Original Paper

Palaeoenvironmental reconstruction of the basal Cretaceous vertebrate bearing beds in the Northern part of the Aquitaine Basin (SW France): sedimentological and geochemical evidence

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Abstract The Purbeckian facies of the northern margin of the Aquitaine Basin is exposed in the Cherves-de-Cognac section (SW France), considered as basal Cretaceous in age. Two lithological units have been identified. The basal unit (U1) is composed of an alternation of gypsum and finely bedded black dolomitic marlstone, occasionally stromatolitic in nature. It represents mostly hypersaline, dolomitic tidal flat, lagoonal, and sabkha-type environments. The upper unit (U2) consists of variably fossiliferous limestone-marl alternations that contain a diverse fauna and flora. In the upper part of this unit, a 4-m-thick level has yielded a rich vertebrate fauna. The preservational quality of the vertebrate fossils varies within the section. On the basis of faunal, floral, sedimentological and mineralogical information the vertebrate remains accumulated in brackish water environments in which the influence of freshwater has progressively increased towards the top of the section. The close association of environments representing varying degrees of marine and continental influence suggest an estuarine setting.

Keywords Lower Cretaceous · SW France · Facies · Palaeoenvironment · Vertebrates · Biota

Introduction

The Cherves-de-Cognac section with a thickness of about 30 m is located about 8 km NW of Cognac in the northern margin of the Aquitaine basin (SW France; Fig. 1). The deposits consist of gypsum-laminites alternations in the lower part of the section (U1), and dolomitic marly-limestone alternations in the upper part (U2). As identified via a borehole, Cherves-de-Cognac section is immediately overlying marine limestone dated as Tithonian.
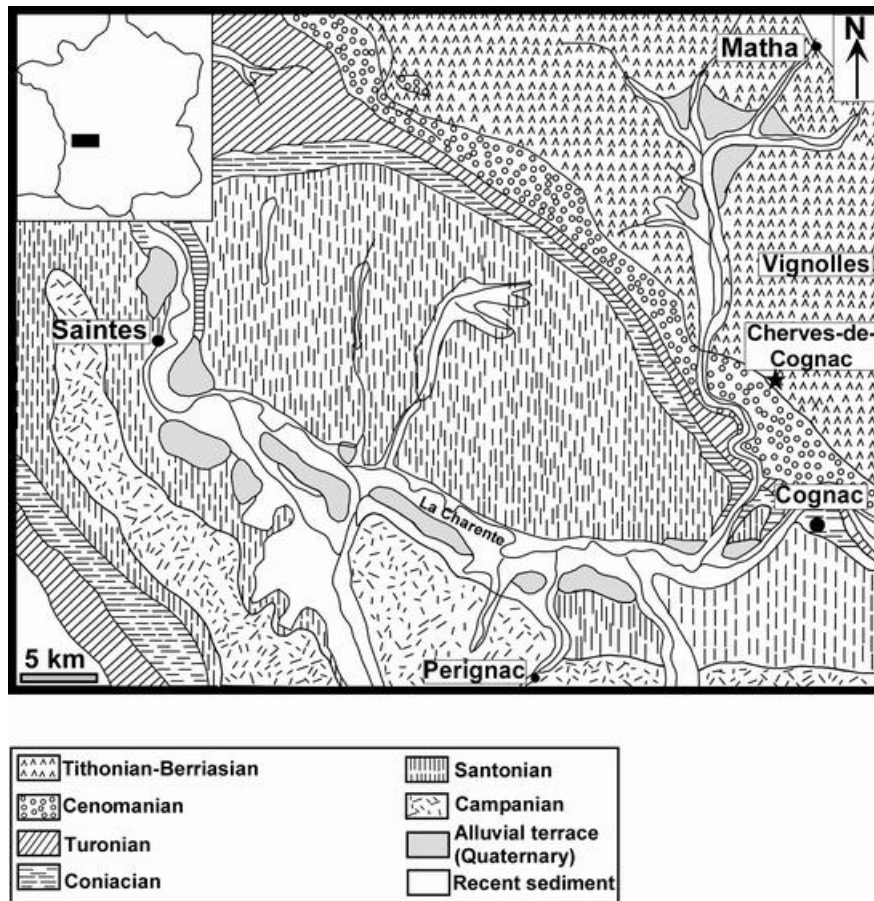
Fig. 1 Locality and geological map of the study area

Regional dip is lower than 2°, which facilitates facies mapping. Sedimentology in combination with palaeontological studies provides additional information in order to understand palaeoenvironmental and palaeoecological evolution of the faunal habitat.

Cherves-de-Cognac section is considered to be an important geological section in regards to the understanding of the palaeoenvironmental evolution of the Lower Cretaceous interval in the northern part of the Aquitaine Basin. This section is the first Lower Cretaceous outcrop described in this area (Colin et al. 2004). For this reason, an integrated sedimentological and palaeontological analysis was carried out across the section (i.e. 30 m thick) in order to produce a geological model for the palaeoenvironmental reconstruction of this area.

The low-diversity macroinvertebrate fauna, which consists of bivalves and gastropods, is summarized in this study. The biostratigraphy has been established based on ostracode, charophyte and dinoflagellate assemblages. The section, until now considered as uppermost Jurassic in age (Coquand 1858a, 1858b; Vigneaux 1975; Gabilly et al. 1978; Moreau 1980; Bourgueil et al. 1986; Ziegler 1988), yielded rich and diverse associations of brackish to fresh-water ostracodes, charophytes and dinoflagellates, allowing for them to be dated as Berriasian (Colin et al. 2004)

and to correlate the succession with the lower part of the Middle Purbeck of southern England. These levels also yielded a diverse vertebrate fauna composed of tetrapod and fish remains. Taphonomic and palaeoecological aspects of the vertebrate assemblages are described here for the first time.

Whereas most studies of Cherves-de-Cognac section have focused on a description of the vertebrate content (Buffetaut et al. 1989; Hervat and Hervat 1993; Vignaud et al. 1994; Le Loeuff et al.1996), little attention has been paid to sedimentological, taphonomic and palaeoecological aspects of the fossil occurrences.

The study is based mainly on sedimentological field observations taken on the microfacies analysis of thin-sections and on micropalaeontological (ostracodes and charophytes) and palynological analysis during several field seasons. The aim of the present study is to (1) document the relationship between sedimentary facies and palaeoenvironment, (2) integrate the sedimentary and palaeontological data in order to arrive at a comprehensive depositional model and (3) discuss the palaeoecology and taphonomic fate of the fossil assemblages.

Stratigraphic framework and geological setting

This important fossiliferous succession, which probably is a condensed sequence, has undergone several revisions (Buffetaut et al. 1989; Hervat and Hervat 1993; Vignaud et al. 1994; Le Loeuff et al.1996) which include palaeontological data. A micropalaeontological and palynological analysis of the section, until now considered as uppermost Jurassic in age, has provided rich and diversified associations of brackish and fresh-water ostracodes, charophytes and dinoflagellates, allowing for them to be dated as basal Cretaceous.

In the lower unit (U1; Fig. 2), grey shales interbedded with gypsum are characterized by monospecific assemblages of the ostracode *Fabanella boloniensis* (Jones, 1882; Fig. 3/7). The middle part of this unit yielded an assemblage represented by *Paranotacythere* (*Unicosta*) cf. *rimosa* (Martin, 1940), *Asciocythere* sp. (Fig. 3/8) and *Macrodentina* (*Dictyocythere*) ex gr. *mediostricta* (Sylvester-Bradley, 1941), clearly indicating a Berriasian age (Malz 1958; Donze 1964; Bassiouni 1974; Colin et al. 1984; Colin and Oertli 1985).
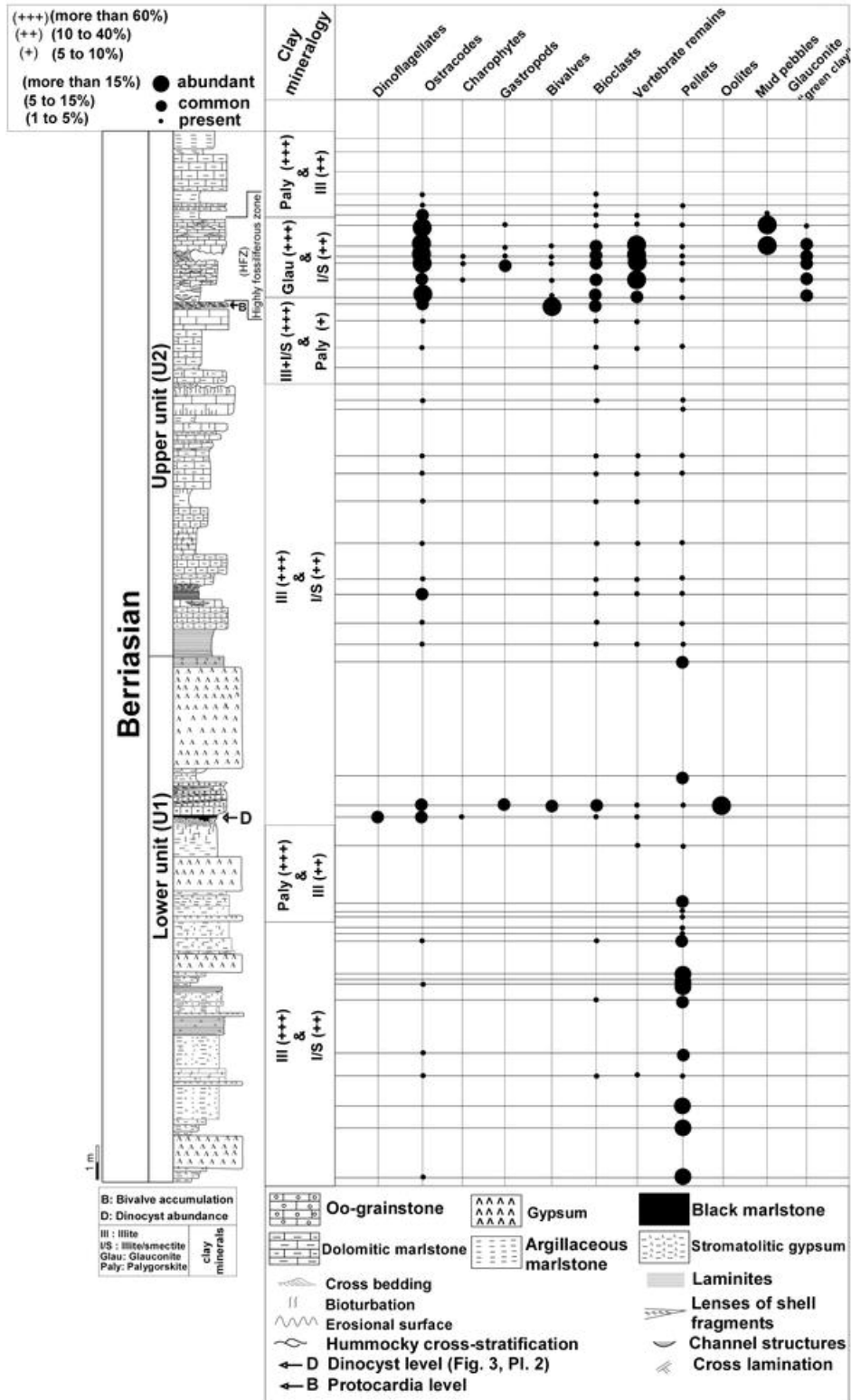
Fig. 2 Lithostratigraphy, clay mineralogy and microfacies of the Cherves-de-Cognac section
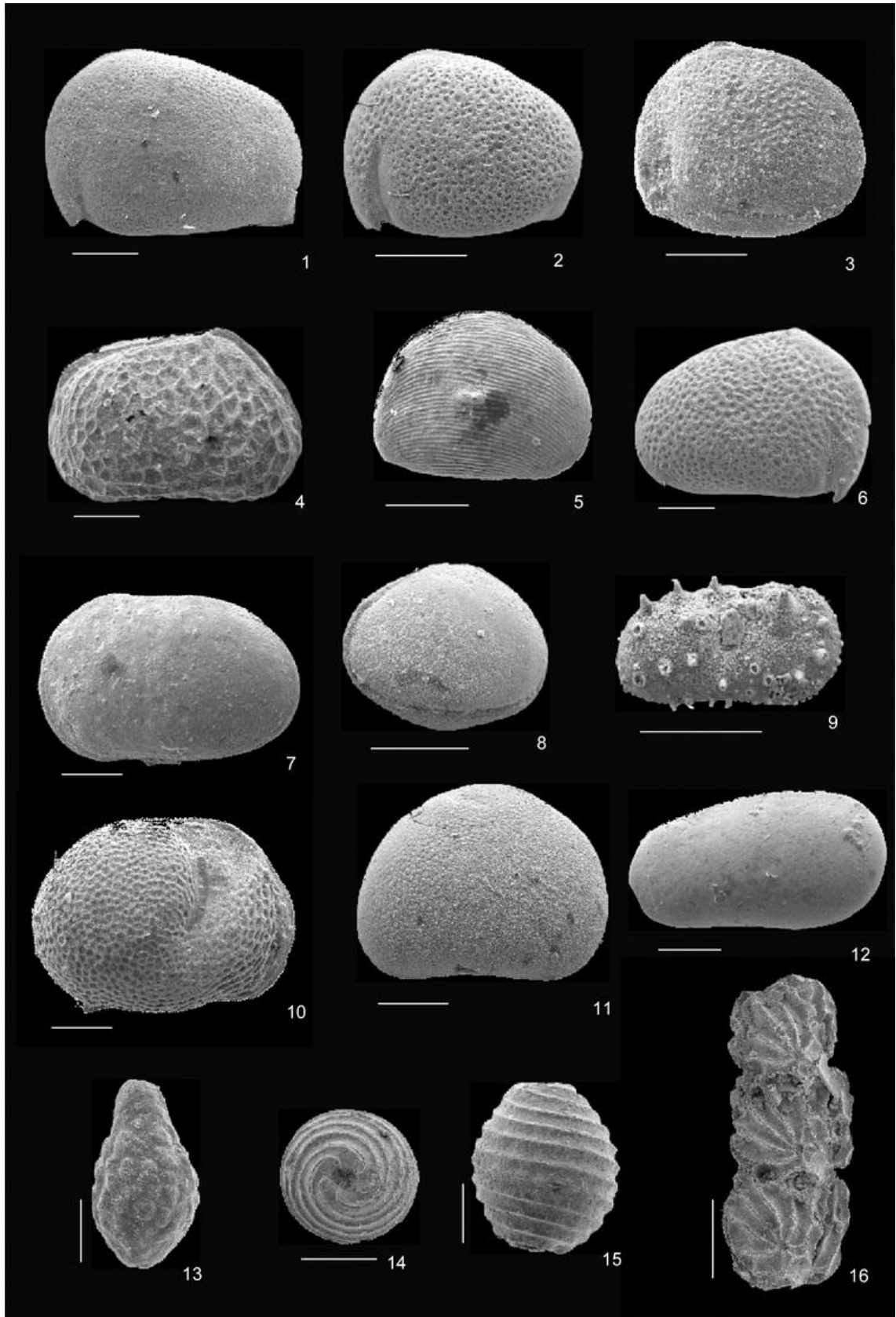
Fig. 3 Ostracodes and charophytes. The scale bar (250 μm) in Fig. 1 applies to all the photographs: *1 Cypridea* cf. *sagena* Anderson 1971, carapace, left lateral view; *2 Cypridea* cf. *swanagensis swanagensis* Anderson 1971, carapace, left lateral view; *3 Cypridea* sp., carapace, left lateral view; *4 Macrodentina* (*Dictyocythere*) ex gr. *mediostricta* (Sylvester-Bradley), 1941, carapace, right view; *5 Cetacella armata*

Martin, 1958, carapace, right view; *6 Cypridea* sp., right valve; *7 Fabanella boloniensis* (Jones, 1882), carapace, left view; *8 Asciocythere* sp., carapace, right view; *9 Rhinocypris jurassica* (Martin, 1940), carapace, right view; *10 Theriosynoecum forbesii* (Jones, 1885), carapace right view; *11 Mantelliana* sp., right valve; *12 Darwinula oblonga* (Roemer, 1839), left valve; *13 Nodosoclavator bradleyi* (Harris, 1939) Grambast, 1969; *14*, *15* "*Porochara*" *kimmeridgiensis* ex gr. *douzensis* (Feist and Grambast-Fessard, 1984) Schudack 1986a; *14* apical view; *15* lateral view; *16 Clavator grovesii* var. *grovesii* (Harris, 1939) Martín-Closas 1966, fertile phyloid with 3 utricules

Palynomorphs are poorly preserved, except at one level where they are abundant. Most abundant are gymnosperm pollen followed by dinoflagellate cysts and chitinous foraminiferal linings. Among the dinoflagellate cysts, representatives of the genus *Systematophora* are most common. Other relative common forms include *Circulodinium*, *Canningia* and *Hystrichodinium*. Smooth cysts, tentatively assigned to *Batiacasphaera*, are regularly recorded. The following forms are considered to be of stratigraphic significance: *Amphorula metaelliptica* (Dodekova) Monteil 1990 (Fig. 4/1–3), *Systematophora* sp. A Monteil, 1993 (Fig. 4/4–8), *Systematophora* sp. I Davey, 1982, *Systemaophora palmula* Davey, 1982 (Fig. 4/9–10), and *Dichadogonyaulax bensonii* Monteil 1992. Of these taxa *Systematophora* sp. A has been described by Monteil (1993) from the Late Berriasian, whilst *Systematophora palmula* is known from the Ryazanian and the Valanginian of the Boreal Realm (Davey 1982). *Dichadogonyaulax bensonii* ranges throughout most of the Berriasian and into the Early Valanginian (Monteil 1992). *Amphorula metaelliptica* seems to represent the most significant stratigraphic marker. According to Monteil (1990), the range of this species covers most of the Berriasian. However, it shows significant morphological changes within its range. The form recognised shows the typical morphology of Late Berriasian representatives, i.e. semicircular and denticulate margins of the septae (morphotype d). Other taxa, which are known to appear at the base or within the Berriasian such as *Biorbifera johnewingii* or the *Spiniferites/Achomosphaera* group, have not been found in the present material. Based on the composition of the dinoflagellate cyst assemblage, the section can be dated as Berriasian, and possibly attributed to the Late Berriasian *boisseri* ammonite zone.
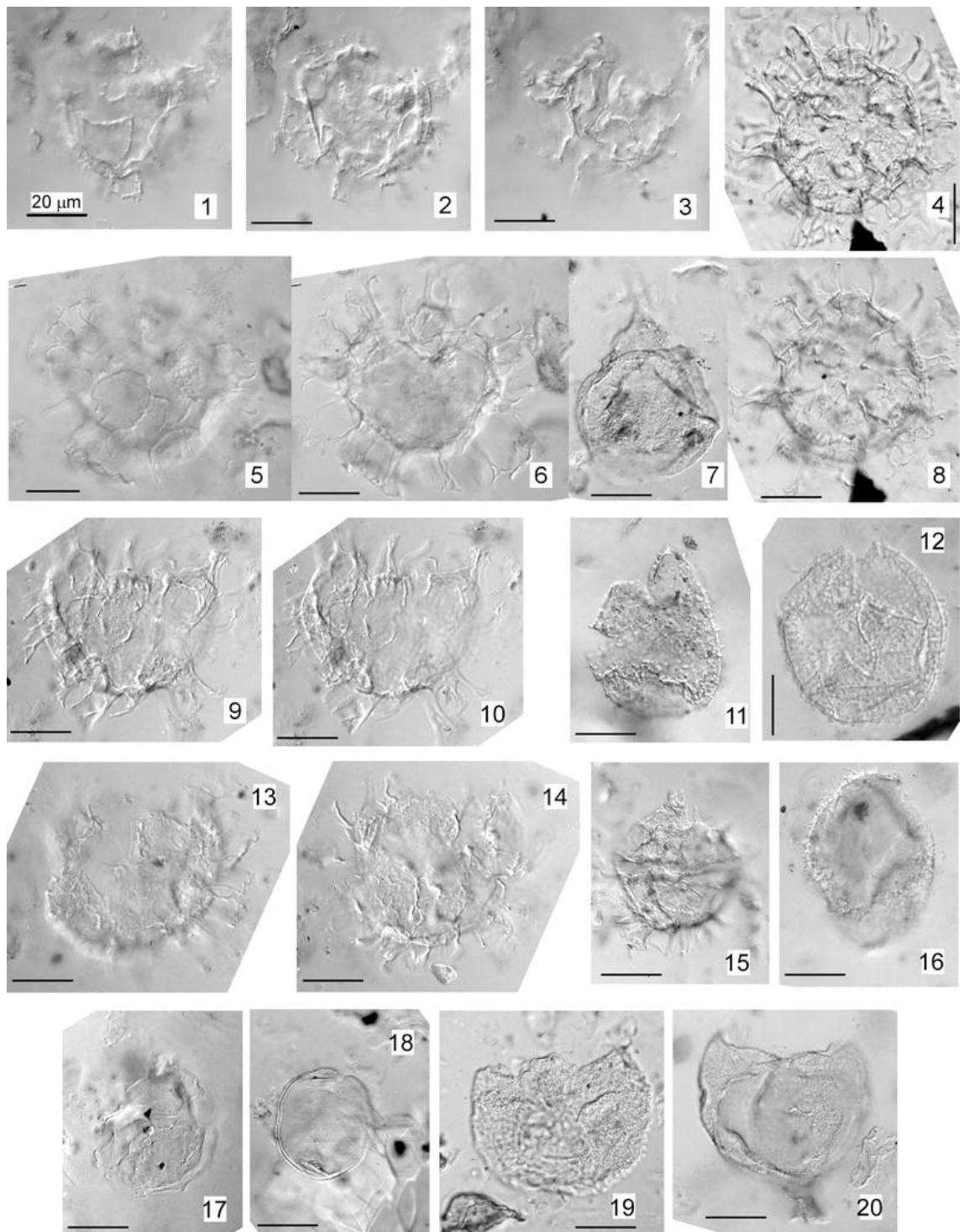
Fig. 4 (dinoflagellates). The scale bar (20 μm) in Fig. 1 applies to all the photographs. *1–3 Amphorula metaelliptica* (Dodekova) Monteil 1990; *4, 8 Systematophora* cf. sp. A Monteil, 1993; *5–6 Systematophora* cf. *areolata* Klement 1960; *7 Pareodinia ceratophora* Deflandre, 1947; *9–10 S*ystematophora palmula Davey 1982; *11 Aprobolocysta varigranosa* Duxbury, 1977; *12 Chamydophorella* sp.; *13–14 Systematophora* sp. A Monteil 1993; 15: *Hystrichodinium* sp.; *16 Trichodinium ciliatum* (Gocht) Eisenack and Klement, 1964; *17 Geiselodinium* sp.; *18 Batiacasphaera* sp.; *19 Circulodinium* sp.; *20 Circulodinium compta* (Davey) Helby 1987

The upper unit (U2) has provided rich and diverse associations of ostracodes characterized by *Cypridea* spp. (Fig. 3/1–3–6), *Theriosynoecum forbesii* (Jones, 1885; Fig. 3/10), *Theriosynoecum verrucosa* (Jones, 1885), *Rhinocypris jurassica* (Martin, 1940; Fig. 3/9), *Cetacella armata* Martin, 1958 (Fig. 3/5), *Aliceluna leguminella* (Forbes, 1885), *Darwinula oblonga* (Roemer, 1839) (Fig. 3/9), *Damonella ellipsoidea* (Wolburg, 1962), *Mantelliana* sp. (Fig. 3/11) and *Macrodentina* (*D*.) ex. gr. *mediostricta* (Fig. 3/4).

Of the *Cypridea* species, *Cypridea* cf. *sagena* Anderson, 1971 (Fig. 3/1), and *Cypridea* cf. *swanagensis swanagensis* Anderson 1971 (Fig. 3/2) are limited to the lower part of the Middle Purbeck until the so-called Cinder Beds, indicating the *Cypridea granulosa* Zone (Horne, 1995). According to the work of Mojon (2002), this interval might be correlated with the uppermost part of the Lower Berriasian (Couches Nymphéennes) and the basal part of the Middle Berriasian (Pierre-Chatel Formation *pro parte*) of the French and Swiss Jura. The presence in Cherves of *Macrodentina* (*D*.) ex. gr. *mediostricta* is an argument to propose an equivalency with the lower part of the Pierre-Chatel Formation. *Cetacella armata,* a species which was considered until now to be limited to the Kimmeridgian-Tithonian (Schudack 1989) is well represented. The rest of the ostracodes show an important affinity with the microfauna of the Purbeck Limestone Group (PLG) in the south of England (Anderson and Bazley 1971; Anderson 1985; Horne 1995, 2002).

This ostracode assemblage is associated with numerous charophytes represented by "*Porochara*" *kimmeridgiensis* gr. *douzensis* (Feist and Grambast-Fessard, 1984) Schudack, 1986 (Fig. 314–15), "*Mesochara*" *harrisi* (Mädler, 1955) Shaïkin, 1967, *Nodosoclavator bradleyi* (Harris, 1939) Grambast, 1969 (Fig. 3/13) and *Clavator grovesii* var. *grovesii* (Harris, 1939) Martín-Closas, 1966 (Fig. 3/16). A Berriasian age is confirmed by *Clavator grovesii* var. *grovesii*. According to Martín-Closas and Schudack (1996) and Feist et al. (1998), this species occurs in three charophyte biozones, i.e. *maillardii*, *incrassatus* and *nurrensis*. These biozones comprise all of the Berriasian stage according to correlation with ammonite zones (Détraz and Mojon 1989). These new biostratigraphic results entail major palaeogeographical consequences, which will be discussed below.

Materials and methods

Precise data on lithofacies, microfacies, thickness, sedimentary structures, and fossil assemblages have been recovered from the Cherves-de-Cognac section. Eighty (80) samples (see Fig. 2) were taken throughout the section for micropalaeontological investigations. The taphonomic

characteristics were studied in the field and in the laboratory. The material studied has been deposited in the collections of the University of Poitiers (France).

Clay mineral analysis was carried out at the University of Poitiers. The clay fractions (<2 μm) were obtained by centrifugation after destruction of organic matter with diluted H_2O_2. Treatment of the specimens included Ca-saturation ($CaCl_2$-N), drying and weighing. X-ray diffraction (XRD) patterns of samples were performed using a Siemens diffractometre with Ni-filtered Cu-Kα radiation. The diffractograms were recorded numerically by a DACO-MP recorder piloted by a microcomputer using the Diffrac AT software (SOCABIM, France). XRD diagrams from randomly-oriented powders and oriented preparations were recorded for 0–2 and 2–50 μm fractions (3–65° 2θ, step 0.025° 2θ Cu Kα). A semi-quantitative estimation of the relative proportions of different clay species present in the samples was performed using the intensity of their representative d(001) peaks.

Microchemical analyses of the green pellets were performed using a scanning electron microscope (SEM) JEOL 5600 LV, equipped with an Oxford energy dispersive analysis-system (EDS). The amounts of major elements from Na to Fe were measured using silicate standards. Analytical conditions were 15 kV, and the probe current was 6.10–10 A.

Results

Lithofacies, sedimentary structures and depositional environments

Precise data on lithofacies, microfacies (Fig. 5), thickness, sedimentary structures and fossil assemblages (Fig. 2) were obtained from the Cherves-de-Cognac section. In the mixed lithofacies succession, the geometry and thickness of the lithological units vary within the section. The gypsum-clay-marlstone alternations observed in the lower unit of the section (U1) contain a finely laminated mudstone interbedded with stromatolitic gypsum and bedded gypsum.
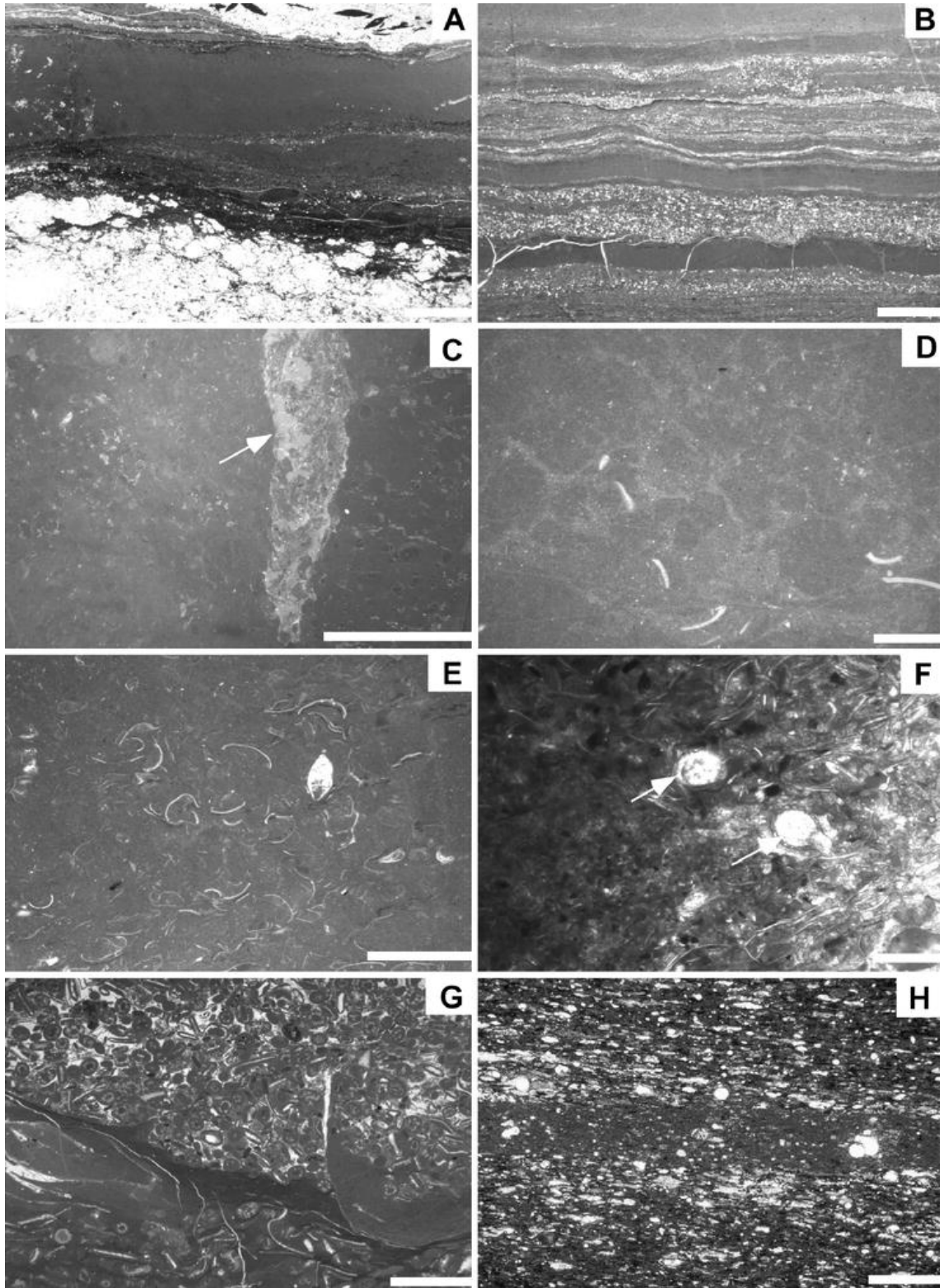
Fig. 5 Microfacies of the Berriasian Cherves-de-Cognac section. **A** Stromatolitic gypsum (lithofacies 1). *Scale bar* 0.5 mm, **B** laminated dolomitic gypsiferous marlstone. Note alternations of grey clayey peloidal marlstone and gypsum, laminated at a millimetre-scale (lithofacies 3). *Scale bar* 1 mm. **C** and **D** Dolomitic clay bioturbated layers. Note the rare fauna mainly consists of shells of ostracodes (lithofacies 4). *Scale bar* 1 mm. **E** Wackestone to packstone with numerous ostracodes (lithofacies 5). *Scale bar* 1 mm. **F** Packstone with scattered angular quartz grains and a microfauna of ostracodes and charophytes (*arrowed*; lithofacies

6). *Scale bar* 1 mm. **G** Oograinstone and lenses of shell fragments (ostracodes, bivalves, and gastropods; lithofacies 7). *Scale bar* 2 mm. **H** Finely laminated black marl. *Thin dark laminae* are mainly composed of clay mixed with organic substances. In the *lighter laminae*, ostracodes, echinid spines and phosphatic fish remains (lithofacies 8). *Scale bar* 0.5 mm

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Within the marl-limestone alternations observed in the upper unit (U2), the calcareous beds are commonly composed of mudstone, packstone, and occasionally grainstone, showing reactivation surfaces and concentrations of skeletal elements in the uppermost part of this unit.

Macro- and microfacies analysis (Fig. 5) of the section revealed eight lithofacies types including: stromatolitic gypsum (Fig. 5A); bedded gypsum; laminated dolomitic, gypsiferous marlstone (laminites; Fig. 5B); indurated dolomitic clay (Fig. 5C, D); wackestone–packstone (Fig. 5E); skeletal limestone (Fig. 5F); ooid grainstone (Fig. 5G) and black laminated marlstone (Fig. 5H).

Lithofacies 1

This facies consists of stromatolitic gypsum with no sign of desiccation cracks and erosional scours (Figs. 5A and 6A, B). Centimetre to millimetre-scale cryptomicrobial laminations are observed. This type of evaporite is interpreted as subaqueous because it shallows into intertidal cryptalgal laminite. The characteristics of this facies indicate ephemeral coastal salinas and gypsum (sabkha-like) mud flats.
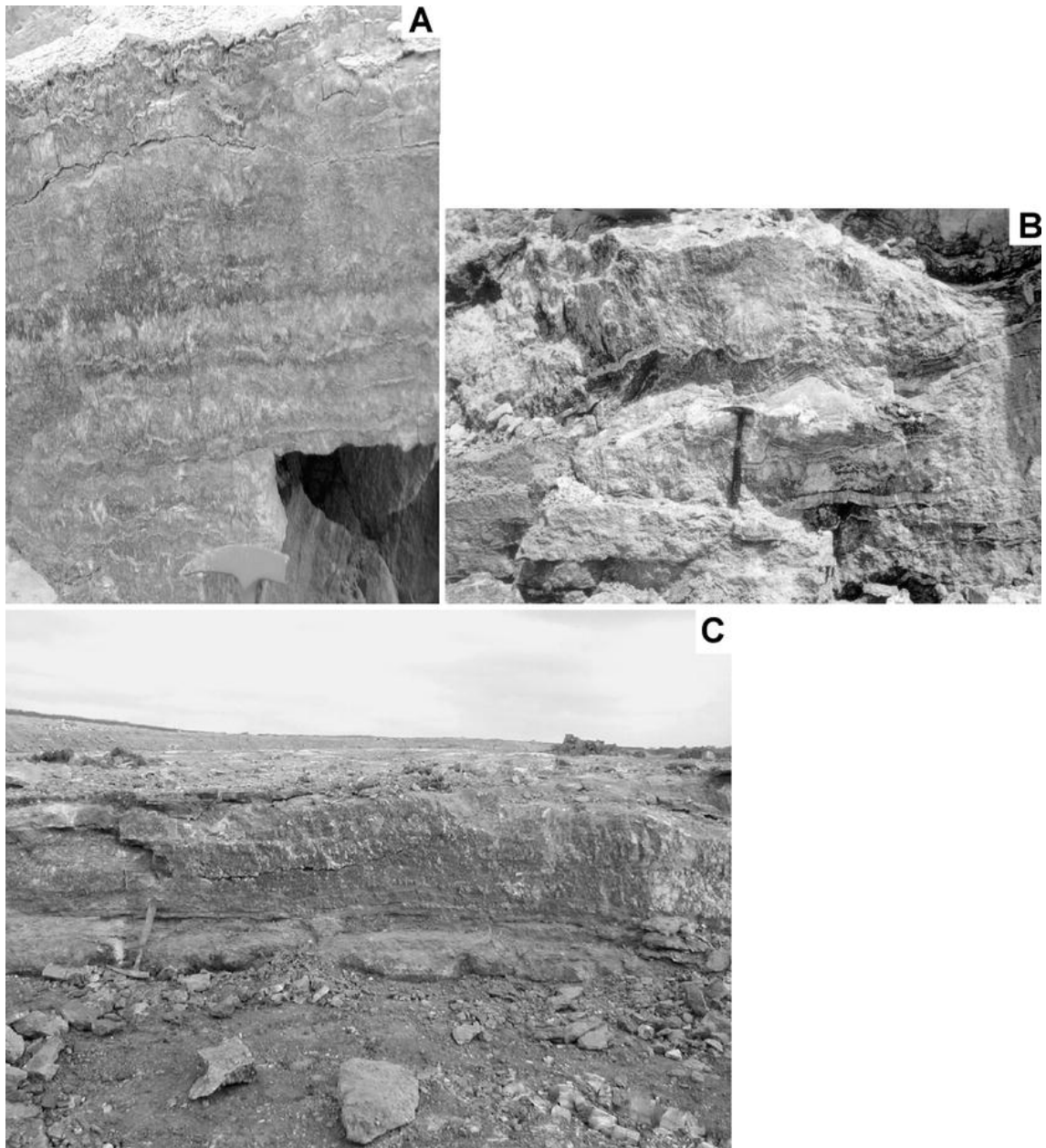
Fig. 6 Characteristic lithofacies of the lower part (*UI*) of the Cherves-de-Cognac section: **A** stromatolitic gypsum (lithofacies 1), **B** Enterolithic and nodular structures (lithofacies 1), **C** Bedded gypsum (lithofacies 2)

Lithofacies 2

The lithofacies is represented by decimetre-scale bedded gypsum with crystals randomly oriented within a marly gypsum matrix (Fig. 6C). Occasionally, this facies passes laterally (decimetre scale) into stromatolitic gypsum. Sulphate nodules, isolated or coalescent, chicken-wire structures, cryptomicrobial lamination, scattered peloids, ripples and wood debris characterise this lithofacies.

The most likely environment is a shallow water (a few metres deep) inner platform-lagoon or salina with saline brines and frequent fluctuations of the pycnocline.

Lithofacies 3

Lithofacies 3 consists of dolomitic gypsiferous marlstone (laminites) consisting of alternations of grey clayey peloidal marlstone (Fig. 7A) and gypsum, laminated at a millimetre-scale. Occasionally, lenticular and diffuse bedding is observed, which is often associated with lenticular channel fills. The faunal content is poor, represented by fish teeth. These features suggest a shallow inner platform-lagoon environment subject to tidal influence.
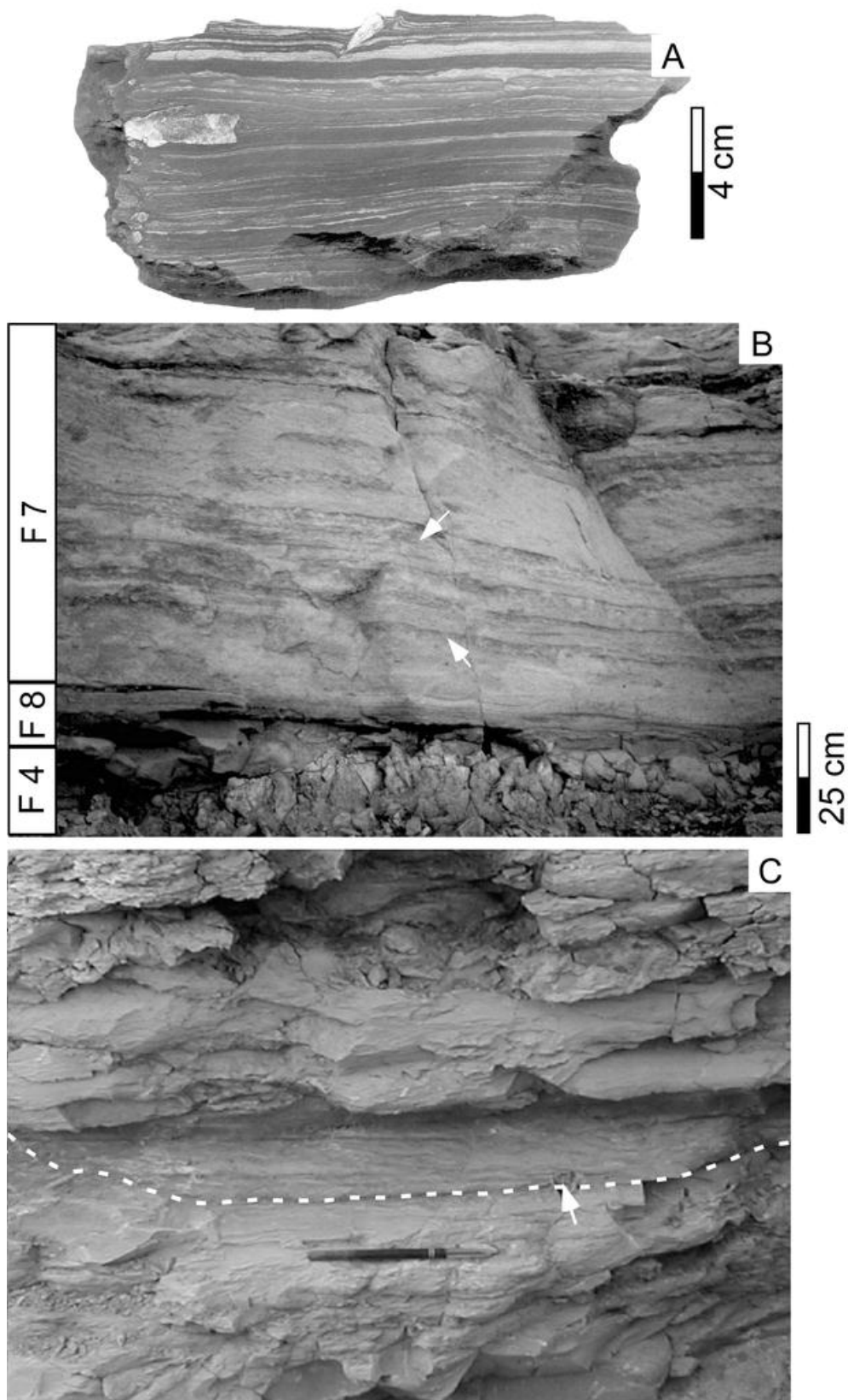
Fig. 7 A Lithofacies 3 (laminated dolomitic gypsiferous marlstone) **B** Transition between lithofacies (*F4*), (*F8*) and (*F7*) illustrating rapid increase in palaeodepth leading to fully marine conditions. Note intercalated lenses (*arrowed*) of shell fragments. **C** Channel structures intercalated in lithofacies 5 showing tangential, oblique lamination and an erosional base.

Lithofacies 4

Lithofacies 4 consists of indurated dolomitic clay with intercalations of greenish silty clay forms continuous bioturbated layers, which are several centimetres thick (Fig. 7B). The rare fauna mainly consists of shells of ostracodes and fish debris. The combined evidence from the biofacies and lithofacies indicates deposition in a very shallow, brackish, high-stress environment subject to high evaporation.

Lithofacies 5

The lithofacies is composed of beige-coloured limestone and structureless wackestone to packstone with no evidence of reworking (Fig. 7C). The carbonate layers are several centimetres thick and laterally (decimetre scale) very consistent. Numerous faecal pellets and mud pebbles are mixed with ostracodes, bivalves, and vertebrate fragments. These features indicate a transitional environment between lower and upper shoreface in a protected setting.

Lithofacies 6

This lithofacies is represented by a skeletal limestone with intercalated calcareous channel fills that occur scattered within marl (Fig. 8A–C). The limestone laterally forms a thick continuous unit. The lower surfaces of the beds are erosional and are often associated with lenticular marlstones beds. A rich and diverse vertebrate fauna occurs that is composed of the remains of selachians, fishes (Semionotidae, Coelacanthidae), chelonians, mesosuchian crocodilians (*Gonophiolis* sp., *Pholidosaurus* sp.), sauropod and theropod dinosaurs, and a lepidosaur (Sphenodontidae; Buffetaut et al. 1989; Hervat and Hervat 1993; Vignaud et al. 1994; Le Loeuff et al. 1996). Reptile eggshells were found in the upper unit (U2) of the section (G. Garcia, personal communication). A recent systematic excavation yielded remains of selachians, fishes, chelonians, crocodilians, pterosaurs, sauropod and theropod dinosaurs. The microfacies is a packstone to grainstone with scattered angular quartz grains and a microfauna of ostracodes and charophytes. Gastropods and bivalves are also present. Sedimentary structures are hummocky cross stratification (HCS) and low angle cross-bedding (Fig. 8/B). These features point to a foreshore to shoreface environment and deposition by periodic waning flow, typical of storm origin.
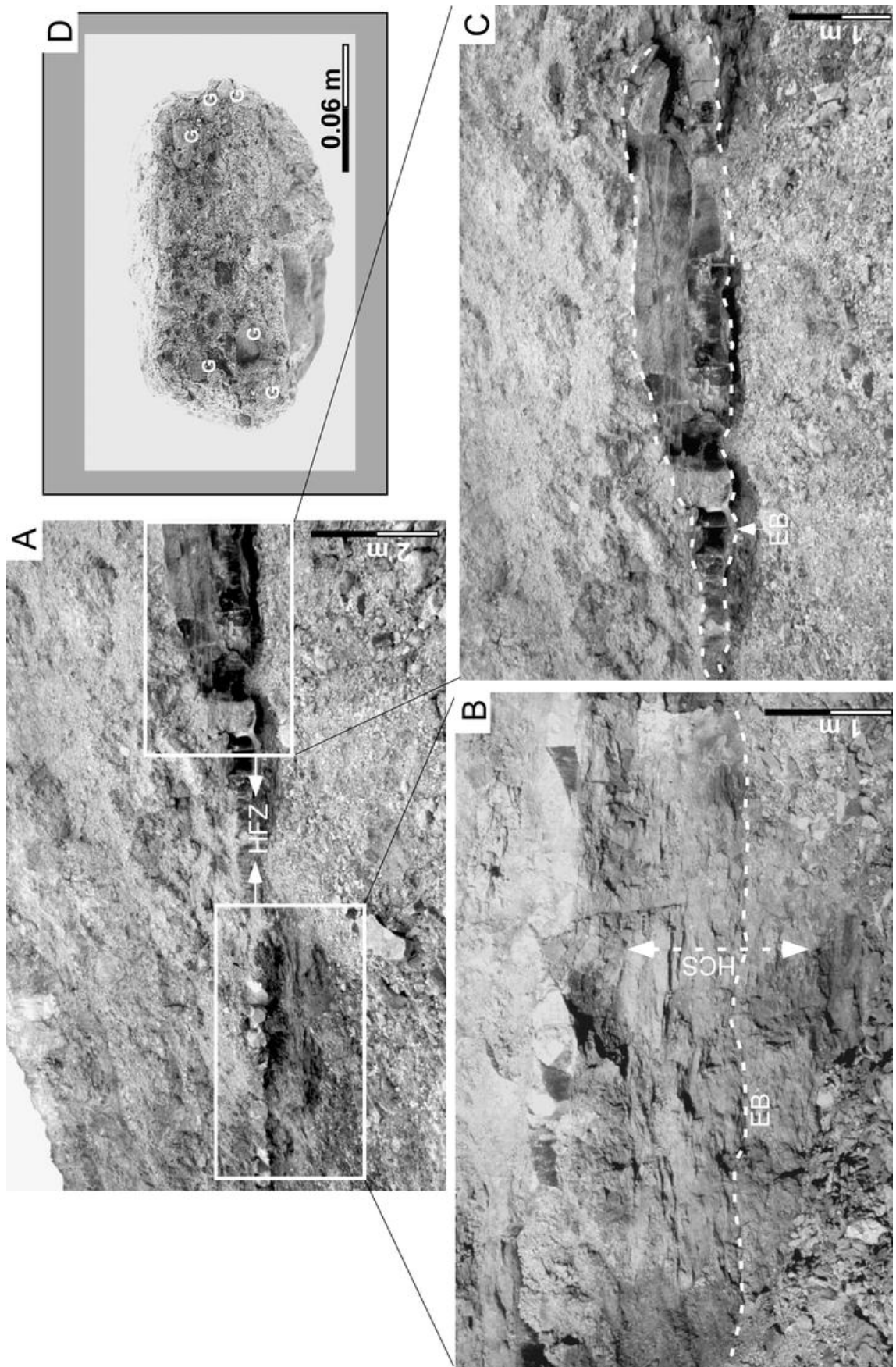
Fig. 8 Facies architecture observed in the fossiliferous zone of (*U2*): **A** general view of the highly fossiliferous zone (HFZ), **B** Detail of lithofacies 6, showing amalgamated hummocky cross stratification (*HCS*) and

erosional base (*EB*), **C** Oblique cross-lamination and erosional base (*EB*) of wackestone, **D** Sample from the highly fossiliferous zone (*HFZ*) shows scattered glauconitic pellets (*G*)

Lithofacies 7

This lithofacies is represented by an 1-m-thick oograinstone, which is intercalated between black marls of lithofacies 8 and stromatolitic gypsum of lithofacies 1 (Fig. 7B). Reactivation surfaces are common. Intercalated within the oograinstone are 2–3-cm-thick lenses of shell fragments (ostracodes, bivalves and gastropods).

Judging from its position, the oolite body most likely represents the relict of a small bar that separated a marine-influenced environment—the black marls (see below)—from a highly restricted sabkha environment documented by stromatolitic gypsum.

Lithofacies 8

Lithofacies 8 is composed of finely laminated black marl (Fig. 7B) with some signs of bioturbation, but without any macrofauna, except for fish remains. The thin dark laminae are mainly composed of clay mixed with organic substances. In the light laminae, ostracodes, echinoid spines and phosphatic fish remains are present. In this facies, palynomorphs of marine origin are very common, including dinoflagellate cysts and chitinous foraminiferal tests.

Fossil content

Vertebrate fauna

In contrast to the lower unit (U1), the upper unit (U2) yielded a diverse vertebrate fauna (see above). A particular feature of this fossiliferous level of U2 is a high glauconite content being replaced, at the top the section, by palygorskite (Fig. 2).

The taphonomic signatures of the material are not uniform throughout the outcrop. On the basis of the nature and occurrences of the skeletal assemblages, three taphofacies (see below) can be distinguished. The vertebrate remains include fragments of bones and dermal bony plates of selachians, fishes, chelonians, crocodilians, pterosaurs, sauropod and theropod dinosaurs. The skeletons of some fishes and reptiles (mostly crocodilians and chelonians) are incomplete and semi-articulated or complete and articulated (crocodilians and a lepidosaur). Most of the tetrapods collected from the section have lived in land habitats.

Invertebrate fauna

Ostracodes (Fig. 3/1–12

The lower unit of the section (U1) is characterized by monospecific populations of the euryhaline ostracode *Fabanella boloniensis* (Jones 1882), sometime extremely abundant and forming beds of ostracodite. The middle part of this unit yielded a marine assemblage represented by rare specimens of *Paranotacythere* (*Unicosta*) cf. *rimosa*, *Asciocythere* sp.and *Macrodentina* (*Dictyocythere*) ex. gr. *mediostricta*.

The upper unit (U2) contains rich and diverse ostracode assemblages of various salinity tolerance—after Brenner 1976 and Schudack 1993a: (1) freshwater: *Alicenula leguminella*; (2) freshwater-oligohaline: *Cypridea* spp. (generally dominant), *Darwinula oblonga*; (3) freshwater-brackish: *Theriosynoecum forbesii*, *Theriosynoecum verrucosa*, *Rhinocypris jurassica*, *Cetacella armata* and (4) brackish-marine: *Mantelliana* sp., *Macrodentina* (*D.*) ex gr. *mediostricta,* this last species being only present and abundant at the base of the interval (U2). Towards the top of the fossiliferous interval, the proportion of freshwater-oligohaline species increases progressively (Fig. 9). Nevertheless the occurrence of brackish water species in various percentages is found throughout the section. The upper part of the section above the vertebrate fossiliferous interval shows the return to monospecific ostracode faunas with *Mantelliana* sp., suggesting the onset of a restricted saline environment (Fig. 9).
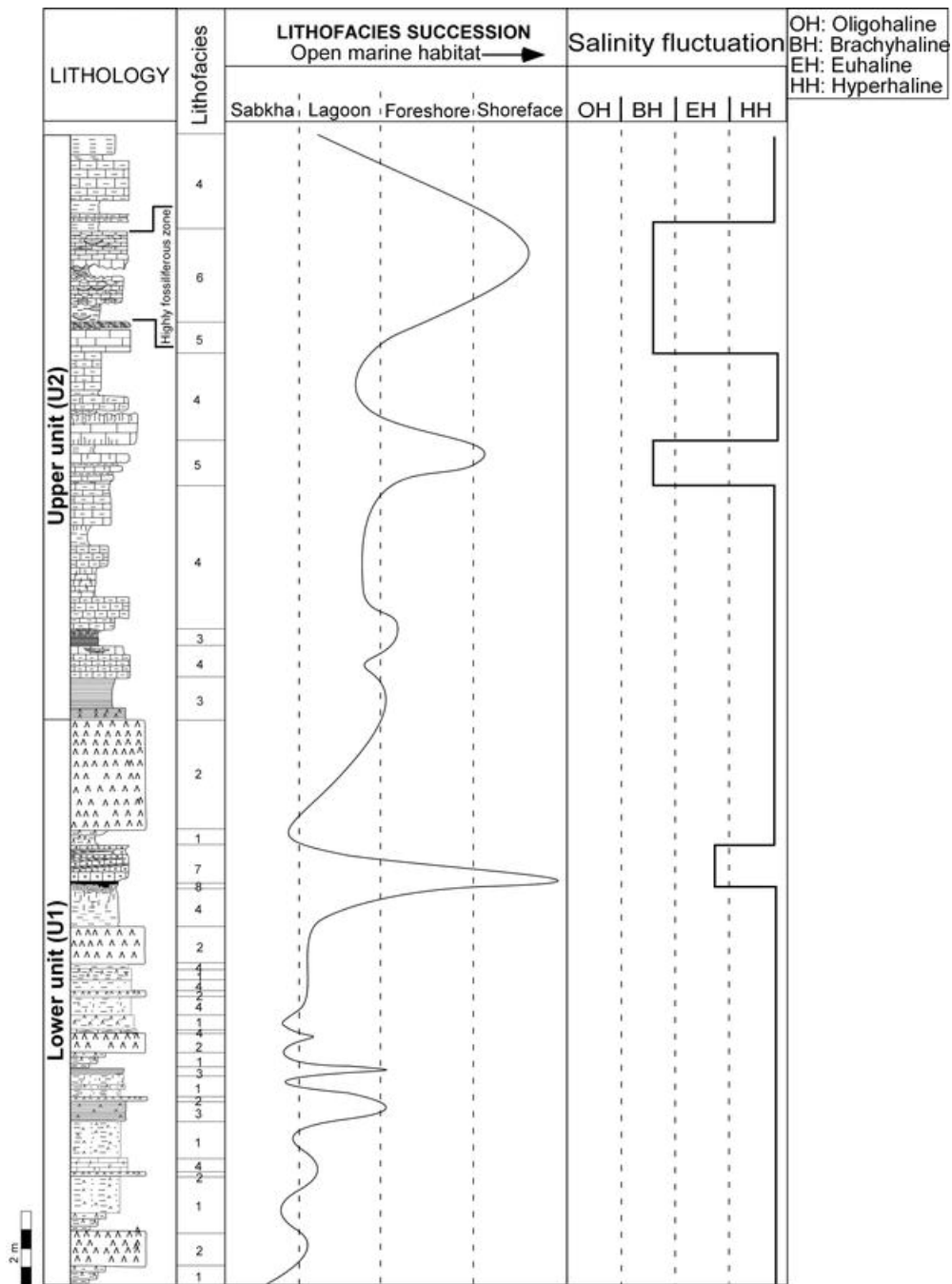
Fig. 9 Lithofacies succession in the Cherves-de-Cognac section, palaeobathymetric curve and palaeosalinity fluctuation

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Bivalves and gastropods

Three species of bivalves have been recorded: *Protocardia intexta* (Münster, 1837; Fig. 10/1) representing 69.4%; *Corbula inflexa* (Roemer, 1836; Fig. 10/2) representing 29.4% and a pectinid indet. representing 1.2% in terms of relative abundance. The bivalve assemblage is characterized by a very low species richness (number of species: 3) and evenness. Diagenetic distortion as a reason for the low diversity can be excluded as originally aragonitic shells (*Protocardia*) are

preserved as composite moulds. The bivalves form matrix-supported shell beds, 10–15 cm in thickness in lithofacies 5. Biostratinomic distortion by sorting can be excluded, as the bivalves represent a wide size range. Most shells are disarticulated, only 3% are articulated. This suggests short-term reworking, but apparently not major transport. The same is indicated by the fine-grained nature of the substrate. The low species diversity thus reflects adverse living conditions (high degree of environmental stress). As both *Protocadia* and corbulids are know to be euryhaline (this has been repeatedly demonstrated in Jurassic environments, e.g. Fürsich 1994; Fürsich and Werner 1986), salinity appears to have been the limiting factor. Based on the occurrence of the taxa elsewhere in the Jurassic, a mesohaline environment seems likely.
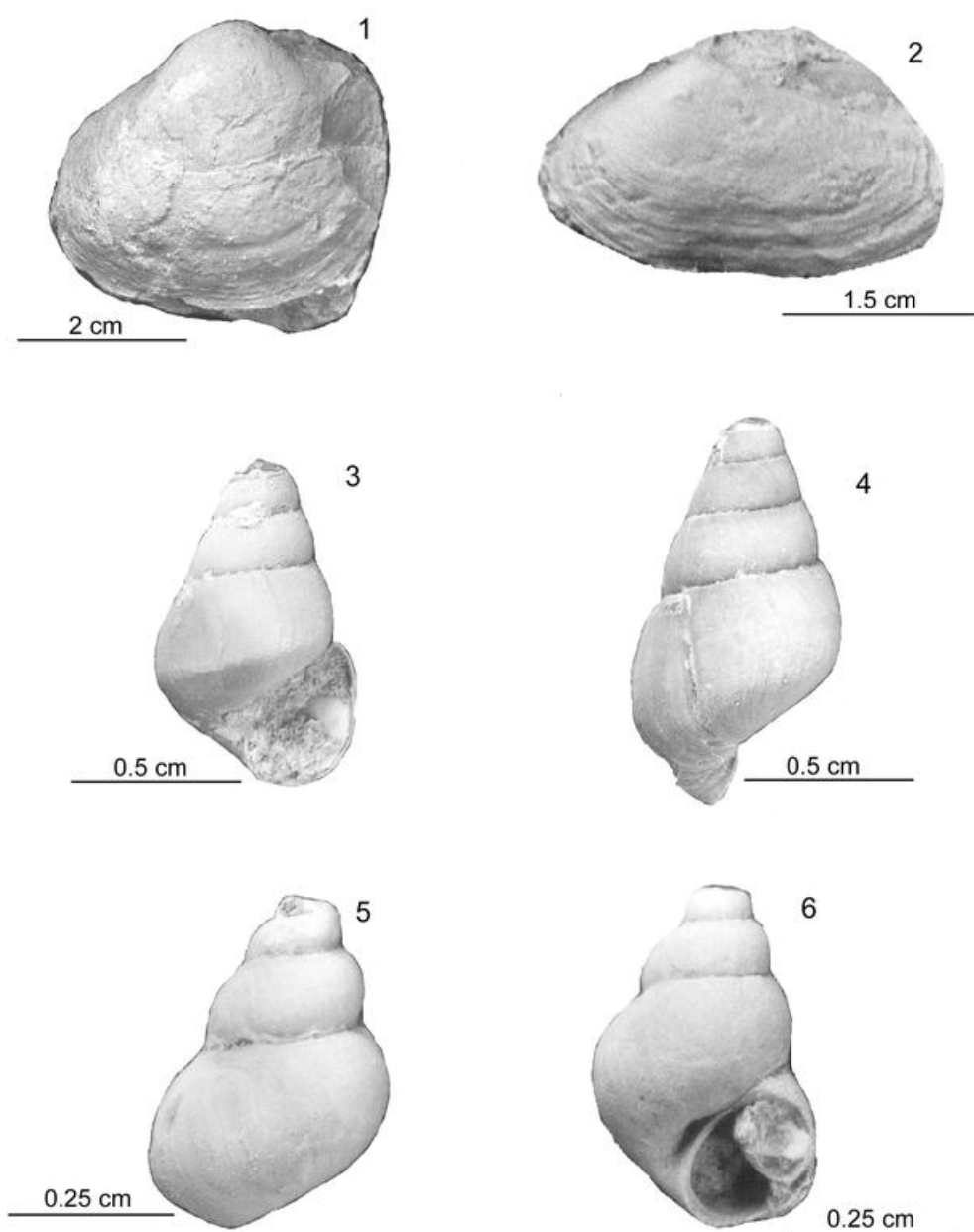
Fig. 10 (Bivalves and gastropods). *1 Protocardia intexta* (Münster 1837); *2 Corbula inflexa* (Roemer 1836); *3, 4* Hydrobiid form A; *5, 6 Viviparus* sp.

Gastropods are represented by hydrobiid form A (Fig. 10/3–4) and *Viviparus* sp. (Fig. 85–6). This assemblage is characteristic of brackish to freshwater environments. In the uppermost part of the section, the low diversity molluscan fauna (*Viviparus*, hydrobiid and *Unio*) suggests fluctuating freshwater to oligohaline conditions.

Charophytes

The association of charophyte fructifications (Fig. 3/13–16) observed in the highly fossiliferous zone (HFZ; Unit 2) is dominated by porocharacean gyrogonites (*Porochara kimmeridgensis*) with subordinated presence of clavatoracean utricles (*Clavator grovesii* subsp. *grovesii* and *Nodosoclavator bradleyi*). Only rare characean gyrogonites (*Mesochara harrisii*) were found. All the fructifications are well preserved. Clavatoracean utricles are even attached in groups to phylloids, which is evidence of autochthony. However, no vegetative remains of porocharaceans or characeans were found. This may indicate parautochthony, i.e. that gyrogonites were gently transported from an adjacent growing area, or that vegetative remains were not calcified.

The dominance of porocharaceans in Early Cretaceous charophyte floras has been considered to be an indication of brackish water, especially when the whole assemblage is formed by gyrogonites of this family. In the Barremian of the Iberian Chain, Martín-Closas and Grambast-Fessard (1986) reported the presence of porocharacean assemblages in estuarine facies associated with brackish ostracodes, foraminifera and reworked marine fauna. Mojon (1989) related polymorph porocharacean assemblages of the Berriasian of the Jura Mountains to environments with an increased salinity. In contrast, clavatoraceans appear to dominate in most freshwater environments of the Early Cretaceous. This has not only been shown by sedimentological and palaeontological evidence but also with isotopic data (Schudack 1993a, 1993b; Poyato-Ariza et al. 1998).

The presence of clavatoracean utricles attached to vegetative remains agrees with the general interpretation of a freshwater environment for the palaeontological site. However, abundant porocharacean remains may indicate that brackish conditions prevailed in some periods or in neighbouring areas.

Palynomorphs

Palynomorphs (Fig. 4) are absent or poorly preserved throughout the section, except at one level in the middle part of (U1) where they are abundant. Most abundant are gymnosperm pollen; palynomorphs of marine origin are also very common, including dinoflagellate cysts and chitinous foraminiferal linings. The dinoflagellate assemblages are dominated by representatives of the genus *Systematophora*. Other relative common forms include *Circulodinium*, *Canningia* and *Hystrichodinium*. Smooth cysts, tentatively assigned to *Batiacasphaera*, are invariably present.

Among the terrestrial palynomorphs (Fig. 11) the *Classopollis* group (Cheirolepidiaceae) is most abundant. Considerable numbers of pollen can be attributed to the *Exesipollenites* and to the *Inaperturopollenites/Perinopollenites* groups (Bennettitales, Taxodiaceae), bisaccate pollen (*Alisporites*, *Podocarpites*); the representatives of the *Araucariacites*/*Cerebropollenites* group and pteridophytes spores (*Deltoidospora, Cyathidites*) are comparatively rare; other rare gymnosperm pollen include *Vitreisporites pallidus* (Caytoniales), *Eucommidites troedssonii* (Cycadales), *Ephedripites* spp. (Gnetales).
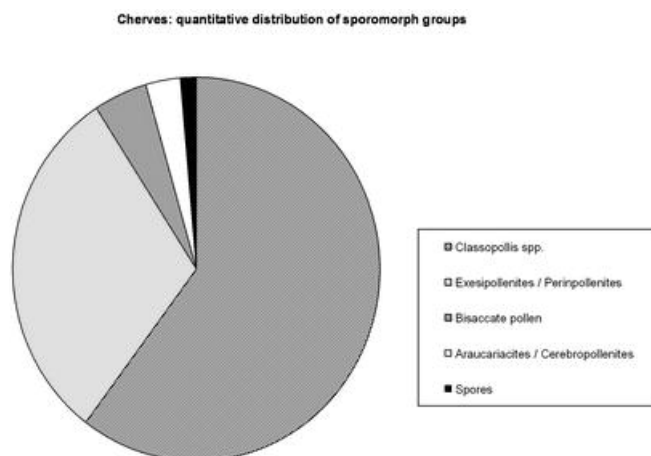

Cherves: quantitative distribution of sporomorph groups

☑ Classopollis spp.
☐ Exesipollenites / Perinpollenites
☑ Bisaccate pollen
☐ Araucariacites / Cerebropollenites
■ Spores

Fig. 11 Quantitative distribution of sporomorph groups in Ul (sample from level D mentioned in Fig. 2)

The abundant occurrence and the diversity of the marine palynomorph assemblage and the presence of chitinous foraminiferal linings indicate marine conditions. The remains of the algae *Botryococcus* and probably also of the dinoflagellate cyst *Geiselodinium* spp. suggest freshwater influx. On the other hand, the abundance of spore-pollen and of phytoclasts reflects a strong terrestrial influx. The presence of a few fragments of charcoal documents the occurrence of wild fires. The dominance of the *Classopollis* group and the relatively rare occurrence of bisaccate pollen and pteridophytes spores suggest at least seasonally dry climatic conditions.

Mineralogical and geochemical data

The clay mineral assemblage of the section is mainly represented (in order of decreasing abundance) by mica-illite, illite/smectite randomly ordered mixed layer and palygorskite. The whole section is homogeneous and monotonous with respect to the mica-illite and mixed layer minerals (Fig. 12). Green clays have been observed as rounded pellets (glauconite) or coating (verdine) according to Giresse et al. 1980; Odin and Gupta 1988. XRD patterns (Fig. 12) show that they are composed by a glauconite/smectite randomly oriented mixed layer (Thompson and Hower 1975). This is coherent with their average chemical composition which shows (Table 1) a K_2O content of 5.29% (Thompson and Hower 1975).
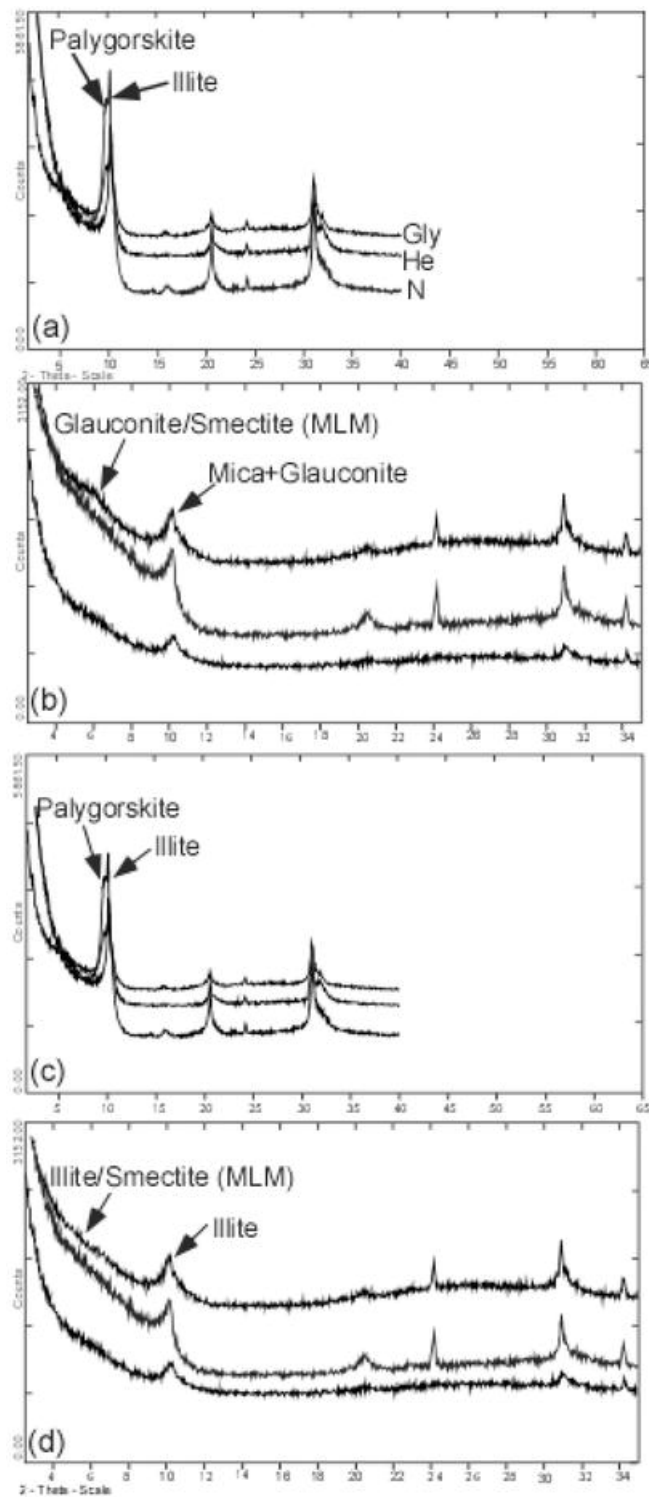
Fig. 12 Clay X-ray diffraction. **A** Sample from the lower part of the unit 1 (*U1*). **B** Sample from the upper part of the unit 1 (*U1*). **C** Sample from the highly fossiliferous zone (*HFZ*) in the upper unit (*U2*). **D** Sample from the top part of the upper unit (*U2*)

The first occurrence of palygorskite is in low concentration in the middle part of unit 1 (Fig. 2). The percentage increases considerably above the glauconitic zone (Fig. 2). Thus, the distribution

of clay minerals in the section (Fig. 2) seems to be facies dependent; palygorskite occurred in the zone devoid of macrofauna (i.e. middle part of U1 and uppermost part of U2), whereas green clays are most abundant in the more fossiliferous sediment (U2).

Discussion and interpretation

The lithofacies succession identified in the sections represents typical nearshore facies strongly influenced by sea-level fluctuations that determined the degree of continental influence.

Depositional environments

Unit 1 (U1)

In the lower part of the section, the gypsum lithofacies represents two types of environments:

1. A shoreline system consisting of sabkha coastal flats and salinas including coastal lagoon to mud flats (Fig. 9). In modern environments, such associations are typically characterized by a gradual transition, both laterally and vertically, from shallow water to subaerial facies; by nodular and enterolithic structures and by lenticular gypsum associated with microbial mats. Most of these features are considered as main criteria for recognising sabkha to coastal lagoon mud-flat environments (Shearman 1985; Rouchy et al. 1994). In this type of facies, fauna is rare, represented by fish remains and by monospecific ostracode assemblages (*Fabanella boloniensis*) that tolerated hyperhaline conditions (Figs. 2 and 9).

2. The second type of environment is a shallow-water inner platform to lagoon. The facies consists of bedded gypsum. Based on the rare occurrence of ripples and on the absence of other high-energy sedimentary structures, the shallow water facies most likely was deposited in partly restricted platform environments (Kasprzyk 1995; Kendall and Harwood 1996). Levels with plant fossils intercalated between the gypsum facies of U1 are represented by the genus *Agathoxylon* (M. Philippe, personal communication) exhibiting different sizes and shapes. Philippe (1993) suggested that this conifer grew in nearshore environments.

Laminated dolomitic gypsiferous marlstone intercalated between the gypsum facies is often associated with lenticular channel fills. These features point to a tide-influenced shallow inner platform. The faunal content is poor, solely represented by fish teeth. These kind of deposits results from seasonally or climatically controlled variations in water inflow, temperature or evaporation rate (Kendall 1984). Some of the finely-laminated sediment originated by the rain of fine crystals formed by evaporation at the water surface (Dean and Anderson 1982). The finest of these are

millimetres in scale and probably represent seasonal cycles. Fluctuations in water depth throughout the unit could have had an impact on the intensity of evaporation and might have induced normal marine conditions occasionally (Fig. 9). Black laminated marlstone rich in palynomorphs, including dinoflagellate cysts and chitinous foraminiferal linings superseded by oograinstone, both intercalated between evaporitic sediments, implies a sudden marine inundation of the area.

The clay mineral assemblage of the whole unit is homogeneous and monotonous with respect to the mica-illite minerals (Figs. 2 and 12). Palygorskite is occasionally present in the middle part of this unit and is significantly more abundant in a grey-green claystone facies containing traces of fluid migration linked to high evaporation. This fibrous mineral is confined to evaporitic environments with high magnesium concentrations derived from soil through wind dust and from nearshore by currents (Singer and Galan 1984; Chamley 1989; Meunier 2003).

Unit 2 (U2)

Unit 1 ends with a gypsum bed several metres thick. The transition between U1 and U2 is gradual and consists of laminated gypsiferous marlstone. Deposition took place in brackish waters, the salinities of which varied from euryhaline in the basal part to freshwater towards the topmost part of U2. Clay and dolomitic marlstone alternations devoid of fauna except for some ostracode shells comprise the lower part of this unit. This indicates a change from saline to more or less brackish conditions. Erosional truncation, interpreted as an emersion surface, is observed in this part and supports an increased continental influence (Fig. 2). Upwards, these facies give way to mostly bioclastic limestone. Sedimentary structures in this facies are lenticular channel-fills associated with amalgamated hummocky cross-stratification (HCS) and low angle cross-bedding that commonly grades upward into a zone of planar lamination (Dott and Bourgeois 1982). This facies indicates a foreshore to shoreface setting (Walker 1984) and deposition by periodical waning flow, typically of storm origin. The HCS facies occurs in the middle to upper part of U2 (lithofacies 6) and consists of laminated limestone intercalated with clay-marlstone and fossil accumulations. Soft sediment deformation features indicate phases of rapid sedimentation (Nelson 1982; Saxov and Nieuwenhuis 1982).

The *Protocardia* level (Fig. 2) underlies a 4-m-thick glauconitic zone. Glauconitic minerals occur abundantly as green grains concentrated in nongraded centimetric layers below and within the HCS beds which in turn are overlain by green clay (Fig. 2). Sedimentological and petrographic constraints indicate that the glauconitic minerals are autochthonous. Numerous studies (e.g. Odin and Matter 1981; Logvinenko 1982; Dias and Nittrouer 1984; Bornhold and Giresse 1985; Hughes

and Whitehead 1987; Odin 1988; O'Brien et al. 1990; Bremner and Wills 1993; Rao et al. 1993) concluded that glauconitic minerals form at mid-shelf or even greater depths, i.e. at a water depth greater that 50 m. Most of these studies imply that glauconitic minerals form at sites of very slow accumulation. Glauconite could not have been derived by erosion because the Berriasian deposits are underlain by limestones that lack glauconitic minerals. Some authors (e.g. Cudzil and Dreise 1987; Chafetz and Reid 2000), however, suggest that glauconite mineral-rich accumulations formed on tidal-flats. Lithofacies and sedimentary structures observed in the middle part of U2 corroborate this hypothesis. However, above the glauconitic zone, the grey-green clay devoid of fauna except for some rare unionid bivalves and the gastropod *Viviparus* is composed of palygorskite. This autigenic fibrous mineral forms under semi-arid to arid climatic conditions, either under evaporitic conditions in confined environments and/or in soils (Singer and Galan 1984; Chamley 1989; Meunier 2003).

Hallam (1984) suggested that during the Early Cretaceous (Berriasian to Barremian) the climate in the Aquitaine Basin was generally humid. West (1975), Sladen and Batten (1984) and Allen (1998) favoured a semi-arid, Mediterranean-type climate during the Tithonian-Berriasian, which became progressively wetter towards the end of the Berriasian.

This hypothesis is not supported by the sedimentological and mineralogical data presented in this study, which reveal that the Berriasian climate in the northern part of the Aquitaine Basin was mostly arid but became progressively humid. The same conclusions were reached for the environments of the Purbeck Limestone Group (West 1975; Batten 2002).

The general changes in lithofacies indicate a depositional setting evolving from a marine lime mud, deposited during the Tithonian, to mixed brackish-freshwater environments via a hypersaline evaporitic environment. This succession reflects a gradual regression towards the end of the Berriasian inducing a greater continental influx.

There is no evidence of regional tectonics in the studied area during the Jurassic (Jacquin et al. 1998). Eustatic and climatic fluctuations are the likely origin of the facies pattern.

Palaeoecology and taphonomy

The fossil content observed in the glauconitic zone (Fig. 2) is composed of abundant and diverse remains of invertebrates and vertebrates. The invertebrate fauna is dominated by bivalves, gastropods, ostracodes and charophytes, which are particularly abundant in U2 and indicate brackish conditions with increasing influence of freshwater towards the top of this unit (see above). Tidal flats subjected to the influence of freshwater could be envisaged as a depositional environment of

the invertebrate fauna. Although plant remains are usually characteristic of such an environment, their absence in the studied section does not imply that they were not present initially.

The vertebrate fossil assemblage in the HFZ is composed mainly of continental forms, most of them clearly reworked. Most of the skeletal material was transported from the land towards the inner shallow shelf during exceptional events such as storms (Fig. 8B). The presence of HCS corroborates this hypothesis. The occurrence of a lens-shaped body with lenticular bedding within the glauconitic strata indicates a low-sinuosity tidal channel. This facies association suggests an environment influenced by both marine and continental processes (see "Invertabrate fauna") such as an estuarine setting (e.g. Cuny et al. 1991; Barrett 2000; Smith et al. 2001; Néraudeau et al. 2003).

The main taphonomic features, qualitatively observed in this study, from which the degree of allochthony was deduced are the degree of articulation, size, orientation, sorting and abrasion. As a result, three taphonomically controlled assemblages (taphofacies) could be distinguished (Fig. 13).
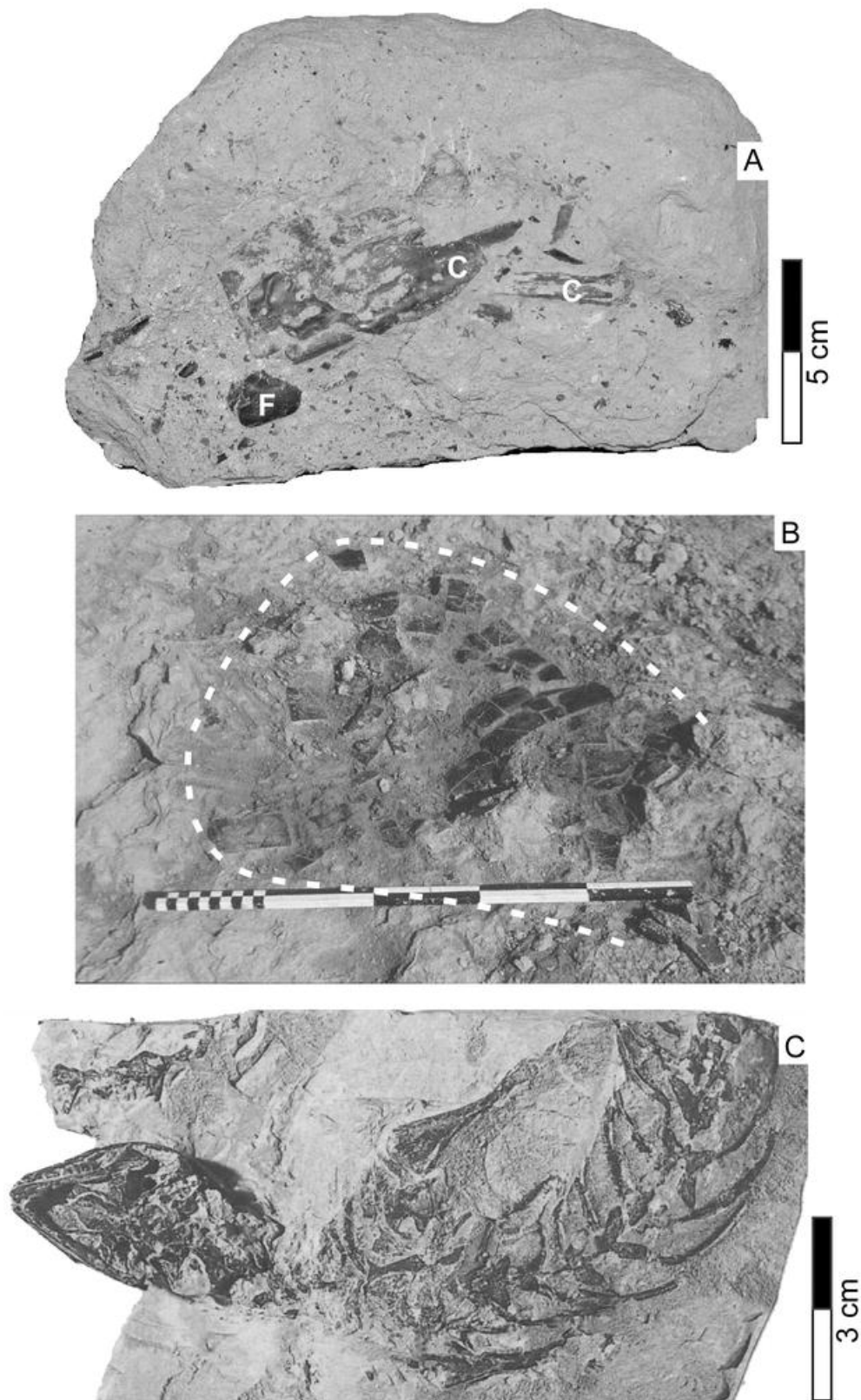
Fig. 13 Examples of the three vertebrate taphofacies. **A** Isolated, fragmentary crocodilian remains (*C*) and numerous isolated and fragmentary fish scales (*F*; taphofacies A). **B** Semi-articulated chelonian skeleton, *scale bar* 50 cm (taphofacies B). **C** A nearly completely articulated lepidosaur *Homoeosaurus* (Sphenodontidae; from Buffetaut et al. 1989) Fig. 5

Taphofacies A

Most common are completely disarticulated skeletons, which occur highly concentrated in lenses within argillaceous marlstone and limestone (Fig. 13A). Generally, the bones differ in size and shape, and are randomly oriented and abraded—features that point to considerable transport. All identifiable skeletal elements from this zone are fish remains, bone fragments and dermal bone plates of chelonians and crocodilians, bone remains of sauropod, pterosaurs and theropod teeth. The concentration of vertebrate debris in the fossiliferous zone of U2 (HFZ) is probably due to the rapid sedimentation involving input from onshore material transported into the depositional setting during several storms events.

Taphofacies B

Semi-articulated skeletons of fishes and reptiles have been excavated from the mudstone in U2 (Fig. 13B). The bones are not broken and lack surface markings. Most bones belong to crocodilians and chelonians. The terrestrial animals apparently became buried close to where they died. The carcasses could have been transported towards the burial site by floating during a period of inundation. Therefore, the skeletons were affected only slightly by physical and biological agents between death and final burial.

Taphofacies C

In a few cases, complete articulated skeletons of small crocodilians and a lepidosaur (Sphenodontidae) were found side by side with their ventral surfaces pointing downwards (Fig. 13C). They have been excavated from a lenticular bed within marly claystone (lithofacies 6). The preservation is excellent and none of the bone shows any sign of cracking or abrasion. This indicates quick burial after death by suspended sediment, thus removing the carcasses from scavengers and physical agents.

Palaeogeography, sea-level signal and depositional model

The Cherves-de-Cognac section, dated as Berriasian, is the only outcrop of Lower Cretaceous rocks in the northern part of the Aquitaine Basin (Fig. 9). It is worth noticing that a similar ostracode assemblage (*Cypridea, Fabanella*) has been reported in a borehole near Mirambeau, Charente-Maritime (Oertli 1963) and that a similar Lower Cretaceous (Berriasian-Hauterivian) palynological association has been identified in a borehole underneath the Cenomanian at Saint-Romain de Benet (between Royan and Saintes, Charente-Maritime; Deak and Combaz 1967).

According to previous studies (Hantzpergue 1979; Bourgueil et al. 1986; Fourcade et al. 1991, 1993; Jacquin et al. 1998), the uppermost part of the Jurassic correspond to an important fall of eustatic sea-level that considerably expanded the global area of emerged land. Consequently, these authors suggest a major erosional unconformity between the Upper Jurassic (Tithonian) and the Upper Cretaceous (Cenomanian). However, at the northern margin of the Aquitaine Basin, Lower Cretaceous (Berriasian) deposits demonstrate that the regression that started near the Kimmeridgian–Tithonian boundary continued into the Cretaceous. The Cherves-de-Cognac section is unconformably overlain by Cenomanian strata (Hantzpergue 1979; Bourgueil et al. 1986).

The Berriasian deposits characterize a tidal flat environment evolving from a hypersaline sabkha to brackish/freshwaters environment, overlying marine limestones. Previous studies (Ziegler 1988; Fourcade et al. 1991, 1993; Benton et al. 1997; Jacquin et al. 1998) suggested that, as a result of substantial regression, the Tithonian–Cenomanian time interval corresponds to a phase of emergence and denudation because of an extensive drop in sea level, manifested in most parts of western Europe in the form of a major erosional unconformity. An unconformity exists in the studied section between the Berriasian and the Cenomanian. This conclusion supports the proposal of Hallam (2001) that the relative fall in sea level at the end of the Jurassic in western Europe is a result of regional tectonic activity rather than eustatic.

A depositional model for the Berriasian of the northern part of the Aquitaine Basin includes the following environments (Fig. 9):

1. In the lower part of the section, the gypsum lithofacies indicates a shoreline system such as sabkha coastal flat system including coastal lagoonal mud-flats. Criteria for this interpretation is the succession of evaporitic lithofacies that points to a decrease in palaeodepth and a regular supply of marine water.

2. Full marine conditions were established occasionally during relative sea-level rise leading to deposition of grey-black laminated marl and oograinstones

3. During sea-level fall, bottom mud was eroded and winnowed, leading to concentration of coarse material (shell debris). These processes were mainly driven by storms. Big storms led to deposition of thick hummocky cross-stratified beds and to the formation of channels by rip-currents that were filled with calcarenites.

The depositional model allows the reconstruction of a water-depth curve for the Berriasian (Fig. 9). The studied section illustrates (1) rapid and frequent fluctuations of water depth, (2) increased reworking by storm waves during decreasing water depth and (3) continued reworking of skeletal material by storm processes.

Conclusions

The lower part of the Cherves-de-Cognac section (U1) can be interpreted as a restricted lagoon-tidal flat environment under arid conditions. Deposition was governed by the combined influence of marine waters and evaporation, especially in the adjacent supratidal sabkha environment. These conditions were inimical to colonisation by a shelly micro- and macrofauna.

Sedimentary fabric and microfacies reveal that the evaporitic conditions decreased progressively throughout the upper unit of the section (U2) due to an increased exchange with fully marine waters and a subsequent higher input of freshwater. As a result, the fauna is a mixture of freshwater and brackish water taxa. No exclusive marine faunas are known. The close association of the various environments and faunas suggests a setting subject to marine and continental influence such as an estuarine environment.

The combined evidence from biota and lithofacies indicates deposition in a very shallow, brackish high-stress environment subject to fluctuation in salinity and temperature.

The main taphonomic features of the vertebrate skeletal elements indicate that most of them were transported from the coastal plain towards the inner shallow shelf during exceptional events such as storms. Rare semi-articulated and articulated skeletons of fishes and reptiles are present and indicate that carcasses were transported by floating towards their burial sites, probably during periods of inundation. The carcasses were quickly buried by suspended sediment, thus being beyond the reach of scavengers and physical agents.

The Purbeckian facies in the northern part of the Aquitaine Basin yielded microfaunas and microfloras, which are characteristic of the Berriasian stage. On grounds of these new biostratigraphic data, the assumption, engrained in the literature, of a general marine regression in the area at the end of the Tithonian, accounting for an hiatus spanning the whole Lower Cretaceous (about 40 My), must be refuted.

[Tab1 will appear here. See end of document.]

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[Tab1]

Oxide	Pellets
SiO_2	57.57
Fe_2O_3 [a]	8.02
Al_2O_3	16.58
K_2O	5.29
MgO	3.94
CaO	0.86
Na_2O	0.25
TiO	0.15
Total	92.66

[a]Total iron expressed as Fe_2O_3