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Milankovitch cyclicity and high-resolution sequence stratigraphy in lagoonal–peritidal carbonates (Upper Tithonian–Lower Berriasian, French Jura Mountains)

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ABSTRACT

Three sections of the Tidalites-de-Vouglans and Goldberg Formations have been studied in the French Jura. The sedimentary record consists of well-stratified carbonates which represent shallow-lagoonal, intertidal and supratidal depositional environments where salinities ranged from normal marine to hypersaline or fresh water.

The beds display a hierarchical stacking which is probably related to climatically induced sea-level fluctuations in the Milankovitch frequency band. Elementary sequences (commonly corresponding to an individual bed) would represent the 20-ka precession cycle, larger composite sequences the 100- and 400-ka eccentricity cycles.

Elementary and larger sequences can, partly and on a small scale, be analysed in terms of sequence stratigraphy. Sequence boundaries mark the top of the beds and in many cases are erosive. Low-stand deposits comprise calcrete, conglomerates and marls with freshwater fossils, or are missing altogether. Thin transgressive deposits follow a generally well-defined transgressive surface and contain reworked pebbles and mixed marine and freshwater fossils. High-stand deposits make up the bulk of the sequences and generally exhibit a shallowing-upward facies evolution. A large part of the sea-level cycle, however, was dominated by non-deposition, reworking and erosion. The time framework given by the inferred Milankovitch cyclicity permits estimation of rates of sediment accumulation and of diagenetic processes.

Detailed analysis of depositional sequences interpreted to have been induced by Milankovitch cycles suggests a duration of about 3.6 Ma for the two formations studied. Larger sequences are difficult to identify, but partial time control by ammonites and charophyte–ostracod assemblages allows for a tentative correlation with the global sea-level chart of Haq *et al.* (1987). Difficulties with and the validity of such a comparison are discussed.

INTRODUCTION

Most ancient shallow-water carbonates which formed on platforms or ramps are well stratified. The stratification results from stacking of small depositional sequences, which in many cases display a facies evolution with a dominant shallowing-upward trend (James, 1984). Elementary sequences usually correspond to a bed in the stratigraphic record and form part of larger sequences with regressive or transgressive trends of facies evolution (Goodwin & Anderson, 1985; Anderson & Goodwin, 1990). The more or less regular recurrences of depositional sequences imply that cyclic processes controlled carbonate production and/or deposition.

It has been demonstrated by several authors (e.g. Fischer, 1964; Grotzinger, 1986a, b; Hardie *et al.*, 1986; Heckel, 1986; Schwarzacher & Haas, 1986; Goldhammer *et al.*, 1987, 1990; Goldstein, 1988; Read & Goldhammer, 1988; Goldhammer & Harris, 1989; Koerschner & Read, 1989; Read, 1989) that the cyclicity found in ancient shallow-water to peritidal carbonates has time periods in the order of a few tens of thousands to a few hundreds of thousands of years and shows Milankovitch characteristics. It is therefore suggested that cyclic perturbations of the Earth's orbit (Milankovitch, 1941; Berger, 1980; Berger *et al.*, 1989) induced climatic

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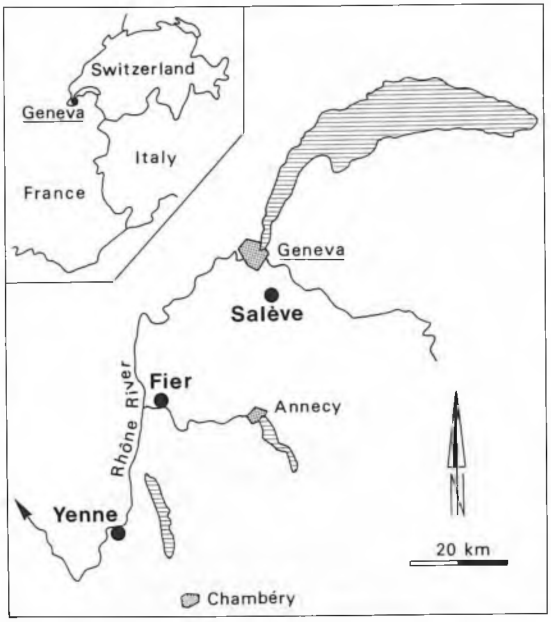

Fig. 1. Location map of the sections studied.

cycles which in turn controlled, directly or indirectly, carbonate productivity and eustatic sea level.

The peritidal carbonate sediments of late Tithonian and early Berriasian age in the Swiss and French Jura Mountains were deposited on the northern passive margin of the Tethys Ocean. They show well-developed cyclic stacking of elementary sequences (Strasser, 1988a). Unfortunately, outcrop conditions are such that only three continuous sections could be sampled, which cover the Upper Tithonian (Portlandian) Tidalites-de-Vouglans Formation (Bernier, 1984) and the Lower Berriasian (Purbeckian) Goldberg Formation (Häfeli, 1966). The section of Salève has been studied along the footpath of Grotte de la Mule on the northwestern face of Mount Salève, close to Geneva (Strasser, 1988b). The section of Fier is situated in the quarry next to regional road D 14, which winds through the canyon of Val du Fier. The third section has been sampled just west of Yenne, in a quarry and along national road N 504, where the Rhône River cuts through the Cluse de la Balme (Fig. 1).

The aim of this paper is to present an analysis of the sections studied in terms of facies evolution and high-resolution sequence stratigraphy, and to discuss the validity and potential applications of a time framework based on Milankovitch cyclicity. Independent time control is given locally by fossils and allows for a tentative correlation with the global eustatic sea-level curve of Haq *et al.* (1987).

DEPOSITIONAL SEQUENCES

The stratigraphic record of the Tidalites-de-Vouglans and Goldberg Formations commonly shows well-defined beds. Bed thicknesses vary between a few centimetres and 4.50 m. Facies indicate shallow-subtidal, intertidal and supratidal depositional environments, comprising marine and restricted lagoons, beaches and sand bars, tidal flats, algal marshes, coastal sabkhas, freshwater lakes, and land (Chevallier & Strasser, 1985; Strasser, 1988a; see also Wright, 1984, for a general description of peritidal facies models). Many sequences display a shallowing-upward trend which is expressed by a gradual change from deeper to shallower facies, or by intertidal to supratidal overprinting of subtidal facies.

The stacking of elementary sequences leads to sequences of a higher order, which equally have a shallowing-upward tendency (Fig. 2). These larger sequences, a few tens of centimetres up to 10 m thick, commonly terminate with marls, conglomerates or pedogenic caps and are easy to pick out in the field. They generally consist of four, five or six elementary sequences.

Continuous shallowing-upward from deeper to shallower facies can be explained by progradation or lateral migration of the depositional system (Ginsburg, 1971; Pratt & James, 1986). Local erosion may be due to tidal or storm-induced currents. Widespread erosional features and pedogenic overprinting of subtidal facies, on the other hand, suggest a drop of relative sea level (Strasser, 1991). It is therefore probable that sea-level fluctuations controlled, at least partly, the deposition of the carbonate sequences.

Sequence stratigraphy defines depositional systems and surfaces related to changes of eustatic sea level. Sequences resulting from high-amplitude sea-level fluctuations are delimited by sequence boundaries and can be decomposed into systems tracts (e.g. Vail *et al.*, 1984; Vail, 1987; Sarg, 1988). Beds and bedsets formed by smaller sea-level changes are defined as parasequences which are bounded by marine flooding surfaces (van Wagoner *et al.*, 1990). On a small scale also, the studied

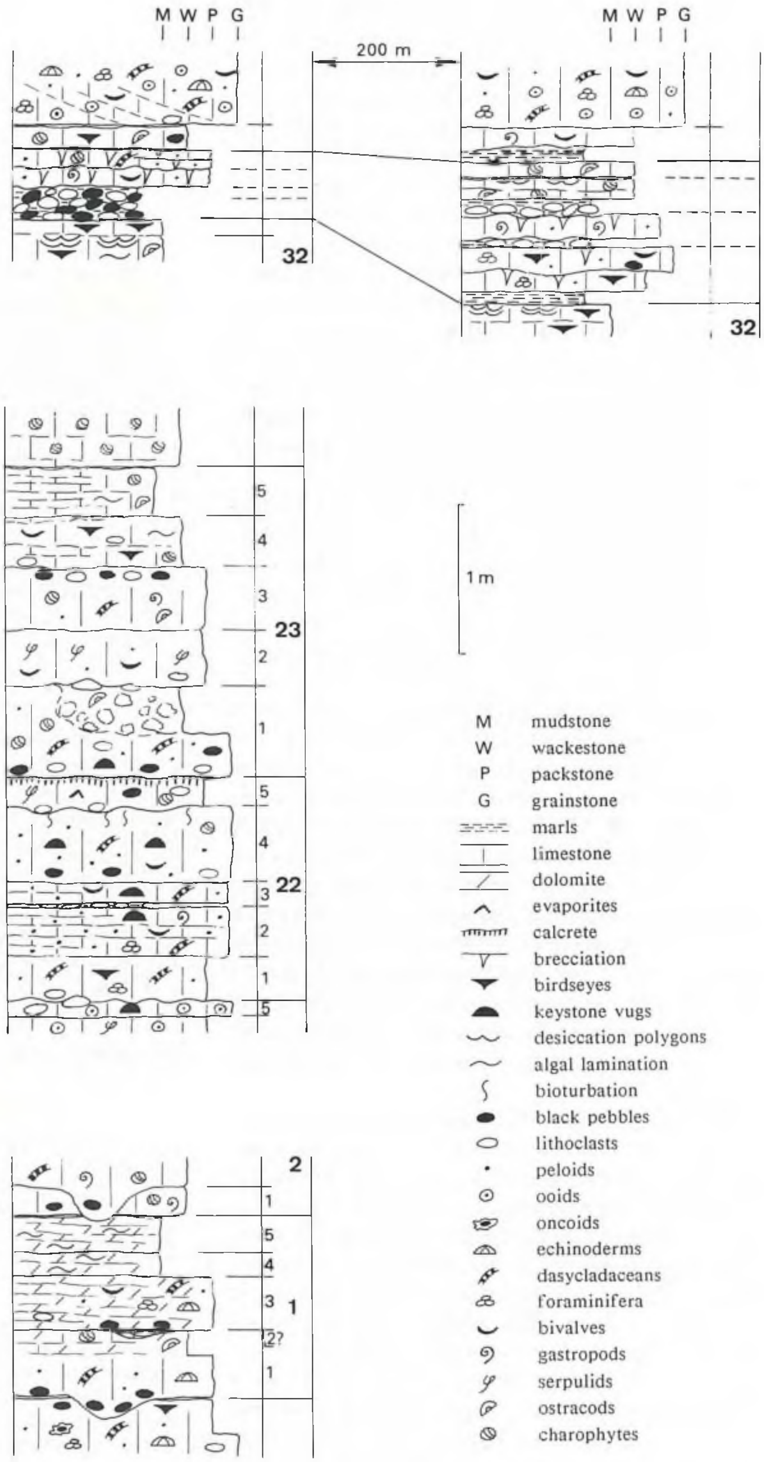

Fig. 2. Detailed sequences of the Salève section. Larger sequences are composed, on average, of five elementary sequences. Sequences of both orders express a shallowing-upward trend of facies evolution. Lateral changes (upper part of figure) demonstrate how some sequences may be reduced by non-deposition, erosion, or reworking. Large numbers in right column correspond to the numbers of supposed 100-ka sequences in Fig. 8. Compare also with Figs 7 and 9.

elementary sequences and the larger composite sequences contain many elements which can be described in terms of sequence stratigraphy. In the very shallow depositional environments of the formations studied the typical geometry of the systems tracts could, of course, not develop. Sediments accumulated basically through vertical aggradation. However, emersion surfaces, transgressive surfaces and facies changes indicating maximum flooding and shallowing-up can be identified in many cases. It is therefore preferable to call the studied beds and bedsets 'small-scale' and 'composite, larger sequences' instead of 'parasequences', and to delimit them with sequence boundaries. This integration of sequence stratigraphy in the description of small-scale sequences provides a more dynamic picture of their depositional history.

Sequence boundaries in the formations studied commonly correspond to the upper bedding surfaces and are characterized by erosion, pedogenetic brecciation, root traces, or desiccation polygons. These features formed during a drop of relative sea level. The overlying low-stand deposits are represented by calcrete crusts, conglomerates and marls. Lithoclasts have been reworked from the underlying sequence, and abundant black pebbles are impregnated by terrestrial organic matter, which in some cases had been burnt by forest fires (Strasser & Davaud, 1983). Green marls contain authigenic illite, which formed during repeated wetting by sea water and drying (Deconinck & Strasser, 1987). Charophytes, ostracods and gastropods in the marls point to the presence of freshwater lakes (Mojon & Strasser, 1987). Low-stand deposits are commonly thin but well developed on the top of the larger sequences, but may be reduced to a film of marls or missing completely between the elementary sequences.

The transgressive surfaces are mostly well defined. Transgressive deposits contain reworked lithoclasts and black pebbles, mixed lagoonal and freshwater fossils, and locally birdseyes or keystone vugs, which indicate intertidal to supratidal conditions. In some cases, the marls below the transgressive surface already contain a mixed fauna. This may indicate reworking by storms and spring tides, and suggests that the observed well-developed transgressive surface does not necessarily correspond to the initial transgressive movement, but to the stage when the location of the section studied was actually flooded. The transgressive deposits of the small-scale sequences are usually thin and in some cases missing,

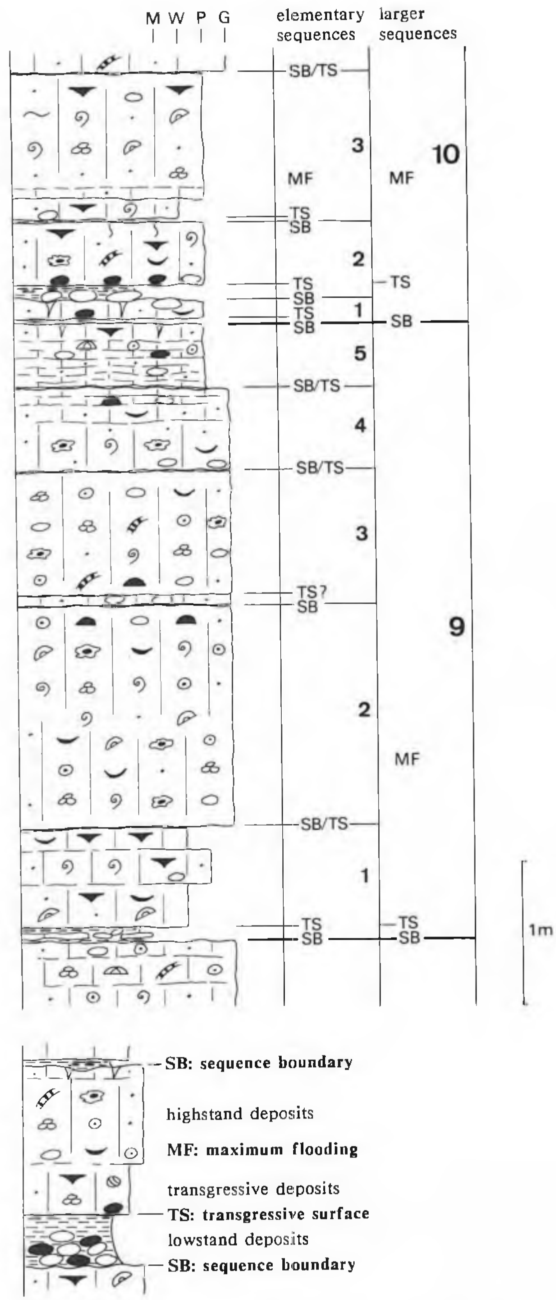

Fig. 3. Larger sequences 9 and 10 (supposed 100-ka sequences) interpreted in terms of sequence stratigraphy. Compare also with Fig. 6. The hypothetical section at the bottom shows positions of sequence boundaries, transgressive surface and approximate maximum flooding, as well as of deposits formed during one transgressive–regressive cycle. Symbols as in Fig. 2.

which is probably due to reduced carbonate production after prolonged intertidal to supratidal exposure.

Once sea level had risen enough to create new lagoons, carbonate production could set in again. During sea-level high-stand, sediments accumulated up to the water surface, which led to a shallowing-upward facies succession. Transgressive deposits commonly pass into regressive high-stand deposits. Actual surfaces of downlap or maximum flooding (Posamentier *et al.*, 1988) can only rarely be recognized in the small-scale sequences studied (in Fig. 3, the approximate level of deepest facies has been labelled MF: maximum flooding). High-stand deposits make up the bulk of the sequences in the formations studied. Sediments of the late high-stand may exhibit birdseyes or keystone vugs indicating intertidal to supratidal exposure, they may be dolomitized or contain evaporites, or be rich in freshwater fossils. A sequence boundary then terminates the sequence.

In many cases, the accommodation potential (defined by the combined rates of subsidence and eustatic sea-level change) was insufficient to permit deposition of complete sequences. Non-deposition, erosion and reworking resulted in incomplete or missing sequences. Elementary sequences may be represented only by a conglomerate or by a brecciated layer. Larger sequences may contain only one or two beds, or may themselves be reduced to a conglomerate (e.g. Fig. 2, top).

SEDIMENTARY RECORD AND TIME CONTROL

The sections studied show a trend from thicker beds in the Tidalites-de-Vouglans Formation to thinner beds in the Goldberg Formation (Fig. 4), which indicates a general decrease of accommodation potential on the platform. Facies evolve from rather marine-lagoonal to rather restricted lagoonal and fresh water. In detail, however, the sedimentary record is a complex stacking of depositional sequences (Figs 5 and 6).

At the base of the Salève section, thick-bedded marine-lagoonal limestones are truncated by an erosion surface (below sequence 1 in Figs 2 and 7). The following two larger depositional sequences (1 and 2) exhibit dolomitized algal mats and charophytes (Fig. 2, bottom). This rapid facies change is interpreted to coincide with the boundary

Fig. 4. Section of the northwest face of Salève Mountain, displaying a general trend of thinning-upward in the Tidalites-de-Vouglans and Goldberg Formations. The cliff is about 100 m high.

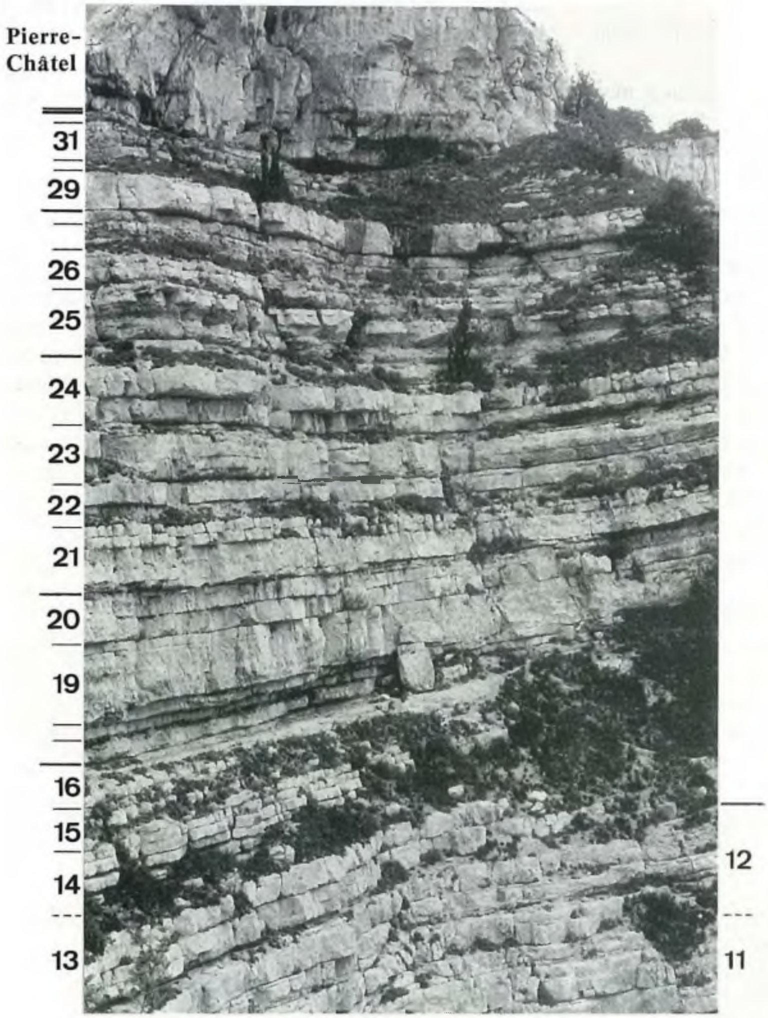

Fig. 5. Goldberg Formation at Salève exhibiting hierarchical stacking of sequences. Inferred 100-ka sequences (numbered as in Fig. 8) show bundling which implies modulation by a 400-ka orbital cycle. Sequence 19 is 2.10 m thick.

between the underlying Couches-du-Chailley Formation and the Tidalites de Vouglans (Bernier, 1984). In the sections of Fier and Yenne, facies changes are less pronounced. Concentration of black pebbles and dolomitization, however, may be the lateral equivalent of the restricted facies encountered at Salève (Fig. 8).

Facies of the overlying sequences are mostly marine (example in Fig. 3), and many of the sequences are partly dolomitized (Fig. 8). Black pebbles commonly occur in low-stand and transgressive deposits. The limit between the Vouglans and Goldberg formations has been set where, in the Salève section, the first well-developed black-pebble conglomerate appears (top of sequence 12, Fig. 8).

The sequences of the Goldberg Formation generally show more restricted and lacustrine facies and display abundant calcrete (at Salève, example of Fig. 2, centre) and pedogenic brecciation (at Yenne).

The sequences at the very top of the Goldberg Formation are commonly much reduced (Figs 2, top, and 9). Green marls and black-pebble conglomerates are common. Following a thin transgressive bed, coarse grainstones and packstones of the Pierre-Châtel Formation (Steinhauser & Lombard, 1969) then mark the change to fully marine conditions.

The depositional sequences as defined above show a hierarchical stacking. On average, five elementary sequences compose one larger sequence

Fig. 6. Detail showing superposition of beds (inferred 20-ka sequences) which form larger sequences corresponding to the 100-ka orbital cycle. Numbers as in Fig. 8. Sequence 10 is 2.70 m thick.

Fig. 7. Base of Tidalites-de-Vouglans Formation at Salève. Note irregular eroded bed surfaces. Sequence numbers correspond to those in Fig. 8. Hammer for scale.

(Figs 2, 6 and 8). Furthermore, especially in the Salève section, four larger sequences are in many cases grouped together to form sequences of a still higher order which display well-marked erosional tops or thinning-upward of beds, or which are followed by well-developed low-stand deposits. The definition of sequences and the correlation between the sections of Salève, Fier and Yenne presented in Fig. 8 is, of course, not unequivocal. It is rather a best-fit solution which, for the upper half of the sections, has been completed by the study of 24 other sections in the Jura Mountains (Strasser, 1988a). In Fig. 8, the larger sequences have been numbered.

Independent timing of the sequences is difficult. Ammonites have been found only in the uppermost part of the Goldberg Formation and in the lower part of Pierre-Châtel (Clavel *et al.*, 1986; Waehry, 1988). The base of Pierre-Châtel is situated in the *privasensis* subzone (Middle Berriasian). An ammonite of the *grandis* subzone (Lower Berriasian) has been cited at Cluse de Chaille by Clavel *et al.* (1986), in a bed that probably corresponds to sequence 33 (Fig. 10). Mojon (in Detraz & Mojon, 1989) established a zonation based on charophyte and ostracod assemblages which is calibrated with ammonites and calpionellids. Some sequences of the sections studied could thus be dated (Fig. 8); some are dated by correlation with other sections.

The erosion surface at the very base of the Salève section and the important facies changes in all three sections studied imply a sea-level fall and may, in terms of sequence stratigraphy, be interpreted as a sequence boundary of a larger-scale sea-level cycle (short-term cycle of Haq *et al.*, 1987). The dolomitized and freshwater-dominated sequences 1 and 2 (and partly 3) would correspond to low-stand and/or earliest transgressive deposits (Figs 2, bottom, and 7). A well-marked thinning-upward trend at Salève points to diminishing accommodation potential as high-stand deposits fill in the platform, and thus to a possible larger sequence boundary on top of sequence 16 (Fig. 5). Other sections in the Jura, however, show a rapid change from dolomitic to limestone facies at the top of sequence 12. The thick bed of sequence 19 indicates rapid deepening of water and could correspond to a time of maximum flooding of the platform. Other possible large-scale sequence boundaries may occur on top of sequences 24 or 28 (followed by thicker beds and/or

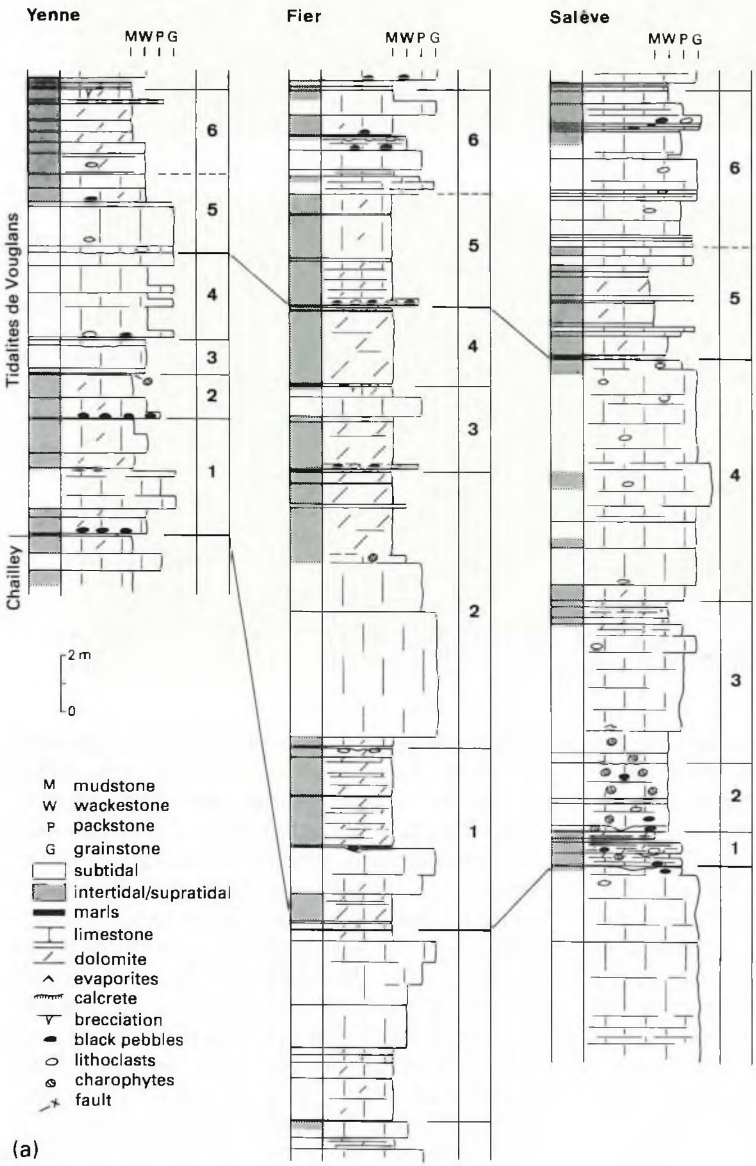

Fig. 8. Studied sections of Salève, Fier and Yenne with simplified facies interpretation. Inferred 100-ka sequences are numbered, limits of 400-ka groups are marked with heavy lines. *M1b* to *M3* are charophyte–ostracod assemblages of P.O. Mojon (personal communication). For discussion refer to text.

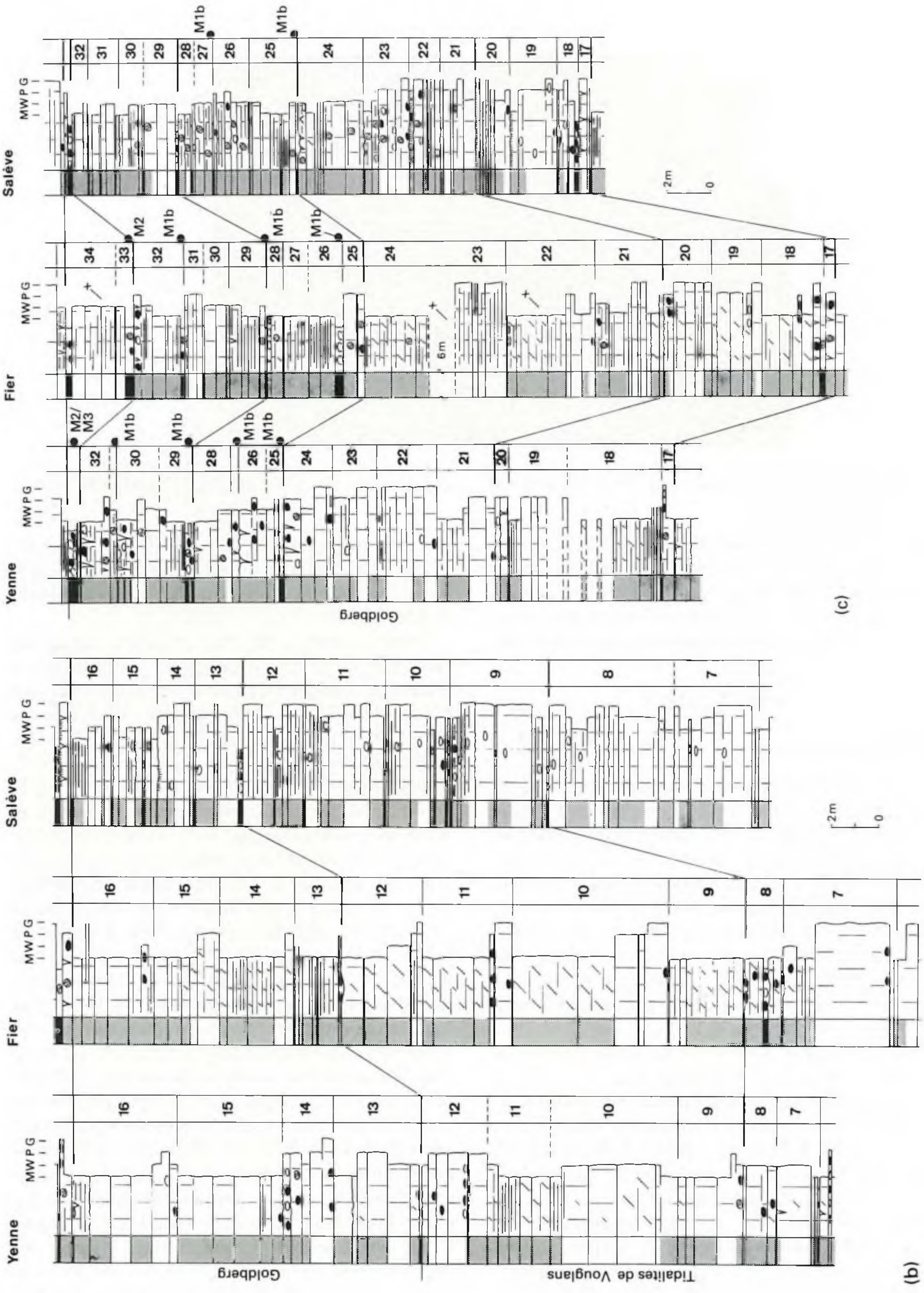

Fig. 8. *Continued.*

Fig. 9. Top of Goldberg Formation at Salève. Sequences are strongly reduced, reworked, or missing. Hammer for scale.

deeper facies in sequences 29 and 30), and at the top of sequence 32, after which the beds are much reduced and reworked. The rapid change to fully marine conditions at the base of Pierre-Châtel then indicates an important transgression (Figs 9 and 10).

DISCUSSION

Milankovitch cyclicity

Stacked shallowing-upward sequences in shallow-water carbonates can form by autocyclic or allocyclic processes (Strasser, 1991). Autocyclic processes include progradation of shorelines and lateral migration or shifts of tidal channels, tidal inlets and bars, or islands (Ginsburg, 1971; Matti & McKee, 1976; Wong & Oldershaw, 1980; Pratt & James, 1986; Selg, 1988). Such processes are inherent to shallow platforms, and the resulting sequences are limited to specific depositional environments. Allocyclic processes, on the other hand, are controlled by factors such as basin-wide or global changes of sea level or sediment production rates.

The fact that many sequences of the Tidalites-de-Vouglans and Goldberg Formations display pedogenic caps and widespread erosional features implies that drops of relative sea level were involved, which could have been due to periodic tectonic uplifts or to eustatic sea-level falls. It has been suggested by Cisne (1986) that high-frequency tectonic movements at the platform edge can form successive shallowing-upward sequences. Differential subsidence did influence the Jura platform (Wildi *et al.*, 1989), but the observed hierarchical stacking of small sequences can be better explained by climatically controlled eustatic sea-level changes.

Glacial eustasy was very effective during the Quaternary and has been proven to be linked to insolation changes induced by cyclic perturbations of the Earth's orbit (Milankovitch, 1941; Hays *et al.*, 1976). In Late Jurassic and Early Cretaceous times, climate was more equable (Barron, 1983). Nevertheless, Frakes & Francis (1988) suggested the presence of polar ice whose waxing and waning could have influenced sea level. Other climatically tuned factors modifying eustatic sea level are presence or absence of Alpine glaciers (Fairbridge, 1976), changing evaporation rates (Donovan & Jones, 1979), and thermal expansion of the upper layers of the ocean (Gornitz *et al.*, 1982). The thicknesses of the studied small-scale sequences suggest that the high-frequency sea-level fluctuations were in the order of only one to a few metres. Any of the factors mentioned above could have produced such low-amplitude sea-level fluctuations. Climatically controlled changes in the rate of organic and inorganic carbonate production could equally have influenced the sedimentary conditions. Climatically induced presence or absence of terrestrial vegetation may have held back or released clay minerals which could slow down carbonate production. Furthermore, climatically controlled changes in water circulation could lead to nutrient excess and plankton blooms, which reduced water transparency and thus the vitality of carbonate-producing organisms (Hallock & Schlager, 1986).

The hierarchy of the stacked sequences suggests superimposed cycles of eustatic sea-level changes which reflect a Milankovitch cyclicity. As a working hypothesis it is assumed that the elementary sequences correspond to the precession cycle of the equinoxes which, in the Early Cretaceous, had a duration of about 20 000 years (Berger *et al.*, 1989). The larger sequences (composed of an average of five elementary sequences) would represent the 100 000-year eccentricity cycle, and the groups of four larger sequences the second cycle of eccentricity of 400 000 years (Milankovitch, 1941; Berger, 1980; Berger *et al.*, 1989). Obliquity cycles could not be identified. Considering the fact that many beds in the outcrops studied have eroded tops, that some beds may be missing, that compaction rates vary from one facies to another, and that autocyclic processes cannot be excluded, a statistical analysis of bed thicknesses or simple facies alternations (e.g. Schwarzacher & Haas, 1986) has not been undertaken. The recognition of such a hierarchy is therefore based mainly on facies evolution and comparison with other sections.

It has been shown by Weedon & Jenkyns (1990) that bundling of elementary sequences can also be caused by climatic variations not related to orbital eccentricity cycles. Furthermore, Laskar (1989) argued that the chaotic behaviour of the solar system excludes predictability of the orbital parameters of the Earth for times older than a few tens of millions of years. Even though it cannot be proven to what extent the observed stratigraphic record was controlled by orbital cycles, it is practical to assume such a control as a first approximation. This allows a tentative time framework to be established, which can then be compared with the framework given by the larger sea-level variations and by biostratigraphy.

Superposition of Milankovitch cycles on larger sea-level cycles

High-frequency sea-level cycles of the Milankovitch type are superimposed on larger cycles of eustatic sea level with durations of one to several million years and amplitudes of several tens of metres (Goldhammer *et al.*, 1990; Osleger & Read, 1991). The resulting fluctuations of sea level, together with probable cyclic carbonate production and differential subsidence, control water depth and thus facies evolution. Shallow-lagoonal and peritidal depositional environments respond to the slightest modifications of these three parameters, which leads to a very complex sedimentary record.

The most detailed sea-level curve available for the Mesozoic is the one published by Haq *et al.* (1987), although it is controversial in places (Schlager, 1991). In Fig. 10, the supposed Milankovitch cycles are compared with the short-term sea-level cycles of Haq *et al.* (1987). The total number of supposed 100-ka sequences is inferred from the detailed analysis and correlation of the studied sections (Fig. 8). The brecciated beds and conglomerates especially at the top of the Goldberg Formation, and the condensation of the charophyte–ostracod assemblages *M2*/*M3* (Fig. 8), imply that some sequences are much reduced or missing (Fig. 2, top). The suggested number of 36 is therefore rather a minimum estimate (Fig. 10).

The sequence boundary at the base of the Tidalites-de-Vouglans Formation could not be dated by palaeontological means. However, it represents a major break in the sedimentary record and is tentatively correlated with sequence boundary 134 of Haq *et al.* (1987), which occurs at the base of the *jacobi* subzone. Three other possible sequence boundaries can be proposed (Fig. 10), but it is not known to what extent they are due to a larger cycle or to a strongly expressed superimposed Milankovitch signal. One is placed in the *jacobi* subzone (dated indirectly by correlation with charophyte–ostracod assemblage *M1a*; Mojon, in Detraz & Mojon, 1989). The two other possible sequence boundaries appear in the *grandis* subzone, one of them probably at its very top. In a recent study of deeper-water carbonates in south-eastern France, Jan du Chêne *et al.* (1993) propose two sequence boundaries in the *jacobi grandis* zone, one at the base of the *subalpina* subzone, and one at its top which corresponds to sequence boundary 131.5 in Haq *et al.* (1987). This may suggest that more time needs to be accounted for at the top of the Goldberg Formation, and that sequence boundary 134 in Haq *et al.* could also be represented by the boundary placed at the top of sequences 12 or 16 (Fig. 10). More biostratigraphic data are needed, and detailed platform-to-basin correlations will have to be carried out before the positions of these sequence boundaries can be established with confidence (in Fig. 10 the first possibility has been taken into account). The transgressive surface corresponding to the base of the Pierre-Châtel Formation has been well dated

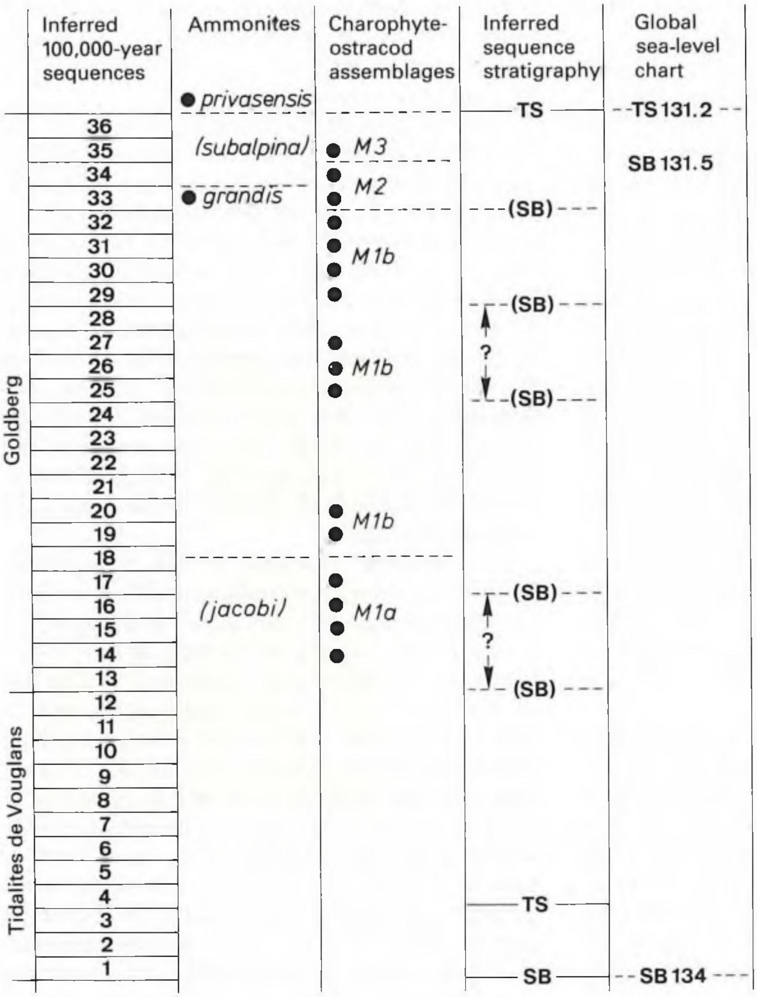

Fig. 10. Tentative comparison between Milankovitch cyclicity and large-scale sequence stratigraphy. Charophyte–ostracod assemblages after Mojon (in Detraz & Mojon, 1989), global sea-level chart after Haq *et al.* (1987). For discussion refer to text.

by ammonites and can be correlated with the large-scale transgression at about 131.2 Ma (Haq *et al.* dated the maximum flooding at 131 Ma).

Thirty-six sequences of possibly 100 ka imply a timespan of 3.6 Ma for the formation of the Tidalites de Vouglans and Goldberg successions. However, according to the sea-level chart of Haq *et al.* (1987) and the proposed correlations, only 2.8 Ma are available. Another approach is counting the beds in the studied sections, and multiplying by 20 ka (assuming each bed to be an elementary sequence). This gives the following values: 3.3 Ma for Salève, 2.8 Ma for Fier, and 2.4 Ma for Yenne. Some beds may, of course, be due to autocyclic processes, many have been eroded, or time may have passed without deposition.

It has to be kept in mind that the top of the Goldberg Formation commonly shows condensation due to non-deposition, reworking or erosion, so that dates furnished by fossils often cannot be attributed to a particular sequence. Interpretation and correlation of supposed 100-ka sequences is in many cases a best-fit solution, and dating by sequence correlation may well be out by 100–200 ka. Furthermore, the ages of sequence boundaries of Haq *et al.* (1987) are indicated with steps of 0.5 Ma for the time period here concerned, and the absolute time scales are not very well established. According to Haq *et al.* (1987) the Berriasian has a duration of 6 Ma, according to Harland *et al.* (1990, p. 58) only 5 Ma. Finally, on a shallow platform, a strong Milankovitch signal can modulate a sea-level drop leading to an important sequence boundary and displace its strongest physical expression by a few hundred thousand years. These uncertainties may explain some of the discrepancies in Fig. 10.

Rates of sedimention and diagenesis

If it is assumed that an elementary sequence comprises about 20 ka, a time framework for estimating rates of sediment production and accumulation, of facies evolution, and of diagenetic processes is given.

In order to evaluate the initial sediment thickness, compaction has to be considered. Dewatering and mechanical compaction may account for a porosity loss of about 10% in grainstones and of 30% or more in shallow-water carbonate muds (Shinn & Robbin, 1983; Moore, 1989, pp. 244–247). For deep burial producing pressure solution and stylolitization, values between 20 and 30% of chemical compaction seem to be reasonable (Moore, 1989, pp. 247–251). Depending on the facies, total compaction can accordingly be estimated to have varied between 30 and 60% or more.

Allowing an average compaction of 50%, no significant erosion and a timespan of about 3.5 Ma for the deposition of the two formations studied, the average subsidence rate can be estimated at about 0.05 m/ka (Grotzinger, 1986b, indicates 0.05–0.1 m/ka for mature passive margins). The varying thicknesses of time-correlated sequences (Fig. 8) can be explained by differential subsidence on the faulted Jura platform (Wildi *et al.*, 1989).

Figure 11 illustrates schematically that, in a peritidal setting, a great part of the 20 ka of an elementary cycle is spent in non-deposition or erosion. Decompacted bed-thicknesses suggest that accommodation space and thus relative sea-level fluctuations were in the order of a few metres. The estimated subsidence of about 0.05 m/ka was greatly outpaced by sedimentation which was first slow during a certain lag time, but which later reached 1 m/ka (Schlager, 1981, indicates this value as an average for ancient carbonate platforms; Hardie & Ginsburg, 1977, suggest 0.3–3 m/ka for Recent tidal-flat accumulation). Sea-level rise is estimated at about 0.2 m/ka on average (as calculated from an average accumulation up to the intertidal zone of 2 m/10 ka of non-compacted sediment), but reached 0.4 m/ka at its fastest point. Using these theoretical values, it is clear from Fig. 11 that the space available for sediment accumulation is soon filled up, even before the sea-level curve reaches its culmination. The base of the resulting sedimentary sequence will consist of a lag deposit and transgressive facies, until deepest water is reached at maximum flooding. Water depth then diminishes and a shallowing-up facies succession is deposited, which soon attains emersion. Falling sea level starts to erode the previously accumulated sediment. If a freshwater lens is present, cementation will occur and stabilize the carbonate, which will then be exposed to pedogenesis, vadose diagenesis and karstification.

This model suggests that, in a peritidal carbonate system, sediment production and accumulation occurs mostly during a rise of eustatic sea level, when accommodation space is created. Transgressive de-

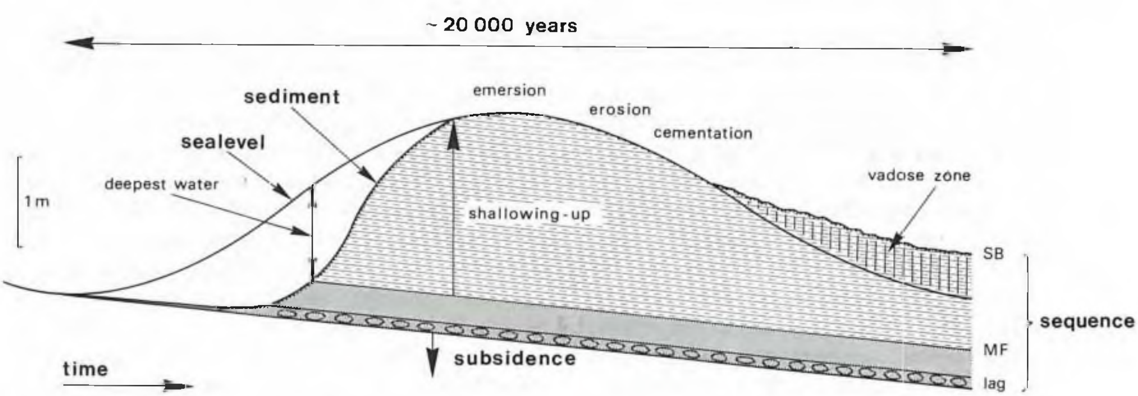

Fig. 11. Model of deposition of one small-scale peritidal carbonate sequence during a sea-level cycle of about 20 ka. Sediment accumulation takes place only during eustatic sea-level rise. Some sediment is exported as sea level starts to fall, but cementation soon prevents further erosion. Sea level drops below the sediment surface, thus creating a vadose diagenetic zone. MF, maximum flooding; SB, sequence boundary. For discussion refer to text.

posits with a deepening-upwards trend develop only at the beginning of eustatic sea-level rise. As soon as sediment accumulation outpaces sea-level rise, a shallowing-upward high-stand deposit is created. It is evident that only a few thousand years are needed to deposit such a sequence, and that much time is available for erosion, diagenesis and reworking.

Taking for example the lagoonal grainstones of elementary sequence 2 (part of sequence 9, Fig. 3), decompacting them by 30% and dividing by 4 ka accumulation time (as suggested in Fig. 11) gives a sedimentation rate of about 0.5 m/ka. The packstones of elementary sequence 5 (Fig. 3), decompacted by 50%, imply a sedimentation rate of 0.17 m/ka. These values are rather small when compared to Recent production rates. They might suggest that even less time is needed to accumulate an elementary sequence. Quinn & Matthews (1990) estimated that in post-Miocene atoll carbonates less than 10% of lapsed time was recorded by sediment accumulation. Some of the sediment may have been exported by currents and storms, as for example has been documented by Wilber *et al.* (1990) for the Holocene of the Great Bahama Bank, where during sea-level high-stand large quantities of bank-derived sediment accumulated on the slope. It is also possible that Tithonian–Berriasian production rates were lower than modern ones. More data are needed to clarify this point.

Cementation in a freshwater lens can be very fast (Halley & Harris, 1979, have shown that oolite was cemented within 1 ka). The reworked clasts at the base of small-scale sequences testify to such rapid consolidation of the underlying sediment. Cathodoluminescence shows complex patterns of early cementation which are difficult to correlate in a vertical section. This is probably due to repeated exposure at the top of small sequences, allowing for the installation of freshwater lenses and early cementation of each sequence, before the following one was deposited. Horbury & Adams (1989) and Sun (1990) have illustrated in detail such cyclic cementation in shallow-water carbonates.

Studies of oxygen isotopes performed on Purbeckian micrites have shown an evolution towards heavier $\delta^{18}O$ values at the top of 100-ka sequences, indicating increased evaporation (Joachimski, 1990). Carbon isotopes generally become lighter towards the top of 100-ka sequences, which is probably due to the enrichment of the pore waters by light carbon from soil gas (Joachimski, 1990).

CONCLUSIONS

The shallow-lagoonal and peritidal carbonates studied display a hierarchical stacking of beds. One bed represents in most cases an elementary depositional sequence. An average of five elementary sequences composes larger sequences, which again form groups of four. The sequences of all three orders generally display a shallowing-upward trend of facies evolution. Recurring pedogenic caps and widespread erosion surfaces imply repeated drops of sea level, and thus sea-level fluctuations.

As the formation of the sequences is, at least partly, controlled by sea level, the concept of sequence stratigraphy may be applied in their description and interpretation. This underlines the dynamic evolution of depositional sequences in response to changing accommodation potential. Bed surfaces are in many cases erosive and are interpreted as sequence boundaries, the overlying calcretes, conglomerates and marls as low-stand deposits. Transgressive surfaces are mostly well defined. Transgressive deposits contain reworked pebbles and mixed marine and freshwater fossils. High-stand deposits commonly exhibit subtidal, marine to restricted facies in their lower part, then shallow up into intertidal and supratidal, hypersaline or freshwater facies.

The hierarchical stacking of sequences is probably due to sea-level fluctuations controlled by orbitally induced climatic cycles in the Milankovitch frequency band. The elementary sequences may correspond to the 20-ka cycle of the precession of the equinoxes, the two larger orders of sequences to the eccentricity cycles with periods of 100 and 400 ka.

Dating by fossils allows correlation of some sequences of the studied sections with the global sea-level curve of Haq *et al.* (1987). Large-scale features of sequence stratigraphy are not always easy to recognize: in the peritidal depositional environments, high-frequency sea-level fluctuations overprinted many of the signals of a general sea-level change.

More biostratigraphical and palaeomagnetic work, very detailed analyses of facies evolution and sequential patterns, and comparisons with other, widely spaced sections are needed to resolve this incoherency and to test the tentative correlation presented in Fig. 10. If it can be demonstrated that the recognized sequences indeed represent Milankovitch cycles with periods of 20, 100 and 400 ka, and if time correlations of the sequences are well established, a very precise framework of absolute time will be available.

Within this framework it becomes possible to estimate rates of sediment production and accumulation, as well as of diagenetic processes. There is the potential that, through very precise studies of the ecological, sedimentological and diagenetic record, the evolution of an ancient sedimentary system can be monitored on a time scale which is comparable to that of the Holocene.

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