relies on the relationship
361 between the relative pollen abundance of each individual taxa and climate, defined after
362 comparison with more than 6,000 present-day pollen records distributed worldwide. This

363 method accounts not only for the presence/absence criterion but also pollen percentages to
364 provide more reliable reconstructions (Fauquette et al., 1998). The estimated mean annual
365 temperatures (MAT), mean temperatures of the coldest (MTC) and warmest (MTW) months
366 and mean annual precipitation (MAP) concern low-elevation vegetation because meso-
367 microthermal and microthermal taxa (*Cedrus*, *Fagus*, *Tsuga*, *Cathaya*, *Podocarpus* *Abies* and
368 *Picea* which live today at higher elevations in tropical-subtropical regions) were excluded from
369 the process (but not from the percentages) to avoid a cold bias linked to transport from higher
370 elevations. *Pinus*, which may inhabit different vegetation belts, is also excluded from the
371 calculation. The excluded taxa were defined based on the distribution of vegetation today.
372 Indeed, the types of vegetation deduced from our pollen data are found in South-eastern China
373 today at around 25°N and 110 to 120°E (Hou, 1983). In this region, the vertical distribution of
374 the vegetation is characterized, from the base to the top of the massifs by evergreen broad-
375 leaved forest, mixed evergreen and deciduous (*Betula*, *Acer*) broad-leaved forest,
376 *Cathaya/Tsuga* forest, *Picea/Abies* forest and high mountain meadows (Hou, 1983). In the
377 Climatic Amplitude Method, the estimates for each climatic parameter are given as an interval
378 (minimum and maximum values of the parameter). A most likely value (MLV) is calculated,
379 which corresponds to a weighted mean. The MLV has been statistically tested on modern pollen
380 data and has provided reliable results (Fauquette et al., 1998).

381

382 **3.3 Geochemical modelling of strontium and sulfur isotopes on sulfates**

383 Strontium and sulfur isotope compositions of gypsum and anhydrite have been proved to be
384 reliable markers of the origin of the waters from which they precipitated and geochemical
385 modelling approaches make it possible to quantify the proportions of different salt waters within
386 a mixture (Denison et al., 1998).

387 **3.3.1 Sampling and measurements**

388 Five anhydrite samples from Pierrefeu-1 well (Vistrenque Basin, see position in [Fig. 5](#)) and
389 three anhydrite samples from Les Fumades wells (SC-1 and SC-2, Alès Basin, see position in
390 [Fig. 4](#)) have been selected for $\delta^{34}\text{S}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ laboratory measurements.

391 Strontium isotope measurements were carried by the SARM-CRPG laboratory
392 (Vandoeuvre-les-Nancy, France). Samples have been powdered (<50 μm), weighted and mixed
393 with HNO_3 and HF and after evaporation, mixed with concentrated HCl. After complete
394 digestion of the sample and Sr separation, $^{87}\text{Sr}/^{86}\text{Sr}$ was measured by using a TIMS Triton Plus
395 (Thermo electron) in static mode. The standard NBS987 has been used as a reference. All
396 measurements have 2σ error are lower than 0.000012.

397 S isotopic composition of sulfates from anhydrite and gypsum samples and elemental
398 (native) sulfur was measured by combustion using an Elementar vario PYRO cube elemental
399 analyzer (Elementar GmbH) in-line with an Isoprime 100 mass spectrometer (Manchester, UK)
400 in continuous flow mode at the University of Burgundy in Dijon, France. Isotope data are
401 expressed in delta notation and reported in units per mil (‰). The $\delta^{34}\text{S}$ data are reported with
402 respect to the international standard Vienna Cañon Diablo Troilite (VCDT). Analytical errors
403 are ± 0.3 ‰ (2σ) based on replicates for standard materials.

404

405 **3.3.2 Modelling of strontium and sulfur isotope composition of mixed waters**

406 The Sr isotope composition of two-component mixtures/endmembers has been described in
407 detail by [Faure \(1986\)](#) and applied to Sr and S isotopes ([Andersson et al., 1992](#); [Denison et al.,](#)
408 [1998](#)). The isotopic ratio ($^{87}\text{Sr}/^{86}\text{Sr}$ and $^{34}\text{S}/^{32}\text{S}$) I_m is computed as follows:

409
$$I_m = [f_1 \cdot C_1 \cdot I_1 + (1-f_1) \cdot C_2 \cdot I_2] / [f_1 \cdot C_1 + (1-f_1) \cdot C_2] \quad (1)$$

410 Where I_1 and I_2 represent the isotopic ratios of the first and second end member, respectively.
411 C_1 and C_2 are the Sr or SO_4^{2-} concentration in the first and second end members, respectively
412 and f_1 is the volume fraction of the first end member water in the mixture.

413 Various endmembers have been selected for the modelling: 1) seawater, 2) continental water
414 whose Sr and S content is controlled by the leaching of Triassic evaporites, 3) continental water
415 whose composition derived from the leaching of metamorphic rocks.

416 The Sr concentration of Paleogene seawater (15 ppm) is derived from the estimations by
417 [Vollstaedt et al. \(2014\)](#); such a value is close to modern concentrations (~8 ppm). Sulfur
418 concentration was assumed to be similar to that of modern seawater (2800 ppm). The $^{87}\text{Sr}/^{86}\text{Sr}$
419 values for Priabonian to Chattian seawater range from 0.7077 to 0.7083 ([Mc Arthur et al., 2012](#))
420 while $\delta^{34}\text{S}$ is assumed to be close to modern values (+20‰).

421 Riverine waters influenced by the leaching of Triassic evaporites have been considered to
422 have retained the $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{34}\text{S}$ of the original gypsum or anhydrite. $^{87}\text{Sr}/^{86}\text{Sr}$ values ranging
423 from 0.7076 to 0.7080 have been reported for Triassic (Keuper) evaporites from the French
424 Pyrenees ([Albarède and Michard, 1987](#)), Italy ([Dinelli et al., 1999](#)), Spain ([Alonso-Azcarate et](#)
425 [al. 2006](#); [Ortí et al., 2014](#)), while $\delta^{34}\text{S}$ values range from +10 ‰ to +17 ‰ ([Utrilla et al., 1992](#);
426 [Dinelli et al., 1999](#); [Boschetti et al., 2011](#)).

427 Riverine waters draining metamorphic or igneous bedrocks should have higher $^{87}\text{Sr}/^{86}\text{Sr}$
428 ratios as shown in present time in the Cevennes Massif, with values ranging from 0.712 to 0.714
429 for waters draining granites and from 0.714 to 0.717 for waters draining schists ([Petelet-Giraud](#)
430 [et al., 2006](#)). Regarding sulfur isotope composition, magmatic and metamorphic rocks are
431 known to be characterized by $\delta^{34}\text{S}$ ranging from -12 ‰ to +12‰ ([Chaussidon et al., 1989](#);
432 [Giacometti et al., 2014](#)).

433

434 **4. Results and interpretation**

435

436 **4.1 U-Pb dating**

437 Among the examined 12 samples, only three samples meet the conditions of the U-Pb dating
438 method: (a) G9 13D, (b) G9 7, and (c) G9 K35. Relevant samples and associated ages are
439 summarized in [Table 1](#).

440

441 **4.1.1 G9 13D Sample: *subaerial exposure on top of the Série Calcaire***

442 In this sample, microstalactitic calcite (A1) lines the walls of a dissolution vug. It is post-
443 dated by an anisopachous calcite cement (A2) which is in turn post-dated by an isopachous
444 equant sparry calcite cement (I1) ([Fig. 6A](#)). Only cement A1 displays dull luminescence while
445 the following cements are non-luminescent and thus cannot be distinguished under
446 cathodoluminescence. However, observations under confocal microscope made it possible to
447 distinguish the cement generations ([Fig. 6C](#)). Uranium concentrations are very low in the A2
448 and I1 cements thus precluded dating analyses ([Fig. 6B](#)). However, the cement stage A1
449 displays enough U and Pb thus allowing the dating method to be applied ([Fig. 6D](#)). The
450 calculated age of the early diagenetic microstalactitic cement A1 is 31.27 +/- 1.90 Ma which
451 gives a early to middle Rupelian age after GTS2012 ([Gradstein et al., 2012](#)).

452

453 **4.1.2 G9 7 sample: *vadose cement within the lowermost interval of the Série Rouge***

454 This sample displays anisopachous pendant microsparite cements, up to 600 µm thick
455 around clasts in a polymictic conglomerate ([Fig. 7A](#)). In this sample, carbon and oxygen
456 isotope analyses on the calcite yielded very negative values ($\delta^{18}\text{O} = -5.11 \text{‰ V-PDB}$ & $\delta^{13}\text{C} =$

457 -5.59 ‰ V-PDB) thus indicating meteoric origin of the precipitation water. In addition, the
458 anisopachous nature of the cement suggests precipitation under vadose meteoric conditions.
459 Such cements represent the earliest phase of cementation and formed prior to burial and
460 mechanical compaction. The cement therefore likely formed shortly after deposition and infill
461 of the fluvial channel, in a vadose environment within an alluvial plain. U and Pb concentrations
462 are favourable thus making it possible to test the dating method. 74 spots have been used and
463 the concentrations show sufficient dispersal of the U/Pb ratio thus enhancing the accuracy of
464 the method (**Fig. 7B**). The U-Pb age found for this carbonate phase using the Tera-Wasserburg
465 diagram is 27.88 +/- 1.71 Ma which indicates a late Rupelian to early Chattian age according
466 to the GTS (**Gradstein et al., 2012**). The initial composition ratio of $^{207}\text{Pb}/^{206}\text{Pb}$ is 0.8321 +/-
467 0.034.

468

469 **4.1.3 G9 K35 sample: calcite veins within the lower Série Grise**

470 The K35 sample is from the terrigenous-rich *Série Grise* Formation. In this sample, the
471 calcite analysed for U-Pb dating consists of the filling of fractures (veins) within the silty
472 marlstones host rock (**Fig. 7C**). The vein is about 1 mm wide and it is filled with equant to
473 fibrous calcite, the crystals sizes average 200 µm.

474 Under cathodoluminescence, the calcite vein is non-luminescent (**Fig. 7D**). In the calcite
475 vein, U and Pb concentrations are favourable to the dating method (**Fig. 7E**). The calculated
476 Tera-Wasserburg U-Pb age for the calcite vein infill is 21.46 +/- 2.19 Ma.

477

478 **4.2 Calcareous nannofossils**

479 Calcareous nannofossils are recorded in seven samples (**Supplementary data: Table S2**),
480 supporting some marine water incursions into the Alès Basin during the Priabonian (crossroad

481 D716/D981 sample), in agreement with the occurrence of dinoflagellate cysts and mangrove
482 pollen grains. Some other marine water incursions are indicated in the Gallician 1 borehole at
483 depths 1810 m (from the lowermost *Série Calcaréo-salifère* Formation ascribed to late
484 Chattian) and 1594 m (ascribed to earliest Aquitanian), consistently with the occurrence of
485 marine dinoflagellate cysts in the studied samples from the Canet 1 borehole. The calcareous
486 nannofossil assemblages identified from the Alès and Vistrenque basins (Crossroad
487 D716/D981, Maruéjols 1 433 m, Gallician 1 1810 m and 1594 m) are poor in species with a
488 short biostratigraphic range: only *Reticulofenestra bisecta* and *R. lockeri* point out a
489 chronological interval from ca. 38 Ma to ca. 23 Ma ([Anthonissen and Ogg, 2012](#) in [Gradstein
490 et al., 2012](#)) i.e., covering the time interval investigated in this study including the Priabonian
491 and the entire Oligocene. More accuracy is provided by the calcareous nannofossil assemblages
492 from the Canet 1 borehole ([Table S2](#)): sample at 1701 m can be referred to biozones NP23–
493 NP24 (32–26.8 Ma), sample at 1470 m to biozones NP24–NP25 (29.7–23.2 Ma), sample at
494 1100 m to biozones NP25–NN1 (26.8–22.8 Ma) ([Martini, 1971](#); [Raffi et al., 2006](#); [Anthonissen
495 and Ogg, 2012](#)).

496

497 **4.3 Pollen-based reconstructed paleoclimates and climatostratigraphy**

498

499 **4.3.1 Results**

500 A total of 122 taxa have been identified in the 18 pollen records ([Table S3](#)). These pollen
501 floras show prevalent mega-mesothermal plants and, secondarily, mesothermal plants and the
502 conifers *Cathaya* and *Podocarpus*. Megathermal elements are mostly present in the Priabonian
503 samples where they show relevant variations. Steppe elements mainly occur in the Rupelian
504 samples. The other plant groups are intermittently represented.

505 Pollen record of five samples from wells in the Vistrenque Basin (Gallician 1 1648m,
506 Gallician 1 1775m, Gallician 4 1580m, Gallician 9 2530m, and Vauvert 1 3200m; [Fig. 8](#), see
507 location in [Fig. 5](#)) was relatively poorly diversified and poorly preserved. Indeed, these pollen
508 grains have been partially vitrified and therefore some of their morphological characters
509 (ornamentation, structure) are severely altered. A certain amount of pollen can still be identified
510 even though a great percentage of undeterminable pollen grains may lead to lessen the
511 significance of some of these microflora (percentage of unidentifiable pollen grains: Gallician
512 1 1648 m: 8.19%; Gallician 4 1580 m: 37.36%; Vauvert 1 3200 m: 10.81%).

513 In addition, some of these pollen floras are characterized by a low number of taxa (Gallician
514 1: 24 taxa at 1648 m, 19 taxa at 1775 m; Gallician 4 1580 m: 13 taxa; Gallician 9 2530 m: 20
515 taxa). Among the possible hypotheses to explain such biases in preservation and plant diversity
516 (oxidation, transport, diagenesis), the usual occurrence of oil traces during the sample
517 processing points to a thermal diagenesis in relation with sediment maturation within the oil
518 window. In the Gallician samples, the dominant pollen grains are those of Gymnosperms which
519 remain often identifiable despite their poor preservation, especially of meso-microthermal
520 (*Cathaya*, *Podocarpus*, and some *Tsuga*) and microthermal (*Abies*) trees which may reflect the
521 relief of the Pyrenees and subsidiarily of the Alps.

522 The pollen record of the Gallician 9 2530m sample shows the dominance of mega-
523 mesothermal (Cupressaceae papillate pollen representative of the former ‘Taxodiaceae’ family)
524 and both *Cathaya* and *Podocarpus* but a significant feature of this sample is the occurrence of
525 some mesothermal plants, Cupressaceae (*Cupressaceae-Juniperus*-type) and *Ephedra* (steppe
526 plants).

527 In [Figure 8](#), the vertical arrangement of samples first follows the stratigraphic knowledge of
528 the studied basins ([Gottis, 1958](#); [Clauzon, 1990](#); [Séranne, 1999](#); [Lettéron et al., 2017, 2018,](#)
529 [2022](#)) and chronology is specified thanks to informations provided by (1) mammal faunas

530 (Depéret, 1917; Rémy, 1985; Rémy, 1994; Rémy and Fournier, 2003; Rémy and Lesage, 2005)
531 and (2) calcareous nannofossils that have been searched in the samples containing frequent to
532 abundant marine dinoflagellate cysts: they are specified below and in the **Supplementary data**
533 (**Table S2**).

534 The climate has been quantified for all the pollen spectra except for Gallician1 1775 m,
535 Gallician 4 1580 m and Saint-Jean de Maruéjols – Pit hill because of the low taxa diversity.
536 The results are given, for each climatic parameter, as an interval and a Most Likely Value for
537 each site (**Table 2**).

538

539 **4.3.2 Interpretation**

540 The analysed pollen records allow to reconstruct the local and regional vegetation, from low
541 altitude to elevated reliefs (**Fig. 8**). Lower places were sporadically occupied by *Avicennia*
542 mangrove with probably Rhizophoraceae, suggesting nearby marine environments, which are
543 also supported by the record of marine dinoflagellate cysts. Occurrence of lakes is revealed by
544 frequent freshwater plants (*Aglaoreidia*, *Myriophyllum*, Oenotheraceae, Restionaceae, etc.) and
545 the *Botryococcus* microalga. The coastal environments and lake banks were also inhabited by
546 riparian swamps with *Taxodium-Glyptostrobus* (i.e., illustrated by the *Taxodium*-type pollen
547 grains). Lowlands were occupied by an evergreen subtropical forest rich in mega-mesothermal
548 plants (*Alangium*, *Engelhardia*, *Embolanthera*, *Distylium*, *Nyssa*, *Mussaenda*-type, *Rhoiptelea*,
549 Sapotaceae, *Symplocos*, *Uncaria*-type, Cupressaceae former ‘Taxodiaceae’, etc.) including
550 some megathermal plants (*Amanoa*, *Bombax*-type, *Afzelia-Peltophorum*-type, *Canthium*-type,
551 *Croton-Jatropha*, *Peltophorum*-type, *Mappianthus*, *Phyllanthus*, *Peltogyne*-type, *Sapindaceae*,
552 *Thunbergia*, etc.). Vicinity of higher lands is attested by abundant mesothermal plants (*Acer*,
553 *Araliaceae*, *Carpinus*, *Carya*, *Eucommia*, *Liquidambar*, *Parrotia*, *Pterocarya*, *Quercus*, *Ulmus*,
554 *Zelkova*, etc.), which constituted a mesophilous deciduous forest. The development of

555 altitudinal forest vegetation (*Cathaya, Podocarpus, Cedrus, Tsuga, Abies, Picea*) suggests the
556 occurrence of reliefs, especially of high reliefs to the south as evidenced by Canet 1 well and
557 Gallician wells pollen floras.

558 Cupressaceae trees (*Cupressus-Juniperus*-type) may contribute to the lowland and higher
559 vegetation as they can be represented by diverse taxa growing today in subtropical to high
560 altitude forests, because of our inability to distinguish their pollen. Sclerophyllous
561 Mediterranean elements (*Olea* mainly, *Phillyrea, Quercus ilex*-type) episodically developed,
562 simultaneously with decrease in taxa requiring great humidity and increase in herbaceous taxa.
563 It is possible to conceive that these plants already grew on drier soils and tolerated less humid
564 periods. Drier conditions are revealed by development of steppe assemblages (mainly
565 constituted of *Ephedra*), in parallel with reducing of taxa requiring humid climate.

566 Variability observed in the Priabonian pollen assemblages appears to be referred to climate
567 fluctuations during a warmer phase. All these pollen records come from exposed sections and
568 are not concerned by biases in preservation which often affect deep sediments from boreholes.
569 They mainly consist in opposed amounts of thermophilous forest elements (megatherms and
570 mega-mesotherms) and herbaceous and steppe elements (*Ephedra*) pointing to more open and
571 drier environments. Variability observed in the Oligocene pollen assemblages could refer to
572 climate fluctuations during a cooler phase resulting in alternations of drier and more humid
573 episodes.

574 All the Oligocene pollen records come from drilled sediments in which pollen preservation
575 may be poor, that makes uncertain their paleoenvironmental interpretation. However, these
576 major (Priabonian–Rupelian transition) and minor (intra-Priabonian and intra-Rupelian–
577 Chattian) changes displayed by pollen assemblages are consistent with the reference oxygen
578 isotope curve ([Fig. 8](#); [Westerhold et al., 2020](#)). For example, the sample Gallician 9 (2530 m)
579 is understood as illustrating the major change in climate marking the Eocene–Oligocene

580 transition because of scarcity in megathermal plants in opposition to the abundance of *Ephedra*.
581 Finally, the two samples Gallician 1 (1775 and 1648 m) are correlated with two successive
582 warmer episodes during the late Chattian because of high amount of mega-mesothermal plants
583 and the persistence of *Ephedra* in low percentage.

584 Paleogeographic reconstructions indicate the existence of elevated topography southwards
585 to the Camargue and Languedoc basins (Benedicto et al., 1996). These reliefs supplied detrital
586 sediments and pollen grains of high-altitude plants that have undergone low to moderate
587 transport to the depositional areas of the Vistrenque and of the Alès basins. The abundance of
588 *Podocarpus* in the Gallician samples, a marker of the Pyrenean flora during the Paleogene,
589 indicates that the pollen of these samples is sourced from these highlands.

590 In the Alès Basin, the climatic deterioration at the Eocene-Oligocene transition is expected
591 to follow the Montchamp pollen flora, indicating persistent warm conditions. The reconstructed
592 MAT and MTC are very high for this location (Table 2). Because of their low percentage in
593 megathermal plants in contrast to the occurrence of *Ephedra*, the pollen records of Monteils
594 and of the Pit hill of Saint-Jean de Maruéjols attest less warm and weakly drier conditions than
595 the Crossroads D716/D981, Célas, and Montchamp microfloras. The estimated MAT at
596 Monteils is the lowest for this time period (Most Likely value around 18.7°C instead of 20 to
597 21°C, Table 2). Some cooling is also evidenced by the Serre de Cauvel pollen assemblage with
598 respect to decreased megathermal plants and increased Mediterranean sclerophyllous elements.
599 However, this cooling should be less important as it is not observed in the estimated climate.
600 The Monchamp microflora contains *Avicennia* and Rhizophoraceae pollen grains. The latter are
601 also recorded at Serre de Cauvel while *Avicennia* is also recorded at Saint-Jean de Maruéjols
602 Pit hill, Célas Tunnel and Crossroads D716/D981. Mean temperature of the warmest month
603 (MTW) is stable all along the period (Table 2). Euzet Hill, Serre de Cauvel, Crossroads
604 D716/D981, Maruéjols 1 798 m, and Saint-Jean de Maruéjols Pit hill samples contain high

605 proportions of conifers (*Podocarpus*, *Cathaya*) that do not result from preservation bias because
606 of their high floristic diversity (>30 taxa) but from high pollen supply from mid-altitude.

607 In the Vauvert 1 3200 m sample, the presence of relatively frequent pollen of Mediterranean
608 sclerophyllous plants may point to the climatic cooling at earliest Oligocene, supported by few
609 megathermal plants, reduced mega-mesothermal plants and increasing herbaceous open
610 environments in a context of shortening freshwater bodies. This cooling and lower humidity
611 are also well marked in the estimated mean annual temperature (MAT), mean temperature of
612 the coldest month (MTC) and mean annual precipitation (MAP) (**Table 2**). The estimated MAT
613 at Vauvert is in agreement with the value obtained at Saint-Lions, located 150 km northeastward
614 of the Camargue, presently in the Digne thrust, for the same period (Fauquette et al., 2015). In
615 the Gallician 9 2530 m sample, some aridification of the climate is suggested by the local
616 expansion of *Ephedra* that leads to a low estimate of mean annual precipitation (**Table 2**).
617 Pollen assemblages of Gallician 4 1580 m and Gallician 1 1648 m are consistent with a Late
618 Oligocene age.

619 Our ascription of the studied interval of Canet 1 well (1701–1100 m) to Oligocene is based
620 on the occurrence of above-mentioned calcareous nannofossils (**Table S2**) and corresponds to
621 the presence-abundance of *Podocarpus* pollen, never recorded in Southern France since the
622 earliest Aquitanian (Bessedik, 1984). Considering the calcareous nannofossil range, the sample
623 Canet 1 (1701 m) is ascribed to a warmer and still dry episode during the late Rupelian because
624 of increased percentage in megathermal plants and a significant occurrence of *Ephedra*.
625 Similarly, the sample Canet 1 (1470 m) is referred to a cooler episode of the early Chattian as
626 supported by the absence of megathermal plants and a relative high presence of *Ephedra*
627 associated to *Calligonum*. The sample Canet 1 (1186 m) is located in an intermediate cooler
628 episode of the mid-Chattian because of the absence of megathermal plants, a relatively weak
629 occurrence of mega-mesothermal plants and the persistence of *Ephedra* in a low proportion.

630 Finally, the uppermost Canet 1 (1100 m) sample is ascribed to a lesser warm episode just before
631 the Chattian–Aquitainian transition because of its lower amount of mega-mesothermal plants
632 and greater percentage of mesothermal plants. Climate reconstruction of Canet 1 well show that
633 MAT are 1 to 2°C and MTC are 1 to 5°C lower than during the Priabonian. MAP are also
634 slightly lower than during the Priabonian ([Table 2](#)).

635

636 **4.4 Geochemical modelling of the strontium and sulfur isotopes of sulfates**

637

638 **4.4.1 Pierrefeu-1 well (Vistrenque Basin)**

639 Anhydrite samples from Pierrefeu 1 well display $^{87}\text{Sr}/^{86}\text{Sr}$ values ranging from 0.70777 to
640 0.708201 and $\delta^{34}\text{S}$ values comprised between +10.92 ‰ and +17.10 ‰ ([Table 3](#)). Anhydrites
641 from core K2 fall within the domain of Triassic evaporites while samples from cores K5 and
642 K6 display significantly higher $^{87}\text{Sr}/^{86}\text{Sr}$ values ([Fig. 9A](#)).

643 Mixing fluid models revealed that Sr and S isotope composition of anhydrites from
644 Pierrefeu-1 is consistent with a formation from a mixed water composed of a riverine end-
645 member whose Sr and S content is controlled by the leaching of Triassic evaporites and a marine
646 end-member. The Sr and S concentrations and isotope composition of the volume fraction of
647 each end-member for the best-case scenario, are given in Supplementary Materials ([Table S4](#)).
648 Matching between mixed-water models and isotope measurements on anhydrites integrates the
649 effect of fractional precipitation which may lead to a difference of up to +2 ‰ in $\delta^{34}\text{S}$ between
650 sulfates and precipitating water ([Raab and Spiro, 1991](#)).

651

652 **4.4.2 SC-1 and SC-2 wells (Alès Basin)**

653 Anhydrite from the Alès Basin (SC-1 and SC-2 wells) display a narrow range of $^{87}\text{Sr}/^{86}\text{Sr}$
654 values (0.70768-0.70790) while $\delta^{34}\text{S}$ is comprised between +12.11 ‰ and +26.98 ‰ (**Table**
655 **3**). The sample from SC-1 well fall within the domain of Triassic evaporites while samples from
656 SC-2 exhibit $\delta^{34}\text{S}$ values which are significantly higher than those of Priabonian sea-water
657 (**Figure 9B**).

658 The high $\delta^{34}\text{S}$ values of gypsum minerals from SC-2 most likely arise from isotope
659 fractionation during microbially mediated reduction of sulfates. If sulfate reduction takes place
660 in a closed basin, the $\delta^{34}\text{S}$ of residual dissolved sulfates will be higher compared to the original
661 fluid ([Utrilla et al., 1992](#); [Palmer et al., 2004](#)). Additionally, measurements on native sulfur
662 formed within anhydrite-bearing horizons in SC-2 well yielded negative $\delta^{34}\text{S}$ values ranging
663 from -5.99 ‰ to -6.43 ‰. These negative $\delta^{34}\text{S}$ values strongly suggest that the elemental sulfur
664 from SPr3 evaporitic interval is a byproduct of sulfate-reducing bacterial activity ([Lindtke et](#)
665 [al., 2011](#)).

666 As a consequence, although the SC-1 sample unequivocally indicates precipitation from a
667 water influenced by the dissolution of Triassic sulfates, the bacterial sulfate-reduction processes
668 affecting the anhydrites from SC-2 prevent to draw any conclusion regarding a possible mixing
669 with marine water.

670

671 **5. Discussion**

672

673 **5.1 Chronostratigraphic framework of the Paleogene of the Vistrenque Basin**

674 Sedimentological and diagenetic studies, and petrographical observations on core from the
675 Paleogene succession in the Gallician 9 well revealed than the top of the *Série Calcaire* and the

676 whole overlying *Série Mixte* are affected by repeated subaerial exposition (Semmani, 2022) as
677 suggested by the occurrence of pedogenic limestones and karst features. The development of
678 dissolution vugs and the subsequent formation of anisopachous calcite cements (meteoric
679 vadose environment) in the sample G9 13D (Gallician 9: 1960 m depth) are linked to these
680 repeated stages of subaerial exposition affecting the top of the *Série Calcaire* Formation and
681 the whole overlying *Série Mixte* Formation. The 31.2 Ma age obtained for the subaerial
682 exposures towards the top of the *Série Calcaire* (G9 13D) represents the oldest possible age for
683 the deposition of the overlying *Série Mixte* Formation (Fig. 10).

684 The 27.88 Ma age obtained within an early vadose cement from a fluvial conglomerate, in
685 Gallician 9 well at 1984 m, suggests a late Rupelian to early Chattian age for the lower part of
686 the *Série Rouge* Formation. The difference between the two absolute ages (~ 3.4 Ma)
687 corresponds therefore to the time deposition of the *Série Mixte* and lower part of *Série Rouge*.
688 Such a long duration, compared to the preserved thickness (~ 45 m) is consistent with low
689 sedimentary rates and the occurrence of hiatuses punctuating the sedimentation as suggested
690 by subaerial exposures affecting the interval (Semmani, 2022).

691 In addition, pollen-based climatostratigraphic approach suggests that the sample from
692 Vauvert 1 at 3200m deposited very close to the Priabonian to Rupelian transition, thus
693 indicating likely a Late Eocene (Priabonian) age for the lowermost part of the *Série Grise*
694 Formation (Fig. 10). In Gallician-9, the 31.2 Ma age obtained at 1960 m and the early Rupelian
695 age at 2530 m suggest sedimentation rates greater than 200 m/Myr in the upper *Série Grise* and
696 *Série Calcaire* interval. Correlations with Vauvert-1 (Fig. 5) suggest sedimentation rates
697 ranging from 300 to 500 m/Myr. The base of the *Série Grise* being not reached at 3630 m in
698 Vauvert-1, extrapolating such sedimentation rates below 3200 m would suggest that the
699 formation covers large parts of the Priabonian – if not the entire stage.

700 The late Priabonian oolitic lacustrine carbonates evidenced north of the Vistrenque Basin
701 ([Semmani et al., 2022](#)) would therefore represent a marginal lake, lateral equivalent of the *Série*
702 *Grise* Formation from the basin depocenter. The *Série Grise* Formation may also have deposited
703 coevally with part or all of the Priabonian fluvial and lacustrine succession from the
704 neighbouring Alès, Saint-Chaptes and Issirac basins ([Lettéron et al., 2022](#)).

705 Pollen records from Gallician 4 1580m and Gallician 1 1648m suggest a Late Oligocene
706 (early Chattian) age for the lowermost part of the *Série Calcaréo-salifère* Formation. These
707 findings agree with Chattian to Aquitanian ages derived from the Sr and S isotope signatures
708 of sulfates from this interval in Pierrefeu 1 well ([Fig. 9](#)). Based on these age constraints, the
709 *Série Rouge* Formation is late Rupelian to early Chattian in age ([Fig. 10](#)). Finally, the
710 Aquitanian absolute age (21.46 +/- 2.19 Ma) of the calcite vein affecting the *Série Grise* in
711 sample G9-K35 from Gallician 9 well is consistent with the infill of a fracture formed during
712 the Oligocene-Aquitanian rifting of the Gulf of Lion margin ([Séranne et al., 1995](#)).

713

714 **5.2 Tectonic and geodynamic implications**

715 The here-defined chronostratigraphic framework of the Vistrenque Basin evidences the
716 occurrence of a thick Priabonian to lower Rupelian sedimentary succession, thus being coeval
717 with the fluvial-lacustrine sedimentation occurring west of the Nîmes fault in the Alès, Saint-
718 Chaptes and North Montpellier basins ([Séranne et al., 2021](#); [Lettéron et al., 2022](#)). The regional
719 mapping of syn-depositional structures within these basins evidenced a left-lateral shearing of
720 the area comprised between the NE-trending Cévennes and Nîmes faults during the Priabonian
721 ([Séranne et al., 2021](#)). The elevated sedimentation rates, greater than 200 m/Myr, revealed in
722 the Vistrenque Basin are consistent with a basin subsidence controlled by the major Nîmes
723 strike-slip fault. In contrast with Languedoc basins where early to middle Rupelian are lacking,
724 the sedimentation in the Vistrenque Basin suggests that the strike-slip movement of the Nîmes

725 fault was still active during the Rupelian. In addition, the sharp decrease in sedimentation rates
726 between the upper part of the *Série Grise* (31.2 Ma in Gallician-9) and the *Série Rouge* (27.88
727 Ma in Gallician-9) suggest that the strike-slip movement of the Nîmes fault, associated to the
728 ongoing shortening in the Spanish Pyrénées, ceased in the middle to late Rupelian times. The
729 *Série Grise* Formation from the Vistrenque Basin records therefore the latest stages of Pyrenean
730 compression until the Rupelian together with the earliest stages of the dismantling of the
731 Languedoc-Provence segment of Pyrénées. Finally, the Chattian evaporitic succession (*Série*
732 *Calcareo-salifère* Formation) and the overlying Aquitanian terrigenous sequence were
733 deposited during the Liguro-Provençal Rifting stage (Benedicto, 1996; Séranne et al., 2021).

734

735 **5.3 Evidence of marine incursions into Priabonian to Chattian continental basins from** 736 **Southeast France**

737 Saline lake sedimentation associated with the deposition of sulfates (gypsum and anhydrite)
738 occurred during the Priabonian and/or Rupelian in various basins from SE France: Alès, Saint-
739 Chaptes and Issirac basins (Lettéron et al., 2017, 2018, 2022) as well as in the Mormoiron–
740 Carpentras and Apt–Manosque–Forcalquier basins (e.g. Triat and Truc, 1974; Cavelier et al.,
741 1984). The present work documents saline lake conditions and deposition of evaporites in the
742 Vistrenque Basin as early as the early Rupelian (within the *Série Grise*) and during the Chattian
743 (*Série Calcaréo-salifère*).

744 The origin of dissolved ions (Briot, 2008) in the Paleogene saline lake waters, and the
745 possibilities and pathways of salinization of these lacustrine systems of Southeast France and
746 Western-European rift system are still discussed (e.g., Lettéron et al., 2017, 2018, 2022;
747 Semmani et al., 2022). Lettéron et al. (2017) considered the relevance of the occurrence of
748 benthic foraminifera and halophile molluscs in the lacustrine deposits from the Issirac Basin to
749 demonstrate marine connections and discarded evidence of marine connections based on these

750 faunal contents. Moreover, these organisms have been shown to be tolerant to salinity variations
751 and can thrive in athalassic lakes (Plaziat and Younis, 2005). Nevertheless, strong evidence of
752 incursions of marine-influenced waters within the ASCI lake system during the Priabonian and
753 the Vistrenque Basin from the Late Eocene to Late Oligocene can be provided by the occurrence
754 of calcareous nannofossils, dinoflagellate cysts and halophilous plant pollen grains, and by the
755 contribution of geochemical modelling.

756 In the ASCI system, the occurrence of marine dinoflagellate cysts in Serre-de-Cauvel and at
757 the crossroad D716/D981 (Saint-Chaptes Basin: Fig. 4) is indicative of marine connections as
758 early as the early-to-middle Priabonian. Additionally, the presence of *Avicennia* pollen grains
759 in the Saint-Chaptes (Crossroads D716/D981) and Alès basins (Célas Tunnel, Saint-Jean de
760 Maruéjols Pit hill and Montchamp) suggests the persistent influence of marine water from the
761 middle to the latest Priabonian. The occurrence of Rhizophoraceae pollen grains from Serre de
762 Cauvel and Montchamp is consistent with such an interpretation. Finally, the Sr and S isotope
763 signatures of evaporites from the Ales Basin, although altered by sulfate-reduction processes
764 likely derive from a mixture between a continental water influenced by Triassic evaporites and
765 seawater.

766 In the Vistrenque Basin, the presence of the dinoflagellate *Deflandrea phosphoritica*
767 (chronological range: 54.6-21.2 Ma; Powell et al., 1996) in the *Série Grise* (Gallician 9 well at
768 2530 m depth) provides evidence of marine incursion into the Vistrenque Basin during the early
769 Rupelian times. The presence of pollen grains of *Ephedra* is a characteristic feature of this
770 pollen record. The present-day species of *Ephedra* are all living in arid and semi-arid regions
771 (González-Juárez et al., 2020). The few species growing on coastal sands are not salt adapted
772 and thus are not considered as halophytes (Halophytes Database). For example, *Ephedra*, which
773 is currently frequent along the Mediterranean coastline (*E. distachya* L.: Coste, 1937), is
774 represented by very scarce pollen grains in present-day pollen assemblages from the Camargue

775 and Roussillon coastal areas (Cambon et al., 1997; Beaudouin et al., 2005a; Suc and Fauquette,
776 2012). It is also very scarce in the pollen records of warm phases (Holocene and older
777 interglacials) although it is frequent to abundant during the drier episodes corresponding to cold
778 phases (Beaudouin et al., 2005b; Tesson et al., 2011; Arnaud-Fassetta and Suc, 2015). This
779 comparison with modern to recent pollen records supports the interpretation of *Ephedra* as
780 marker of both cooling and aridification phases rather than of marine incursion. On the other
781 hand, the Sr and S isotope signatures of sulfate evaporites from the *Série Calcaréo-salifère*
782 Formation and mixing-water modelling strongly suggest an intrusion of marine water into the
783 Vistrenque Basin during the late Chattian.

784

785 **5.4 Paleogeographic reconstructions of Southeast France during the Late Eocene and** 786 **Oligocene**

787 The potential pathways of the marine incursions into the Southeast France continental basin
788 are displayed in the palaeogeographic reconstructions of **Figures 11, 12, and 13**. During the
789 Priabonian and Rupelian, the Southeast France lake basins as well as the West Alpine Sea were
790 bounded to the south by the EW-trending Pyrenean-Corsica-Sardinia Massif (Joseph and
791 Lomas, 2004; Séranne et al., 2021). This relief likely yielded most of the terrigenous supply of
792 the ASCI and Vistrenque lake basins (Lettéron et al., 2022; Semmani et al., 2022) and deep-
793 marine West Alpine foreland Basin (Joseph and Lomas, 2004). Moreover, it was likely
794 sufficiently continuous and elevated to prevent from connections with the Western Neotethys
795 to the south (**Fig. 11** and **Fig. 12**). In addition, the Atlantic shoreline was located at more than
796 300 km west of the Alès Basin during the Priabonian and Rupelian times (Gely and Sztrákos,
797 2000; Sztrákos and Steurbaut, 2017), and fluvial sedimentation dominates in south-western
798 Languedoc basins (Calvet et al., 2021; Séranne et al., 2021) thus making unlikely marine
799 intrusion from the Atlantic Ocean into Languedoc, Rhône Valley and Camargue areas. Finally,

800 the demise of lacustrine sedimentation in the ASCI basins during the latest Priabonian or earliest
801 Rupelian and the depositional hiatus of most of the Rupelian interval (Lettéron et al., 2022) do
802 not support connections with the marine realm west of the Nîmes fault during the Rupelian
803 (Fig. 12).

804 In contrast, the proximity of the West Alpine foreland (<30 km from the Manosque-
805 Forcalquier Basin, and <50 km from the Valence Basin), and the probable interconnection
806 between the different SE France saline lake basins, as suggested by previous studies (Lettéron
807 et al., 2022; Semmani et al., 2022) makes marine intrusions more plausible from the West
808 Alpine Sea during the Priabonian and Rupelian (Fig. 11 and Fig. 12).

809 The reconstruction of Pyrenean structures and their differentiation from later Alpine
810 deformation (Balansa et al., 2022) provides a structural framework allowing a realistic
811 reconstruction of continental paleo-reliefs during the Priabonian and Rupelian and the
812 identification of two potential marine incursion pathways, from the West Alpine Sea to the
813 Southeast France lake basins (Fig. 11 and Fig. 12). A northern potential pathway would connect
814 the West Alpine Sea with the Valence Graben, north of the Diois-Barronies High. This
815 corresponds with the “Crest Sill” identified by Sissingh (2001) as a possible marine corridor
816 supplying seawater into the Western European rift basins. A connection of the Valence lake
817 Basin with the Mormoiron and Vistrenque to the south and finally with the ASCI system during
818 periods of maximum lake expansion would therefore explain the occurrence of calcareous
819 nannofossils, dinoflagellate cysts and mangrove pollen grains within the Alès Basin during the
820 Priabonian and in the Vistrenque Basin during the Rupelian.

821 A southern potential pathway of marine incursion would connect the West Alpine Sea with
822 the Manosque-Forcalquier, Mormoiron and Vistrenque-ASCI basins through a set of Pyrenean
823 synclines in the Haut-Var region (Bauduen, Montmeyan, Salernes and Rians basins). The
824 hypothesis of such a marine corridor is corroborated by the presence of Paleogene marine

825 markers such as calcareous nannofossils and dinoflagellate cysts in the “Sables Bleutés du Var”
826 Formation in the Montmeyan Basin (Châteauneuf et al., 2019) even though the age of these
827 deposits remains very much debated (e.g., Philip et al., 2017). Such a southern sea-water
828 pathway may also explain the occurrence of dinoflagellate cysts in the Rupelian from the
829 Marseilles Basin (Châteauneuf and Nury, 1995).

830 The Chattian paleogeography of SE France (Fig. 13) differs significantly from that of
831 Priabonian-Rupelian times, since the West Alpine Sea closed as a result of sedimentary infill
832 and westward accretion of the Alpine orogenic wedge (Joseph and Lomas, 2004) during the
833 late Rupelian. In addition, the Chattian is regionally characterized by widespread active rifting
834 that formed NE-SW oriented rift-basins, onshore and offshore in the Gulf of Lion. This rifting
835 led to the collapse of the Pyrenean-Corsica-Sardinia. This resulted in marine intrusions from
836 the southern Western Neotethys, into Provence as evidenced by the occurrence of late Chattian,
837 strictly marine, shallow-water carbonate sediments west of Marseilles (*‘Côte Bleue’* shoreline:
838 Oudet et al., 2010a) and marine biological markers including dinoflagellate cysts, coelenterates
839 and marine fishes in brackish-water lacustrine/lagoonal deposits from the Aix-en-Provence
840 Basin (Nury and Thomassin, 1994). The marine influence revealed by strontium and sulfur
841 isotope signatures of Chattian evaporites from the Vistrenque Basin could therefore results from
842 a marine connection to the south probably through the offshore Vistrenque Basin, the Central
843 Graben and the Catalan fault zone domain (Fig. 13). Such a marine water pathway, suggested
844 by Oudet et al. (2010b) is supported by the presence of Chattian to Aquitanian planktonic
845 foraminifera in well Tramontane 1 in the Central Graben (Cravatte et al., 1974). The Vistrenque
846 Basin may also have been connected with the Sardinian Graben (via Offshore Vistrenque and
847 Grand Faraman Graben) where the earliest marine ingression occurred during the latest
848 Chattian-early Aquitanian (e.g. Casula et al., 2001). The Chattian carbonate and evaporite
849 sediments from the *Série Calcaréo-salifère* Formation in the Vistrenque Basin could therefore

850 have deposited in a saline lake with transient connections with seawater during sea-level or
851 lake-level highstands, or within a coastal sabkha with periodic marine intrusions.

852

853 **5.5 Paleoclimatic implications**

854 This present study, based on both botanical pollen identification and counting, robustly
855 documents for the first time the climate evolution of the 38–23 Ma interval in South of France,
856 which encompasses the Eocene–Oligocene transition. The four pollen floras from the Canet 1
857 borehole complete those from the Alès and Vistrenque basins for documenting the climate
858 knowledge during the late Rupelian and early Chattian.

859 According to our pollen data, we demonstrate that the Eocene–Oligocene transition is
860 marked by the suddenness and the great amplitude of the climate deterioration with lowering
861 temperature and increasing dryness at low elevations while high humidity continued in higher
862 altitude. The climate parameters estimated from analyses of pollen from the Vistrenque samples
863 do not show a drastic climate deterioration. This may be due to the large climatic tolerance
864 intervals attributed to the plants, some of them may live under large temperature and/or
865 precipitation amplitudes at the genus or family level. However, the cooling between the
866 Priabonian and the Rupelian is indicated by a decrease in mean annual temperature, mean
867 temperature of the coldest month and in mean annual precipitation at Vauvert but more
868 particularly at Gallician 9 2530 m. Following that event, temperature and precipitation increase,
869 although they remain lower than during the Priabonian. Vegetation and climate changes,
870 deduced from the relative abundance of megathermal and mega-mesothermal vs. herbaceous
871 and steppic plants in the pollen diagrams, seem to indicate that the cooling in Southeast France
872 was brief and took place at the very early Rupelian. From a vegetation and climatic point of
873 view, the Mediterranean region is considered as a very particular region since the Paleogene as

874 it was certainly sheltered from cold air masses (Popescu et al., 2021). The cooling phases were
875 thus certainly less pronounced than elsewhere in Europe.

876 Finally, the upper Chattian succession shows a climate evolution towards the Aquitanian
877 conditions with very scarce megathermal plants as described by Bessedik (1984), Zheng (1990)
878 and Suc et al. (2018), despite persistence of *Podocarpus* in the mountains up to the latest
879 Chattian.

880

881 **6. Conclusion**

882

883 The definition of a robust chronostratigraphic framework for the Vistrenque Basin and the
884 neighboring Paleogene basins, combined with the analysis of a set of micropaleontological and
885 geochemical data, has led to significant improvements in knowledge of the geodynamic
886 evolution, the paleogeographic framework and the paleoclimatic setting of the Upper Eocene-
887 Oligocene lacustrine basins from South-East France:

888 1) The *Série Grise* Formation (Priabonian to early Rupelian) from the Vistrenque Basin
889 was deposited in a highly subsident basin associated with the strike-slip movement of
890 the Nîmes fault and records the latest stages of the Pyrenean shortening. Drastic
891 decrease in sedimentation rates above the *Série Grise* suggests that the strike-slip
892 movement of the Nîmes fault ceased around the middle-to late Rupelian. The evaporitic
893 sedimentation of the *Série Calcareo-salifère* Formation (Chattian) is related to the stage
894 of Liguro-Provençal rifting.

895 2) The pollen data recorded during this study allow climatostratigraphic correlations with
896 the reference oxygen isotope curve and thus help to specify the age of the studied
897 sections. The floral assemblages from the Priabonian and Rupelian of the neighbouring

898 Languedoc and Camargue areas constitute a powerful tool to document the climatic
899 deterioration at the Eocene-Oligocene transition. In addition, pollen analyses made it
900 possible to reconstruct a mangrove and freshwater lake vegetation in the Alès Basin,
901 and a dominant evergreen subtropical forest in the surroundings of the lake which also
902 record fluctuations with a high-altitude vegetation in the southern paleo-Pyrenean relief
903 during the Priabonian. Vegetation cover has been shown to be rather dominated by
904 mesothermal and herbaceous plants. During the early Rupelian and Chattian times, a
905 clear influence of altitude vegetation is referred to the inherited Pyrenean relief, south
906 of the study area. Simultaneously, cooler and drier climate conditions affected the
907 surroundings of the Camargue area.

908 3) The use of the Climate Amplitude Method allowed evidencing a short but significant
909 stage of climate cooling and aridification in the early Rupelian which could result from
910 the global climate cooling following the Eocene-Oligocene Transition.

911 4) Strong evidence for successive intrusions of marine-influenced saltwater into the
912 Languedoc and Camargue areas during the Priabonian, early Rupelian and Chattian
913 intervals is provided by the occurrence of calcareous nannofossils, dinoflagellate cysts
914 and the halophilous *Avicennia* and Rhizophoracea plants documented by their pollen.
915 Strontium and sulfur isotope signatures of sulfates from the Série Calcaréo-salifère
916 Formation strongly suggest incursions of marine water into the Vistrenque lacustrine
917 system during the Chattian.

918 5) During the Priabonian and Rupelian, marine water likely derived from the Western
919 Alpine Sea. Two possible pathways of seawater intrusion are suggested from
920 paleogeographic reconstructions: the Crest Sill north to the Diois-Barronies High and/or
921 the Pyrenean synclines in the Haut-Var area south of the Diois-Barronies High. The
922 paleogeographic setting of south-east France significantly changed as a result of the

923 closure of the Alpine Sea and the formation of rift basins in the Gulf of Lion during the
924 Chattian have made possible marine incursion into the Vistrenque Basin from the
925 Mediterranean domain to the south.

926

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942

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1294 **Figure and table caption**

1295

1296 **Figure 1:** A) Paleotectonic map of Western Europe during the Oligocene-Aquitanian times
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1299 France and location of the Vistrenque Basin among the various Cenozoic continental basins,
1300 modified after Benedicto (1996). Sampling loci for pollen analyses, U/Pb dating, and
1301 Sulfur/Strontium isotopes purposes are located in the Alès, Issirac and Saint-Chaptes basins
1302 (AB, IB, SCB), Vistrenque Graben (VG) and Roussillon Basin (RB), geographic coordinates
1303 are given in Supplementary data (Table S1). C) Geological section across the Gulf of Lion
1304 margin (modified after Benedicto, 1996).

1305 **Figure 2:** A) Map of the Bouguer gravity anomaly, modified after Chauvin and Follin-Arbelet
1306 (1985). B) interpreted seismic profile SG3 in the Northern Vauvert compartment, after
1307 Benedicto (1996), (see location in Fig. 3 hereinafter). C) NW-SE geological cross-section
1308 through the Vistrenque Basin on the northern Vauvert compartment (modified after Benedicto
1309 et al., 1996). D) Stratigraphic synthesis of the Vistrenque Basin compiled from the boreholes
1310 data by Gorini (1993), modified after Bache (2008).

1311 **Figure 3:** Vistrenque Basin: A) Lithological columns and correlations of Gallician 9 and
1312 Pierrefeu 1 wells (after Semmani, 2022); B) Structural map of the Vistrenque Basin and well
1313 location (after Benedicto et al., 1996); C) Location map of wells and seismic profiles from the
1314 Gallician and Pierrefeu area (location: black rectangle on Fig. 3B).

1315 **Figure 4:** A) Geological map of the Alès-Saint-Chaptes-Issirac (ASCI) basins and location of
1316 the pollen sampling. B) Chronostratigraphic chart of the ASCI lake system (after [Lettéron et](#)
1317 [al., 2022](#)) and location of palynological and sulfate samples analyzed in this study.

1318 **Figure 5:** Correlation panel of wells Gallician 1, Gallician 4, Gallician 9, Vauvert 1 and
1319 Pierrefeu 1 from the Vistrenque Basin (after [Semmani, 2022](#)) showing the sedimentary units,
1320 lithologies and lithostratigraphic correlations. Lithostratigraphic correlations are carried out
1321 using lithological similarities and gamma ray (GR) signal. Drill core locations and the positions
1322 of samples used for U/Pb dating (squares) and pollen analyses (circles), and $^{87}\text{Sr}/^{86}\text{Sr}$ & $\delta^{34}\text{S}$
1323 measurements (triangles) are also plotted.

1324 **Figure 6:** A) Microphotograph of the cavity in thin section of the sample G9 13D from
1325 Gallician 9 well (depth ~ 1960 m) displaying the growth of successive cement stages:
1326 microstalactitic cements A1 & A2, and coarse bladed calcite I1 with further bitumen infill. B)
1327 elemental mapping of the red box in A) showing the concentrations of ^{238}U and ^{206}Pb . C)
1328 Confocal microscopy photograph of the cavity in (A) where the fluorescence allows to observe
1329 the different generations of cement. The cementation stages A2 and I1 are non-luminescent and
1330 therefore indistinguishable under cathodoluminescence. D) Tera-Wasserburg plots displaying
1331 $^{238}\text{U}/^{206}\text{Pb}$ versus $^{207}\text{Pb}/^{206}\text{Pb}$ from the A1 cement (early diagenetic anisopachous cement).

1332 **Figure 7:** A) Thick geological section scan (sample G9 7; Gallician 9 well, depth ~ 1894 m)
1333 showing the yellowish beige pendant anisopachous cement around clasts in a fluvial
1334 conglomerate. B) close-up view of the rectangular box in A) displaying the position of the laser
1335 ablation spots alongside the cement. C) Tera-Wasserburg plots displaying $^{238}\text{U}/^{206}\text{Pb}$ versus
1336 $^{207}\text{Pb}/^{206}\text{Pb}$ from the anisopachous cement of the G9 7 sample (number of spots = 74). D) and
1337 E) Microphotographs of the vein calcite infill within the G9 K35 sample (Gallician 9, depth ~
1338 2487 m) under plane polarized light and cathodoluminescence respectively. Note the dull

1339 luminescence of the calcite fill (right hand picture). F) Tera-Wasserburg plots displaying
1340 $^{238}\text{U}/^{206}\text{Pb}$ versus $^{207}\text{Pb}/^{206}\text{Pb}$ from the calcite vein infill of the G9 K35 sample (number of spots
1341 = 45).

1342 **Figure 8:** Synthetic pollen diagrams (*Pinus* excluded) illustrating (1) to the left the local to
1343 regional paleovegetation (including altitudinal trees) and (2) to the right the local
1344 paeovegetation (the latter trees excluded) – their proposed climatostratigraphic correlations
1345 with the reference oxygen isotope curve (smoothed curve over 20 ka in blue, smoothed curve
1346 over 1 Ma in red; [Westerhold et al., 2020](#)). Pollen diagrams are vertically arranged according
1347 to the basin stratigraphy and available chronostratigraphic information (mammal faunas,
1348 calcareous nannofossils). Time-intervals corresponding to the Priabonian and Chattian stages
1349 are shaded in light grey to make easier the chronostratigraphic correlations. Pollen group
1350 composition is specified in the text and more in **Supplementary data Table S3**.

1351 **Figure 9:** $\delta^{34}\text{S}$ vs $^{87}\text{Sr}/^{86}\text{Sr}$ crossplot for Paleogene anhydrites from SE France: A)
1352 Vistrenque Basin (Pierrefeu 1 well); the solid line represents the water-mixing model for a
1353 mixture of a Late Oligocene seawater with a riverine water whose composition is influenced by
1354 recycling of Triassic evaporites (see [Table 3](#) for Sr and S isotope compositions and
1355 concentrations of each end-member); the dashed area represents possible isotope compositions
1356 of sulfates having precipitated from the modelled water mixture by considering the fractional
1357 crystallization effect; B) Alès Basin (Les Fumades: SC-1 and SC-2 wells). The arrow indicates
1358 how bacterial sulfate reduction results into higher $\delta^{34}\text{S}$. The Triassic (Keuper) evaporite domain
1359 is compiled from [Albarède and Michard \(1987\)](#), [Dinelli et al. \(1999\)](#), [Alonso-Azcarate et al.](#)
1360 [\(2006\)](#), [Ortí et al. \(2014\)](#), [Utrilla et al. \(1992\)](#) and [Boschetti et al. \(2011\)](#). The granite and
1361 metamorphic rock domain derives from [Petelet-Giraud et al. \(2006\)](#), [Chaussidon et al. \(1989\)](#),
1362 [Giacometti et al. \(2014\)](#).

1363

1364 **Figure 10:** Chronostratigraphic framework of the Paleogene succession of the Vistrenque
1365 Basin. Stratigraphic attributions for the main lithological units are obtained using U/Pb absolute
1366 dating (blue squares), pollen analyses and geochemical modelling on sulfates, see text for
1367 details about the dating results. Reference oxygen isotope curve (smoothed curve over 20 ka in
1368 blue, smoothed curve over 1 Ma in red; [Westerhold et al., 2020](#)). Climatic events and Antarctic
1369 ice-sheets coverages are derived from [Zachos et al. \(2001\)](#).

1370 **Figure 11:** Paleogeographic map of Southeast France during the late Priabonian. Location of
1371 continental basins are compiled from [Lettéron et al. \(2017, 2022\)](#) and [Semmani et al. \(2022\)](#).
1372 Paleogeography of marine domain is modified from [Joseph and Lomas \(2004\)](#). The structural
1373 framework is compiled from [Séranne et al. \(2021\)](#) and [Semmani et al. \(2022\)](#) west of the Diois-
1374 Barronies High and from [Balansa et al. \(2022\)](#) for Northern and Eastern Provence.

1375 **Figure 12:** Paleogeographic map of Southeast France during the early-middle Rupelian.
1376 Location of continental basins are compiled from [Nury \(1990\)](#), [Lettéron et al. \(2017, 2022\)](#),
1377 [Semmani et al. \(2022\)](#). Paleogeography of marine domain is modified from [Joseph and Lomas](#)
1378 [\(2004\)](#). The structural framework is compiled from [Séranne et al. \(2021\)](#) and [Semmani et al.](#)
1379 [\(2022\)](#) west of the Diois-Barronies High and from [Balansa et al. \(2022\)](#) for Northern and
1380 Eastern Provence.

1381 **Figure 13:** Paleogeographic map of South-East France during the Chattian. Location of
1382 continental basins are compiled from [Cavelier et al. \(1984\)](#), [Nury \(1990\)](#), [Séranne et al. \(2021\)](#).
1383 Paleogeography of marine domain is modified from [Oudet \(2008\)](#).

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1388 **Table 1:** Ages obtained in the Vistrenque Basin using U/Pb dating on calcite, pollen-based
1389 climatostratigraphy, Sr and S isotope signatures of sulfates.

1390 **Table 2:** Climatic reconstruction based on pollen data. The succession of pollen sites is that
1391 shown in Figure 8. Mean annual temperatures (MAT), mean temperature of the coldest (MTC)
1392 and of the warmest (MTW) months and mean annual precipitation (MAP) are reconstructed
1393 using the Climatic Amplitude Method ([Fauquette et al., 1998](#)). The results are given as an
1394 interval and a Most Likely Value (in bold) for each site.

1395 **Table 3:** $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{34}\text{S}$ measurements on anhydrite/gypsum samples and native sulfur from
1396 Pierrefeu-1 well (Vistrenque Basin), SC-1 and SC-2 well (Alès Basin). The stratigraphic
1397 sequences of the Alès Basin are defined in [Lettéron et al. \(2022\)](#).

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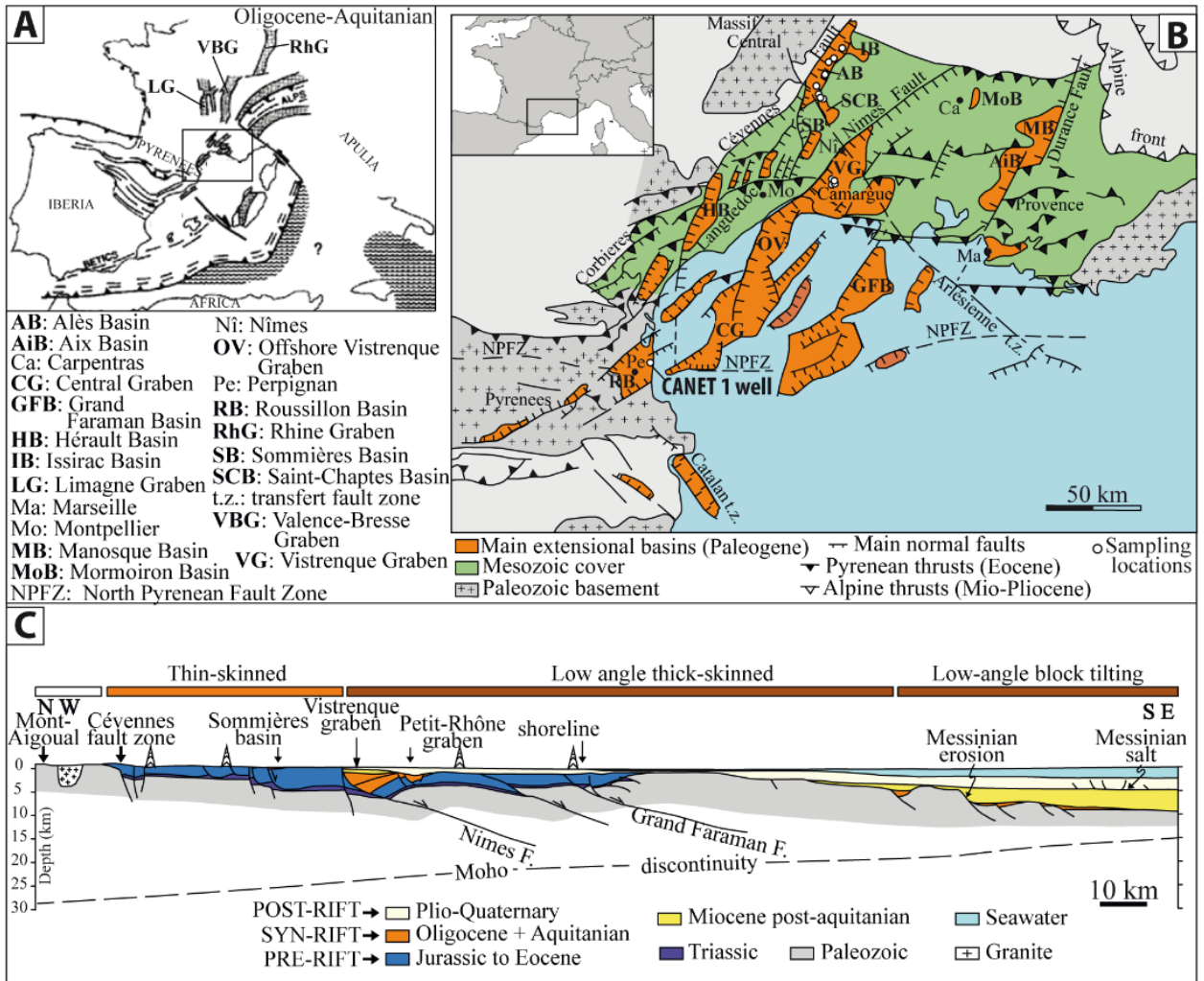
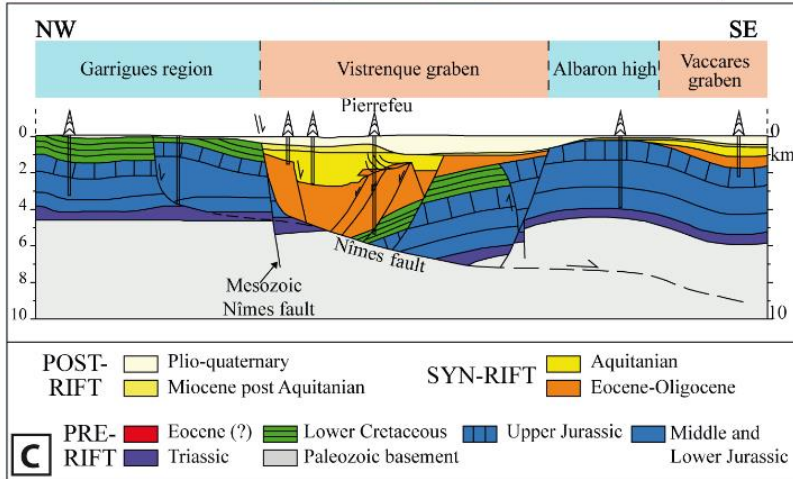
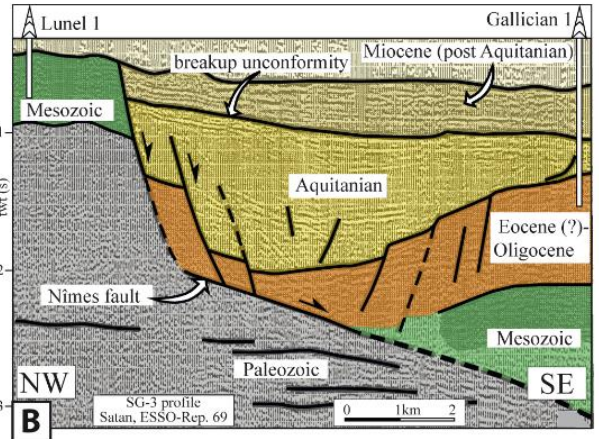
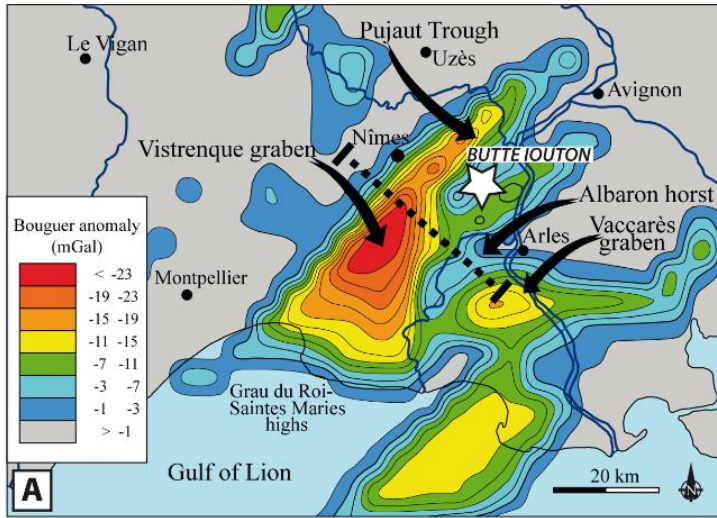


Figure 1



AGE / FORMATION		LOG	FACIES
PLIOCENE			Clays Sandstones Sandy claystones
MIOCENE	BURDIGALIAN		Glauconite-rich sandstone Chalky limestones Biocalcarenites
	AQUITANIAN		Sandy claystones with interbedded sandstones
OLIGOCENE (EOCENE ?)	Série calcaréo-salifère		Halite - Anhydrite Marlstones Dolomites Limestones
	Série rouge		Ochre sandy claystones Fine sandstones Sandy limestones
	Série grise		Marlstones Argillaceous limestones Sandstones, conglomerates, lignites
MESOZOIC			Locally karstified carbonates

Figure 2

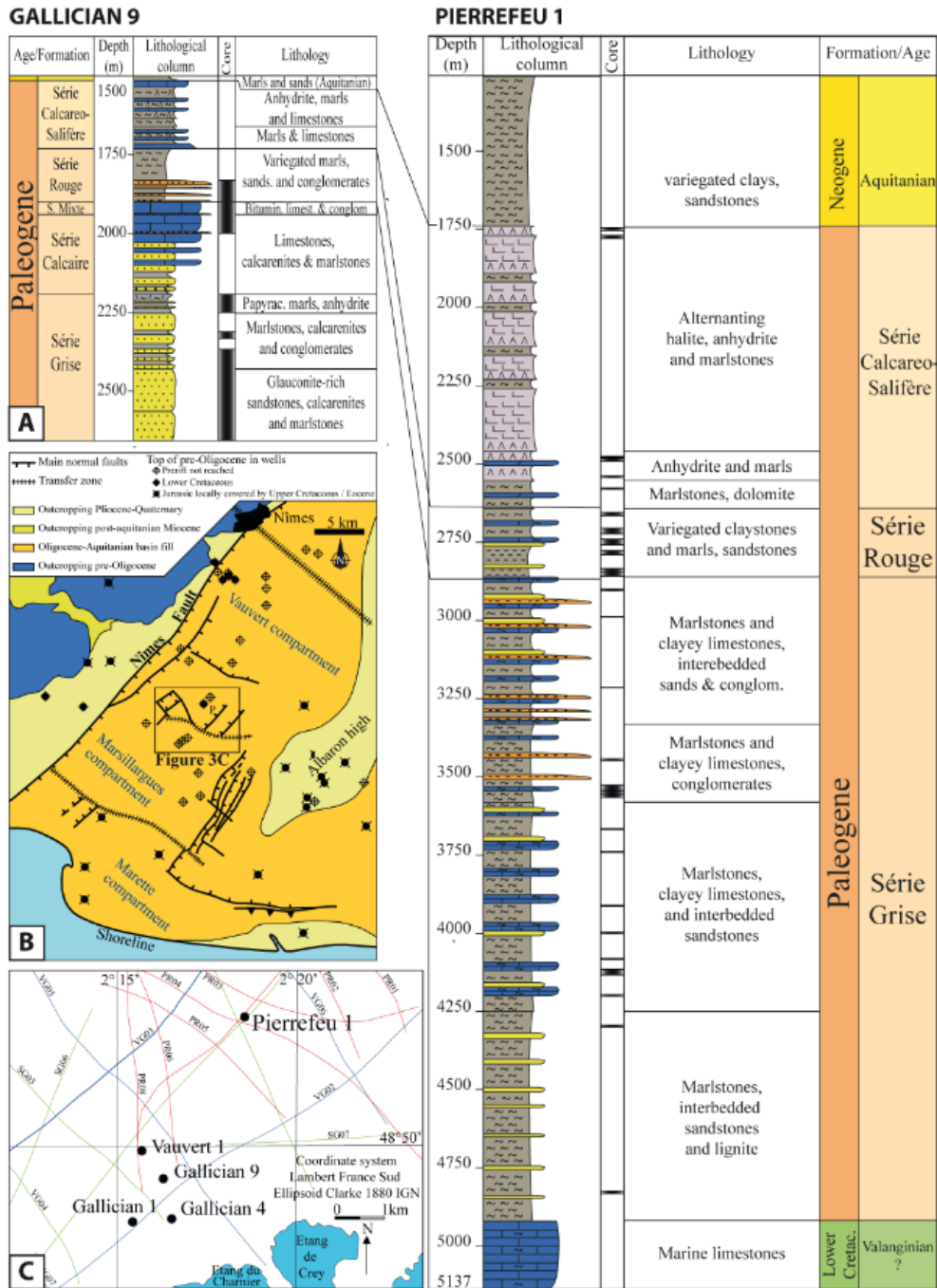


Figure 3

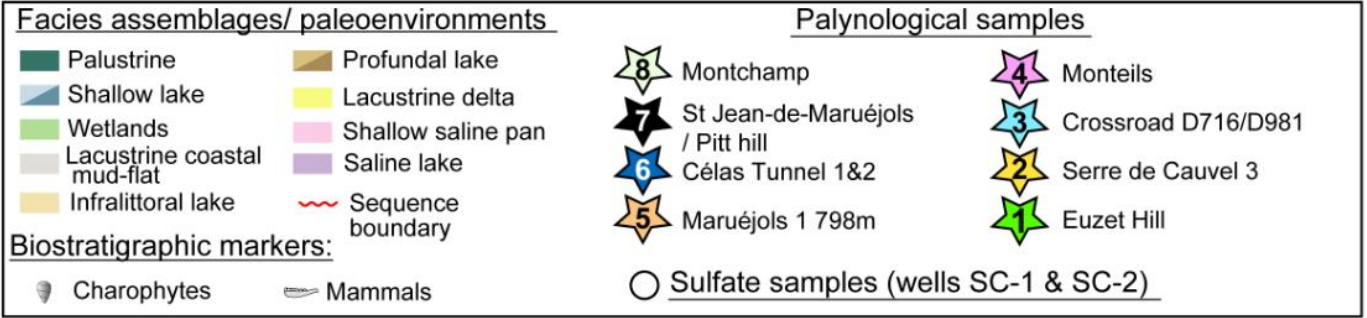
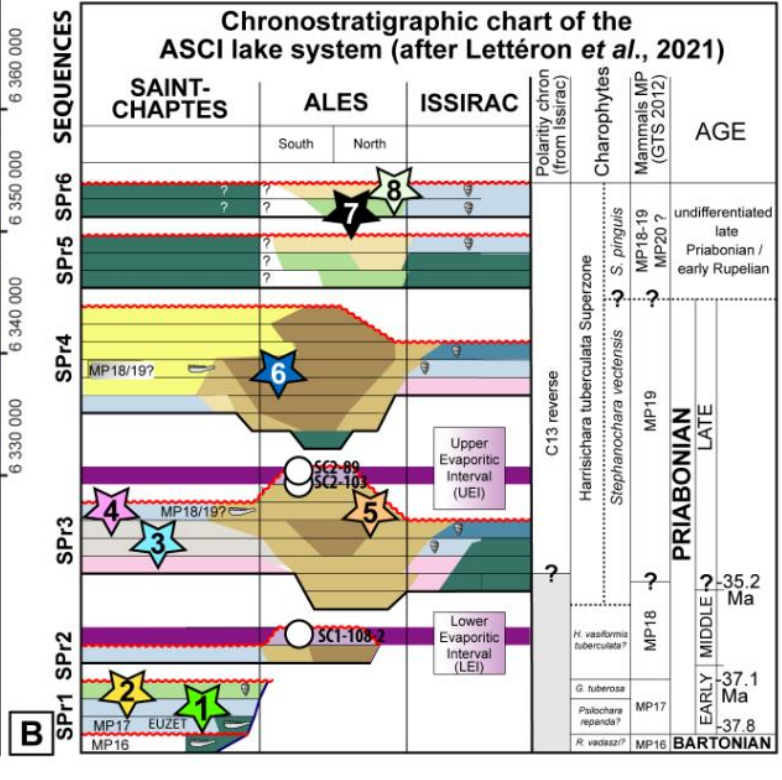
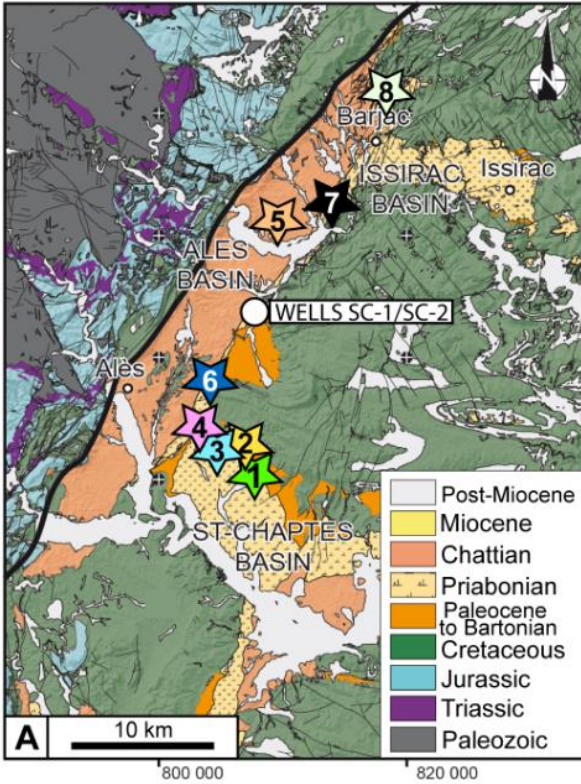


Figure 4

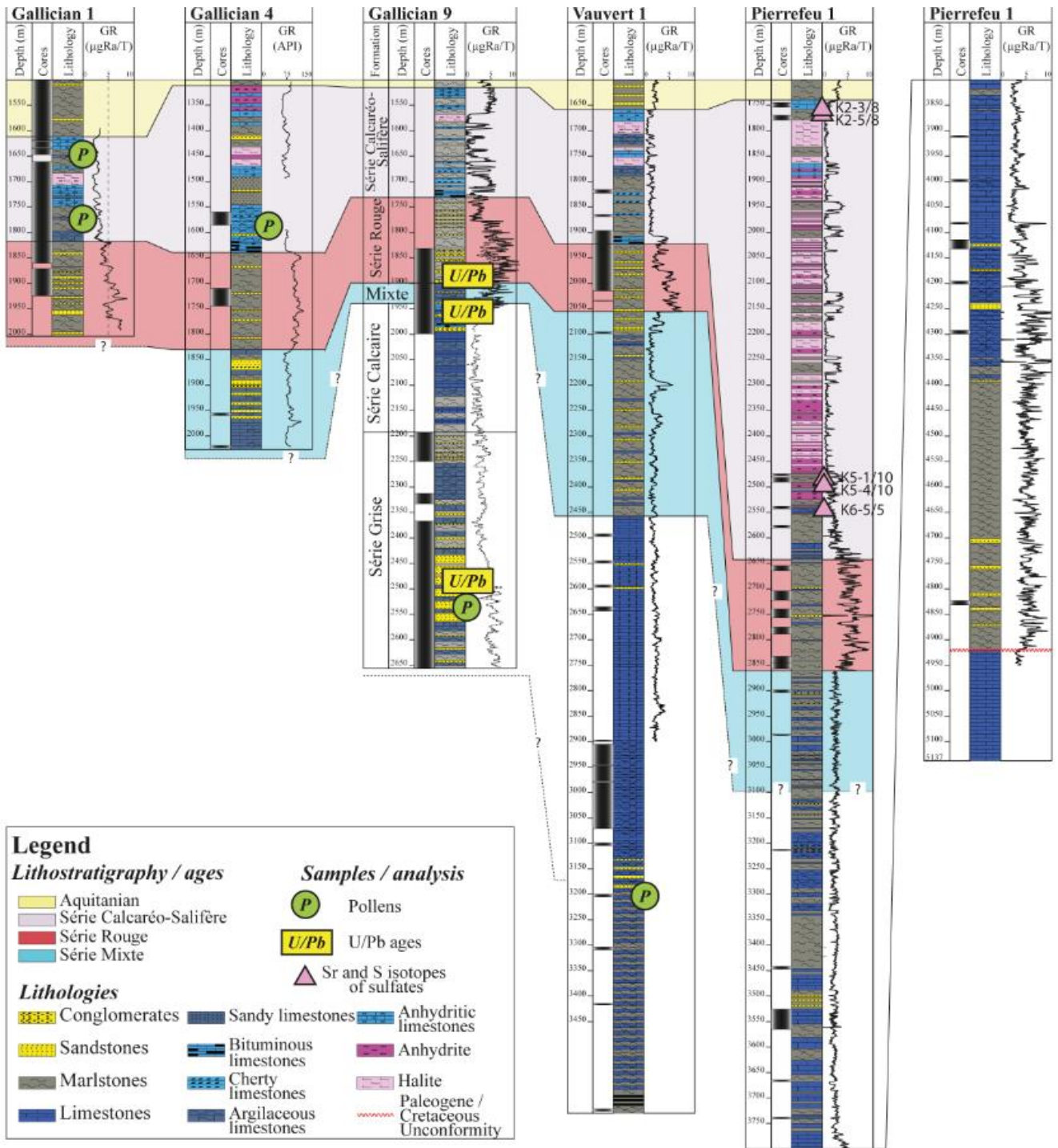


Figure 5

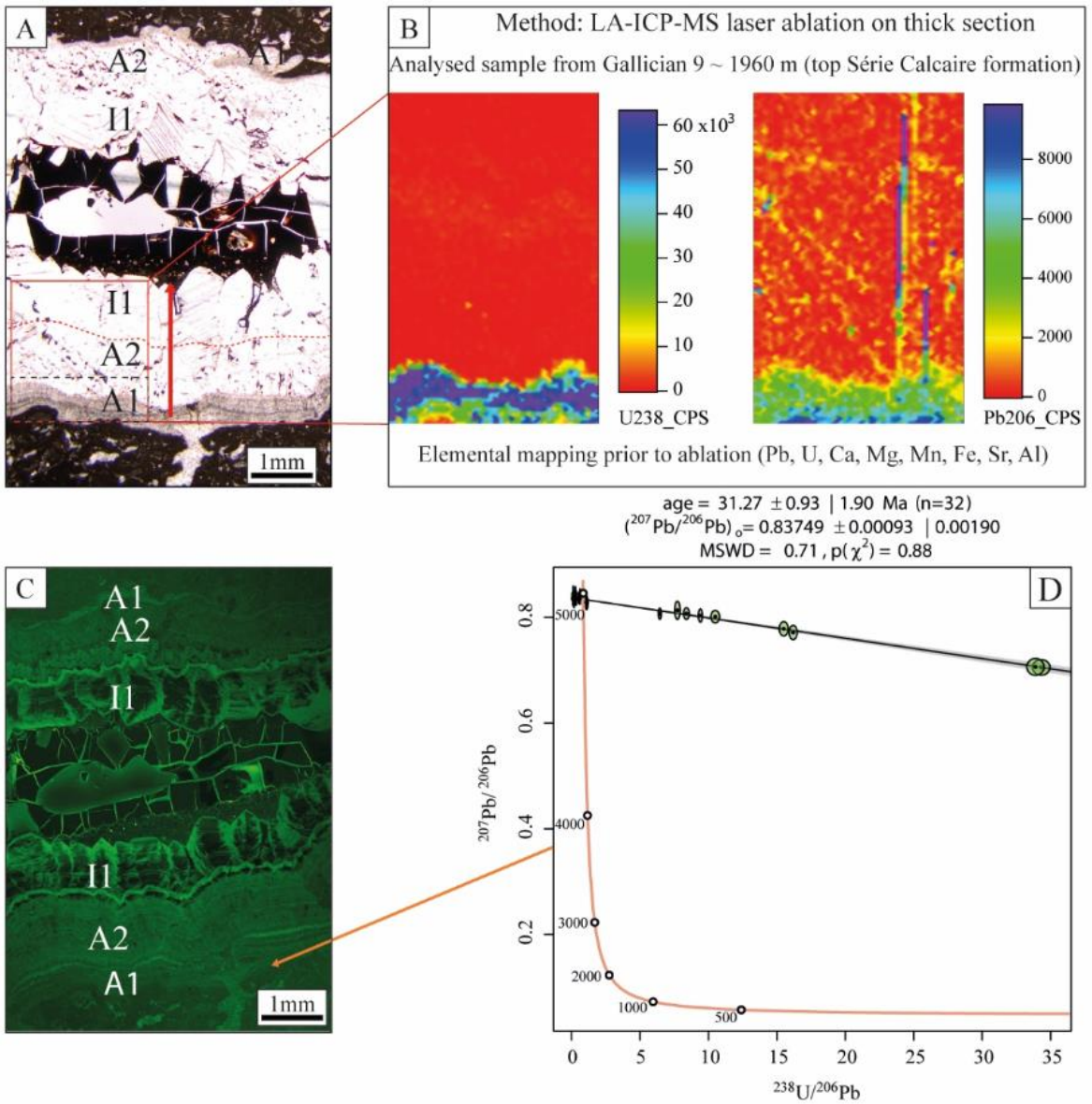


Figure 6

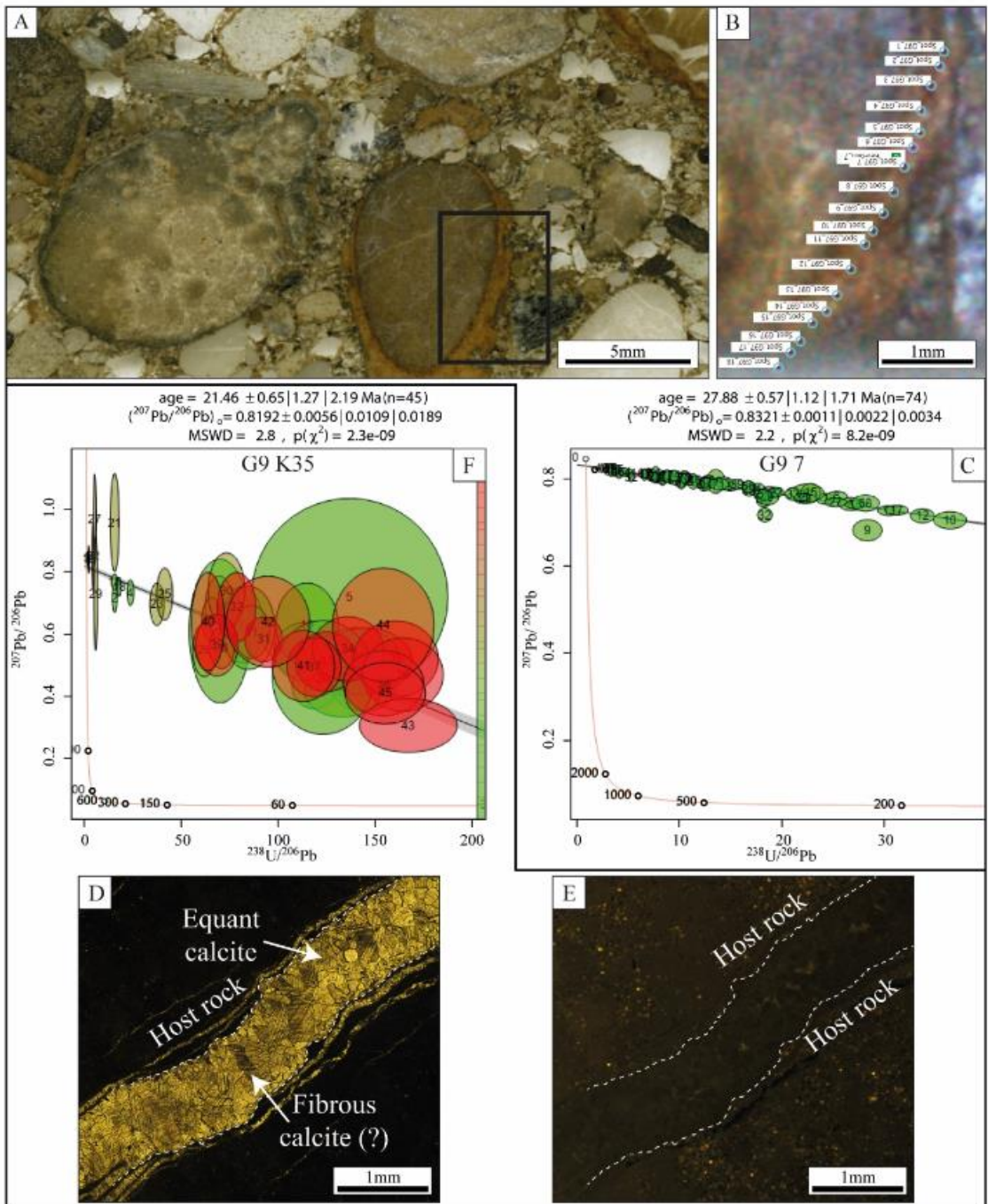


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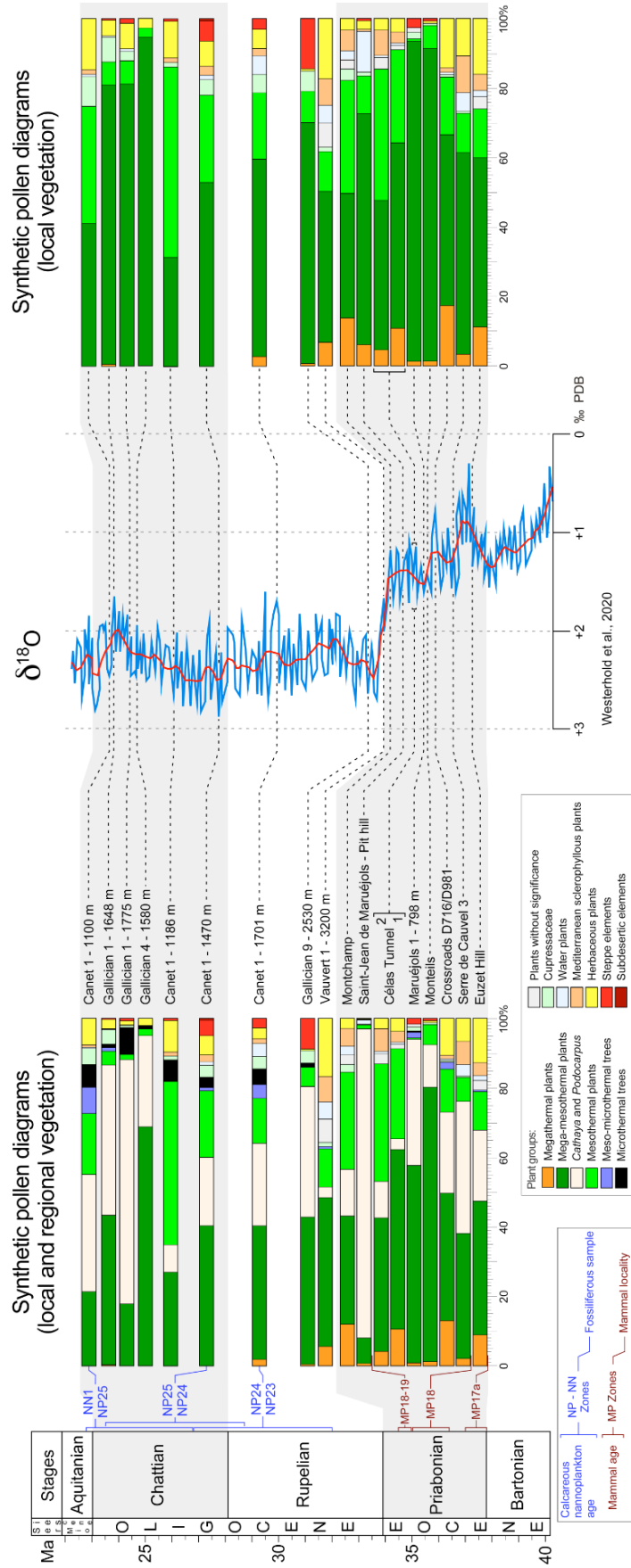


Figure 8

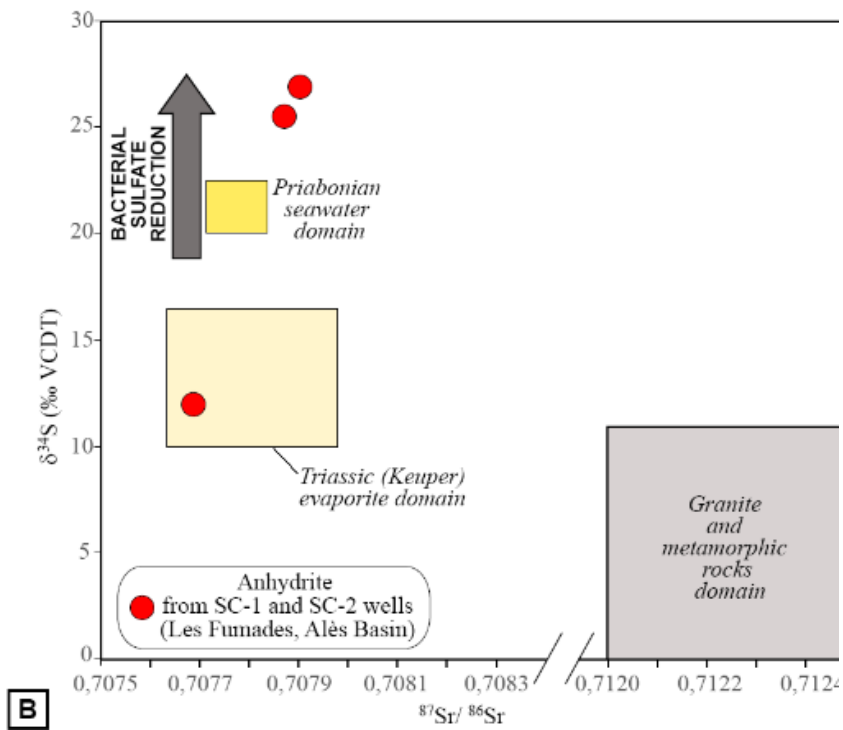
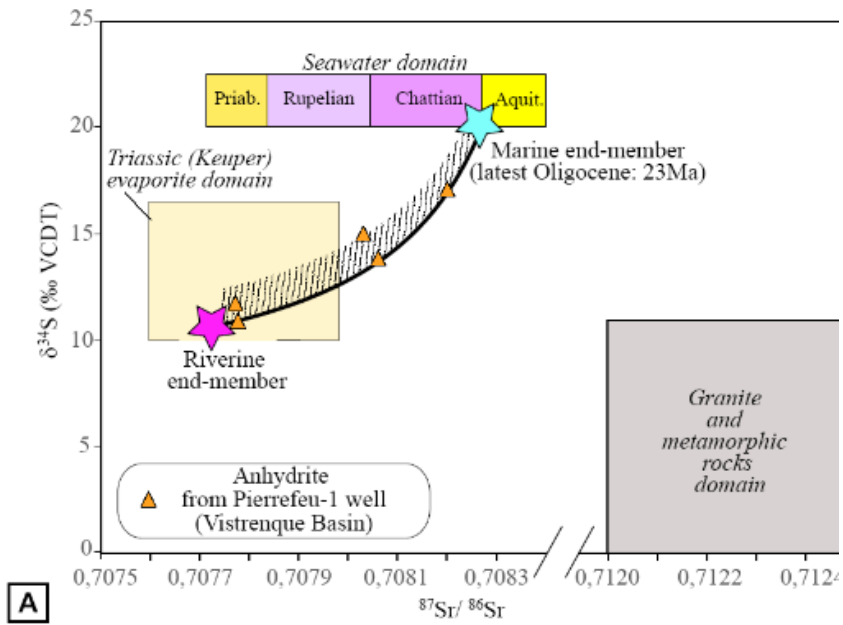


Figure 9

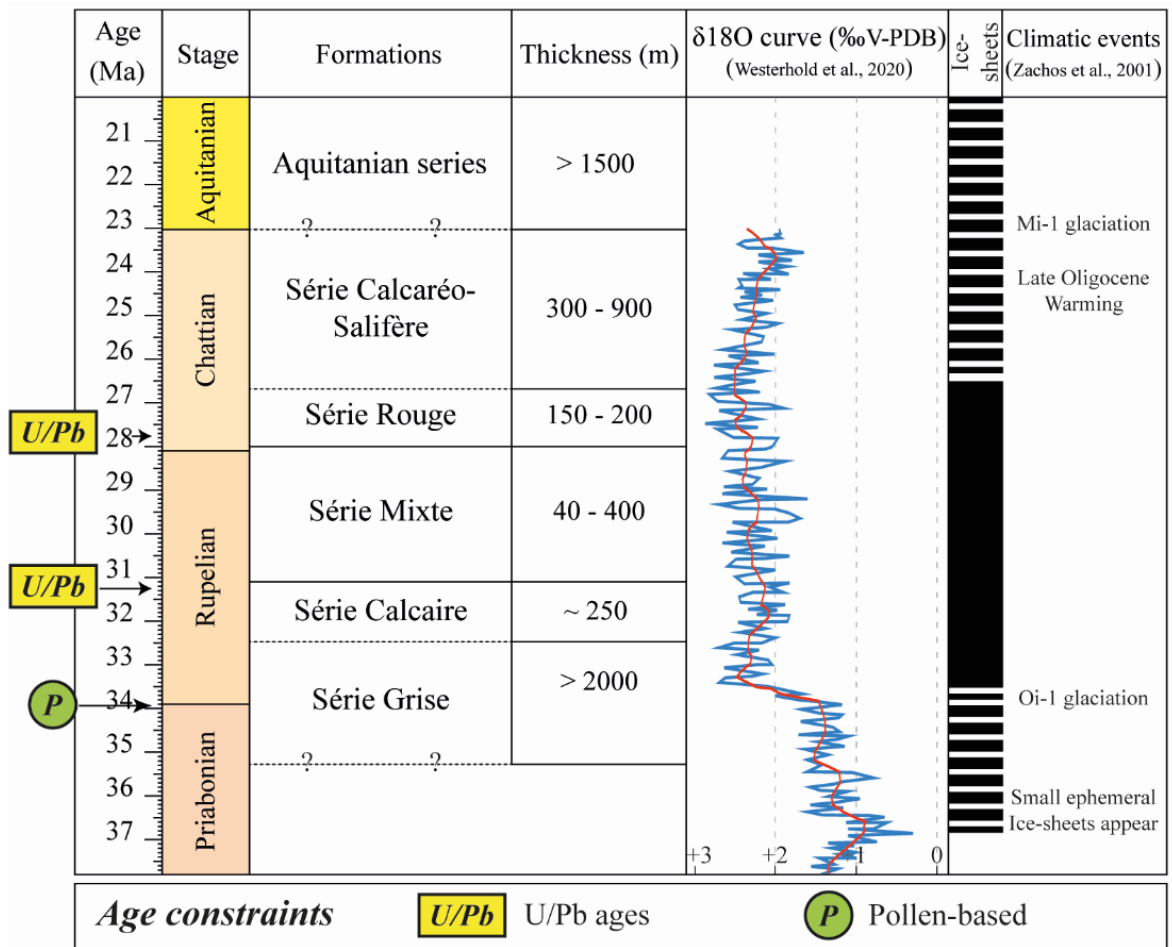


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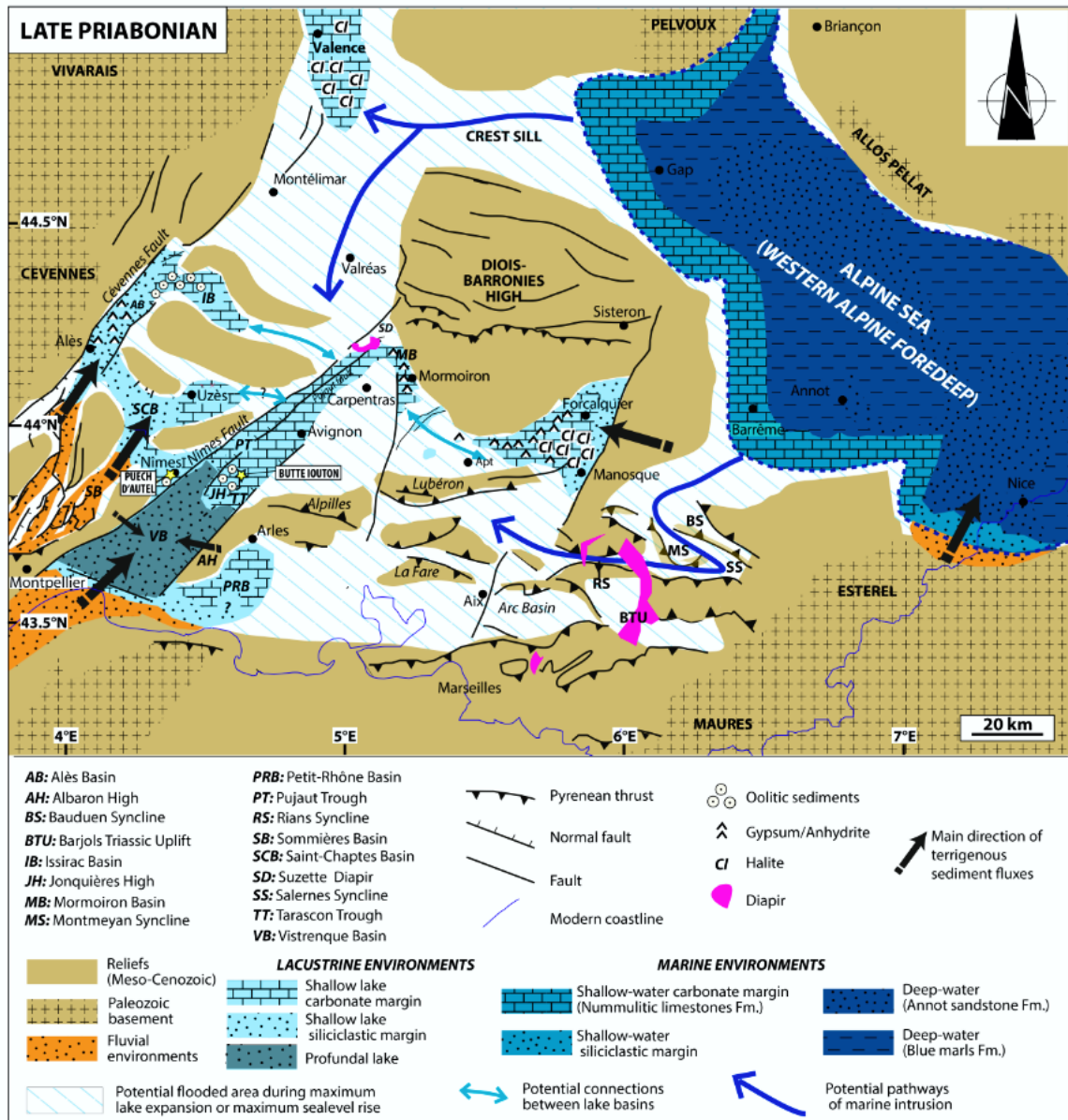


Figure 11

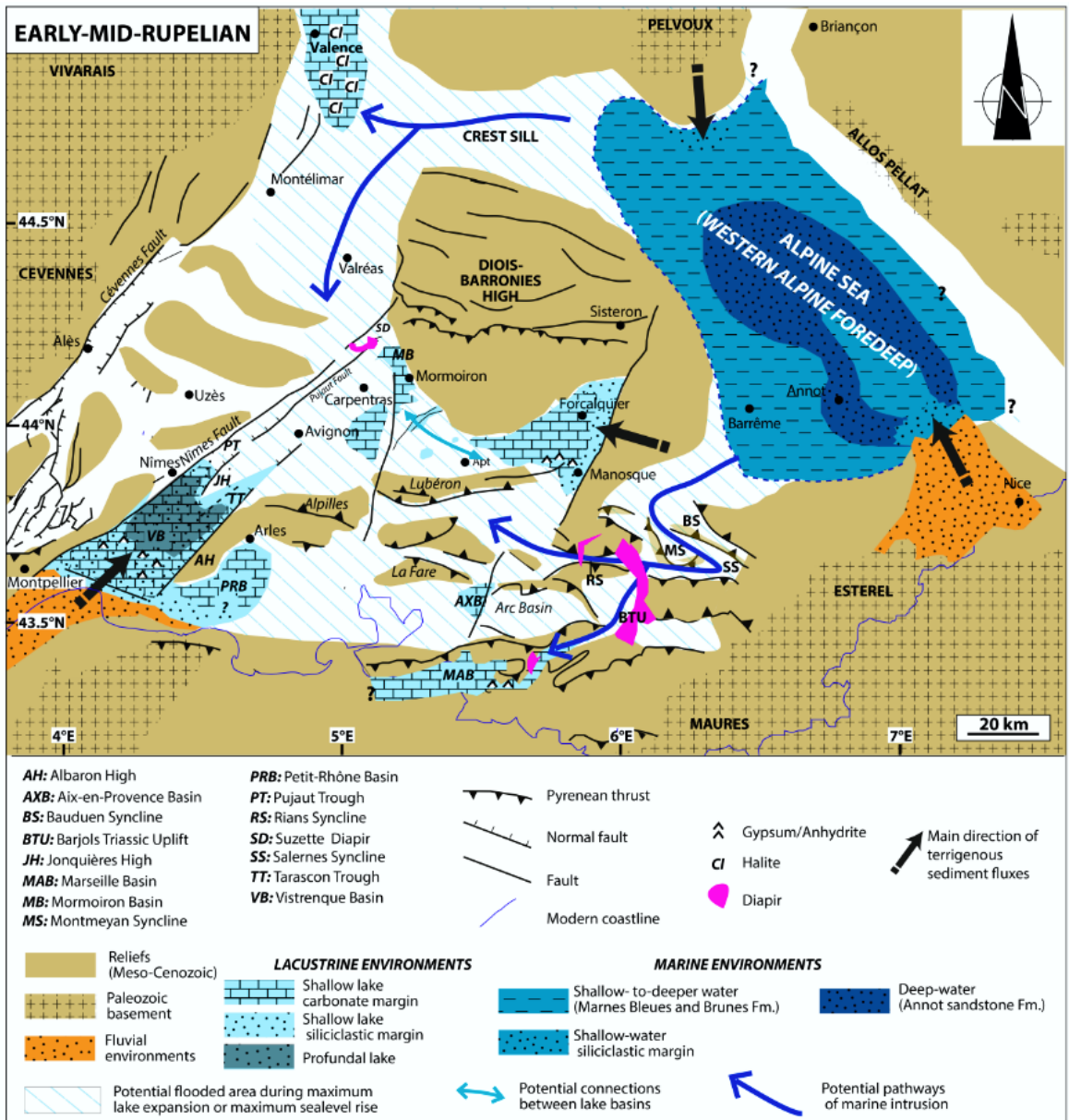


Figure 12

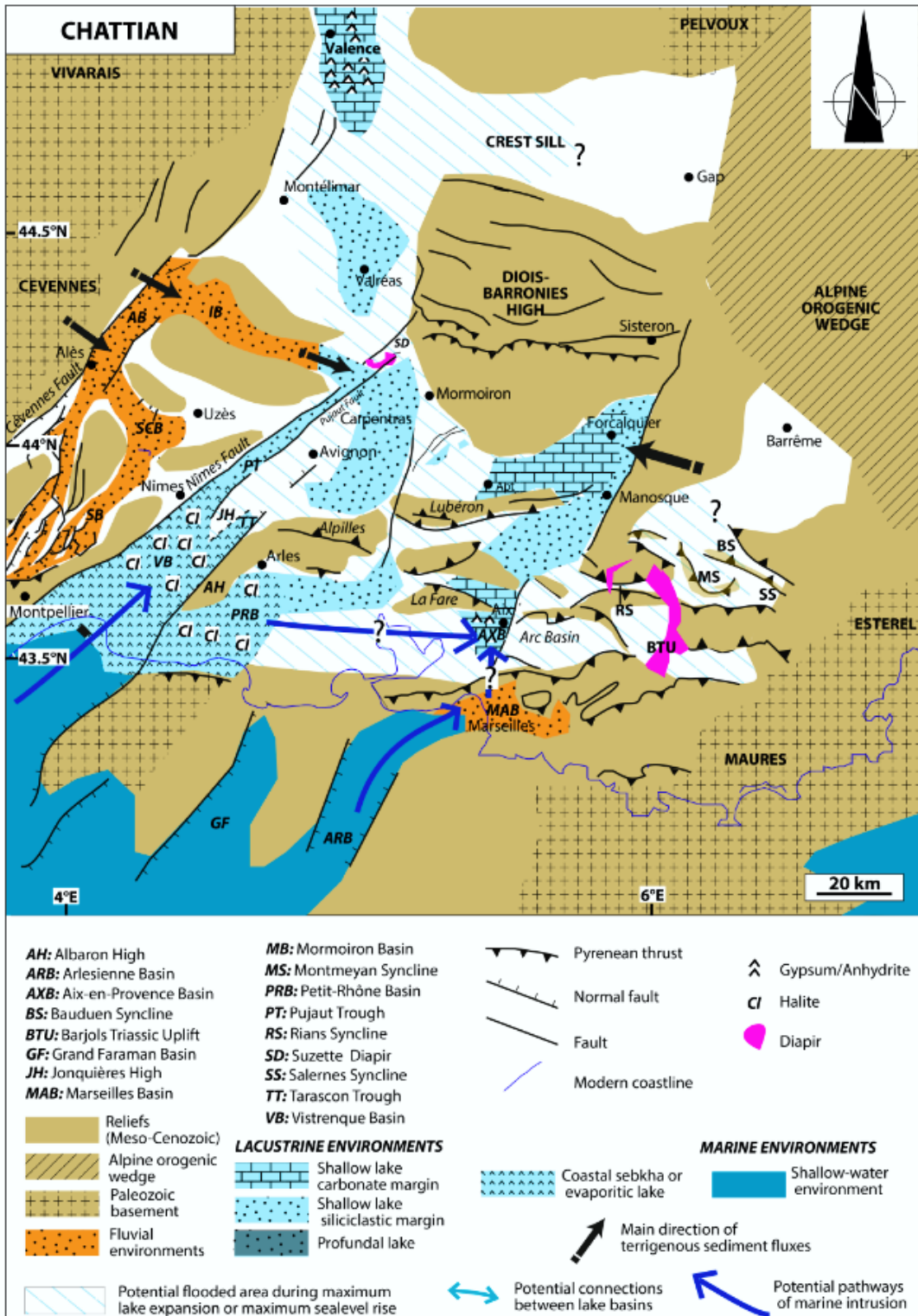


Figure 13

Lithostratigraphic units	Age	Dating approach	Analysed sample	Well – depth (m)
Série Calcaréo-salifère	Late Chattian to earliest Aquitanian?	Geochemical modelling on sulphates	Anhydrite	Pierrefeu 1 – 1750 1775 – 2485 – 2545
	Early to middle Chattian	Pollen climatostratigraphy	Pollen assemblage	Gallician 1 – 1648 Gallician 1 – 1775 Gallician 4 – 1580
Série Rouge	Early Chattian ^(a)	U/Pb dating * Absolute age: 27.88 +/-1.71 Ma ^(b)	Vadose cement	Gallician 9 – 1894
Série Mixte	Middle Rupelian to early Chattian	Bounding	/	/
Série Calcaire	Early to middle Rupelian ^(a)	U/Pb dating * Absolute age: 31.27 +/-1.90 Ma ^(b)	Vadose cement	Gallician 9 – 1960
Série Grise	Priabonian (?) to early Rupelian	Pollen climatostratigraphy	Pollen assemblage	Gallician 9 – 2530 Vauvert 1 – 3200

^(b) Ages are calibrated with the Geological time Scale after Gradstein et al. (2012).

^(a) Errors include measurements errors and errors associated with statistic calculations, considering 95% confidence interval

Table 1

Site	Basin	MAT (°C)	MTC (°C)	MTW (°C)	MAP (mm)
Canet 1 - 1100 m	Roussillon	16-19-25	10-11.6-14	25-26.2-29	1100-1640-2200
Gallician 1 - 1648 m	Vistrenque	16-18.9-25	5-9-14	25-26.2-29	1100-1560-1960
Canet 1 - 1186 m	Roussillon	15-18.4-25	2.5-10.4-14	25-26.2-29	1000-1260-1400
Canet 1 - 1470 m	Roussillon	16-19.1-24	10-11.7-14	25-26.1-28	1100-1230-1300
Canet 1 - 1701 m	Roussillon	19-20.7-25	10-12.7-16.5	26-26.7-28	1200-1530-1960
Gallician 9 - 2530 m	Vistrenque	12-15.8-20	2.5-7.3-14	20-23.3-27	800-870-2200
Vauvert 1 - 3200 m	Vistrenque	17-19.7-25	12-13.2-15	25-26.2-28	1200-1325-1400
Montchamp	Alès	20-21.4-25	12-14.4-15	26-26.4-28	1100-1530-1800
Celas Tunnel 2	Alès	19-20.9-25	12-14.5-17	25-26.7-29	1500-1670-1800
Celas Tunnel 1	Alès	19-20.9-25	10-12.5-15	26-26.9-28	1500-1760-2000
Maruéjols 1 - 798 m	Alès	19-20.9-25	12-14-17	26-27.1-29	1100-1630-2000
Monteils	Saint-Chaptes	15-18.7-25	10-11.7-14	25-26.1-28	1500-1650-1800
Crossroads D716/D981	Saint-Chaptes	19-21.1-25	12-13-14	26-27-29	1000-1400-1560
Serre de Cauvel 3	Saint-Chaptes	18-20.2-25	12-12.8-14	25-26.2-28	1100-1540-1800
Euzet Hill	Saint-Chaptes	17-20.1-24	12-13.9-16	25-26.3-28	1200-1530-1600

Table 2

Well	Formation/ Sequence	Sample ID	Lithology	Age	⁸⁷ Sr/ ⁸⁶ Sr	δ ³⁴ S ‰VCDT
Pierrefeu 1 (Vistrenque Basin)	Calcaréo- salifère	K2-3/8	anhydrite	Oligocene	0,707777	+10,92
	Calcaréo- salifère	K2-5/8	anhydrite	Oligocene	0,707772	+11,75
	Calcaréo- salifère	K5-1/10	anhydrite	Oligocene	0,708061	+13,87
	Calcaréo- salifère	K5-4/10	anhydrite	Oligocene	0,708031	+15,02
	Calcaréo- salifère	K6-5/5	anhydrite	Oligocene	0,708201	+17,11
SC-1 well (Alès Basin) SC-2 well (Alès Basin)	Sequence SPr2	SC1-108-2	anhydrite/gypsum	Priabonian	0,707685	+12,11
	Sequence SPr3	SC2-103	anhydrite/gypsum	Priabonian	0,707903	+26,98
	Sequence SPr3	SC2-89	anhydrite/gypsum	Priabonian	0,707870	+25,59
	Sequence SPr3	SC2-89	native sulphur	Priabonian		-6.42
	Sequence SPr3	SC2-89	native sulphur	Priabonian		-5.99

Table 3

SUPPLEMENTARY DATA

MICROPALAEONTOLOGY: CALCAREOUS NANNOFOSSILS AND PALYNOLOGY

The micropalaeontological content (pollen grains and spores, dinoflagellate cysts, calcareous nannofossils) of thirteen locations (boreholes and exposed sections) has been searched. They belong to the Vistrenque Basin (Gallician 1 – 4 – 9, Vauvert 1), the Alès Basin (Maruéjols 1, Euzet Hill, Serre de Cauvel, Crossroad D716/D981, Monteils, Célas Tunnel, Saint-Jean de Maruéjols Pit hill, Montchamp) and the Roussillon Basin (Canet 1) (Fig. Y; Table S1). Occurrences of calcareous nannofossils are presented in Table S2, palynological results are detailed in Table S3.

Location	North Latitude	East Longitude	Elevation (m)	Basin
Canet 1	42°41'23.41"	3°04'66.00"	-1099 -1700	Roussillon
Gallician 9	43°38'35.64"	4°16'58.49"	-2515	Vistrenque
Gallician 4	43°38'13.86"	4°17'06.36"	-1581	
Gallician 1	43°38'14.98"	4°16'58.22"	-1647 -1775	
Vauvert 1	43°38'58.04"	4°16'39.43"	-3177	
Euzet Hill	44°04'35.71"	4°12'41.02"	127	Alès
Serre de Cauvel	44°04'36.90"	4°12'28.10"	120	
Crossroad D716/D981	44°04'50.50"	4°11'57.50"	132	
Monteils	44°05'08.00"	4°11'39.00"	168	
Célas Tunnel	44°07'37.70"	4°10'34.80"	201	
Saint-Jean de Maruejols Pit hill	44°15'59.05"	4°17'48.36"	128	
Maruéjols 1	44°15'35.76"	4°15'20.78"	-633	
Montchamp	44°19'56.20"	4°21'29.30"	220	

Table S1. Latitude, longitude, elevation and reference basin of the studied locations.

For boreholes, elevation refers to depth of samples with respect to elevation of the hole top.

Canet 1 borehole.

Six samples were chosen within clay layers from the lithostratigraphic interval ascribed to Aquitanian–late Oligocene by Gottis (1958) in order to obtain pollen grains, four of them revealed a rich pollen flora (Fig. S1) and three of them contained abundant dinoflagellate cysts. As a consequence, calcareous nannofossils were successfully searched in these last samples (Table S2).

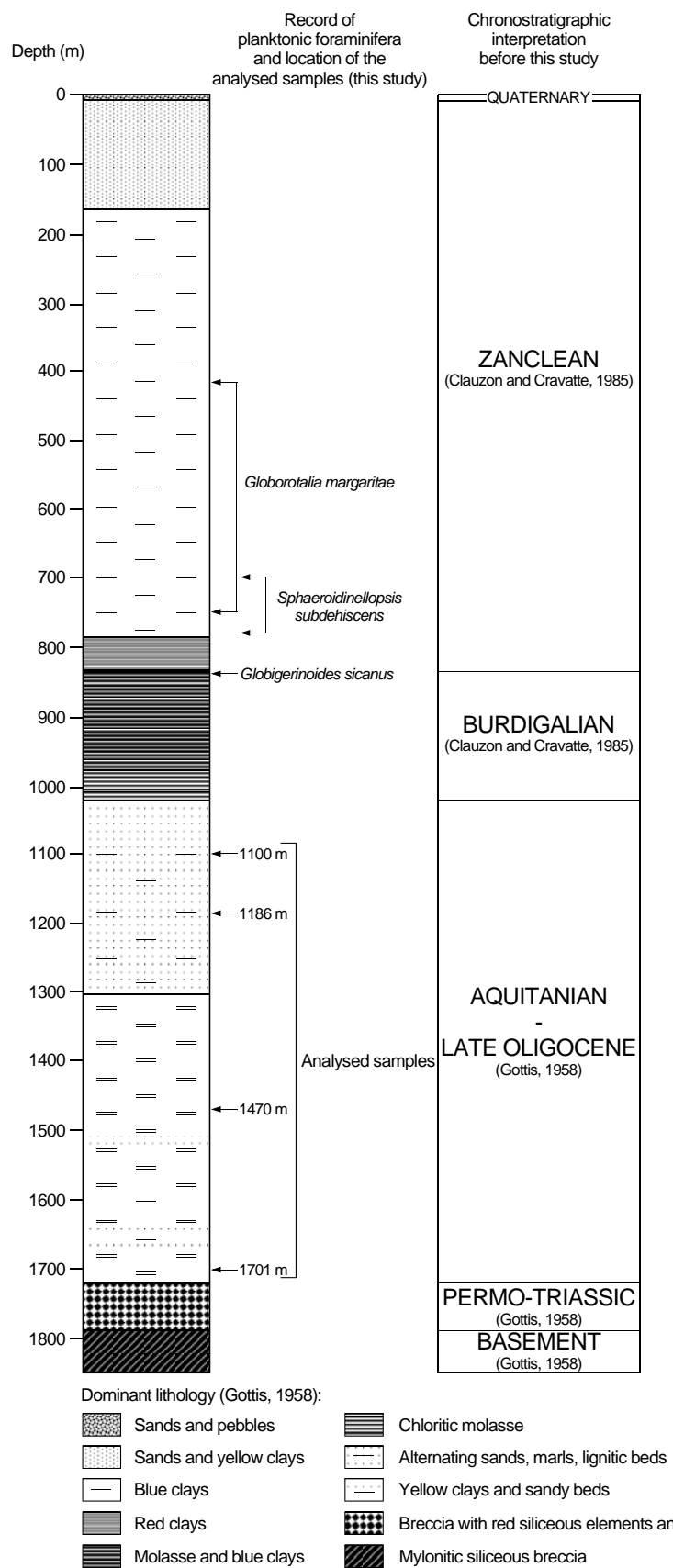


Figure S1. Canet 1 borehole: lithostratigraphic log, biostratigraphic markers, location of the analysed samples in this study, chronostratigraphic interpretation previous to this study.

Samples	Calcareous nannofossils
Gallician 1 – 1594 m	<i>Coccolithus pelagicus</i> , <i>Cyclicargolithus floridanus</i> , <i>Pontosphaera multipora</i> , <i>Reticulofenestra bisecta</i> , <i>R. lockeri</i> , <i>Sphenolithus moriformis</i> , <i>Zygrabliothus bijugatus</i>
Gallician 1 – 1810 m	<i>Coccolithus pelagicus</i> , <i>Sphenolithus moriformis</i> , <i>Zygrabliothus bijugatus</i> , <i>Reticulofenestra cf. lockeri</i>
Canet 1 – 1100 m	<i>Calcidiscus pataecus</i> , <i>Coccolithus pelagicus</i> , <i>Cyclicargolithus abisectus</i> , <i>C. floridanus</i> , <i>Discoaster deflandrei</i> , <i>Helicosphaera carteri</i> , <i>Pontosphaera discopora</i> , <i>P. multipora</i> , <i>Reticulofenestra bisecta</i> , small reticulofenestrids, <i>Sphenolithus cf. delphix</i> , <i>S. moriformis</i> , <i>Zygrhabliothus bijugatus</i>
Canet 1 – 1470 m	<i>Calcidiscus pataecus</i> , <i>Chiasmolithus altus</i> , <i>Coccolithus pelagicus</i> , <i>Cyclicargolithus abisectus</i> , <i>C. floridanus</i> , <i>Discoaster deflandrei</i> , <i>Helicosphaera mediterranea</i> , <i>Pontosphaera enormis</i> , <i>P. multipora</i> , <i>Reticulofenestra bisecta</i> , small reticulofenestrids, <i>Sphenolithus moriformis</i> , <i>Zygrhabliothus bijugatus</i>
Canet 1 – 1701 m	<i>Chiasmolithus altus</i> , <i>Coccolithus pelagicus</i> , <i>Cyclicargolithus abisectus</i> , <i>C. floridanus</i> , <i>Helicosphaera ethologa</i> , <i>Pontosphaera enormis</i> , <i>P. multipora</i> , <i>Zygrhabliothus bijugatus</i> , <i>Reticulofenestra bisecta</i> , <i>Sphenolithus moriformis</i> ,
Maruéjols 1 – 433 m	<i>Coccolithus pelagicus</i> , <i>Cyclicargolithus floridanus</i> , <i>Pontosphaera multipora</i> , <i>Reticulofenestra bisecta</i> , <i>R. lockeri</i> , <i>Sphenolithus moriformis</i> , <i>Zygrabliothus bijugatus</i>
Crossroad D716/D981	<i>Coccolithus pelagicus</i> , <i>Sphenolithus moriformis</i> , <i>Helicosphaera</i> sp.

Table S2. Records of calcareous nannofossils.

1. Advances with respect to previous palynological records.

Several palynological records were previously performed in the studied region. Most of them are characterised by a listing of the most usually identified plants with a limited or missing counting of pollen grains (Provence: Sittler, 1965; Schuler and Sittler, 1976; Marseilles Basin: Châteauneuf, 1977; Alès Basin: Michoux, 1983). Such studies are particularly damaged by the non-recognition of most of the triporate, tricolpate and tricolporate pollen grains, which often belong to subtropical and tropical plants, i.e. meaningful elements for palaeoenvironmental reconstructions. The use of these poor pollen records is thus very limited for understanding palaeovegetation and palaeoclimate. Even lesser elaborated palynological analyses have been performed on few Camargue wells and do not provide significant information (Jan du Chêne, 1989; Buisson, 1993).

Because of improvements in botanical identification of pollen grains achieved in the seventies on the Neogene pollen floras thanks to the use of the rich ISEM pollen collection in Montpellier (Suc, 1976; Bessedik, 1980, 1981; Suc and Bessedik, 1981), supported by pollen photographs, some progress was introduced in Paleogene microfloras (Célas: Gruas-Cavagnetto, 1973; Provence: Châteauneuf and Nury, 1995), unfortunately still devoid of countings. Accordingly, these pollen records have a limited interest.

Our pollen study confirms the same differences and similarities between the Célas macroflora and microflora than previously indicated by Gruas-Cavagnetto (1973) but emphasizes the important role in the local vegetation made by Hamamelidaceae (*Distylium*, *Embolanthera*, *Rhodoleia*), Sapotaceae, Euphorbiaceae (*Croton*, *Amanoa*, *Canthium*-type) in addition to Araliaceae and Menispermaceae listed in the macroflora. One matter persists due to abundant cones of the fossil genus *Doliosstrobos* Marion in the macroflora that Kvacek (2002) ascribed to an extinct family, Doliosstrobaceae, expected close of both Araucariaceae and Cupressaceae. Cupressaceae pollen grains (including those of the former Taxodiaceae) are very scarce in the Célas microflora while those of Araucariaceae have not been observed.

2. Dinoflagellate cysts.

Dinoflagellate cysts have been recorded in some samples (Plate 4): Canet 1 (1100 m, 1470 m, 1701 m), Gallician 4 (1580 m), Gallician 9 (2530 m), Crossroads D716/D981, and Serre de Cauvel (samples 1 and particularly 2, the sample in which dinoflagellate cysts are the most abundant). On the whole, dinoflagellate cysts are not well preserved, often broken and thus identifiable with great difficulty. Many reworked dinoflagellate cysts occur. All the individuals have been observed both in transmitted light microscopy (TLM) and under fluorescent UV light microscopy (FLM) in order to detect the reworking (Doláková and Burešová, 2007 ; Hoyle et al., 2018): the reworked dinoflagellate cysts show a dull brown colour at the difference of the non reworked specimens which show a bright yellow colour as illustrated in Plate 4.

3. Morphological description of some pollen grains.

These descriptions are based on observations at transmitted light microscope (TLM) according to LO-analysis (*Lux* = light vs. *Obscuritas* = darkness) technique and/or scanning electronic microscope (SEM).

Afzelia-Peltophorum-type (Leguminosae) (Plate 1, Figs. 2a-e, 3a-d, 4).

Oblate to equiaxial tricolporate and reticulate pollen grains show large and short non-linear ectoapertures (colpi), endoapertures (pori) being often indistinct. The suprategal reticulum is made of large lumina. Muri are densely micro-echinate. Columellae with large head structure the tectum, also supported by smaller other ones. This pollen has been recorded in several locations (Canet 1, Gallician 9, Crossroads D716/D981, Euzet Hill; Table S3).

Similar pollen types are found in the tribes Detarioideae (*Afzelia*, *Intsia*) and Caesalpinioideae (*Peltophorum*, *Delonix*) (Plate 1, Figs. 1a-e; Banks and Lewis, 2018) but none of the observed species from the ISEM Collection shows small spines.

Peltogyne-type (Leguminosae; Plate 3, Figs. 6a-d, 7).

Oblate tricolporate and clavate pollen with thick costae along the ectoapertures (colpi) and a distinct thin annulus bordering the endoapertures (pori). Large and smaller clavae constitute the ornamentation of the pollen. This pollen has been recorded in the Euzet Hill location.

This pollen morphology is similar to that of the modern species *Peltogyne confertiflora* (Hayne) Benth. (Detarioideae) (Graham and Barker, 1981: plate 12, fig. E).

Croton-Jatropha (Euphorbiaceae; Plate 2, Figs. 3, 5a-b).

Inaperturate spheroidal pollen grain with a coarsely reticulate ornamentation constituted by more or less dense clavae, which have an almost triangular shape that provides the so-called *Croton*-pattern. This pollen has been recorded in several locations (Canet 1, Montchamp, Saint-Jean de Maruéjols Pit hill, Célas Tunnel, Crossroads D716/D981, Euzet Hill; Table S3).

Such very peculiar pollen types are characteristic of *Croton* (Plate 2, Figs. 4a-c) and *Jatropha* genera (Carreira et al., 1996; Ribes de Lima, 2007; Ribeiro de Souza et al., 2020).

Amanoa (Phyllanthaceae; Plate 1, Figs. 6a-c).

Tricolporate oblate pollen showing a large semi-tectate curvilinear reticulum (a thin membrane covers the lumina), with long colpi (ectoapertures) resulting in a small apocolpium, bordered by costae. Endoapertures are rectangular. This pollen has been recorded in several locations (Vauvert 1, Célas Tunnel, Crossroads D716/D981, Serre de Cauvel; Table S3).

This pollen morphology is characteristic of the genus *Amanoa* (Plate 1, Figs. 5a-b; Punt, 1962; Köhler, 1965).

Dodoniaea (Sapindaceae; Plate 2; Figs. 6a-b).

Equiaxial tricolporate pollen, subtriangular in polar view, with prominent apertural areas characterized by thickening endexine, especially around the rectangular endoapertures. The ornamentation can be psilate, rugulate or slightly reticulate. This pollen has been recorded at Célas Tunnel and Crossroads D716/D981 locations (Table S3).

Because of its distinctive shape, this pollen corresponds in part to the fossil 'genus' *Pentapollenites* conceived by Krutzsch (1962), manifestly illustrated at the scanning electronic microscope by Châteauneuf (1980: plate 17, fig. 7), which now receives a robust botanical ascription as *Dodoniaea* (Plate 2, Figs. 7a-c; Merville, 1965), a primitive genus within the Sapindaceae (Muller and Leenhouts, 1976). Henceforth, the name *Pentapollenites* must be rejected as it probably also includes other botanical genera.

Alangium (Cornaceae; Plate 1, Figs. 7, 8).

Prolate tricolporate and reticulate pollen, elliptic in equatorial view, with long ectoapertures (colpi) edged by thick costae. Lalongate endoapertures (pori) are surrounded by a thin annulus. The suprategate reticulum is somewhat lengthened along the pole axis. The tectum is thick and clearly separated from the endexine. This pollen has been recorded at Vauvert 1, Célas Tunnel, Saint-Jean de Maruéjols Pit hill and Monteils locations (Table S3).

Such a pollen is characteristic of several species of the *Alangium* genus (Plate 1, Fig. 9; Reitsma, 1970).

Plate 1. Photographs at TLM and SEM of some fossil and modern pollen grains (shots by J.-P. Suc).
Modern pollen grains originate from the ISEM - Montpellier Collection.

Scale bar = 10 µm.

Figs 1a-e. *Afzelia cochinchinensis* (Pierre)J.Léonard = *A. xylocarpa* (Kurz)Craib (Leguminosae) – ISEM Collection number: 9427 (plant specimen collected in Vietnam); equatorial view aperture facing at TLM.

LO-analysis: a, reticulate ornamentation; b, focus on the head of columellae; c, focus on the foot of columellae; d, optical section.

Figs. 2a-e. *Afzelia-Peltophorum*-type (Leguminosae) – Euzet Hill; equatorial view (intercolpium) at TLM.

LO-analysis: a, reticulate ornamentation; b, focus on the head of columellae; c, focus on the foot of columellae; d, aperture; e, optical section.

Figs. 3a-d. *Afzelia-Peltophorum*-type (Leguminosae) – Crossroad D716/D981; equatorial view (intercolpium) at TLM.

LO-analysis: a, reticulate ornamentation; b, focus on the head of columellae; c, focus on the foot of columellae; d, optical section.

Fig. 4. *Afzelia-Peltophorum*-type (Leguminosae) – Euzet Hill; equatorial view aperture facing at SEM.

Figs. 5a-b. *Amanoa caribaea* Krug & Urb. (Phyllanthaceae) – ISEM Collection number: 41784 (plant specimen collected in Cameroon); equatorial views aperture facing (a) and polar view (b) at TLM.

LO-analysis: a, reticulate ornamentation and apertures; b, optical section.

Figs. 6a-c. *Amanoa* (Phyllanthaceae) – Crossroad D716/D981; equatorial view aperture facing (a-b) and polar view (c) at TLM.

LO-analysis: a, reticulate ornamentation and aperture; b, optical section.

Fig. 7. *Alangium* (Cornaceae) – Célas Tunnel 1; equatorial view (intercolpium) at TLM.

Fig. 8. *Alangium* (Cornaceae) – Saint-Jean de Maruéjols Pit hill; equatorial view aperture facing at TLM.

Fig. 9. *Alangium barbatum* (R.Br. ex C.B.Clarke) Baill. ex Kuntze (Cornaceae) – ISEM Collection number: 17360 (plant specimen collected in Burma); equatorial views aperture facing and optical section at TLM.

Figs. 10a-b. *Bombax*-type (Malvaceae) – Crossroad D716/D981; polar view at TLM.

LO-analysis: a, reticulate ornamentation; b, optical section.

Figs. 11a-b. *Avicennia* (Acanthaceae) – Montchamp; equatorial view aperture facing at TLM.

LO-analysis: a, reticulate ornamentation; b, optical section.

Figs. 12a-c. *Avicennia* (Acanthaceae) – Saint-Jean de Maruéjols Pit hill; equatorial view (intercolpium) at TLM.

LO-analysis: a, reticulate ornamentation; b, focus at base of columellar, colpi; c, optical section.

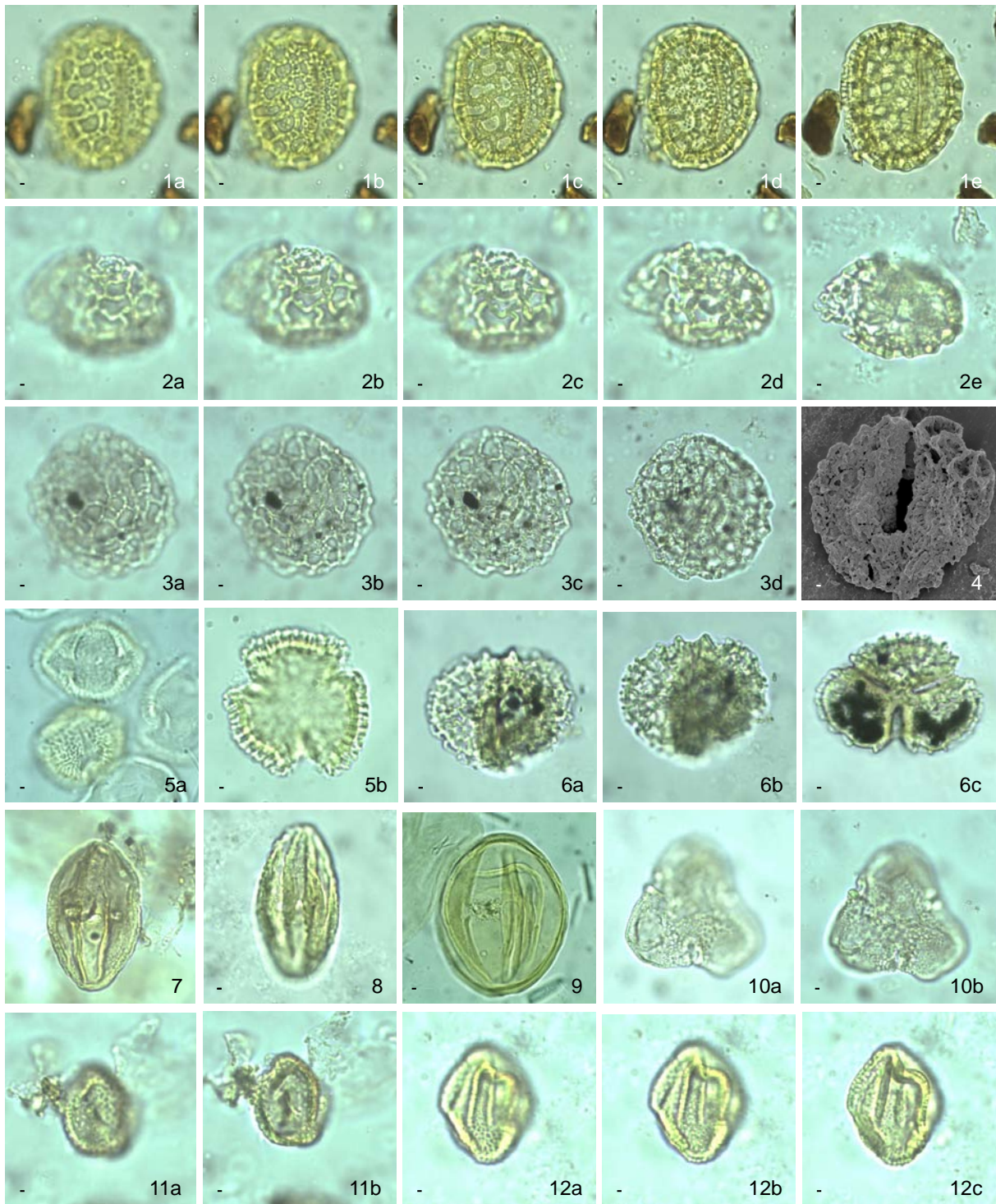


Plate 2. Photographs at TLM and SEM of some fossil and modern pollen grains (shots by J.-P. Suc). Modern pollen grains originate from the ISEM - Montpellier Collection or from the GeoBioStratData – Rillieux la Pape Collection.

Scale bar = 10 μm .

Figs 1a-b. Araliaceae – Célas Tunnel 2.; equatorial view (intercolpium) at TLM.

LO-analysis: a, reticulate ornamentation and apertures; b, optical section.

Figs. 2a-b. Araliaceae – Montchamp; equatorial view aperture facing at TLM.

LO-analysis: a, reticulate ornamentation and apertures; b, apertures and optical section.

Fig. 3. *Croton* (Euphorbiaceae) – Euzet Hill; view at SEM.

Figs. 4a-c. *Croton scabiosus* Bedd. (Euphorbiaceae) – ISEM Collection number: 15339 (plant specimen collected in India); view at TLM.

LO-analysis: a, reticulate ornamentation; b, focus on the foot of columellae; c, optical section.

Figs. 5a-b. *Croton* (Euphorbiaceae) – Saint-Jean de Maruéjols Pit hill; view at TLM.

LO-analysis: a, reticulate ornamentation; b, focus on the foot of columellae and optical section.

Figs. 6a-b. *Dodonaea* (Sapindaceae) – Crossroad D716/D981; equatorial view aperture facing at TLM.

LO-analysis: a, aperture; b, aperture and optical section.

Figs. 7a-c. *Dodonaea triquetra* J.C.We,dl. (Sapindaceae) – ISEM Collection number: 36963 (plant specimen collected in Australia); equatorial view aperture facing at TLM.

LO-analysis: a, psilate ornamentation and apertures; b, aperture; c, aperture and optical section.

Figs. 8-c. *Embolanthera glabrescens* H.L.Li (Hamamelidaceae) – ISEM Collection number: 14245 (plant specimen collected in Vietnam); polar view at TLM.

LO-analysis: a, reticulate ornamentation; b, focus on the foot of columellae; c, optical section.

Figs. 9a-c. *Embolanthera* (Hamamelidaceae) – Vauvert 1 3200 m; polar view at TLM.

LO-analysis: a, reticulate ornamentation; b, focus on the foot of columellae; c, optical section.

Figs. 10a-c. *Fothergilla gardenii* L. (Hamamelidaceae) – GeoBioStratData Collection number: 839 (plant specimen collected in North America); polar view at TLM.

LO-analysis: a, reticulate ornamentation; b, focus on the foot of columellae; c, optical section.

Figs. 11a-c. *Fothergilla* (Hamamelidaceae) – Euzet Hill; polar view at TLM.

LO-analysis: a, reticulate ornamentation; b, focus on the foot of columellae; c, optical section.

Figs. 12a-b. *Mappianthus* (Icacinaceae) – Euzet Hill; equatorial view at TLM.

LO-analysis: a, echinulate ornamentation and aperture; b, optical section.

Fig. 13. *Leea* (Vitaceae) – Saint-Jean de Maruéjols Pit hill; equatorial view at TLM.

LO-analysis: reticulate ornamentation and aperture.

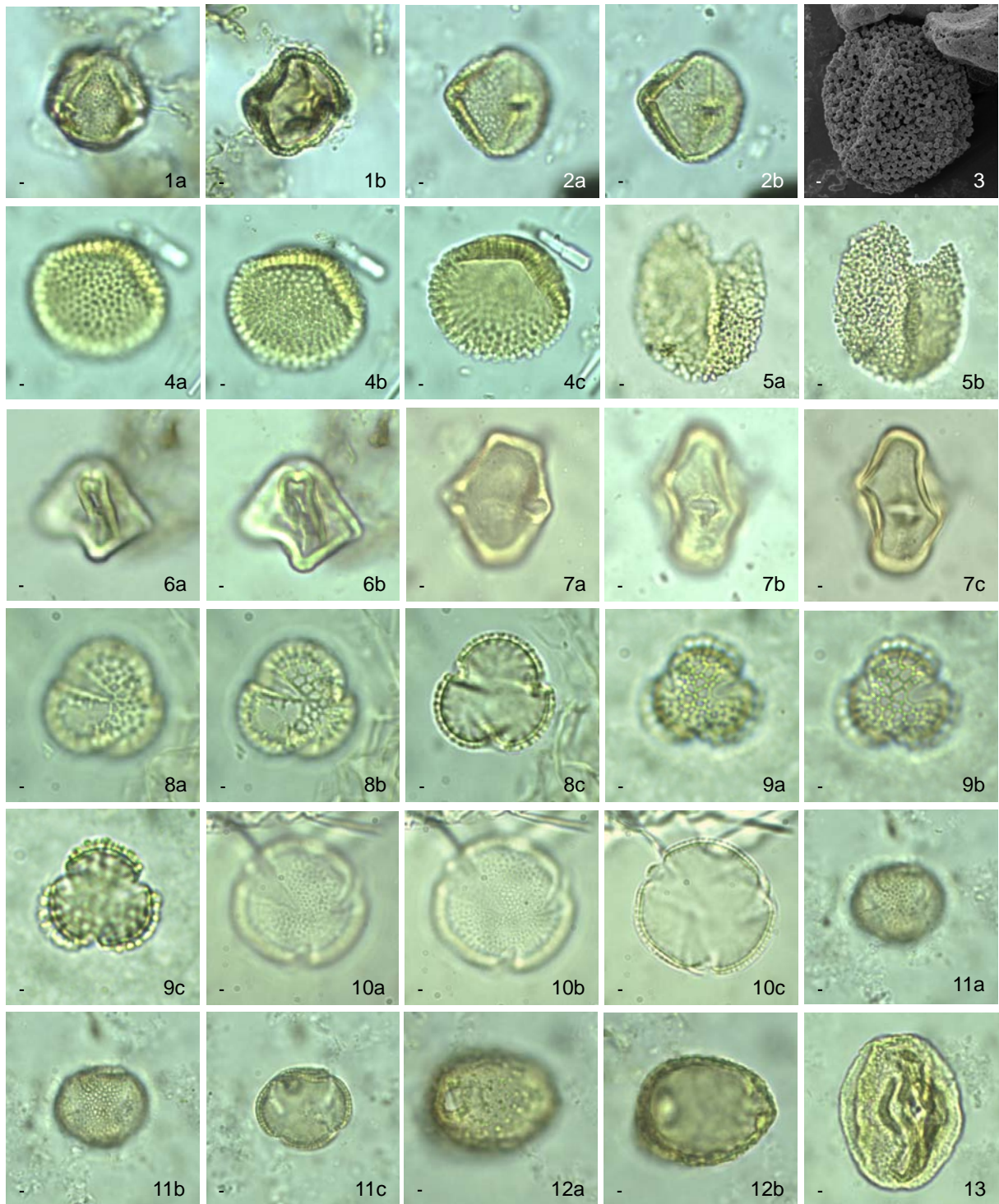


Plate 3. Photographs at TLM and SEM of some fossil and modern pollen grains (shots by J.-P. Suc).
Modern pollen grains originate from the ISEM - Montpellier Collection.

Scale bar = 10 µm.

Figs. 1a-e. *Distylium* (Hamamelidaceae) – Euzet Hill; polar view at TLM.

LO-analysis: a, reticulate ornamentation; b, apertures and optical section.

Figs. 2a-c. Menispermaceae – Euzet Hill; equatorial view aperture facing at TLM.

LO-analysis: a, reticulate ornamentation and aperture; b, focus on the base of columellae; c, optical section.

Figs. 3a-c. *Olea* (Oleaceae) – Euzet Hill; equatorial view (intercolpium) at TLM.

LO-analysis: a, reticulate ornamentation; b, focus on the base of columellae; c, optical section.

Fig. 4. *Mussaenda laxa* (Hook.f.) Hutch. ex Gamble (Rubiaceae) – ISEM Collection number: 9954 (plant specimen collected in India); polar view, optical section at TLM.

Fig. 5. *Mussaenda*-type (Rubiaceae) – Serre de cauvel 3; polar view, optical section at TLM.

Figs. 6a-d. *Peltogyne*-type (Leguminosae) – Euzet Hill; polar view at TLM.

LO-analysis: a, clavate ornamentation; b, focus on the base of clavae; c, apertures; d, optical section.

Fig. 7. *Peltogyne*-type (Leguminosae) – Euzet Hill; view with aperture at SEM.

Figs. 8a-c. *Phyllanthus simplex* Retz. = *P. virgatus* G.Forst. (Phyllanthaceae) – ISEM Collection number: 10100 (plant specimen collected in India); polar view at TLM.

LO-analysis: a, reticulate ornamentation and apertures; b, focus on the base of columellae and apertures; c, optical section.

Figs. 9a-c. *Phyllanthus* (Phyllanthaceae) – Euzet Hill; polar view at TLM.

LO-analysis: a, reticulate ornamentation and apertures; b, focus on the base of columellae and apertures; c, optical section.

Fig. 10. *Phyllanthus* (Phyllanthaceae) – Euzet Hill; view at SEM showing the reticulum and apertures.

Fig. 11. Rhizophoraceae – Montchamp; equatorial view at TLM showing the apertures.

Fig. 12. *Rhoiptelea* (Juglandaceae) – Canet 1 1470 m; polar view, optical section at TLM.

Fig. 13. *Symplocos* (Symplocaceae) – Euzet Hill; polar view showing apertures at TLM.

Fig. 14. *Cedrus* (Pinaceae) – Crossroad D716/D981; profile view at TLM.

Fig. 15. *Podocarpus* (Podocarpaceae) – Célas Tunnel 2; proximal view at TLM.

Fig. 16. *Podocarpus* (Podocarpaceae) – Crossroad D716/D981; distal view at TLM.

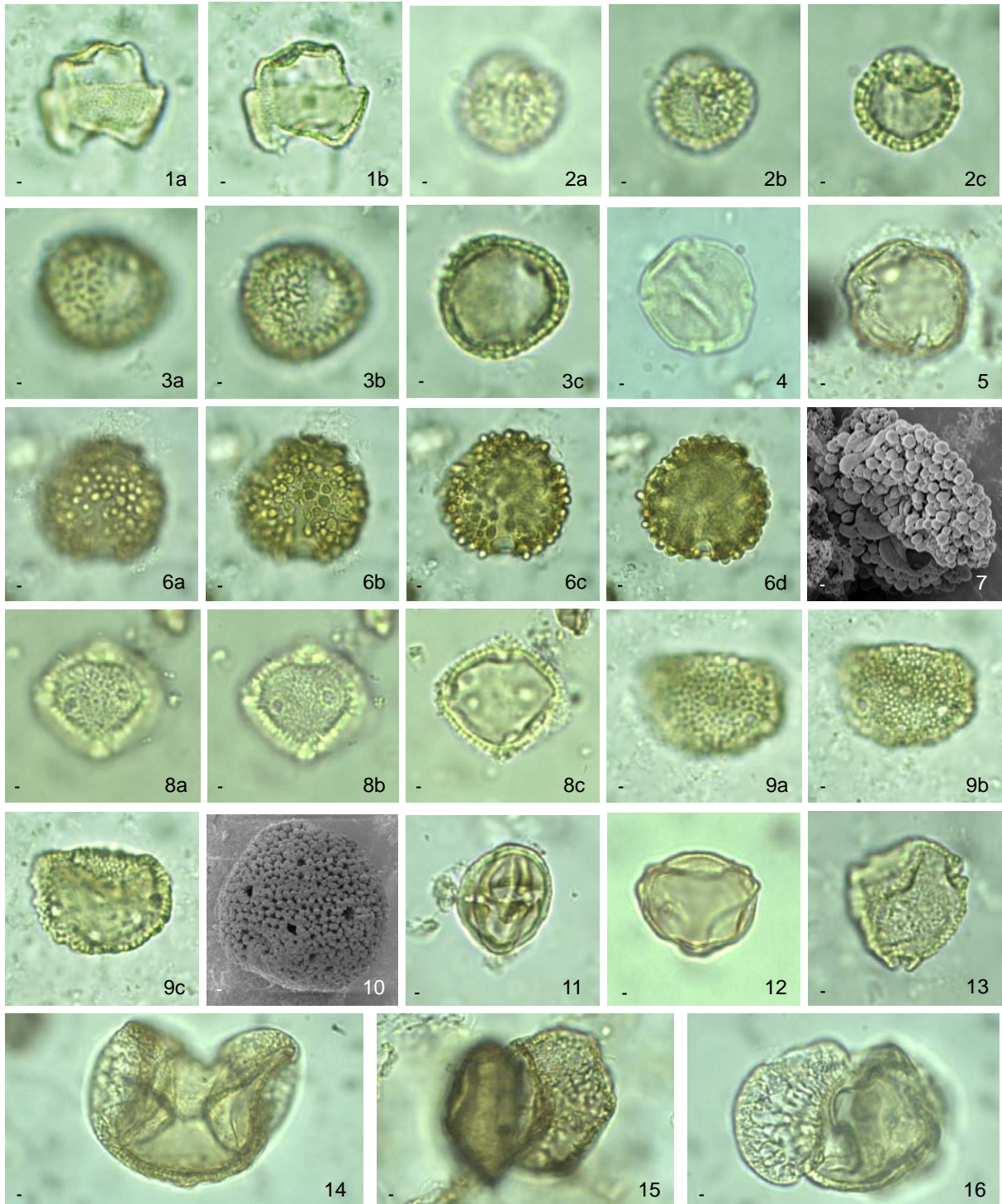


Plate 4. Photographs at TLM and FLM of some fossil dinoflagellate cysts (shots by S.-M. Popescu).

Scale bar = 10 μm .

Figs. 1a-c. *Deflandrea phosphoritica* – Gallician 9 (2530 m): a-b, TLM; c, FLM.

Figs. 2a-c. *Spiniferites* sp. – Gallician 9 (2530 m): a-b, TLM; c, FLM.

Figs. 3a-c. *Nematosphaeropsis* sp. – Crossroad D716/D981: a-b, TLM; c, FLM.

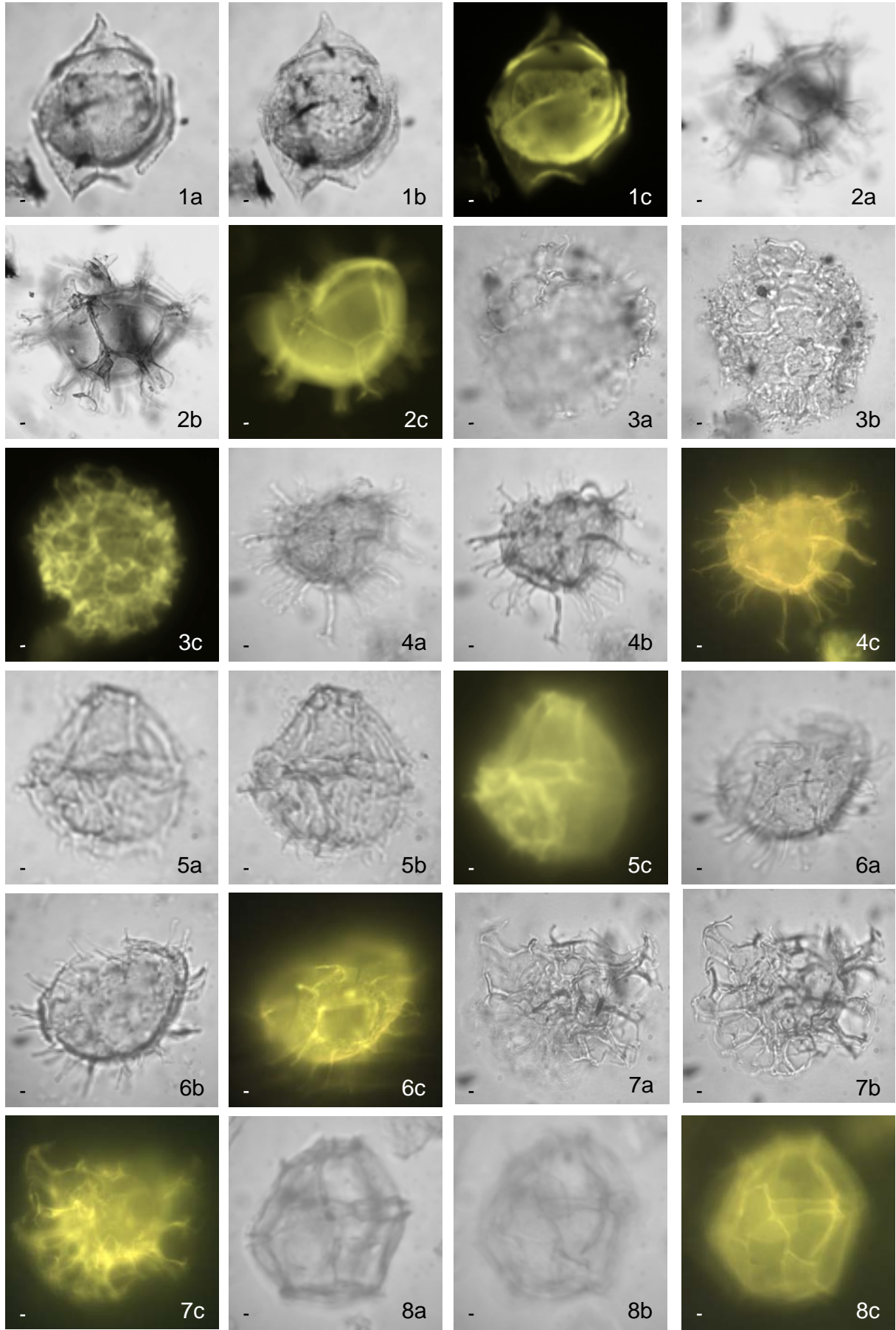
Figs. 4a-c. *Cleitosphaeridium* sp. – Serre de Cauvel (sample 2): a-b, TLM; c, FLM.

Figs. 5a-c. *Impagidinium* sp. – Serre de Cauvel (sample 2): a-b, TLM; c, FLM.

Figs. 6a-c. *Lingulopodium machaerophorum* – Serre de Cauvel (sample 2): a-b, TLM; c, FLM.

Figs. 7a-c. *Glaphyrocysta* sp. – Canet 1 (1100 m): a-b, TLM; c, FLM.

Figs. 8a-c. *Impagidinium patulum* – Canet 1 (1100 m): a-b, TLM; c, FLM.



4. Climatostratigraphy vs. palynostratigraphy.

Two obvious items imply to use pollen data as a climatostratigraphic tool (numerical variability) in contrary to a classical biostratigraphic tool (first occurrence and last occurrence datums):

- plants evolve along geological times but evolution only affects the species level during the Cenozoic period, usually unattainable through the pollen morphology;
- plants shift in latitude and altitude along geological times with respect to changes in temperature and precipitation.

As a consequence, palynostratigraphy based on occurrences of supposed species is to be considered as an old-fashioned approach and must be definitely abandoned. One of the most critical examples of such an obsolete use is provided by the use of the pseudo-species *Boelhensipollis hohli*, which has been proposed as a marker of the Oligocene series (Sittler and Schuler, 1976) and hence abundantly indeed excessively exploited (e.g.: Châteauneuf, 1980; Olivier-Pierre, 1980; Schuler, 1988; Châteauneuf and Nury, 1995; Cavagnetto, 2002; Châteauneuf et al., 2019).

The problem resulting from this deficient concept shows multiple aspects:

- quality of the published photographs is often insufficient to convince that an unique taxon corresponds to the so-called *Boelhensipollis hohli* pollen;
- Sittler and Schuler (1976) suppose that two pollen-types are included within their *Boelhensipollis hohli* that makes more inappropriate the use of a species designation;
- these authors describe the *Boelhensipollis hohli* pollen-type as heteropolar, i.e. non-joined colpi (strictly tricolporate pattern) on one side of the polar view and joined colpi (syncolporate pattern) on the other side, and they propose two possible botanical ascriptions: *Elaeagnus* (Elaeagnaceae) and *Serjania* (Sapindaceae); *Elaeagnus* modern species do not show heteropolar pollen while some *Serjania* modern species show heteropolar pollen (Muller and Leenhouts, 1976);
- in addition, it is difficult to conceive the sudden appearance of the temperate genus *Elaeagnus* at the earliest Oligocene, while it has been already recorded in Northern Canada during the Early Eocene Climatic Optimum (Salpin et al., 2019);

it is also unbelievable that *Serjania*, a tropical genus, appeared simultaneously with a significant climate cooling, while several pollen grains belonging to Sapindaceae have been recorded in the Priabonian samples (Table S3) and are present in Eocene sediments from Southwestern France (Fauquette et al., in progress).

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GEOCHEMICAL MODELLING

	Late Oligocene seawater end-member	Riverine end-member
$^{87}\text{Sr}/^{86}\text{Sr}$	0.70825	0.7077
$\delta^{34}\text{S}$ VCDT	20	11
[Sr]	15	0.1
$[\text{SO}_4^{2-}]$	2800	70

Table S4. Sulphur and Strontium isotope composition and concentrations for the late Oligocene seawater and riverine end-members (best-case scenario).