An overview of the Santonian amber-bearing deposits of the Sainte-Baume Massif, southeastern France

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Abstract – The Upper Cretaceous sedimentary succession cropping out in the Sainte-Baume Massif (Var, southeastern France) is of late Turonian to Campanian age. There, complex imbrication and rapid evolution in space and time of shallow-marine, fluvo-deltaic and lacustrine environments at the front of the North Provence Durancian uplift occur during the Santonian. Marly and/or sandy strata rich in lignite remains and amber grains are interspersed throughout the Santonian series. According to new in situ collections, the features of the amber grains, and their micro-inclusions, are similar to those found in well-known amber-bearing sites from the Bouches-du-Rhône department. This testifies of a widespread resin-producing tree forests in southeastern France at that time.

Keywords: Amber / Santonian / Cretaceous / Sainte-Baume Massif / Var / France

1 Introduction

Upper Cretaceous amber-bearing deposits of southeastern France have been reported in the late XIXth century (Collot, 1890; Vasseur, 1890, 1894). Three main sites of the Bouches-du-Rhône department – namely Martigues, Ensuès-la-Redonne and Belcodène – yield amber grains in Santonian lignite horizons. These amber grains were the object of sedimentological, palaeontological, and geochemical studies in the recent years (Guiliano et al., 2006; Onoratini et al., 2009; Saint Martin et al., 2012, 2013; 2018).

In the nearby Var department, the presence of Upper Cretaceous amber, named as “succin”, was reported by Coquand (1860, 1864) and Collot (1890) at Plan d’Aups, a village located at the foothill of the Sainte-Baume Massif. Subsequent contributions of the XXth century lack mention of amber-bearing deposits in this area (e.g. Philip, 1970 and references therein). More recently Onoratini et al. (2009) reported a single amber fragment at Plan d’Aups (La Brasque Farm) but its stratigraphic position remains unclear. Further, Saint Martin and Saint Martin (2018) described micro-inclusion in amber grains from the nearby Mazaugues area (Glacières de Pivaut).

Therefore, a start has been made on examining localities of the Sainte-Baume Massif, allowing the identification of new amber-bearing sites in the Plan d’Aups-Mazaugues area. The present contribution aims at:

– describing the Mazaugues section and precising the stratigraphic position of the amber grains;
– stressing the in situ sedimentological context and giving the main characteristics of the amber harvested;
– providing a description of the micro-inclusions contained in the amber grains;
– placing these findings in the late Cretaceous regional palaeoenvironmental context.

2 Geographical and geological settings

The Sainte-Baume Massif, in southeastern France (Fig. 1A), has become a world-class site for geologists all around the world since it is the cradles of the overthrusting faulting concept which has given rise to one of the best-known French geological controversies (e.g. Philip, 2012 and references therein). The massif is now interpreted as a 35-km long, northverging thrust sheet cut by several ENE-WSW trending normal faults of Oligocene or Miocene age (Bestani et al., 2015) (Fig. 1B). The footwall of the Sainte-Baume thrust sheet is formed by the Plan d’Aups syncline in the south and the Lare anticline in the north (Bestani et al., 2015). As noticed by those authors, the Plan d’Aups syncline is a narrow structure characterised by a 80° south-dipping overturned southern limb and a 80° south-dipping northern limb.

The core of Plan d’Aups syncline is composed of Upper Cretaceous deposits that rest on lower Cretaceous rocks which are topped by a bauxitic horizon (Philip, 1970) (Fig. 1C). This bauxitic horizon results from a low amplitude, large-scale deformation/c0 the so-called Durancian uplift (Masse and Philip, 1976)– occurring during mid-Cretaceous times (Guyonnet-Benaize et al., 2010). The Durancian uplift caused the North Provence domain to be exposed to subaerial erosion during the latest Early Cretaceous and earliest Late Cretaceous (Marchand, 2019, and references therein).

Above, the Upper Cretaceous deposits are composed of upper Turonian to Santonian transgressive marine platform carbonates evolving into a general lacustrine (“Valdo-Fuvélien” regional stages in litt.) and then continental breccias environments (“Bégudo-Rognacien” local stages in litt.) during latest Cretaceous and early Cenozoic times (Philip, 1970; Fig. 1B). The continental breccias, which occurred up to the Eocene, reflect the initial growth of the Sainte-Baume thrust during the northward propagation of the Pyrenean–Provence deformation front (Bestani et al., 2015).

Three Santonian amber-bearing sites were found in the Plan d’Aups syncline: Mazaugues (point 1 in Fig. 1B), Glacières de Pivaut (point 2 in Fig. 1B) and Plan d’Aups (point 3 in Fig. 1B).

3 Amber-bearing occurrences in the Plan d’Aups syncline

3.1 Mazaugues

The abandoned Equireuil quarry is located at 3.2 km northeast of the Mazaugues village (Fig. 1B). There, the sedimentary succession measured along the low-mural quarry face can be divided into seven lithological units, from bottom to top (Fig. 2 and Fig. 3A):

– unit 1 consists of a decametric lenticular body made of soft sandstone sediments with lamellar, branched corals, and bryozoans (Fig. 3B, D, E). A thin clayed lens containing lignite remains and amber grains has been identified at its top (WGS 84 coordinate: 43°21’43.19”N, 5°57’14.08”E);
– unit 2 comprises 4 to 5-m thick variegated clays and silty marls;
– unit 3 is characterised by a prominent 3-m thick bed (Fig. 3C), containing at its base sandy-clay sediment rich in bryozoans and finely branched and lamellar corals (Fig. 3F), grading upward into a rudist biostrome made of dense aggregate of Hippurites and large Vaccinites beaussetensis and Radiolites galloprovincialis;
– unit 4 (thickness ~12 m with a 4-m gap at its base) starts with soft coarse sandstone sediments changing upward into silty variegated clays and silty marls;
– unit 5 (thickness ~20 m) is dominated by detrital, locally coarse, prograding channels (Fig. 3G) characterised by irregular basal surfaces and contains hydraulic dunes and oblique stratifications. Lenses of variegated silty clays are interfingered with the channels;
– unit 6 exhibits a 5-m thick ledge of silty marls (Fig. 3H). The associated fauna includes Cunmolites solitary corals, scaphopods, gastropods, and bivalves of shallow-marine significance (Fig. 4). This marly ledge yields abundant amber grains (WGS 84 coordinate: 43°21'39.61"N, 5°57'23.80"E). Diverse imprints of plant cuticles were found near the top of the marly ledge (Garrouste and Gomez, personal communication);
– unit 7 starts with a limestone bed made of rudist and coral debris eroding the unit 6 marly ledge (Fig. 3H) and it disappears eastward. It is overlain by overgrown silty marls ending the section.

3.2 Glacières de Pivaut

Despite poor outcropping conditions, the Glacières de Pivaut sedimentary succession observed along the forest pathway, consists of, from bottom to top, greenish sandstones (thickness ~20 m), alternating sand and sandstone banks (~5 m), massive sandstone (~4 m) and coarse soft sandstone (~5 m) containing lignite debris and amber grains (WGS 84 coordinate: 43°21'06.2"N 5°51'15.8"E) (Fig. 5A–B). The amber grains reported by Saint Martin and Saint Martin (2018) originate from organic-rich clayed sediments outcropping directly below black levels with a brackish fauna (WGS 84 coordinate: 43°21'04.1"N 5°51'04.9"E). Precise correlations with the Mazaugues section remain unclear.

3.3 Plan d’Aups

Following Onoratini et al. (2009), we confirmed the presence of amber grains at the Brasque Farm locality, located ~1 km southwest of the Plan d’Aups village (Fig. 1B). These amber grains were collected in a drainage trench opened along a forest pathway (WGS 84 coordinate: 43°19’24.9”N 5°42’23.2”E) (Fig. 6A) and in sandstone sediments outcropping along this pathway (Fig. 6B) (WGS 84 coordinate: 43°19’17.8”N 5°42’06.0”E). Due to poor outcropping conditions, the stratigraphic position of these amber grains remains uncertain with respect to the Mazaugues section. The sediment containing the amber grains consists of organic-enriched black limestones (Fig. 6C–H) including various fossils such as solitary corals (Trochosmilia), bivalves (Cardium) and gastropods (Voluta, Neritina, Cassiope). Additional amber grains were extracted from similar sediment outcropping at the Plan d’Aups village (WGS 84 coordinate: 43°19’40.5”N 5°42’36.7”E) (Fig. 6I–J).

Fig. 2. Lithological succession of the Equireuil Quarry section (Mazaugues), main lithological units (units 1 to 7), and the two collected amber grain spot occurrences (units 1 and 6).
Fig. 3. Field photographs from the Equireuil Quarry section. A: East-West panorama of the Equireuil Quarry and location of the second amber grain spot occurrence (white arrow on the right); B: lower soft sandstone sediments (unit 1) containing lignite debris and amber grains (white arrow); C: composite bed with coral and bryozoans at the base and rudist bioconstruction at the top (unit 3); D: lamellar corals at the base of the lenticular body figured in (C); E: focus on finely branched and lamellar corals of the lenticular body; F: sandy marls with corals and lignite debris under rudist aggregate beds (unit 3); G: sandy bodies and interfingered variegated marls (unit 5); H: close-up view of the second amber grain spot occurrence (white arrow) found in sandy marls containing a shallow-marine fauna (unit 6) and eroding limestone bed (black arrow) made of coral and rudist debris (unit 7).
4 Amber features

The amber grains from the Sainte-Baume Massif occur as millimetric grains in lignite-poor, soft sandstone (Mazaugues and Plan d’Aups) or lignite-rich silty clay (Glacière de Pivaut and Plan d’Aups). The amber grains were extracted manually from sandstones or after washing clayed sediments. Petrographic thin sections were performed on amber grains to characterize their internal characteristics. Examinations with Scanning Electron Microscope (SEM) were performed using Hitachi SU3500 equipment.

When complete, the grains kept the shape of the initial resin drops. They are more or less oblong, but sometimes spherical (Fig. 7A–C) or sharp-edged (Fig. 7D–E). The grains appear in various optical aspects. They are either represented by:

- translucent grains with a predominantly pale yellow to reddish color (Fig. 7F–G);
Fig. 6. Field photographs of the Plan d’Aups area. A: a drainage trench showing amber-bearing fossiliferous levels (white arrow) near the La Brasque Farm; B: the forest pathway starting from the La Brasque farm and the outcropping conditions of the Plan d’Aups ecozone; C: black-coloured fossiliferous limestone containing solitary corals (co) and gastropods; D–H: amber grains (black and white arrows) scattered in the black-coloured fossiliferous limestones containing corals (co), bivalves (Cardium sp.: ca), gastropods (ga) such as Cassiope sp. (ga in E) and Voluta sp. (ga in H); I: limestone level (white arrow) of the Plan d’Aups ecozone outcropping at Plan d’Aups; J: close-up view of (I) showing the fossiliferous limestone bed.
Fig. 7. A: Variation in shape and appearance of the collected amber grains; B–E: views of amber grains under SEM; F–K: close-up views of amber grain thin sections under optical microscope. In details: B: section of translucent grain in the form of an elongated drop-shaped; C: part of elongated drop-shaped grain with surface cracks and peripheral partial colonization by filamentous micro-organisms; D: uniformly opaque grain; E: heterogeneous opaque grain with bubbles; F: translucent grain with orange outline; G: partially colonised translucent grain by a filamentous network (black arrow); H: opaque grain entirely colonised by a filamentous network; I–J: heterogeneous opaque grains with centripetal colonization areas by micro-organisms; K: heterogeneous opaque grain with dense bubbles.
– opaque grains of beige to brown color (Fig. 7H);
– mix the two latter features (Fig. 7I).

Some of the grains have a more complex structure corresponding to various resin flows or are marked by dense bullous inclusions reflected by internal porosity (Fig. 7J–K).

As pointed out by diverse authors, the amber appearance is determined by the presence of micro-inclusions, mainly of organic origin (e.g. Breton et al., 1999, 2013, 2018; Breton and Tostain, 2005; Schmidt and Schäfer, 2005; Schmidt et al., 2010; Girard, 2010; Speranza et al., 2010, 2015; Beimforde and Schmidt, 2011; Saint Martin et al., 2012, 2013; Girard et al., 2013a, 2013b; Saint Martin and Saint Martin, 2018). The more translucent grains often show a reddish peripheral fringe variable in thickness (20–50 µm) corresponding to partial colonization by microbial communities (Fig. 8A–F). By contrast, the opaque grains reflect intense colonization of the initial resin by various micro-inclusions (Fig. 8G–H).
Fig. 9. Upper Cretaceous sedimentary series of the Sainte-Baume Massif. (A) Mazaugues and (B) Plan d’Aups type sections (modified and completed after Philip, 1970).
The micro-inclusions show a great diversity of microorganisms. The thin red coating at the periphery of drop-shaped amber grains is characterised by the development of filamentous tufts with r terminations (Fig. 8A), corresponding to actinomyces described under type A sensu Girard (2010) and Saint Martin et al. (2012, 2013). The same grain coating is also the seat of colonization by fine whorled filaments (Fig. 8B) presumed to be actinomyces, as observed in the Santonian amber of Belcodene (Saint Martin et al., 2013).

Other micro-inclusions occur at the periphery but also in the interior of the grains. This is the case of small isolated clusters of branched filaments (Fig. 8C) or dense networks of partially spiraled filaments (Fig. 8D), both assigned to actinomyces close to the living genus Streptomyces (e.g. Saint Martin et al., 2012, 2013; Néraudeau et al., 2016, 2017). Another enigmatic micro-organism with a foliaceous form and sheathed filaments occupies the same habitus (Fig. 8E). These are referred to as Sphaerotilus-type sheathed bacteria although remaining doubts exist on this identification (see discussion in Néraudeau et al., 2016; Breton et al., 2018).

In addition, Saint Martin and Saint Martin (2018) previously reported dense network of filamentous sheathed bacteria identified as Leptotrichites resinatus in amber grains from Glacières de Pivaut. In thicker coatings, up to the center of the grain, different types of filament networks belonging to different types of actinomyces and sheathed bacteria can be closely entangled (Fig. 8F–H).

5 Discussion

5.1 Stratigraphic correlations

Previous studies (e.g. Lutaud, 1914, 1917, 1925; Philip, 1970; Babinot, 1980) provided a general lithostratigraphy of the Upper Cretaceous deposits of the Plan d’Aups syncline (Fig. 9A). Above the Durancian bauxite horizon, those authors reported four main rudist-bearing banks (named as the Caïre de Sarazin, Crau de Piourian, Grand-Jas, and Vallon des Combes members —; Fig. 9A) separated by four unnamed detrital intervals. Those detrital intervals are thereafter referred to as the Vallon de l’Épine, Bastide du Plan, Equireuil, and Mazaugues members, respectively (Fig. 9A).

At Mazaugues, the lowermost three units logged at the Equireuil Quarry correlate to the upper part of the Grand-Jas Member characterised by alternating rudistid biostromes, sandy limestones, and sandstones (Philip, 1970). The rich rudist fauna – including Vaccinites beaussetensis and Radiolites galloprovincialis – pinpoints a Santonian age (Philip, 1970).

The overlying units 4 and 5 of the Equireuil Quarry correlate to the third detrital interval as understood by Philip (1970). It is here referred to as the Equireuil Member after the name of the abandoned quarry. Its deposits – including sandstone channels and variegated silty clays – testify of the installation of a fluvio-deltaic sedimentation.
The units 6 and 7 of the Equeireil Quarry mark the return of shallow-marine conditions. Imbrication of silty marls and resedimented rudist–coral limestone conform to the sedentation of the Vallon des Combes Member observed westward (Babinot, 1980). According to Philip (1970), this member is still of Santonian age according to the occurrence of radiolitid rudists.

Note that the fourth detrital interval badly crops out at the Equeireil Quarry. Better outcropping conditions are found eastward at Mazauques and consists of whitish to yellowish sands and sandstones including black lignite argillaceous horizons (thickness ~20–25 m). We propose to refer this detrital interval as the Mazauques Member since it forms the basement of the nominative village. The member stops at the overthrusting Liassic front of the Sainte-Baume Massif (Fig. 1B and Fig. 9A).

Eastward, the Grand-Jas and Vallon des Combes members are lacking at the Glacières de Pivaut and replaced by coarse sandstones including brackish bivalves and gastropods, and miliolid-bearing sands with rudist and/or coral debris (Philip, 1970). This conformations to our observations made along the Glacières de Pivaut forest pathway (see sect. 3.2). There, amber grains were harvested from similar sandstone sediments and also in overlying silty clays and black limestones rich in bivalves (Corbula and Melania) and gastropods (Viviparus and Theodoxus) typical of the “Valdo-Fuvélien” regional stage (Philip, 1965a, 1965b).

In the vicinity of Plan d’Aups, at the Brasque Farm locality, the Caïre de Sarrazin Member is overlain by a thick Santonian rudist bank interfingerling with miliolid-bearing calcisiltites and lignitic clays (Philip, 1970; Babinot, 1980) (Fig. 9B). According to Philip (1970), this rudist bank is stratigraphically equivalent to the Vallon de l’Épée, Crau de Pliourian and Bastide du Plan members but their correlation with Mazauques remain unclear. These deposits are overlain by the “zone of Plan d’Aups” (Répelin, 1906; Duboul, 1947; Philip, 1964, 1970; Fabre-Taxy and Philip, 1964, 1966). The “zone of Plan d’Aups” corresponds to a transition of shallow-marine to brackish sedimentation including coelenterate, rudist, oyster and gastropod bioherms at its base. Our amber grains from Plan d’Aups and the Brasque Farm originate from those facies. A Santonian age is assigned to the “Zone du Plan d’Aups” by the record of the rudist species Praeradiolites coquandi, and Apricardia toucasi (see Philip, 1970). Above, the succession consists of pisolithic and/or lignitic clays and marls which mark the onset of continental conditions (Fabre-Taxy and Philip, 1964, 1966; Philip, 1970; Babinot, 1980). The latter being still of Santonian age according to magnetostratigraphy (i.e. inferred age of the Valdonian stage after Westphal and Durand, 1990).

5.2 Palaeoenvironmental significance

The Upper Cretaceous deposits of the Sainte-Baume Massif are characterised by a mixture of shallow-marine (rudist-dominant) and brackish (gastropod-dominant) deposits (e.g. Philip, 1970, 1972, 1974). Such configuration has been explained by the complex imbrication and rapid evolution in space and time of shallow-marine, lagoonal and lacustrine environments at the front of the North Provence Durianian uplift (Fig. 10). In the Sainte-Baume Massif, Philip (1970) showed that the advance of a terrigenous front contributes to the gradual migration towards the west of the Coniacian shallow-marine carbonate platform until its emergence at the end of Santonian and the establishment of the lagoon–brackish conditions (Fig. 9A–B and Fig. 10). The lagoon–brackish conditions are illustrated by the deposition of the Plan d’Aups ecozone (Philip, 1970). In those deposits, the carbonate limestones persisted in the form of kilometre-scale lenses either dominated by rudist and/or corals interfingered with sandstone and silty marl intervals of brackish sedimentation. There, the predominance of neritid gastropods (Neritina) over cassipriotid (Cassiope) and volutid ones (Voluta) conform to strong variations in salinity and periodical influence of fresh water. Indeed, the neritid gastropods usually lives in warm fresh to mesohaline waters (Esu and Girotti, 2010), while the two other genera used to inhabit intertidal and shallower infralittoral zones, with bathymetries up to 50 m (Mennessier, 1984). Those changes in salinity are also confirmed by both the foraminiferal and ostracodal associations of the Plan d’Aups ecozone (Babinot and Tronchetti, 1983).

The amber grains were collected in both lagoon and brackish environments in association with lignite remains. The periodical influence of freshwater supplies may have yielded plant debris, and hardened resin nodules to the surrounding shallow water environments. Such configuration is similarly found in the Santonian amber-bearing deposits of Piolenc (Vaucluse). It has been often stated that the tree areas producing the resin may be quite far from the deposition area. However, the co-occurrence of abundant amber grains and plant cuticles at Mazauques likely pinpoints close vicinity with the amber-producing forests. As further evidence, diverse authors reported the presence of Frenelopsis imprints in the Santonian deposits of the Sainte-Baume Massif (Carpentier, 1937; Depape, 1959; Samuel and Gaillard, 1984). This Cheirolepidiaceae is often related to the production of amber resins, as it has been argued for the Santonian amber grains of Belcodène (Saint Martin et al., 2013). However, apart the case of exceptional inclusion of identifiable plant debris in amber (Néraudeau et al., 2020), the botanical origin of amber still remains widely debated for each amber deposit, even if the chemical composition of amber grains can give some indications (see Seyfullah et al., 2018 and the discussion in Valentin et al., 2020). At Piolenc, various leaf cuticle compressions of Corystospermales, Cycadales, Bennettitales, Gymnosperms and mostly Angiosperms are recorded, and testify of a warm and humid, tropical climate, including a dry season (Gomez et al., 2003).

The Santonian amber-bearing sites of southeastern France mostly contain small automorphic drop-shaped amber grains (Saint Martin et al., 2012, 2013; 2021; Saint Martin and Saint Martin, 2018). Such grains are also observed in Alabama (Knight et al., 2010) and Siberia (Rasnitsyn et al., 2016). According to Saint Martin et al. (2013) this dominance likely reflects a process of grain selection from the place of resin production to the place of deposition, leading to an underestimation of larger flows along the trunks. Micro-inclusions would result of events taking place in the aerial parts of the resin producing plants. The nature of the micro-inclusions indicates early colonization while the resin is still fluid, involving resinicolous micro-organisms (Girard, 2010;
Saint Martin et al., 2012, 2013; Breton et al., 2014, 2018). As discussed by those authors, the resin production in the aerial parts may result from environmental factors. The forest fires or the action of biting insects causing a reaction in the plant have been invoked. Another rarely considered cause could be the activity of pathogenic organisms, such as ascomycete fungi, which can lead to occasional but repeated exudations of resin (Smith et al., 1988; Zlatković et al., 2017). The features of the amber harvested can thus inform on the forest ecosystem, including its negative dimension through the production of resin and its subsequent deposition in the surrounding environments.

6 Conclusions

The collection of amber grains in the Sainte-Baume Massif gives new evidence of a widespread resin-producing environment in southeastern France during the Santonian, and the permanent activity of a microscopic resinicolous community. Our findings extend the record of Santonian amber-bearing sediments to the east of the Sainte-Baume Massif. It is hypothesised that the amber grains may result from Cheilolepidiaceae forests that have proliferated close to the Duriancian uplift front. The grains were subsequently deposited into the surrounding complex shallow-marine and fluviodeltaic system developed in the Sainte-Baume Massif. There is hardly any doubt that new amber spot occurrences can be found there and will better constrain the regional palaeogeography in a near future. Additionally, further analyses of the chemical composition of amber will help identifying the nature of resin-producing plants.

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