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Shallowing-upward sequences in Purbeckian peritidal carbonates (lowermost Cretaceous, Swiss and French Jura Mountains)

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ABSTRACT

Purbeckian carbonates in the Swiss and French Jura (Goldberg Formation, lower Berriasian) comprise shallow-subtidal, intertidal, supratidal, low-energy, high-energy, marine, brackish, freshwater, and hypersaline facies. These facies are arranged in small (0·2–1·5 m thick) sequences which display a dominant shallowing-upward component, and which form the fundamental units of the highly structured Purbeckian sedimentary record.

Six types of small-scale sequences can be recognized. A: intertidal to supratidal overprinting of shallow lagoonal facies; B: algal-marsh sequence with frequent dolomitization; C: sabkha sequence, often associated with collapse breccia; D: tidal-flat sequence with desiccation features; E: lacustrine sequence; F: terrestrial overprinting of subtidal or intertidal facies. Episodic event deposits such as tempestites are superimposed. Thin transgressive beds which rework elements of the underlying facies are frequently found at the base of the sequences. Green marls and black pebbles are common at the top and indicate long subaerial exposure. The sequences are often incomplete, as subtidal facies may be absent, or their upper part can be eroded. Lateral facies changes are common, which is due to the very shallow and partly emergent Purbeckian platform where various depositional environments were juxtaposed. However, many sequence boundaries are well developed and can be correlated over large parts of the study area.

The Purbeckian shallowing-upward sequences were generated by climatically controlled sea-level changes. Autocyclic processes occurred locally, but were overprinted by drops of sea-level affecting the entire platform. The small-scale sequences are most probably related to the 20 000-year cycle of the precession of the equinoxes. Larger sequences with usually well-developed emersion surfaces are attributed to the 100 000 and 400 000-year eccentricity cycles of the Earth's orbit. Identification and correlation of sequence boundaries makes it possible to set up a framework of isochronous surfaces (which often cut across facies boundaries), and thus to interpret in detail the palaeogeographic, sedimentological and diagenetic evolution of the Purbeckian peritidal carbonate environments.

INTRODUCTION

In the Jura, Purbeckian carbonates overlie dolomites and limestones of Portlandian (late Tithonian–early Berriasian) age. Precise dating of a lower limit is difficult, as good biostratigraphical markers are absent. The typical Purbeckian facies assemblage of shallow-subtidal to supratidal and restricted-marine to lacustrine sediments was defined as Goldberg Formation by Häfeli (1966) in the area of Bienne (type section close to section Bi, Fig. 1). Based on ostracod faunas, Häfeli correlated it with the Lower and parts of the Middle Purbeck in Dorset, England. In the southern part of the Jura, however, the formal stratigraphy has yet to be established (Strasser, in prep.).

The Purbeckian is capped by marine limestones (Pierre-Châtel Formation) expressing a major transgression. This upper limit is well defined and can be correlated over the entire study area. Clavel *et al.* (1986) situated the lower part of Pierre-Châtel at the base of the Tethyan *Occitanica*-Zone (Berriasian).

Purbeckian carbonates formed on the wide and very shallow carbonate shelf at the northern margin of the Tethys ocean. They consist of marine, brackish, hypersaline and freshwater facies and were deposited in subtidal, intertidal or supratidal, high-energy or low-energy environments. Outcrop limits and studied sections are indicated in Fig. 1. Marly layers are abundant, especially in the northern part of the study area, resulting in poor outcrop and sections partly overgrown by vegetation.

The first comprehensive work on Purbeckian carbonates in the Jura was carried out by Maillard in 1884. Since then, many authors have contributed to the understanding of Purbeckian stratigraphy, facies and sedimentology (e.g. Joukowsky & Favre, 1913; Carozzi, 1948; Donze, 1958; Häfeli, 1966; Ainardi, 1977). Recent studies include Strasser & Davaud (1982, 1983), Strasser (1986), Mojon & Strasser (1987), and Deconinck & Strasser (1987).

The Purbeckian deposits are fully divisible into small-scale facies sequences displaying a shallowing-upward tendency. Such sequences are encountered in many other shallow-water settings (e.g. Fischer, 1964; Wilkinson, 1982; Wright, 1986; Grotzinger, 1986; Hardie, Bosellini & Goldhammer, 1986). Reviews and models on the formation of shallowing-upward sequences have been published by James (1984), Wright (1984), and Read *et al.* (1986). Goodwin & Anderson (1985) proposed the hypothesis of punctuated aggradational cycles (PACs), where one small-scale sequence represents the fundamental time–stratigraphic unit of the sedimentary record. A series of publications linking small-scale sequences to climatic cycles controlled by the Earth's orbit (Milankovitch cycles) has been gathered in a volume edited by Arthur & Garrison (1986).

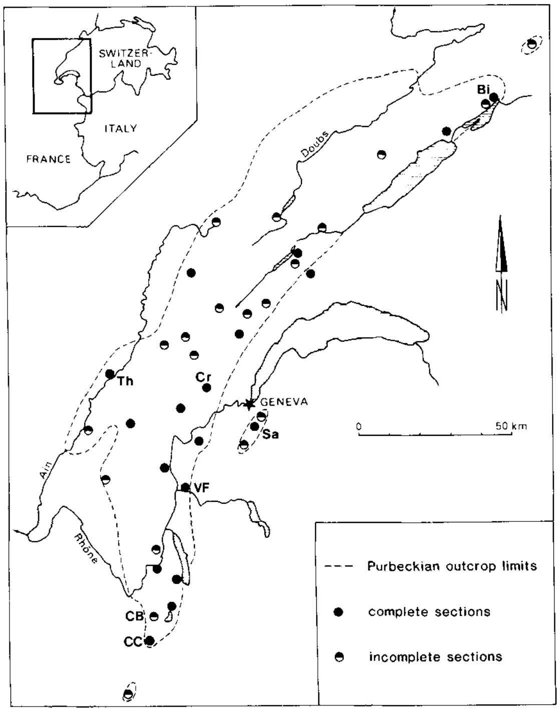


Fig. 1. Purbeckian outcrop limits and studied sections in the Swiss and French Jura (Bi: Bienne; CB: Col du Banchet; CC: Cluse de Chailles; Cr: Crozet; Th: Thoirette; Sa: Salève; VF: Val du Fier). 'Complete sections' include at least the uppermost two 400 000-year cycles (compare with Fig. 8) and show continuous outcrop.

The aim of this paper is to illustrate the small-scale shallowing-upward sequences in the Swiss and French Purbeckian, and to test for a cyclicity of the Milankovitch type. Detailed time correlations will give the framework which allows for a better understanding of the sedimentary and diagenetic processes on the Purbeckian platform. The term 'sequence' is here used to describe an observed facies succession which is limited by distinct boundaries and which formed by cyclic processes.

TYPES OF SMALL-SCALE SEQUENCES

The small facies sequences building up the Purbeckian carbonates are 0·2–1·5 m thick and usually consist of one well-defined bed, which may be subdivided by several bedding planes. Complete sequences display a thin transgressive lag deposit at their base. Shallowing-upward deposits are dominant and commonly start with lagoonal sediments, passing into intertidal and supratidal facies. Incomplete sequences lack subtidal sediments and contain only intertidal and/or supratidal facies. In addition, their upper part may be eroded. Reworking of sediment on the very shallow and partly emergent Purbeckian carbonate platform frequently destroyed non- or only partly-consolidated sequences, so that all facies elements are found mixed together in one bed. Entire sequences can be reduced to a lag deposit. Transitions between the sequence types do occur, but in most cases facies and the depositional environments they represent are well defined.

According to the predominant facies assemblages, six types of sequences (A–F) can be distinguished (Fig. 2). The six types can be identified in about 80% of all sequences recognized. One or two examples have been selected for each sequence type (Fig. 3) and will be discussed in detail.

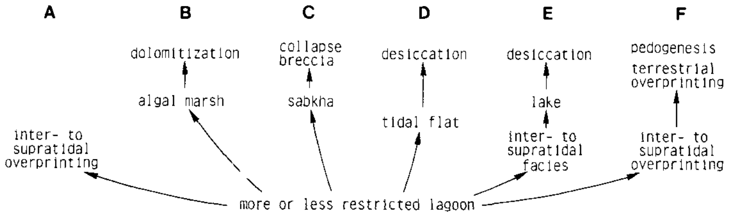


Fig. 2. Types of small-scale shallowing-upward sequences (A–F) and their depositional environments.

Type A

Type A sequences are found associated with subtidal, more or less restricted lagoonal sediments. Dasycladacean algae, benthic foraminifera, thick-shelled bivalves and gastropods commonly occur. Echinoderms are rare and point to more marine conditions. Small, well-sorted ooids with micritic cortices indicate the presence of high-energy sand bars, whereas larger ooids with multilayered radial cortices formed under alternating high- and low-energy regimes in a lagoonal setting (Strasser, 1986). Herringbone cross-stratification occurs locally in oolites and indicates bidirectional tidal currents.

The A-sequence of Crozet (Cr, Fig. 3) displays at its base some pebbles of mudstone, which have been reworked from the underlying semiconsolidated sediment during transgression. Oncoids, dasycladacean algae and benthic foraminifera indicate a lagoonal setting. Some charophyte oogonia have been washed in from a nearby lake. The shallowing-upward tendency is indicated by birdseyes and desiccation fissures which overprint the lagoonal facies in the upper part of the sequence (Fig. 4A), and which resulted from exposure of the lagoonal sediments in the upper-intertidal to supratidal zones (Shinn, 1983a). The sequence ends with a layer of green marls consisting mainly of Fe-rich smectites and illites. The illites originated from transformation of smectite through cyclic wetting by marine waters and drying during subaerial exposure (Deconinck & Strasser, 1987).

The A-sequence of Salève (Sa, Fig. 3) starts with lenses of peloidal grainstone which may be interpreted as local washover deposits. Then follow wackestones of a quiet lagoonal setting, which pass upward into high-energy ooid sands. Keystone vugs at the top of the sequence (Fig. 4B) formed in the upper part of a beach (Dunham, 1970). The surface is very irregular. It is overlain by a bed of oolite (a second A-sequence) which locally is reduced to tilted blocks. They suggest broken slabs of beachrock and thus imply rapid consolidation. Early cementation may have taken place after progradation of the shoreline, which put the sediment into contact with a freshwater lens (Strasser & Davaud, 1986; Halley & Harris, 1979, showed that freshwater cements consolidated a Bahamian ooid shoal in less than a 1000 years). Subsequent emersion then led to erosion and fracturing, as well as to the formation of a thin layer of green marls.

Type B

B-sequences are characterized by finely crystalline dolomite and algal laminations in their upper part (Fig. 4C). Dolomitization is strongest at the top of the sequence, but it may also penetrate into the lower beds. In the case of Val-du-Fier section (VF, Fig. 3), oolitic grainstones contain some reworked clasts at their base, representing the transgressive phase. A layer of mudstone is intercalated, indicating changes in water energy and possibly migration of ooid sand bars over restricted-lagoonal deposits. Shallowing of the lagoon then allowed for growth of algal mats in the supratidal zone, where early dolomitization could take place. Fossils are virtually absent. The sequence ends with a layer of mudstone which locally has been broken into pebbles, and with a veneer of green marls.

The depositional setting of B-sequences may be comparable to that on Andros, Bahamas, where Shinn, Lloyd & Ginsburg (1969) described early diagenetic dolomitization of a supratidal algal marsh. There, subtidal facies are found in the adjacent, restricted shallow-marine zone, in ponds and in tidal channels. The climate is humid in summer and dry in winter (Hardie, 1977).

Type C

C-sequences are typified by evaporites in their upper part. Gypsum has been mined in the northern part of

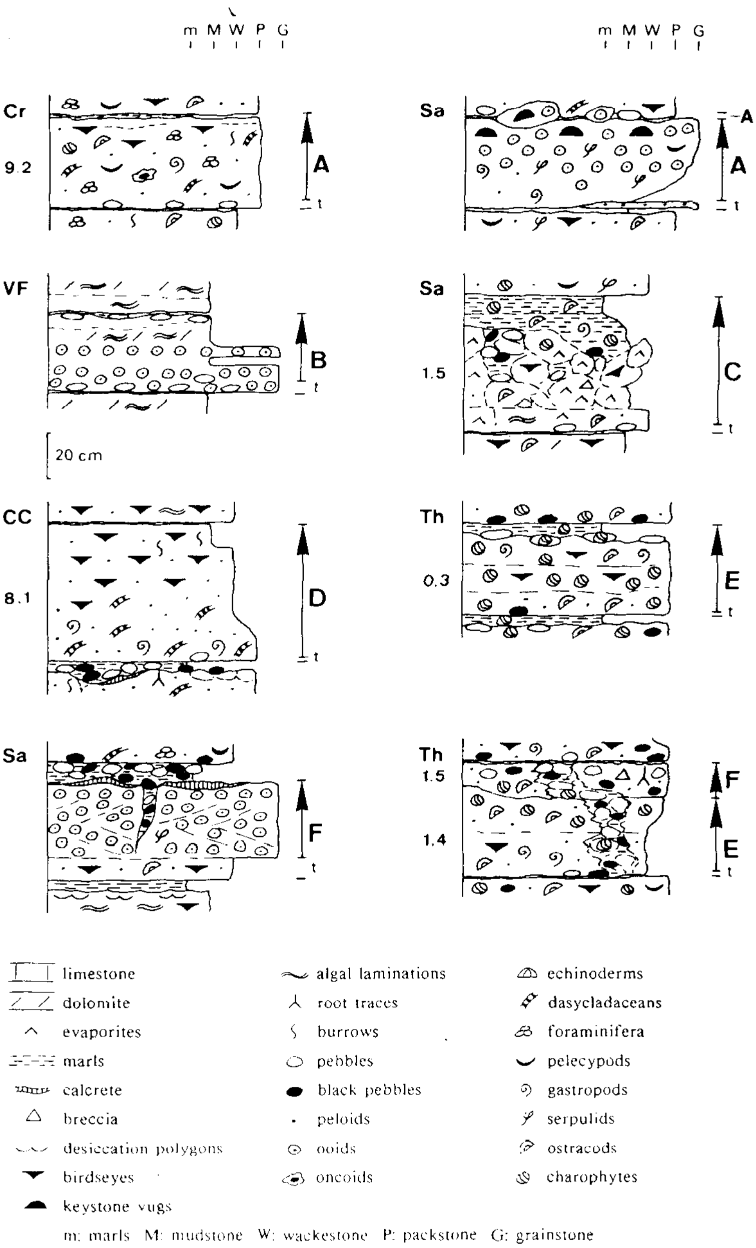


Fig. 3. Examples of small-scale sequences (A–F) from the sections indicated in Fig. 1. Arrows show shallowing-upward tendency, t means transgressive deposit. Numbers at left position the sequences in the sections of Fig. 8 (e.g. 6·2: second small-scale sequence above boundary 6). Examples without number are situated below boundary 0. For discussion refer to text.

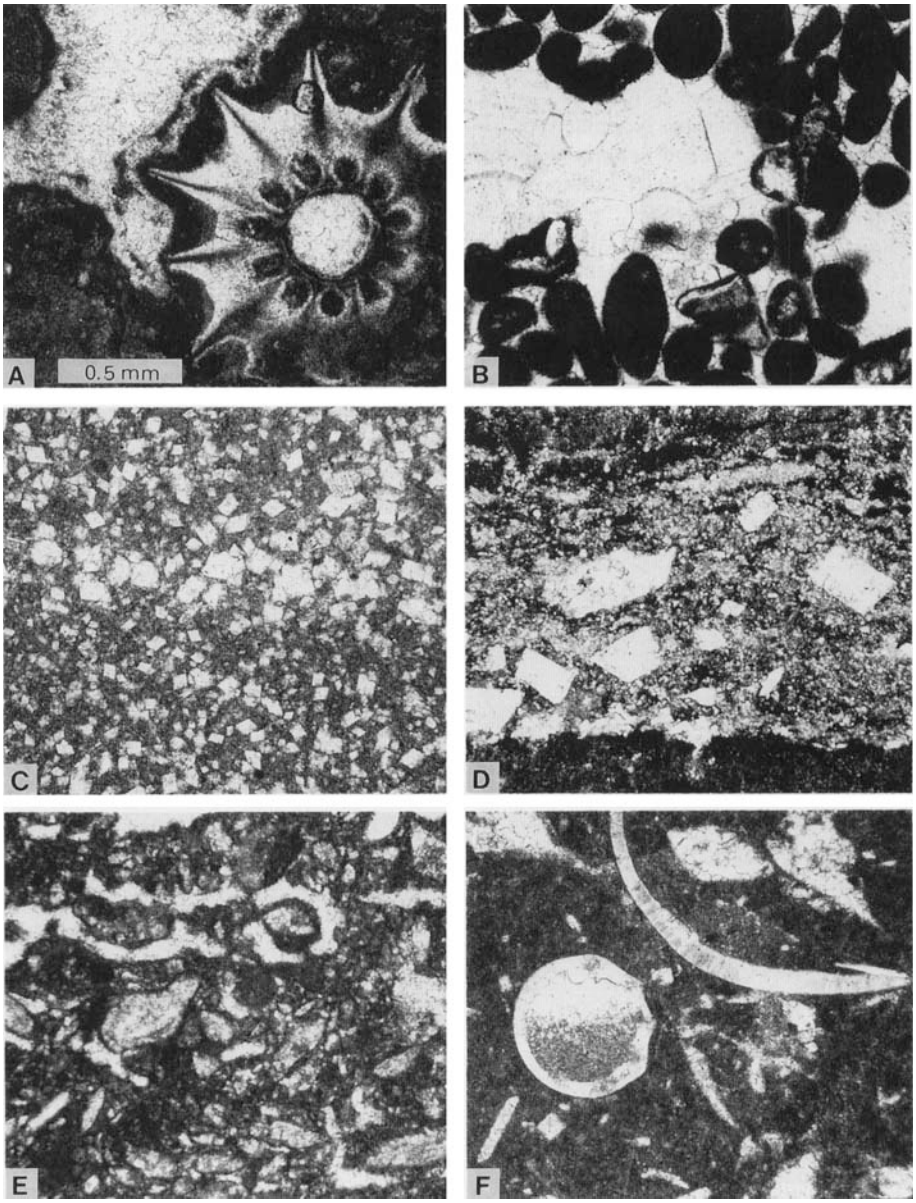


Fig. 4. Thin-section photomicrographs; scale bar on A is valid for all photographs. (A) Top of A-sequence displaying desiccation fissure (left) next to a dasycladacean alga (*Clypeina jurassica*). Note (microbial?) micrite rim on first-generation cement in fissure. (B) Keystone vugs in ooid and peloid grainstone indicate intertidal exposure of A-sequence. (C) Dolomitized algal mat of B-sequence. Primary lamination is emphasized by size differences of dolomite crystals. (D) Pseudomorphs of probably anhydrite in laminated sabkha-type sediment of a C-sequence. (E) Lenticular gypsum pseudomorphs and desiccation fissures at top of C-sequence. (F) Charophyte (gyrogonite of *Porochara*) and freshwater ostracod associated with evaporite (anhydrite?) pseudomorphs. This implies a seasonal Purbeckian climate with humid winters and hot, dry summers.

the study area (Maillard, 1884), but in most outcrops the evaporites are replaced by calcite. Crystal forms suggest primary gypsum and anhydrite (Fig. 4D and E). Locally, the evaporites show replacement by length-slow chalcedony (Mojon & Strasser, 1987). Celestite occurs in some outcrops. Nodular textures resemble 'chickenwire' of coastal sabkha environments (McKenzie, Hsü & Schneider, 1980; West, 1975).

The C-sequence of Salève (Sa, Fig. 3) displays a collapse breccia due to dissolution of the evaporites. Lenticular gypsum pseudomorphs are still present in the micritic sediment. Birdseyes indicate intertidal to supratidal exposure. The upper part of the sequence is dominated by green marls which contain freshwater faunas and charophytes. Here as well as in other C-sequences, freshwater fauna and flora can be found associated with evaporite pseudomorphs (Fig. 4F). This reflects the contrasted climatic conditions which reigned during Purbeckian times. Francis (1983) demonstrated on tree rings of Purbeckian conifers from Dorset that the climate was of Mediterranean type with hot, dry summers and rainy winters. Freshwater not only permitted the life of charophytes, but also led to dissolution of evaporites and consequently to collapse and brecciation of adjacent and overlying, more or less consolidated beds. Fissures are filled with black pebbles of the same facies and with green marls. The black pebbles formed through early cementation and subsequent reworking of sediment impregnated by organic matter. Analyses have shown that in some cases the organic material has been burnt, thus evoking forest fires on nearby islands (Strasser & Davaud, 1983).

Type D

Type D sequences reflect tidal-flat environments. The sediments, usually mudstones and wackestones (less frequently peloidal packstones), are thinly bedded and display abundant birdseyes (Fig. 5A). Algal laminations, mudcracks and desiccation polygons are common. Small vertical tubes (some filled with peloids; Fig. 5B) are locally frequent. They are interpreted as worm burrows, similar to those pictured by Hardie (1977) and Shinn (1983b) from supratidal, low-energy environments. Although the depositional setting was close to that of type B sequences, salinities were less elevated and permitted life of a burrowing fauna. Dolomitization occurred only sporadically.

In the example of Cluse de Chailles (CC, Fig. 3), lagoonal sediments with dasycladaceans pass upward into burrowed wackestones and mudstones riddled with birdseyes. A thin layer of green marls separates this sequence from the following one.

Type E

This type of sequence is characterized by the presence of charophytes, freshwater ostracods and freshwater gastropods. It thus reflects lacustrine conditions (Mojon & Strasser, 1987). The example of Thoirette (Th, Fig. 3) contains exclusively freshwater fauna. Some black pebbles at the base point to reworking of underlying deposits. Birdseyes and shrinkage cracks (Fig. 5C) suggest exposure of the upper part of the sequence. The pebbles at the top may have formed through desiccation and some reworking. Once more, green marls terminate the sequence.

Type F

Type F sequences have been subaerially exposed and show pedogenic overprinting (Fig. 5D). Laminar calcrete (Fig. 5E) is particularly abundant in the Salève section (Strasser & Davaud, 1982) and at Cluse de Chailles. Rhizoliths with associated alveolar texture are common (Fig. 5F; Klappa, 1980). In the example shown in Figs 3 and 6, laminar calcrete encrusts oolitic beachrock. The following (probably several) sequences are completely reworked and represented only by a black-pebble conglomerate with a matrix of green marls.

At Thoirette (Th, Fig. 3), pedogenesis has completely brecciated the exposed lacustrine deposits. Fissures are filled with green marls and black pebbles and reach down even to the base of the underlying sequence. Root traces with alveolar texture occur in the matrix as well as in reworked pebbles. Circumgranular cracking (Fig. 5D; Esteban & Klappa, 1983) indicates desiccation during subaerial exposure.

Distribution of small-scale sequences

The six types of sequences summarize the various depositional environments which existed on the Purbeckian platform. Sequences of types A, B and C dominate in the lower part of the studied sections. The upper part is mostly composed of sequence-types D, E and F. This distribution reflects a general change from lagoonal and hypersaline to tidal-flat, lacustrine and terrestrial conditions. The uppermost sequences

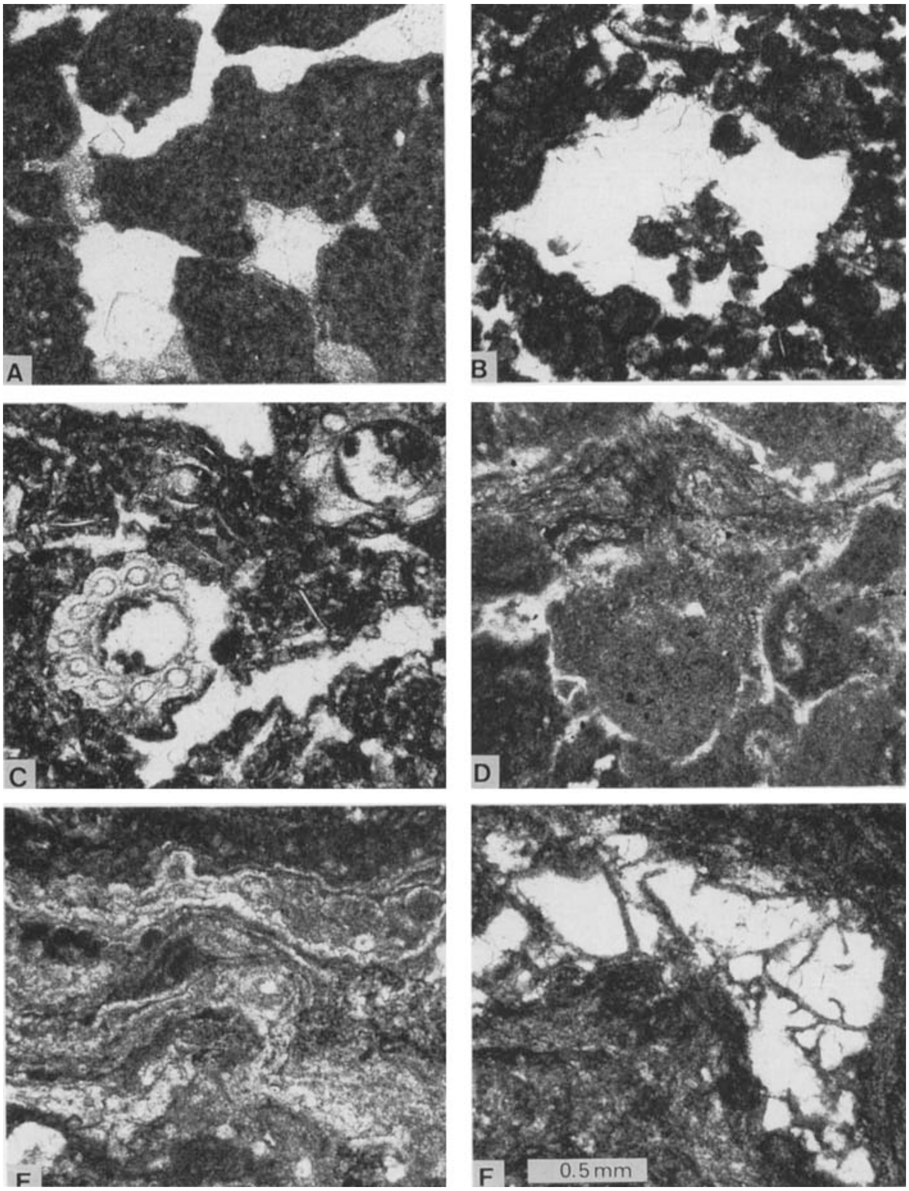


Fig. 5. Thin-section photomicrographs; scale bar on F is valid for all photographs. (A) Birdseyes locally filled with internal sediment (vadose silt?) at top of D-sequence. (B) Agglutinated peloids outline a slightly compacted (?)worm tube in the tidal-flat facies of a D-sequence. (C) Stems of charophytes (*Clavator reidi*) and desiccation fissures define the top of a lacustrine E-sequence. (D) Circumgranular cracking and calcrete-type lamination (at top of photograph) indicate pedogenesis in an F-sequence. (E) Laminar calcrete of F-sequence. (F) Alveolar texture associated with a rhizolith at the top of an F-sequence.

often are again of the A-type and are precursors of the marine transgression of Pierre-Châtel Formation (Figs 7A, B, 8). Furthermore, A-sequences are the most common style of sedimentation in the southeastern part of the study area, whereas sequence-types B and C predominate in the northern and western part. Calcrete is found along the southeastern margin of the study area, where islands separated the open ocean to

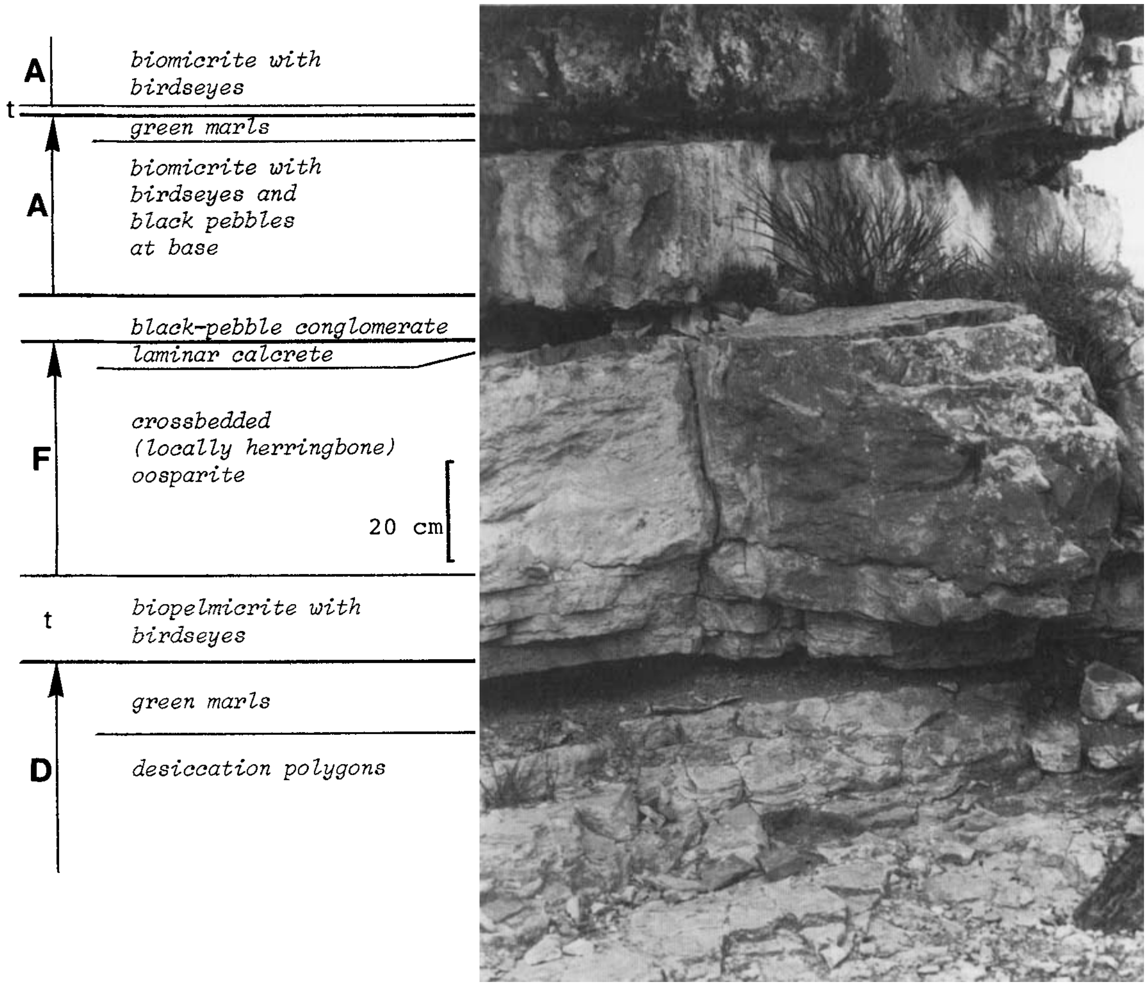


Fig. 6. Part of Salève section displaying D, F and A sequences, including transgressive deposits (t). Black-pebble conglomerate represents probably several partly-deposited and reworked small-scale sequences. Lower portion of photograph is also shown in Fig. 3 (F-sequence, Sa).

the SW from the protected platform to the NW (Davaud, Strasser & Charollais, 1983).

Superimposed on these general trends of facies distribution are rapid vertical and lateral facies changes (Fig. 8). Detailed time correlation of Purbeckian sections based on facies alone is therefore not possible. A common feature to all studied outcrops, however, is the shallowing-upward tendency of the small-scale sequences described above. It is independent of facies and palaeogeographic position. In the following discussion we will therefore no longer concentrate on facies evolution, but on the sequential patterns.

DISCUSSION AND INTERPRETATION

Genesis of shallowing-upward sequences

Progressively shallower facies are deposited as water depth gradually decreases. Change of water depth is basically a function of subsidence rate, eustatic sea-level change, and sediment supply. Periodically, storms can raise water level and allow for sedimentation in the supratidal zone. Vertical stacking of shallowing-upward sequences results from repeated decrease and increase of water depth, which is due to cyclic changes of sea-level and/or sediment supply.

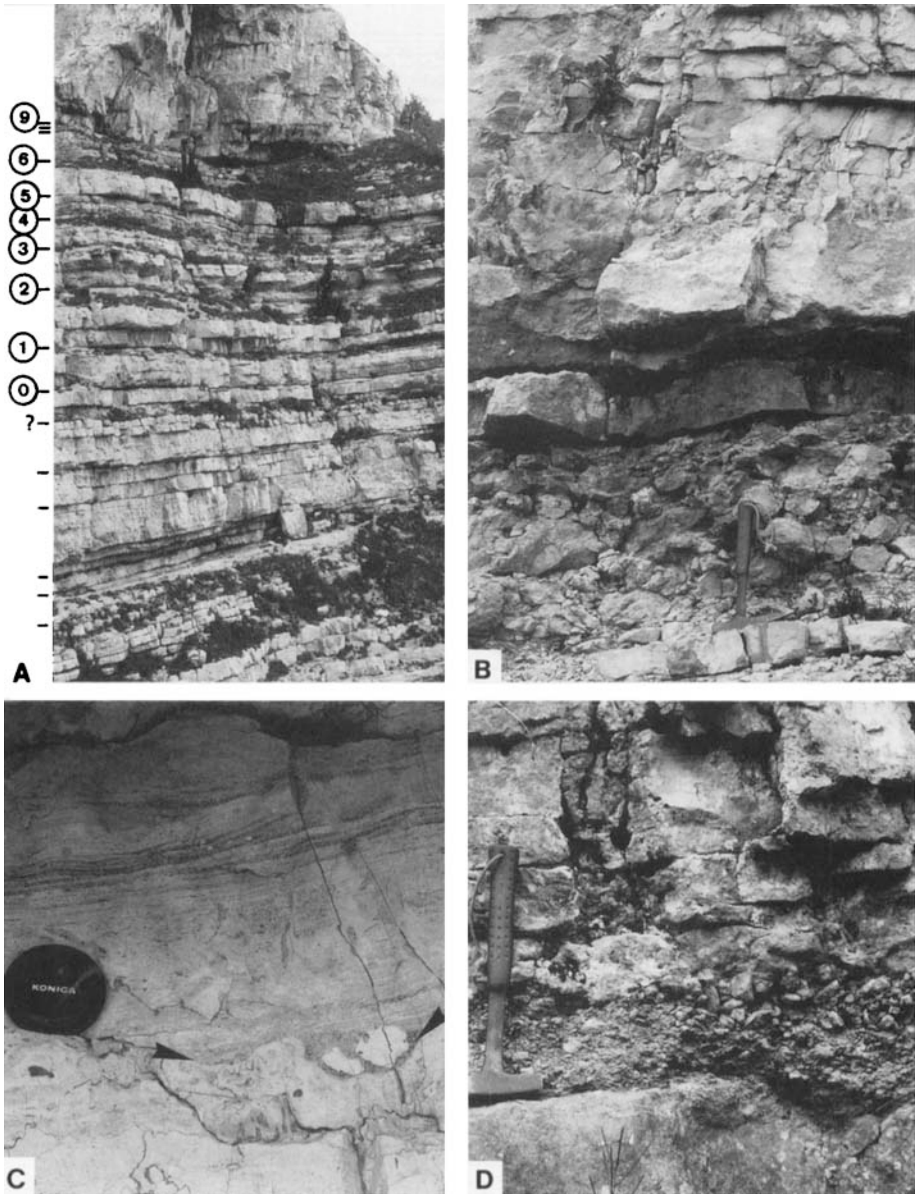
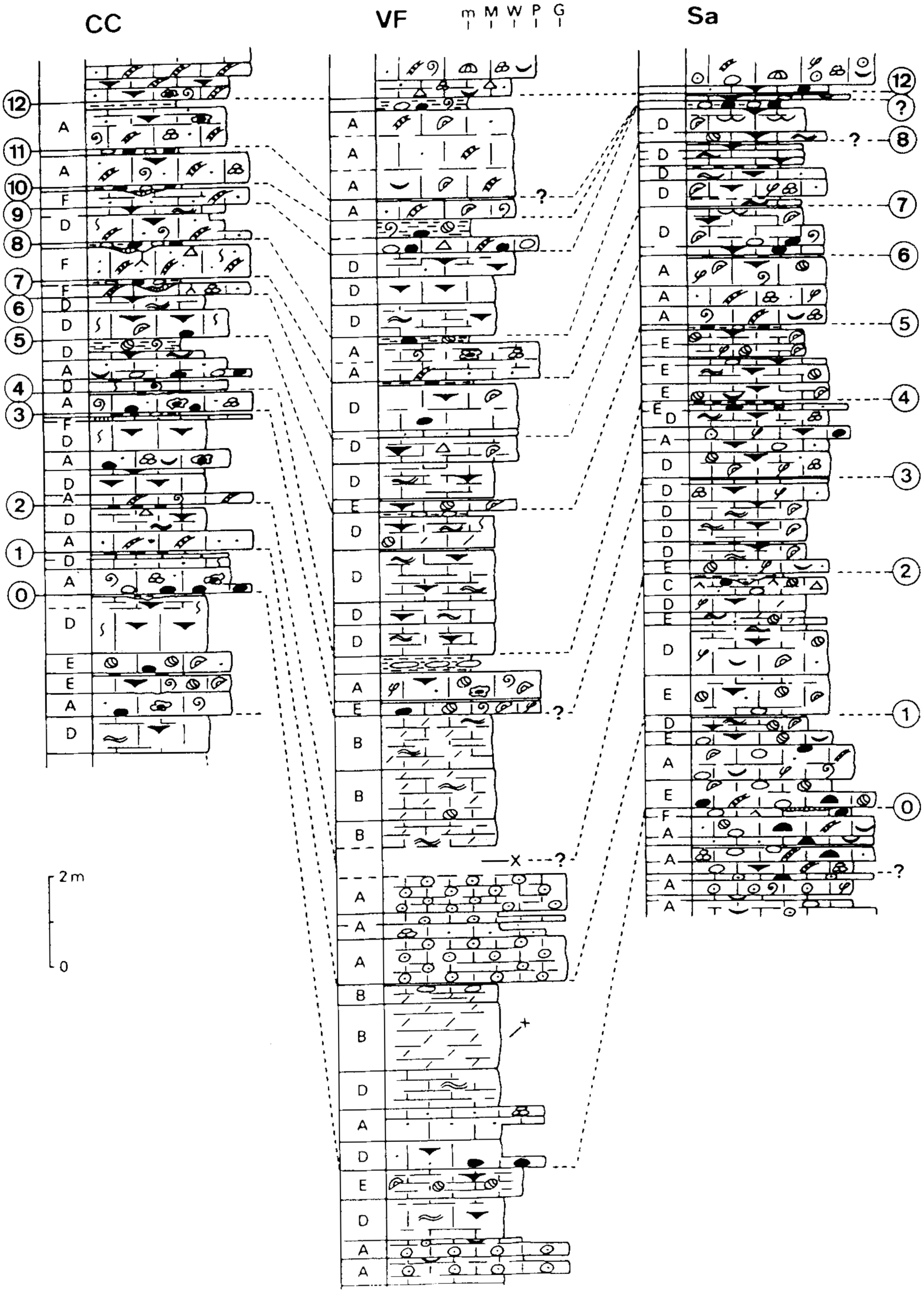


Fig. 7. (A) Highly structured Purbeckian section at Salève, followed (above boundary 12) by the massive limestones of Pierre-Châtel Formation. Boundaries of medium-scale sequences (100 000-yr cycles) are indicated at left; numbers correspond to those on Fig. 8. (B) Marine limestones of Pierre-Châtel (top of photograph) overlie the Purbeckian with a thin transgressive sequence (boundary 12, Salève section). The uppermost 0·4–0·5 m of the Purbeckian are completely brecciated and reworked, representing a period of 300 000 to 400 000 yr. (C) Sedimentary structures in a small-scale A-sequence of Salève indicate channelling and bidirectional tidal currents. The erosion surface (arrowed) is local and not related to sea-level fluctuations. (D) Channelling and formation of conglomerate at the top of a medium-scale sequence (Col du Banchet). This level can be correlated over the entire study area (boundary 1, Fig. 8).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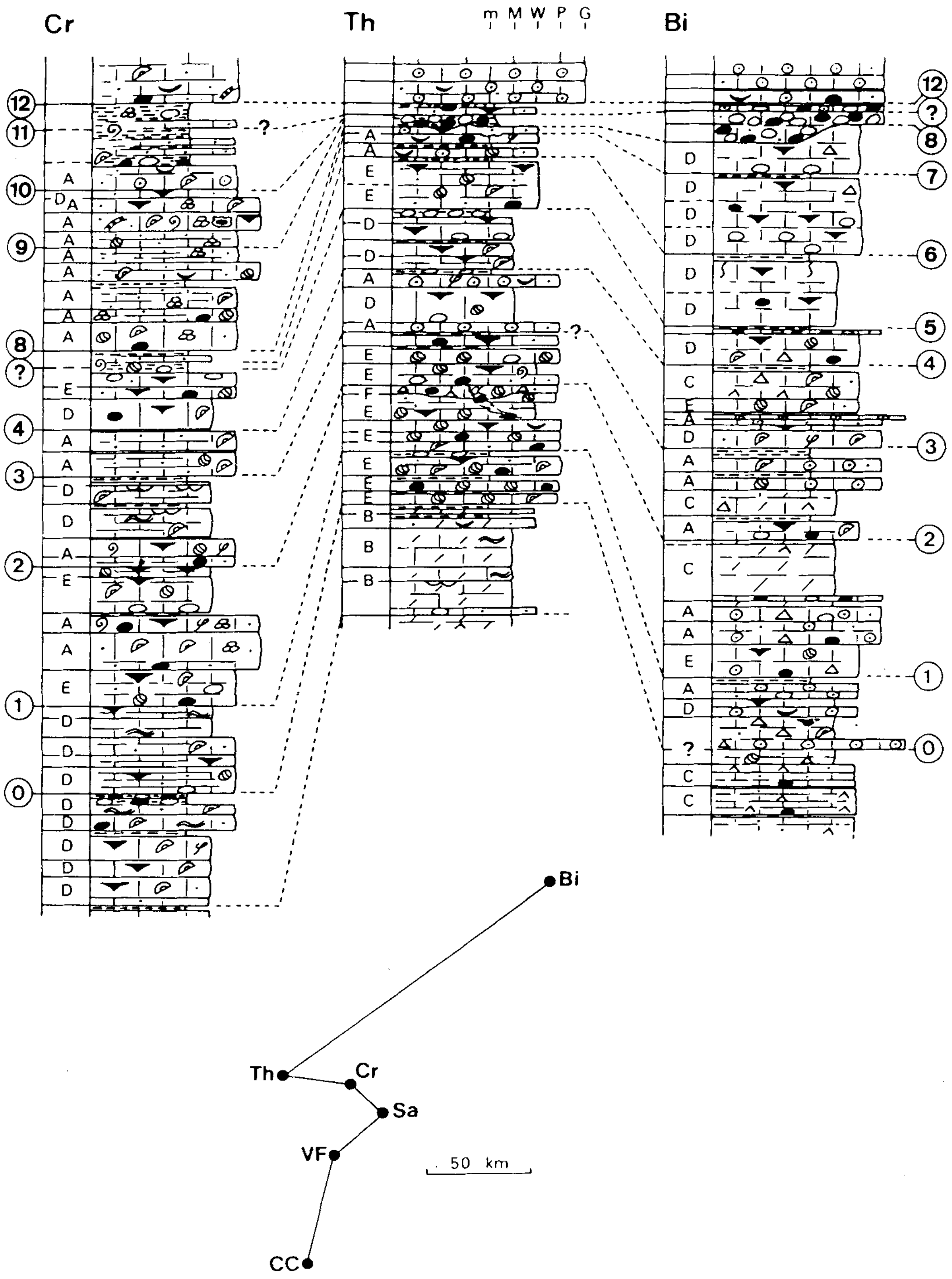

Fig. 8. (This page and opposite) Example of correlation of sequence boundaries in the upper part of the Purbeckian. Dashed lines and numbers correlate isochronous boundaries of 100 000-yr sequences. Purbeckian carbonates terminate with boundary 12, after which follow (commonly with a small transgressive sequence) the marine limestones of Pierre-Châtel Formation. Note lateral facies changes indicated by lateral changes of sequence types (A–F). For positioning of sections refer to Fig. 1. Symbols are as in Fig. 3.

Subsidence rate may change continuously or abruptly (depending on basin-wide or local tectonics). Cisne (1986) proposed a model of cyclic build-up and release of elastic stresses along stick-slip faults bordering the platform, leading to stacked, shallowing-upward sequences on the platform margin. The Purbeckian sequences, however, are equally well developed over the entire platform, so that this kind of tectonic origin can be excluded.

The rate of carbonate accumulation on shallow platforms usually outpaces subsidence (Schlager, 1981), causing sediments to build up to sea-level and then to prograde seawards (Ginsburg, 1971; James, 1984). Grainstones representing high-energy tidal-bar and beach deposits imply rapid sedimentation. In the case of lagoonal sediments with black pebbles and mixed faunas, the particles have been washed back and forth for some time before final deposition. The (relatively) longest time-span, however, is represented by supratidal deposits such as dolomitized algal mats and calcrete crusts, and by pedogenically altered beds. Reworked pebbles and fractured beachrock demonstrate that most sequences were consolidated prior to deposition of the following bed. From cathodoluminescence studies it appears that pore fluids precipitating early cements have changed from one sequence to another (P. Amieux, pers. comm.). Black pebbles and green marls equally imply prolonged subaerial exposure (Strasser & Davaud, 1983; Deconinck & Strasser, 1987). Subaerial exposure and frequent erosion at the top of Purbeckian shallowing-upward sequences can only be explained by significant drops of sea-level. Similar sequences with subaerial exposure surfaces have been described from the Proterozoic by Grotzinger (1986), from the Carboniferous by Goldhammer & Elmore (1984) and Wright (1986), and from the Triassic by Hardie *et al.* (1986).

Lateral shifting of depositional settings was frequent (as implied from the lateral changes of Purbeckian facies; Fig. 8) and could lead to laterally discontinuous shallowing-upward sequences (Pratt & James, 1986). Furthermore, progradation locally was very rapid if sediment supply was high. At the same time, erosion took place in other areas (Fig. 7C; Wright, 1984; Strasser & Davaud, 1986). However, if the drop of eustatic sea-level was large enough to affect most sedimentary environments on the platform, and if the time of exposure was long enough to allow for pedogenic overprinting (F-sequences), supratidal dolomitization (B-sequences), freshwater dissolution of evaporites (C-sequences), cementation, erosion, and the formation of black pebbles and green *marls, the resulting unconformity will be relatively* easy to recognize (Fig. 7D). The deposits overlying the unconformity are younger everywhere on the platform than those below the unconformity (Vail, Hardenbol & Todd, 1984).

Renewed increase of water depth led to transgression. Particles which were not firmly bound in the underlying sequence were reworked and incorporated at the base of the new sequence. Thin beds of transgressive deposits (typically containing pebbles and mixed faunas) are common in the Purbeckian (t in Fig. 3). Birdseyes indicate in some cases that the sediment was still subjected to partial emersion.

Small-scale shallowing-upward sequences are the fundamental units of the Purbeckian deposits and can thus be compared to the small-scale time-stratigraphic punctuated aggradational cycles of Goodwin & Anderson (1985) and Goodwin *et al.* (1986). Local absence or reduced thickness of transgressive deposits led Goodwin & Anderson (1985) to postulate abrupt increases in water depth ('punctuation events'). However, condensed transgressive deposits can also form during slow increase of water depth. After prolonged intertidal to supratidal exposure a lag time is needed before aggradation resumes (Ginsburg, 1971; Read *et al.*, 1986; Brett & Baird, 1986). Rise of sea-level first led to thin transgressive deposits in low-lying areas such as lagoons and channels. At the same time, positive land forms were still exposed to erosion. Transgressive beds are therefore local and need not be strictly isochronous. However, as relief on the Purbeckian platform was very low, continued sea-level rise soon caused flooding of most of the platform and deposition of predominantly subtidal and intertidal sediments. The limit between sediments indicating maximum emersion and the transgressive bed is a sequence boundary, and the surface it defines is (on a geological scale) considered to be isochronous.

Causes of cyclicity

On the very shallow Purbeckian platform, where subtidal zones were separated from each other by emergent areas, each lagoon could develop its own cyclic pattern (autocyclic model: Ginsburg, 1971; James, 1984; Pratt & James, 1986). Bedding planes inside small sequences are often associated with green marls, and cyclic facies patterns can occur in all sequence types. However, they commonly change laterally in the same outcrop and do not correlate with other sections. On the other hand, many sequence boundaries can be followed over large parts of the study area (Fig. 8). Deposition and overprinting of such sequences must accordingly have been controlled by changes in water depth which affected the entire platform. Climate in Purbeckian times was warm and equable, and there is no evidence for permanent polar ice (Barron, 1983). Glacial-eustatic cycles, even with much lesser amplitudes than during the Quaternary, can therefore not be proven. Other conceivable mechanisms to explain short-term eustatic fluctuations are cyclic evaporation of isolated ocean basins (Donovan & Jones, 1979; Hsü & Winterer, 1980), and thermal expansion of the ocean surface (Gornitz, Lebedeff & Hansen, 1982). Climatic cycles equally influenced organic and inorganic precipitation of carbonate and may have accelerated or slowed down sedimentation rates. The linkage of global climatic cycles to astronomical parameters has been documented by many authors (e.g. Milankovitch, 1941; Mesolella *et al.*, 1969; Berger, 1978; Schwarzacher & Fischer, 1982). Cyclic eustatic changes due to instabilities of the geoid have been discussed by Mörner (1984).

Detailed study of the Purbeckian sections shows that a number of small-scale sequences in turn make up sequences of a medium scale (Fig. 7A). In many cases, well-developed emersion surfaces appear after 5 small-scale sequences (e.g. sections Sa and Cr in Fig. 8). Medium-scale sequences equally display a shallowing-upward tendency and are thus comparable to the shallowing PAC sequences of Goodwin & Anderson (1985). The boundaries of medium-scale sequences are usually easy to recognize. In most cases they can be correlated over the entire study area (numbered in Fig. 8). Boundary 12 at the base of Pierre-Châtel Formation is characterized by an abrupt facies change resulting from a major transgression (Fig. 7B). Counting well-developed emersion surfaces downward from this marker level, comparing the sequential patterns between all studied sections and calibration by microfossils (P. O. Mojon, pers. comm.) allows a correlation of the sequence boundaries from one section to the next. Some cases are ambiguous, and a 'best-fit' solution has to be adopted. These correlations then furnish a framework of isochronous surfaces which commonly are not parallel to facies boundaries (Fig. 8). Marked changes in thickness of some sequences (e.g. between VF and Sa) may indicate differential subsidence due to synsedimentary faulting.

Black-pebble conglomerates, pedogenic brecciation and calcrete locally suggest erosion, reworking or primary absence of small-scale sequences (e.g. section CC and tops of sections Sa, Bi and Th; Fig. 7B). In the northern and western part of the study area (exemplified by sections Bi and Th in Fig. 8), boundary 0 separates dolomitic and evaporitic deposits from restricted-lagoonal and lacustrine sediments above. In the southeastern part, this limit is characterized by black pebbles following tidal-flat or lacustrine deposits, or by subaerial exposure surfaces. Other particularly well-developed emersion features appear at boundary 4 (thick green marls, lacustrine and locally evaporitic facies) and boundary 8 (black-pebble conglomerates, brecciation, channels). Sequences below boundaries 8 (section Cr) and 12 (sections Sa, Th and Bi) are strongly condensed. This may be evidence for a larger sequence which groups 4 medium-scale sequences together.

These observations suggest that the Purbeckian sequences are linked to the Earth's orbital cycles: the small-scale sequences, as the smallest unit, would correspond to the precession cycle of the equinoxes (at present day with periods of 19 000 and 23 000 years; Pisias & Imbrie, 1986). The same has been proposed for the punctuated aggradational cycles by Goodwin & Anderson (1985). The first cycle of eccentricity has a period of 100 000 years and played an important role in controlling Pleistocene climate (Pisias & Imbrie, 1986). It was probably responsible for the well-developed emersion surfaces of the medium-scale sequences. Finally, the second cycle of eccentricity (400 000 years) marked boundaries 0, 4, 8 and 12. Obliquity cycles (41 000-year period) could not be identified.

The sequences illustrated in Fig. 8 would therefore represent a time span of about 1 200 000 years. Boundary 12, situated at the base of the *Occitanica*-Zone (Clavel *et al.*, 1986), coincides probably with the global short-term rise of sea-level as documented by Haq, Hardenbol & Vail (1987). However, more precise palaeontological data are needed to establish the exact correlation between Milankovitch-type cycles and the global sea-level curve.

SUMMARY AND CONCLUSIONS

Purbeckian sediments were deposited on a very shallow and partly emergent platform. Shallow-marine influence was important to the southeast of the study area, whereas the northern and western part was dominated by hypersaline and lacustrine conditions. At times, a chain of islands with formation of calcrete developed on the southeastern border of the platform. Superimposed on this general facies distribution are small-scale shallowing-upward sequences which include marine, brackish, freshwater and hypersaline facies. The sequences have been grouped into six types, each type expressing a particular depositional environment: lagoonal sediments with intertidal to supratidal overprinting; dolomitized algal-marsh sequences; sabkha sequences; tidal-flat sequences; lacustrine sequences; subtidal or intertidal sediments with terrestrial overprinting. Storm deposits occur locally.

Purbeckian sequences have formed by climatically controlled small sea-level fluctuations. They usually start with a thin transgressive bed which reworks pebbles and fauna from the underlying facies. Their bulk, however, consists of sediments expressing a shallowing-upward tendency. The tops of the sequences commonly are marked by prolonged periods of subaerial exposure or are eroded, thus indicating sea-level fall. Locally, sequences are subdivided into several beds which may have formed by autocyclic processes. Stacking of the small-scale sequences reflects cyclic changes of water depth. These cycles were controlled by climatic changes linked to parameters of the Earth's orbit. The small-scale sequences most probably correspond to the precession cycles of the equinoxes (about 20 000-year period). Particularly well-developed sequence boundaries have been caused by the two cycles of eccentricity (100 000 and 400 000 years).

Emersion surfaces, which display calcrete, pedogenic breccias, black pebbles and green marls, and which covered large areas on the shallow platform, are good isochronous markers. Most of such sequence boundaries can be correlated over 200 km. Detailed correlation of sequence boundaries makes it possible to work out a framework of isochronous surfaces. This is important for the interpretation of depositional environments where palaeontological dating is not possible. Correlation of boundaries of small-scale sequences also permits detailed analysis of facies evolution on a time-scale much finer than biozonation. Lateral migration of facies belts can thus be monitored in time intervals of some 10 000 years (a first attempt in the upper part of the Purbeckian has been made by Strasser, 1987). Furthermore, an estimation of time involved in diagenetic processes (affecting each small-scale sequence separately) is made possible. The peritidal carbonates of the Purbeckian are very suitable for such studies, as subaerial exposure surfaces are common and relatively easy to recognize.

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