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Ooids in Purbeck limestones (lowermost Cretaceous) of the Swiss and French Jura

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ABSTRACT

Ooids occurring in the shallow-water Purbeckian carbonate sediments of the Jura mountains can be grouped into six types. Gradations from one type to another and coexistence of the various types are common.

Type 1 ooids are small and well rounded. They display fine concentric micritic laminae. In many cases their cortices are dissolved and replaced by void-filling spar. Microsparitic neomorphic replacement occurs locally. Type 2 ooids are large and have irregular shapes. They show fine micritic laminae and occasional layers of fine-radial crystals. They commonly evolve into oncoids. Ooids of type 3 display many fine-radial cortical laminae and are patchily micritized. They are medium in size and mostly well rounded. This type of ooid may pass into large, irregularly shaped coated grains. Type 4 ooids have 1 to 4 cortical laminae with a fine-radial structure and patchy micritization. They are medium in size and well rounded. Type 5 ooids have only one lamina with a coarse-radial structure. They are small and well rounded. Associated are spherical grains containing bundles of elongate crystals. Ooids of type 6 show superpositions of two or more different, radial and/or fine micritic laminae. The cortical structure may also change laterally in the same lamina.

The preferential dissolution of type 1 ooid cortices to form oomoulds indicates a primary composition of unstable carbonate. Sedimentological features and comparison with modern ooid occurrences point to formation on high-energy sandbars in normal-marine waters. Type 2 ooids grew in marine-lagoonal environments with quiet water and abundant cyanobacteria. The radially structured ooid cortices of types 3, 4 and 5 show no dissolution features. This implies that they were originally composed of stable carbonates, or that an unstable carbonate phase was transformed into a stable one at an early stage of diagenesis. Type 3 ooids occur together with marine faunas and indicate high water energy. Ooids of type 4 and type 5 originated probably from relatively quiet water of variable salinity.

Coexistence of different ooid types and mixed forms of type 6 implies gradual or rapid changes in hydrodynamic, geochemical and microbiological conditions which were a feature of the Purbeckian depositional environments.

INTRODUCTION

The chronostratigraphic position of the Purbeck limestones in the Swiss and French Jura Mountains has not yet been established. The term Purbeckian is here applied to a facies association situated in the lowermost Berriasian (Clavel *et al.*, 1986). Outcrop limits and the sampled sections are indicated in Fig. 1. Purbeckian sediments comprise shallow subtidal, intertidal and supratidal, normal marine, brackish, freshwater and hypersaline facies (Fig. 2). The transition from the Portlandian is often marked by dolomites which commonly show algal laminae and rip-up clasts. They are attributed to a supratidal environment. Local brecciation was due to meteoric dissolution of underlying and intercalated evaporites. Brown charophyte limestones with ostracods and freshwater gastropods characterize the lacustrine facies. Micrites and pelmicrites commonly display desiccation cracks and birdseyes indicating intertidal to supratidal conditions. They may contain abundant monospecific faunas (miliolids, ostracods, gastro-

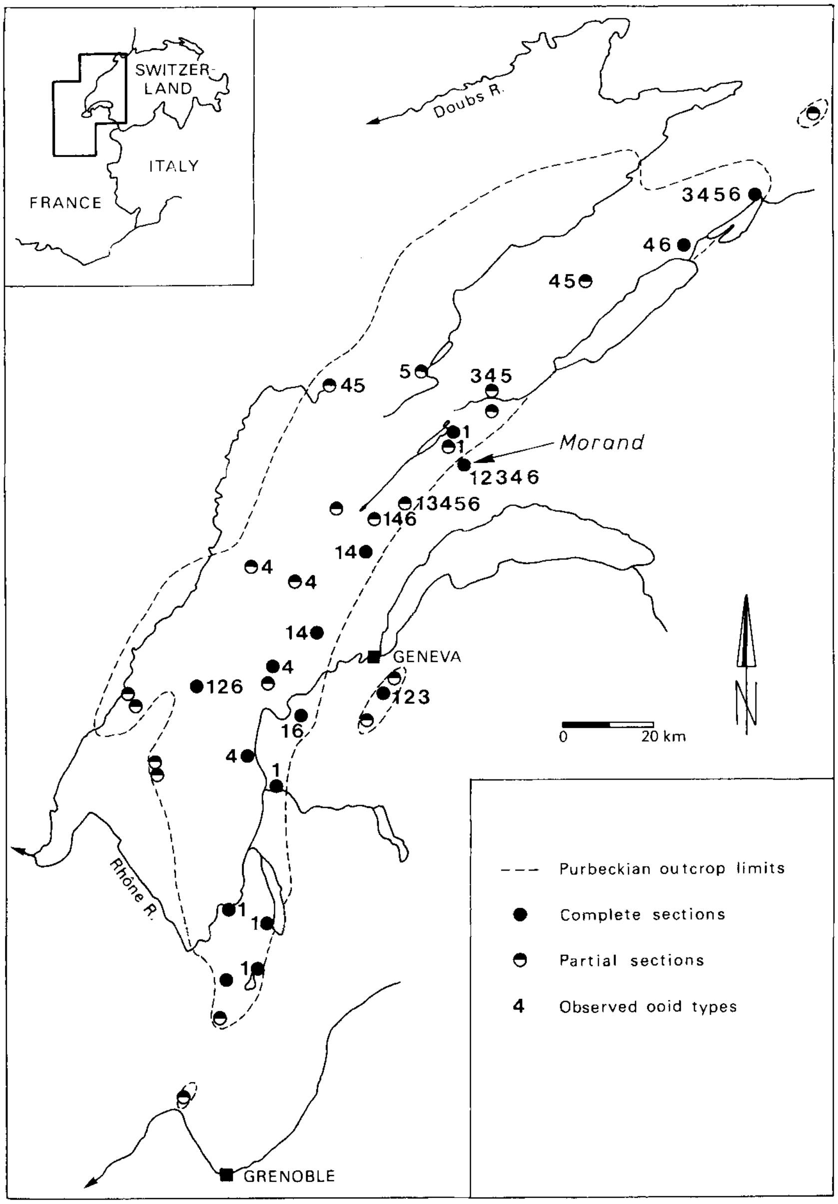


Fig. 1. Studied sections and distribution of ooid types in the Jura. Morand section is shown in Fig. 2.

pods), typical of restricted environments. Grainstones and packstones with dasycladaceans, echinoderms and large agglutinating foraminifera originated under shallow marine conditions.

Black pebbles are found concentrated in conglomerates and storm deposits or dispersed in subtidal, intertidal and supratidal sediments. They indicate subaerial exposure and reworking by waves and storms (Strasser & Davaud, 1983). Calcrete occurs along the south-eastern border of the Purbeckian outcrops. It formed on an island chain separating the shallow and partly emergent Purbeckian platform to the WNW from the open ocean to the ESE (Davaud, Strasser & Charollais, 1983).

Although the Purbeckian facies in the Swiss and French Jura have been studied by several authors (e.g. Carozzi, 1948; Donze, 1958; Häfeli, 1966), little attention has been paid to the ooids. Beds of calcareous ooids were recognized, but the diversity of ooid types and their specific occurrences have never been

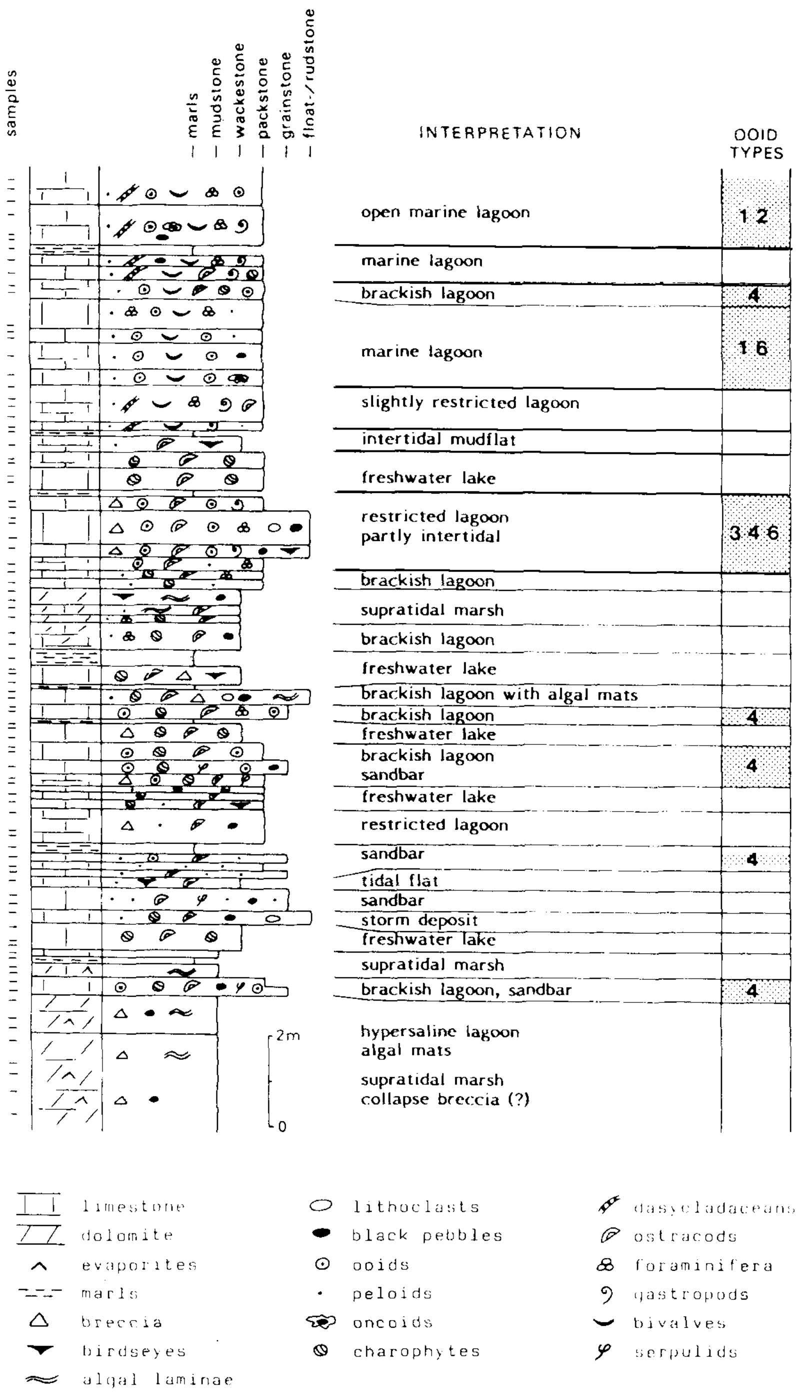


Fig. 2. Example of a Purbeckian facies succession with the related ooid types (Morand section, cores).

documented. In spite of an extensive literature on ooids (for recent reviews see Simone, 1981 and Richter, 1983), some of the physical, chemical and biological factors involved in their formation are not fully understood. However, the present state of knowledge allows ooids to be used as environmental indicators. Comparing the ooid types with Recent and ancient occurrences described in the literature, and inferring the physical, chemical and microbiological conditions of ooid formation, permit a better understanding of Purbeckian depositional settings.

DESCRIPTION OF OOID TYPES

Six types of calcareous ooid can be distinguished in Purbeckian sediments (Fig. 3). Each type displays typical morphological features and a typical cortical structure, but intermediate forms showing the characteristics of two related types are common. Superpositions of laminae of different types resulted in ooids with mixed cortices. Each ooid type is usually related to one specific facies, but two or more related types may coexist in the same sample. Ooid nuclei consist of peloids, intraclasts and micritized or dissolved bioclasts.

Type 1: well rounded micritic ooids with thinly laminated cortices

Ooids of this type have sizes varying between 0·15 and 0·5 mm (mean value about 0·3 mm). They are micritic throughout, but in many cases a darker nucleus can be distinguished from a lighter cortex with many, vaguely visible thin concentric laminae (Fig. 4A). The laminae consist of isometric, anhedral to subhedral crystals 1–5 μm in diameter (Fig. 4B). The ratios between nucleus diameter and thickness of cortex range between 10:1 and 1:3.

Micritic ooids commonly occur in well sorted grainstones, where they constitute up to 90% of the particles. Keystone vugs and rip-up clasts are locally present, suggesting intertidal conditions. Packstones and wackestones also may contain micritic ooids. Rocks which are rich in type 1 ooids are usually poor in fossils. Benthic foraminifera, bivalves, gastropods,

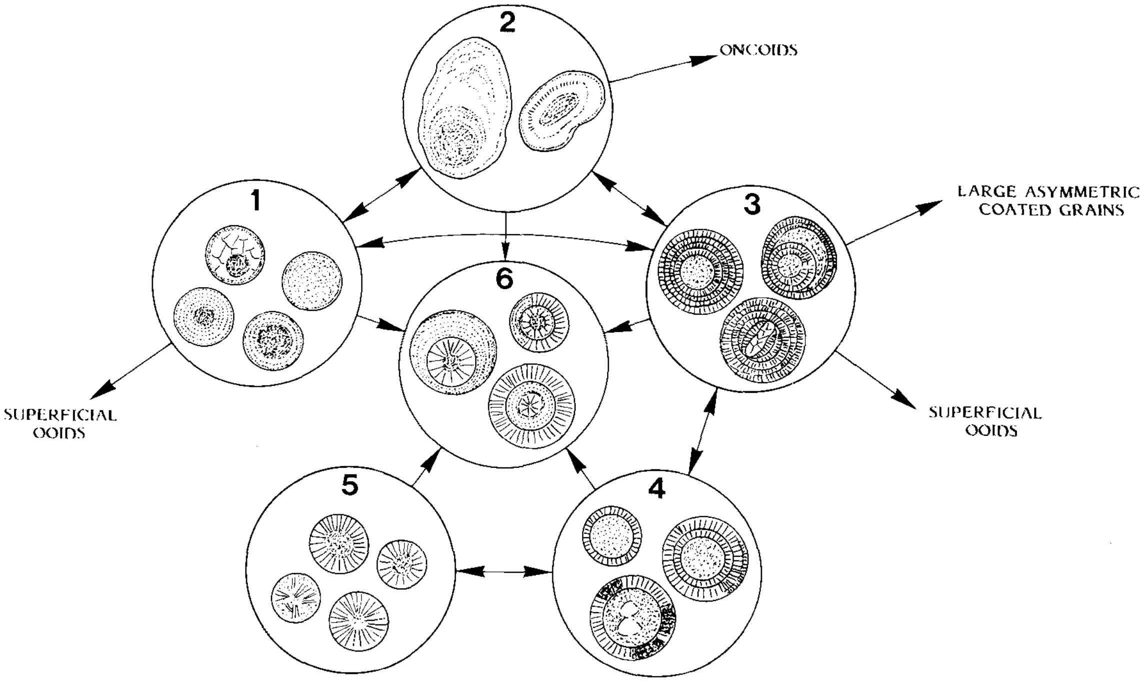


Fig. 3. Schematic representation of the relationships between the six ooid types. Arrows indicate transitions. For further explanation refer to text.

dasycladaceans and serpulids occur sporadically. Faecal pellets, on the other hand, may be abundant. The fauna indicates a marine environment. Sedimentary structures (foresets and herringbone patterns) suggest that these ooids formed on tidally dominated high-energy bars, and were locally washed into quiet-water lagoons or on to the beach. Superficial ooids with just one thin micritic lamina may occur in the same facies. Micritic ooids are also found in facies containing ooids of types 2, 3 and 4, and micritic laminae contribute to the formation of mixed ooids of type 6.

Micritic ooids with partly or totally dissolved cortices occur in packstones (Fig. 4C), wackestones and grainstones. Associated features such as coarsely crystalline stalactitic cements and micritic meniscus cements indicate diagenesis in a vadose freshwater environment. The nuclei were in many cases displaced by gravity, or pushed off-centre by crystal growth of the sparry cement filling the voids (Fig. 4C). The dark outer rims of the ooids are preserved. In other samples, microsparitic fabrics suggest neomorphic replacement (Fig. 4D). SEM pictures locally show small (2–3 μm) rhombic crystals of probable dolomite in the microsparite.

Type 2: irregular micritic ooids with thinly laminated cortices

Ooids of this type are irregularly shaped micritic grains of variable sizes (0·4–3 mm). The cortices show fine laminae which are mostly micritic (Fig. 5). The single laminae are 1–5 μm thick. They first envelop the nucleus concentrically, but later enclose micritic encrustations as well. In the same manner, a second or third nucleus may be incorporated into the grain. Nucleus-to-cortex ratios vary between 10:1 and 2:1. Ooids of this type may grade into oncoids. Alternations of ooidal and oncoidal layers in the same particle are common (Fig. 5B).

Type 2 ooids occur mostly in packstones. Birdseyes, meniscus cements and centrifugal micrite (Purser, 1980, fig. 5B) are locally present and point to intertidal exposure. Associated faunas include benthic foraminifera, codiacean and dasycladacean algae, bivalves, gastropods and echinoderms. The setting was probably protected shallow marine to lagoonal, with abundant growth of codiacean algae and cyanobacteria. Pyrite and (?)chamosite in some of the ooid nuclei indicate locally anoxic conditions. Ooids of type 2 show transitions to type 1 or type 3 ooids. They may also coexist with these types in the same facies. Exceptionally, type 2 laminae are found in mixed ooids.

Type 3: ooids with thinly laminated fine-radial cortices

These ooids have cortices composed of several (3–40) thin laminae which show a fine radial structure and patchy micritization (Fig. 6A, B). SEM pictures show elongate crystals with pointed or rounded ends. The length of the crystals varies between 5 and 30 μm and usually defines the thickness of the lamina. Crystal arrangement is not always strictly radial; bundles of elongate crystals may have a slightly oblique orientation (Fig. 6E). In many cases the laminae are truncated, but individual crystals may reach over the lamina boundary (Fig. 6F). This is thought to be due to early diagenetic epitaxial growth. Strong micritization can completely obliterate the finer patterns and leave ooids with a vague concentric lamination (similar to type 1 ooids, but thicker). Sizes of type 3 ooids vary between 0·2 and 2 mm (mean value about 0·5 mm). The ratios nucleus to cortex lie between 10:1 and 1:6. Ooid shapes are round, elongate or irregularly bumpy (Fig. 6D), but there is usually a tendency to attain sphericity. Laminae on strongly curved edges are commonly eroded and truncated, whereas laminae on less exposed flanks grew continuously and thickened the cortex (Fig. 6C).

Spherical type 3 ooids typically occur in poorly sorted grainstones rich in echinoderms, large benthic foraminifera, thick-shelled bivalves, gastropods and dasycladaceans. This suggests formation in a high-energy marine environment. Later, the ooids were sometimes transported into quiet-water environments and incorporated into packstones and wackestones. Superficial ooids with one type 3 lamina occur locally in the same facies. Type 3 ooids show passages to types 1, 2 and 4, and they may take part in the formation of mixed ooids. In some cases ooids with type 3 laminae show irregular growth forms (resembling 'vadoids' of Peryt, 1983). Such grains are found in beach facies with keystone vugs and micritic vadose cements.

Type 4: ooids with few fine-radial laminae

The cortices consist of one to four laminae which are 10–100 μm thick (Fig. 7A, B). They show a fine radial structure. Individual crystals are slightly thicker than those of type 3 laminae (Fig. 7D). Lateral passage from radial to thinly laminated micritic fabric is

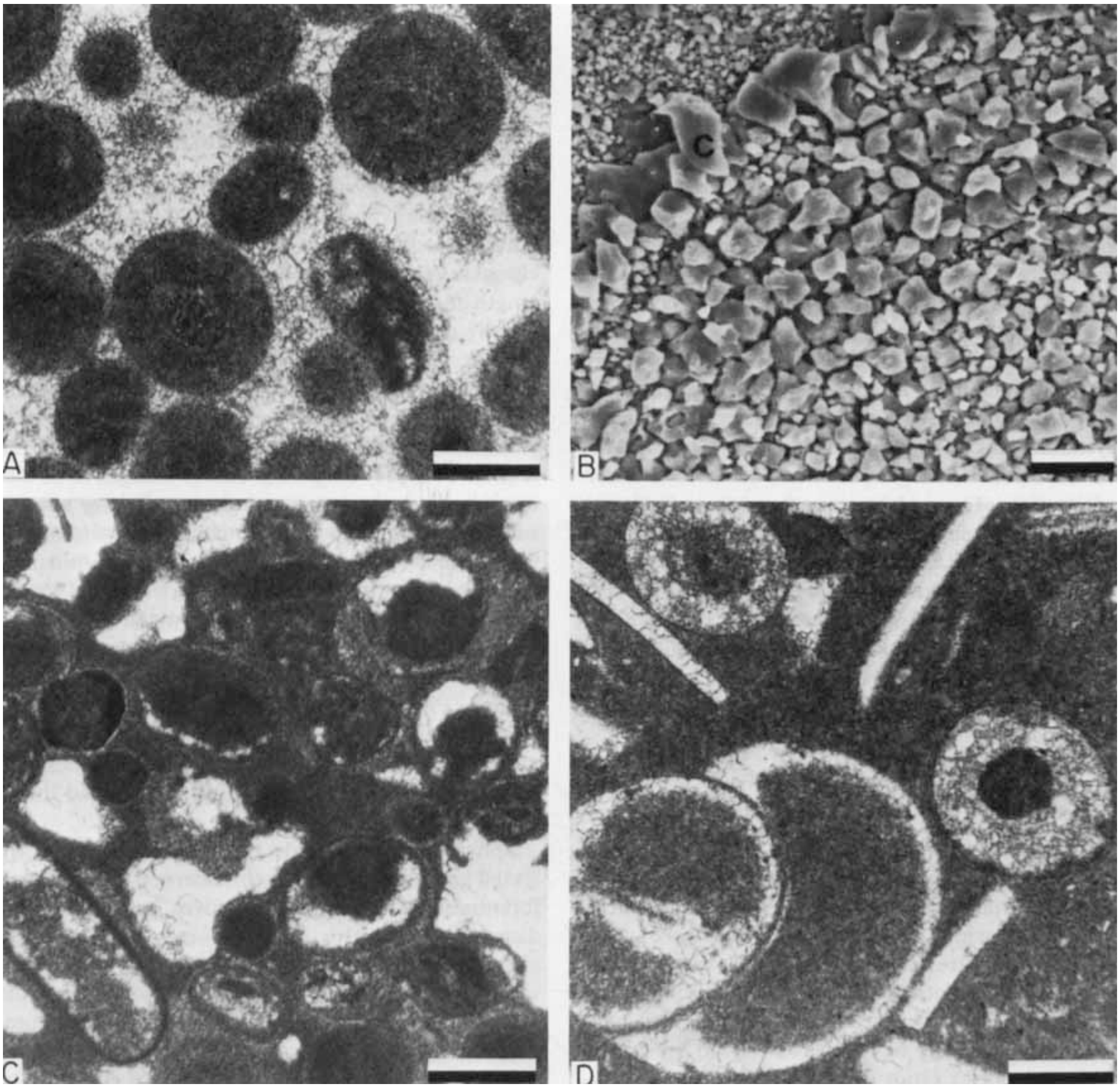


Fig. 4. Type 1 ooids, thin section and SEM photographs. (A) Micritic, well rounded ooids with vaguely visible nuclei and fine concentric laminae. Scale 0.2 mm. (B) Section of cortex showing subhedral and anhedral crystals. Size differences mark primary concentric laminae. Larger crystals (C, upper left) are rim cement. Scale 10 µm. (C) Partly dissolved micritic ooids, the voids now filled with calcite spar. Some of the ooid nuclei have been displaced. Note the dark micritic outer laminae defining the original ooid surfaces. Scale 0.2 mm. (D) Neomorphic replacement of ooid cortices by microsparite. Primary aragonitic gastropod shells have been dissolved and replaced by calcite spar. Scale 0.2 mm.

common (Fig. 7B, C). Micritization is localized to a few areas in the cortex, where it attacked whole sectors from core to surface, or where it spread out along lamina boundaries (Fig. 7C, D). The sizes of type 4 ooids vary between 0·2 and 0·6 mm, the average being about 0·3 mm. They are well rounded. Nucleus-to-cortex ratios range from 20:1 to 1:1. In some samples, ooid nuclei are greenish (?)chamositic peloids. Also charophytes may serve as nuclei.

Type 4 ooids are found in moderately well sorted packstones and wackestones containing miliolid foraminifera, bivalves, gastropods, serpulids, ostracods

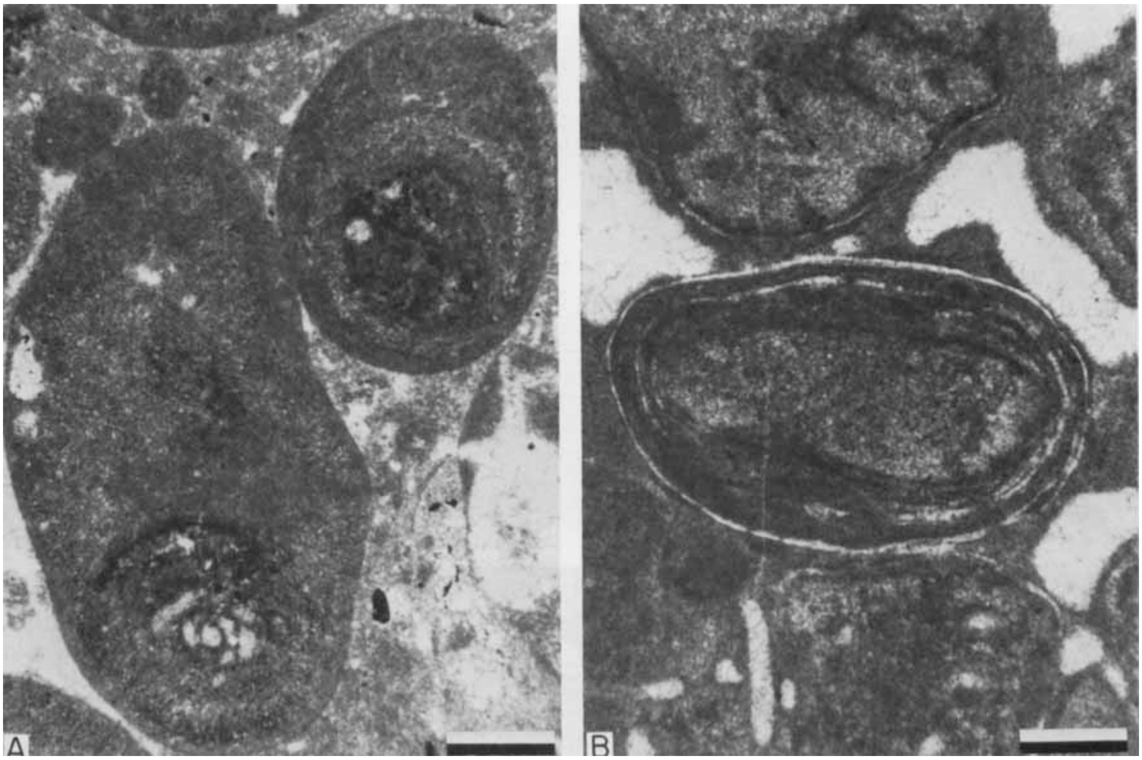


Fig. 5. Type 2 ooids, thin section photographs. (A) Large irregular ooids-oncoids with vaguely discernible micritic laminae. The nuclei display a regular concentric pattern and are pyritized. Scale 0.2 mm. (B) Ooid-oncoid with some thin radially structured laminae (showing white). The pores are coated with centrifugal micrite indicating intertidal exposure.

and charophytes. This faunal association implies a brackish lagoonal environment. Birdseyes, meniscus cements and vadose silt point to temporary intertidal or supratidal exposure (Fig. 7A, B). These ooids show transitions to type 3 and type 5 ooids. In some facies they coexist with ooids of types 1, 3 or 5. Type 4 laminae are commonly found in mixed ooids.

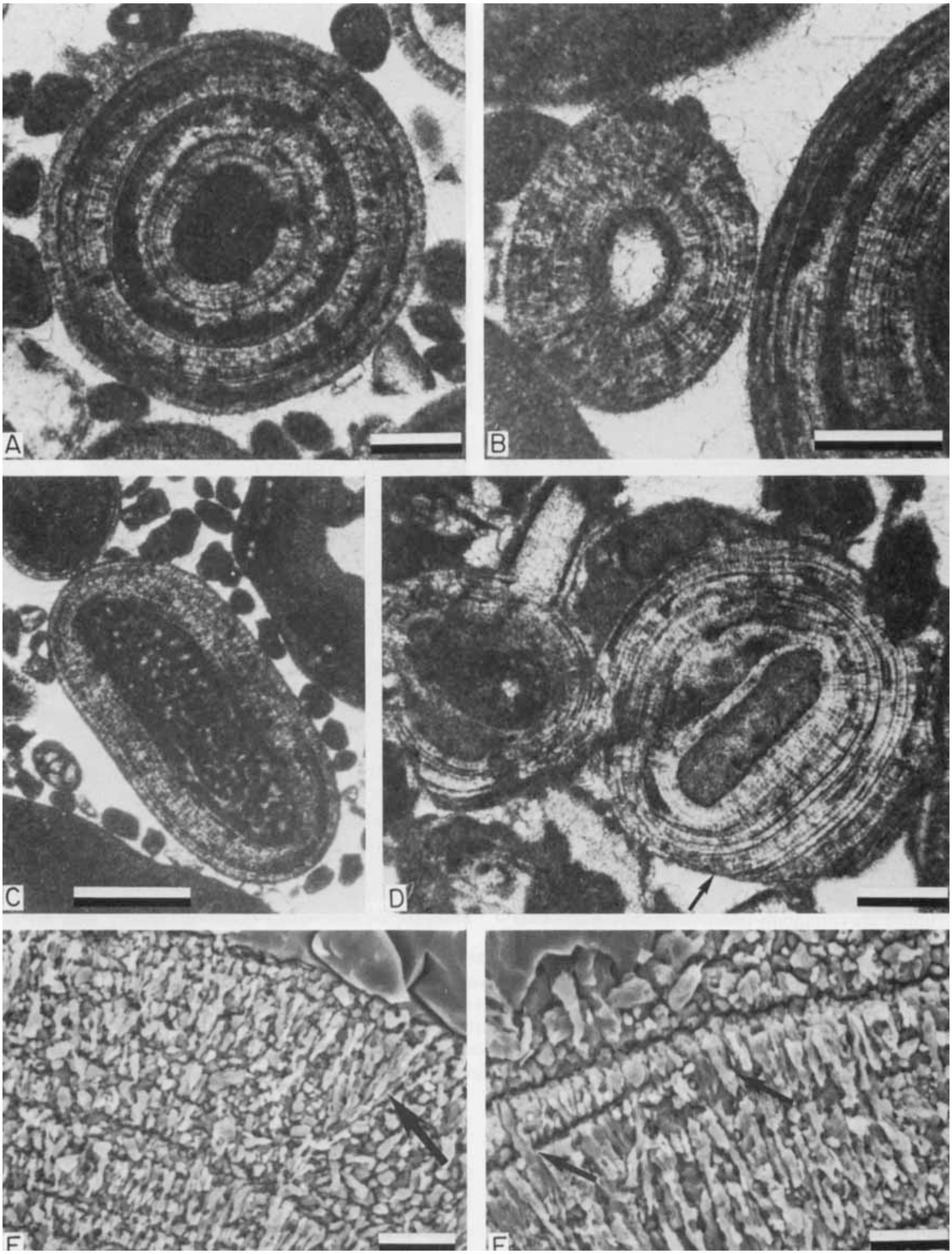
Type 5: ooids with coarse-radial cortices

The cortices of type 5 ooids are made of one (rarely two) lamina with a coarse radial structure (Fig. 8A, B, C). The laminae are 10–60 μm wide, the individual crystals up to 5 μm thick (Fig. 8D). Micritization follows the radial pattern and becomes more intense towards the surface of the grains. The ooids are well rounded. Their diameters vary between 0·15 and 0·5 mm, their nucleus-to-cortex ratios between 5:1 and 1:5. Type 5 ooids are found together with spherical grains with irregular internal structures, commonly consisting of bundles of club-like crystals (Fig. 8D). These grains, 0·1–0·25 mm in diameter, have poorly defined outlines (Fig. 8A, B). Spherical grains with irregular radial structures may develop into regularly structured, coarse radial ooids with sharp outlines.

Coarse-radial ooids occur in usually well sorted grainstones and packstones and are associated with benthic foraminifera, bivalves, gastropods and ostracods. This implies a lagoonal environment with varying water energy. Incorporated beds of dolomicrite and evaporites indicate partly supratidal and hypersaline conditions. Type 5 ooids show transitions to ooids of type 4. They are commonly found in facies containing ooids of types 3 and 4, and they serve as nuclei of mixed ooids.

Type 6: ooids with mixed cortices

The cortices are composed of various types of laminae. The following combinations have been observed (from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core to surface): 3–1, 4–1 (Fig. 9A), 5–1, 3–1–4, 3–1–4–1, 5–1–4 (Fig. 9B), 5–4. Passages from type 4 to type 1 also occur laterally in the same lamina (Figs 7C, 9C, D, E). Type 1 laminae commonly show partial or total dissolution (Fig. 9B, D, F). A very complex coated grain is shown in Fig. 9F: a mixed ooid (3–1–4) has been asymmetrically overgrown by oncoidal laminae of type 2 and by a disrupted lamina of type 4. Sizes of mixed ooids are highly variable (0·1–1 mm), but they are usually well rounded. They always occur together with other ooid types, mostly with those which participated in their formation.

Mixed ooids are found in wackestones and packstones containing lagoonal faunas such as benthic foraminifera, bivalves, gastropods, ostracods and serpulids. Charophytes may be present.

DISCUSSION AND INTERPRETATION

The differences in cortical structure and diagenetic behaviour between the Purbeckian ooid types suggest different geochemical, hydrodynamic and probably microbiological parameters which were responsible for their formation. These parameters define specific environmental settings.

Primary mineralogy

Radially structured ooid cortices (types 3, 4 and 5) appear to have been composed of relatively stable carbonate phases. Except for superficial corrosion (Fig. 9D, F), radial laminae never show signs of dissolution. Even if associated with features of vadose freshwater cementation and diagenesis (stalactitic and meniscus cements, partial dissolution; Figs 6D, 7B), and even if the ooid nuclei have been dissolved (Figs 6B, 7A, B) the radial cortices were not affected. A primary composition of low-Mg calcite could well explain this good preservation of the radial fabrics (Walter, 1985). However, Recent and Pleistocene marine and marine-lagoonal radial-calcitic ooids consist of high-Mg calcite (Marshall & Davies, 1975; Land, Behrens & Frishman, 1979; Milliman & Barretto, 1975), and it has been assumed by Richter (1983) that also ancient radial-calcitic ooids from marine sediments were originally composed of high-Mg calcite.

Purbeckian type 3 ooids are associated with marine faunas. It is therefore possible that their cortices consisted originally of high-Mg calcite. According to Stehli & Hower (1961) and Gavish & Friedman (1969), Mg-calcite converts faster to low-Mg calcite than aragonite when exposed to freshwater diagenesis, without textural changes of the affected crystals. This could explain the differential dissolution of probably primarily aragonitic shells which served as nuclei of type 3 ooids (Fig. 6B).

In hypersaline environments of the Purbeckian one would expect relatively high concentrations of magnesium which would lead to aragonitic or high-Mg calcite precipitation (Bathurst, 1971). Freshwater or brackish influence, on the other hand, would lower the Mg/Ca ratio (through input of leached continental Ca) and favour low-Mg calcite ooids. Type 4 ooids are commonly associated with faunas indicating brackish water. A primary low-Mg calcite composition is therefore probable. Type 5 ooids are in many cases related to evaporitic sediments and may have been composed of high-Mg calcite. Seasonal freshwater inputs, however, could also have led to the formation of low-Mg calcite cortices.

Micritic ooids of type 1 locally show partial or total dissolution of their cortices (Fig. 4C). The displacement of the nuclei indicates dissolution of the cortex prior to the growth of the void-filling cement. Centred nuclei and microsparitic replacement of the cortices (Fig. 4D) suggest that the cortices were primarily micritic or micritized before unstable carbonates were transformed to stable ones (neomorphic microsparitization; Bathurst, 1971). Nuclei and outermost laminae of type 1 ooids commonly resisted dissolution (Fig. 4C). Surfaces of grains serving as nuclei and of the ooids themselves were probably colonized by endol-

Fig. 6. (OPPOSITE) Type 3 ooids, thin section and SEM photographs. (A) Well rounded ooid exhibiting many thin radially structured laminae. Micritization is patchy, or attacks entire layers. Scale 0.2 mm. (B) Fine-radial ooid with dissolved (primary aragonitic ?) nucleus. Scale 0.2 mm. (C) Elongate ooid which formed around large foraminifer. The ooid cortex is thicker on the flat sides and thinner on the pointed ends. Scale 0.5 mm. (D) Fine-radial ooids with irregular shapes. Truncation of cortex (arrow) is probably due to early diagenetic freshwater dissolution. Scale 0.2 mm. (E) Radial arrangement of carbonate crystals in type 3 cortex. Note bundle of elongate crystals (arrow). Large crystals at top right are pore-filling cement. Scale 10 μm. (F) Individual radial laminae are cut off, probably by abrasion. Some crystals reach over the lamina boundaries (arrows) which may indicate secondary growth. The ooid surface is not well defined, as some crystals merge with the pore-filling cement (top left). Scale 10 μm.

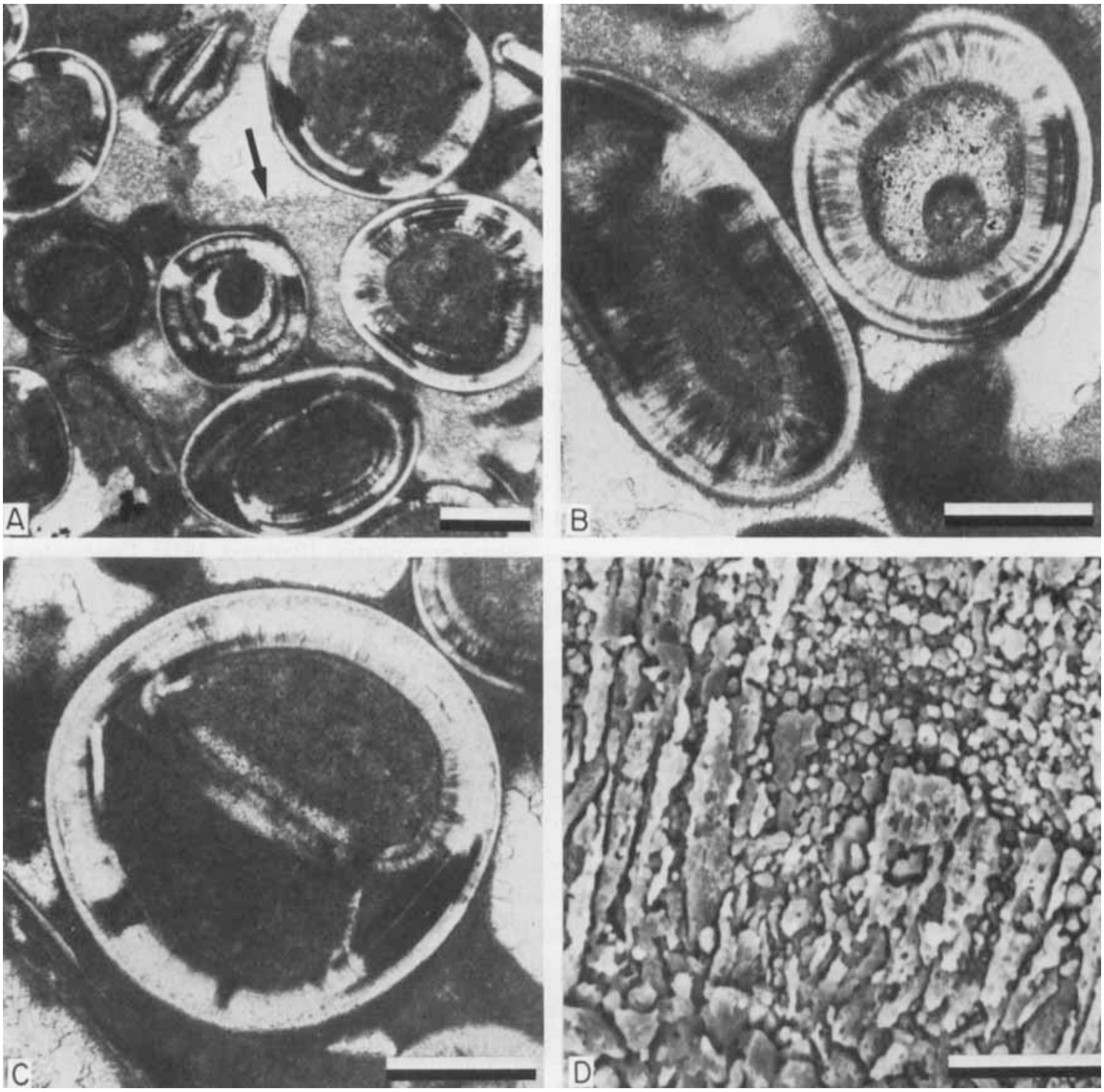


Fig. 7. Type 4 ooids, thin section and SEM photographs. (A) Fine-radial ooids with one to four laminae and patchy micritization. Meniscus cements and stratified internal sediment (arrow) point to deposition in the intertidal zone. The inner cortex of the ooid at the centre of the photograph was composed of unstable carbonate and dissolved. The nucleus was then displaced by crystal growth of the void-filling calcite cement. Scale 0.2 mm. (B) Fine-radial cortical fabric passes locally into thinly laminated micritic fabric. Note well developed micritic meniscus cements and displaced nucleus of ooid at right. Scale 0.2 mm. (C) Fine-radial ooid with complex internal and cortical structures. Lateral passage from radial to micritic-laminated fabric at lower right of picture. Scale 0.2 mm. (D) Corroded, club-like and pointed crystals of a type 4 cortex. Micritization has partly destroyed the radial fabric. Scale 10 μm.

ithic microorganisms causing intense micritization (Bathurst, 1971). Coating of the micrite crystals with organic matter or mineral transformations induced by microbial metabolism may then have prevented the dissolution (Chave & Suess, 1970; Jackson & Bischoff, 1971). Dissolved or neomorphically replaced ooid cortices are found next to dissolved gastropod shells of primary aragonitic composition (Fig. 4D). Further-

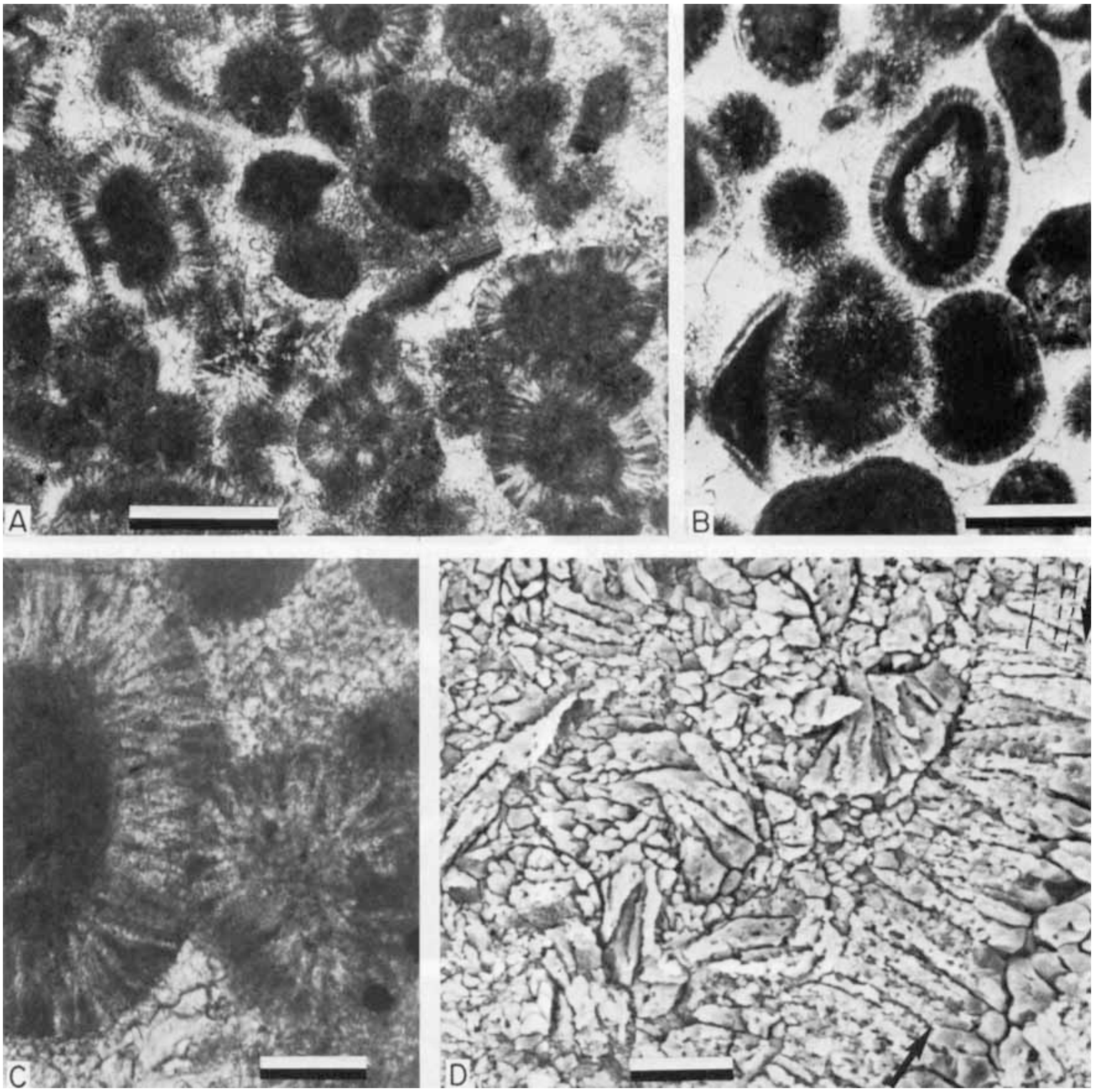
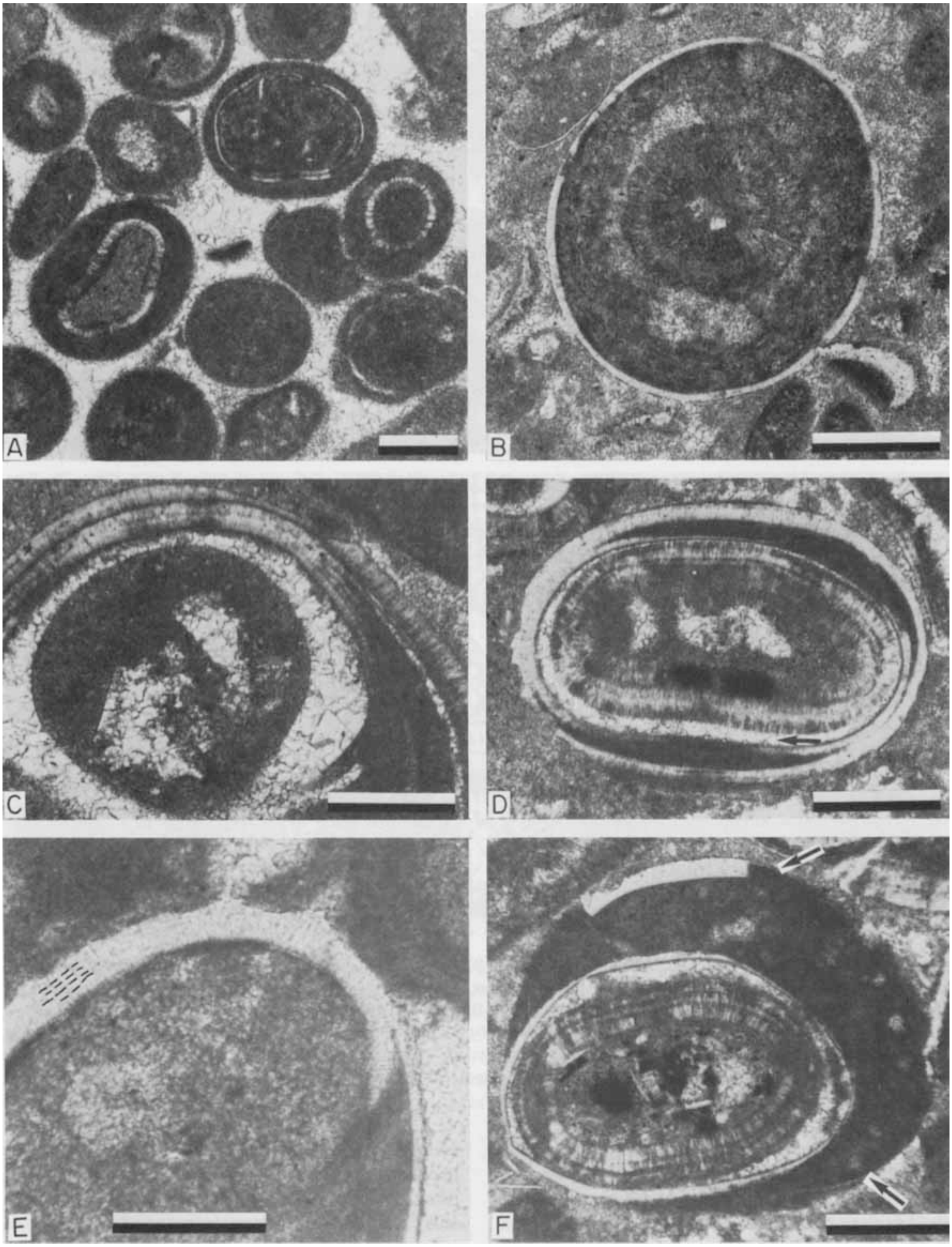


Fig. 8. Type 5 ooids, thin section and SEM photographs. (A, B) Coarse-radial ooids and spherical grains with diffuse outlines and irregular radial structures. Note partly dissolved nucleus (top centre of B). Scales 0.2 mm. (C) Detail showing radial crystals which make up the ooid cortices. Scale 0.05 mm. (D) Bundles of club-like crystals in the nucleus imply crystal growth inside a peloid. The crystals of the radial cortex (right side of photograph) are corroded at their base, but show smooth tips. The ooid surface was probably as marked by arrows, and crystal growth continued epitaxially to form cement. Vaguely visible banding in cortex (enhanced at top right) indicates growth stages. Scale 10 μm.

more, type 1 laminae in mixed ooids show preferential dissolution (Fig. 9B, D, F). This points to a carbonate stability which was about the same as that of aragonite, and less than that of the radial calcitic laminae. This implies a primary aragonitic or high-Mg calcite composition of type 1 laminae. Carbonate stabilities depend not only on the mineralogical composition, but also on the microstructure of the grains (Walter, 1985). Type 1 laminae are composed of small crystals with a high exposed surface area and would have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dissolved faster than radial laminae composed of larger crystals of the same mineralogy. Inclusions of microdolomite observed in some neomorphosed cortices suggest an elevated primary Mg content (Tucker, 1984).

Type 1 cortices do not show elevated strontium values as would be expected for a primary aragonitic composition (Kahle, 1965; Brand & Veizer, 1983; Tucker, 1985). This means that either diagenesis has depleted the sediment of Sr, or that the cortices were not aragonitic. Coarsely crystalline neomorphic calcite replacing aragonite, as recorded from several ancient oolites (Rich, 1982; Tucker, 1984; Wilkinson, Buczynski & Owen, 1984), or aragonite relics (Sandberg, 1975) have not been found in these Purbeckian ooids. On the other hand, a primary high-Mg calcite composition usually leads to radial cortical structures (Richter, 1983) and would be preserved by early diagenetic transformation to stable low-Mg calcite, as it is suggested for the type 3 ooids. The question of whether type 1 cortices were originally composed of aragonite or of high-Mg calcite therefore remains open.

Type 2 ooids show little evidence of dissolution. This could be due to an increased content of organic matter in the oncoidal laminae which protected unstable carbonate crystals from dissolution, to microbiological transformation of unstable carbonate phases into stable ones, or to a primary relatively stable composition.

The role of organic matter in ooid formation and its influence on primary mineralogy has been described by many authors (e.g. Suess & Fütterer, 1972; Davies, Bubela & Ferguson, 1978; Mitterer & Cunningham, 1985). It is probable that the primary mineralogy of Purbeckian ooids was determined not only by physicochemical parameters, but also by organic substances in the water and on the grain surfaces.

Hydrodynamic implications

According to Rusnak (1960) and Land *et al.* (1979), rapid carbonate precipitation on ooid surfaces produces micritic cortical layers with random orientation of the crystals. Slower precipitation and weak agitation cause radially structured laminae, and very slow precipitation coupled with strong agitation leads to tangential orientation of the crystals. Loreau & Purser (1973) concluded that the development of random structures in aragonitic ooids starts with the abrasion of the tips of radial crystals. With increasing grain-to-grain collision during strong agitation the ooid surfaces are mechanically flattened, and the crystals develop a tangential orientation (Davies *et al.*, 1978). The thinly laminated micritic cortices of Purbeckian type 1 ooids could therefore imply a primary random or a micritized primary tangential fabric, i.e. rapid precipitation of the cortical layers and/or high water energy.

Radial cortical fabrics commonly form in calm waters (Suess & Fütterer, 1972; Davies *et al.*, 1978). Primary calcitic radial ooids, however, do not always imply quiet-water formation. Calcite crystals tend to keep their radial arrangement even in high turbulence (Medwedeff & Wilkinson, 1983). Radial type 3 ooids may reflect a succession of growth and sleeping stages (Davies *et al.*, 1978), with frequent abrasion of the ooid surfaces during strong agitation. Types 4 and 5 indicate less and only periodic water turbulence, allowing for a more continuous growth of the radial crystals.

Quiet-water ooids tend to grow asymmetrically (Fig. 5A), because the rounding effect of mechanical abrasion is lacking (Freeman, 1962). Superficial ooids with types 1 or 3 laminae also indicate rather low water energy (Bathurst, 1967). Eccentric ooids (Fig. 6D) formed through phases of quiet-water growth and erosion during transport (Gasiewicz, 1984). On the

Fig. 9. (OPPOSITE) Type 6 ooids, thin section photographs. (A) Mixed ooid with inner radial (type 4) and outer micritic (type 1) cortices. Scale 0.2 mm. (B) Mixed ooid with nucleus of type 5, partly dissolved cortex of type 1, and outer lamina of type 4. Scale 0.2 mm. (C) Detail showing passage from fine-radial type 4 fabric into micritic lamination of type 1. Dissolved and spar-filled inner layer is probably part of a gastropod shell. Note the pseudomorphs after secondary dolomite in the micritic chamber filling. Scale 0.2 mm. (D) Mixed ooid with preferential growth of micritic laminae on the flat sides. At the base of the micritic zones, a radial lamina passes into fine micritic laminae. The dissolved layer at the bottom and on the left of the grain (arrowed) consisted of an unstable carbonate phase (aragonite ?). The surface of the ooid is corroded (left). Scale 0.2 mm. (E) Detail of a lateral passage from fine-radial to micritic-laminated fabric. In the radial part of the cortex, a vague lamination is visible (enhanced at left). The outermost radial layer overrides the micritic laminae at right of photograph. Scale 0.1 mm. (F) Complex mixed ooid displaying a partly dissolved and pyritized nucleus, a radial inner cortex, a mostly dissolved layer, a fine-radial lamina with an irregular corroded surface, an asymmetrical oncoidal overgrowth, and an outermost radial lamina which can be very thin (arrows), or which seems to be implanted on the top of the ooid. Scale 0.2 mm.

other hand, the round shapes of the small radial ooids and radially structured grains of type 5 do not necessarily indicate a high-energy environment. Homogeneous growth of the cortex (consisting only of one lamina) reproduces the round shape of the nucleus, and the tendency of humate coatings to minimize the exposed surface area will lead to a spherical grain (Suess & Fütterer, 1972). Radially structured (although aragonitic) spherulites occur in Recent algal mats in hypersaline pools (Friedman *et al.*, 1973) and in algal tufa (Buchbinder, Begin & Friedman, 1974).

Mixed ooids of type 6 were probably subjected to alternating quiet and agitated hydrodynamic conditions (Reijers & Ten Have, 1983; Poncet, 1984). Ooids with inner radial and outer micritic laminae (Fig. 9A) could have formed according to the model of Heller, Komar & Pevear (1980), where radial fabrics form while the ooids are small and in suspension, and micritic fabrics through abrasion when the ooids are large enough to be transported as bedload. It has been shown by Given & Wilkinson (1985) that fluid shear not only has an influence on the arrangement of the carbonate crystals in the cortex, but may also determine their mineralogy. In fact, the differential dissolution of many type 6 cortices may indicate a different primary composition (Fig. 9B, D, F). Lateral changes of cortical fabric in one lamina (Figs 7C, 9C, D, E) may be due to very localized chemical, biochemical and/or hydrodynamic changes. The polarity of the ooid cortex in Fig. 9D, where fine micritic laminae developed preferentially on the flat sides of the grain, could have been caused by mechanical breaking of radially growing crystals due to rolling on the long axis, leading to a micritic fabric.

Environmental settings

A general trend in the distribution of Purbeckian ooids is clearly expressed in Fig. 1: type 1 ooids occur preferentially to the south and to the east of the studied area, type 2 and type 3 ooids to the east, and type 4, 5 and 6 ooids to the north and to the west.

Following the hypotheses stated above, type 1 ooids formed in normal-marine shallow waters under high-energy conditions. Ooid sizes, sedimentary features and sorting are comparable to those described from the Bahamas (Harris, 1979). Type 1 ooids accumulated on small sandbars under the influence of tidal currents. Migration or transport by storms and springtides deposited some ooids in quiet-water environments, or in the intertidal and supratidal zones. Type 2 ooids formed in a quiet-water lagoonal environment with abundant growth of codiacean algae and cyanobacteria. The radial ooids of type 3 indicate marine conditions and frequent stirring-up of the sediment. Locally, longer periods of quiescence produced irregular ooid shapes. Water chemistry and/or microbial activity were probably somewhat different from those of the type 1 environment, so that precipitation of radial calcite was favoured. Radial ooids of type 4 and 5 represent restricted lagoons of varying salinity with charophytes and ostracods. Hypersaline deposits are often nearby. Water energy was low, but periodic storms could move the sediment and accumulate the ooids in sandbars.

At the Jurassic–Cretaceous boundary the Swiss and French Jura was situated at a palaeolatitude of about 38° north (Barron *et al.*, 1981). Studies of Purbeckian tree rings in Dorset (England) indicate that the Purbeckian climate was of Mediterranean type, with warm and rainy winters, and hot and dry summers (Francis, 1984). Hypersaline pools with evaporites formed in summer, to be replaced by freshwater or brackish ones in winter. Comparable settings are found today in South Australia (West, 1975; Warren, 1982).

On the shallow and partly emergent Purbeckian platform shape and exposure of lagoons and landforms were constantly modified by waves, tides and storms. Rainfall and evaporation changed water chemistry and microbiological conditions. The always shifting depositional environments show well in the stratigraphic record (Fig. 2). This variability of settings is reflected in the many different cortical fabrics of the ooids, and probably already small changes of environmental conditions lead from one ooid type to another. The mixed ooids of type 6 have undergone relatively rapid (maybe seasonal) changes of hydrodynamic regimes and/or water chemistry, either at the locality where they formed, or through transport from one environment to the other. Differential dissolution of ooid cortices, mineral transformations, epitaxial crystal growth (Fig. 8D) and cementation were stimulated in the freshwater vadose and phreatic zones forming on and underneath islands (Longman, 1980).

It has been demonstrated by Mackenzie & Pigott (1981), Sandberg (1983) and Wilkinson *et al.* (1984) that non-skeletal aragonite and high-Mg calcite precipitation was reduced in the Jurassic and Cretaceous due to elevated CO_2 pressure. This coincides roughly with high sea-level. However, the relative lowstand of sea-level during the Purbeckian (Vail, Hardenbol & Todd, 1984) could have permitted some formation of aragonite and high-Mg calcite, as it has been inferred for the ooid types 1 and 3.

The proposed hydrodynamic and geochemical conditions for the formation of Purbeckian ooids are summarized in Fig. 10. A synoptic sketch of possible depositional environments is shown in Fig. 11.

CONCLUSIONS

The six types of calcareous ooid found in the Purbeckian sediments of the Jura Mountains characterize specific depositional environments. The cortical fabrics (micritic and thinly laminated, fine or coarse radial) and the diagenetic behaviour (differential dissolution of cortical laminae) express the various geochemical, hydrodynamic and microbiological parameters which led to ooid formation. These parameters, along with sedimentary structures and faunal associations, permit to define Purbeckian depositional settings: high-energy, tidally controlled sandbars in a fully marine environment (type 1 ooids); low-energy, marine-lagoonal setting with growth of cyanobacteria (type 2); marine environment with intermittent high energy (type 3); restricted-marine to brackish with intermittent high energy (type 4); restricted-marine to hypersaline, probably low energy (type 5).

Frequent transitions from one ooid type to another, coexistence of several types in the same facies, and superposition of various cortical laminae (type 6 ooids) reflect gradual or abrupt changes in hydrodynamic regimes, water chemistry and/or microbiological activity. Such changes have been caused by shifting coastal morphology which opened and closed lagoons, by climatic factors affecting water chemistry through evaporation or rainfall, and by high-energy events such as storms which mixed water and sediment from various sources.

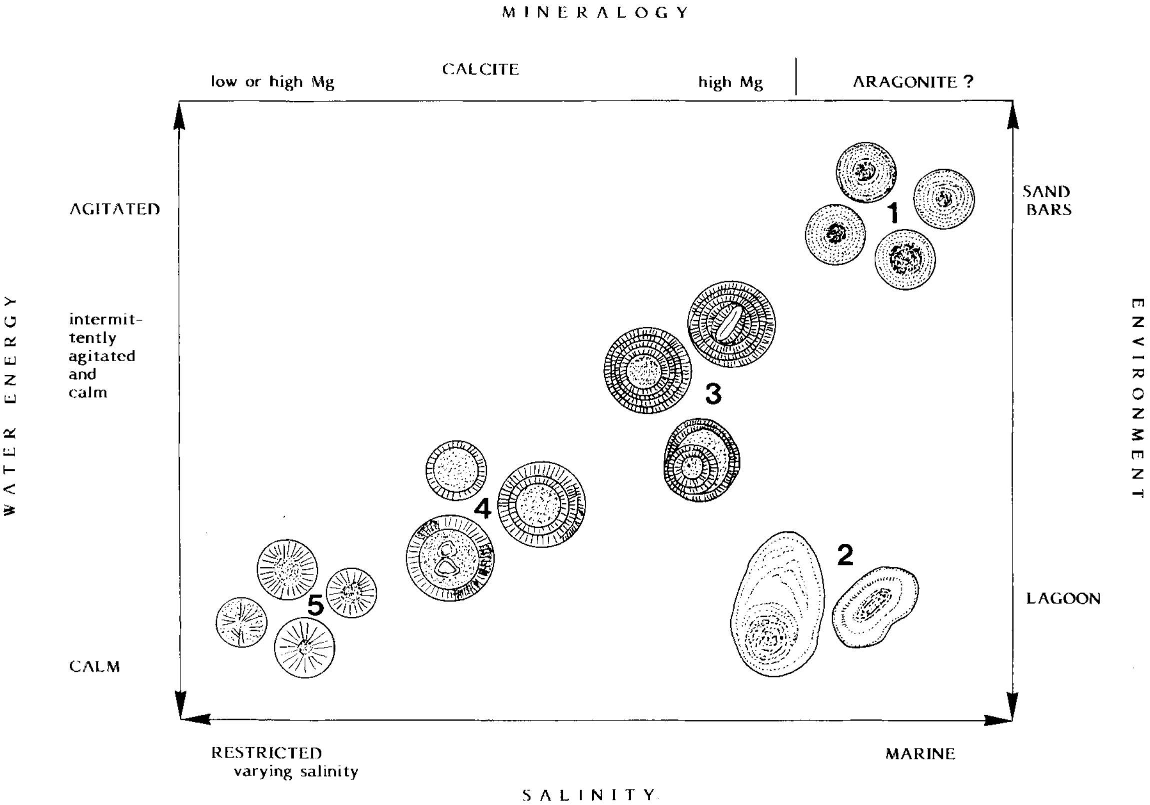

Fig. 10. Schematic representation of inferred primary mineralogy, water energy, salinity, and depositional environment of the ooid types. Type 6 is not represented, as it reflects changing environments.

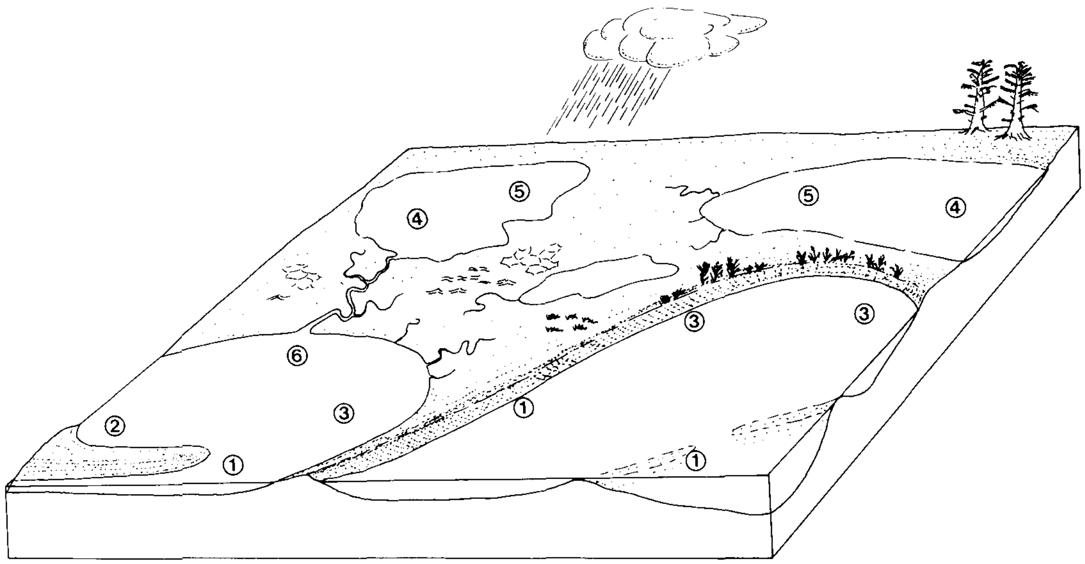

Fig. 11. Synoptic sketch of Purbeckian environments where ooids may have formed (numbers represent ooid types). The picture shows low tide; at high tide or during storms the entire tidal flat was flooded. For further details refer to text.

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