DEPOSITIONAL SEQUENCES IN DEEP-SHELF ENVIRONMENTS: A RESPONSE TO SEA-LEVEL CHANGES AND SHALLOW-PLATFORM CARBONATE PRODUCTIVITY (OXFORDIAN, GERMANY AND SPAIN)

BERNARD PITTET[1], ANDRÉ STRASSER[2], AND EMANUELA MATTIOLI[1]
[1] *UFR Sciences de la Terre, Université Claude-Bernard Lyon I, F-69622 Villeurbanne Cedex, France*
[2] *Institut de Géologie, Université de Fribourg, Pérolles, CH-1700 Fribourg, Switzerland*

ABSTRACT: **Oxfordian deep-shelf deposits of southern Germany and southern Spain are characterized by marl–limestone alternations that are stacked into small-scale, medium-scale, and large-scale depositional sequences. The German sections contain autochthonous sponge reefs and associated fragments of microbialites, whereas the sections studied in Spain display tempestites composed of autochthonous deeper-water and allochthonous shallow-water particles. The facies of the German limestones and marl layers has been analyzed in detail: condensed intervals (implied by glauconitization of particles, abundant cephalopods, intense bioturbation, and generally more marls) are also enriched in sponge reefs and associated particles, and in nannofossils. Limestone-rich intervals, however, contain fewer sponges and fewer nannofossils. Neither bioerosion of sponge reefs nor nannofossil blooms can thus explain the abundance of carbonate mud that forms the limestones. Consequently, it is suggested that most of the carbonate mud is exported from shallow platform areas where carbonate productivity is high. The clay fraction was derived from weathering of massifs in the hinterland.**

The observed depositional sequences can be correlated between the studied sections in Germany and Spain (situated in different paleotectonic and paleoclimatic domains), and also between deeper-water sections and platform sections. This suggests that they formed through allocyclical processes. Comparision with published time scales implies that the small-scale and medium-scale sequences formed in tune with the 100 kyr and 400 kyr orbital eccentricity cycles, respectively. However, the number of marl–limestone alternations is not always consistent with the expected number of 20 kyr precessional cycles (5 per 100 kyr cycle). The large-scale sequences reflect long-term (''third order'') sea-level changes.

The observed marl–limestone alternations are interpreted to have formed through cyclically varying export of carbonate mud from the platform towards the deep shelf, the variations being controlled by climatically induced high-frequency sea-level fluctuations. Enhanced marl deposition on the deep shelf can be related to sea-level fall causing exposure of the shallow platform and reducing the area of carbonate production, or by rapid sea-level rise (maximum flooding) leading to partial or total drowning of the platform, and/or to retrogradation of facies belts. Enhanced carbonate deposition occurs during transgression, when large production areas are created on the platform, or during late highstands, when progradation is forced and carbonate-mud export enhanced. Depending on the long-term trend of sea-level change on which the high-frequency fluctuations are superimposed, one high-frequency (20 kyr) sea-level cycle can thus create one or two marl–limestone alternations, or only marly deposits. Consequently, one 100 kyr eccentricity cycle may be formed of a variable number of marl–limestone alternations (commonly 2 to 8). The studied deeper-water depositional sequences thus are strongly linked to the history of the adjacent shallow carbonate platforms.

INTRODUCTION

Oxfordian deep-shelf environments of epicontinental basins in the northern Tethys realm commonly exhibit marl–limestone alternations. Examples from Spain, France, Germany, and Switzerland have been described by, e.g., Marquez et al. (1991), Davaud and Lombard (1973), Gaillard (1983), Gaillard et al. (1996), and Gygi and Persoz (1986). Marl–limestone alternations in deep-shelf, slope, or basinal environments formed during many geological periods (for a review, see Einsele and Ricken 1991). Their formation is explained by cyclical processes affecting pelagic carbonate productivity, input of clays, dissolution of carbonate, redox conditions, and/or diagenetic redistribution of carbonate (Einsele and Ricken 1991). Furthermore, cyclical exportation of carbonates from Oxfordian platforms to deeper environments has been proposed by, e.g., Davaud and Lombard (1973), Brachert (1992), Gaillard (1983), and Pittet (1996). In hemipelagic or pelagic sedimentary environments, a marl–limestone couplet commonly results from climatically induced changes in environmental conditions, which are driven by the precessional cycle of the Earth's orbit (e.g., Fischer 1991; Giraud et al. 1995). In the Oxfordian, this cycle had a duration of about 20 kyr (Berger et al. 1989).

In southern Germany and southern Spain, the Oxfordian deep-shelf sedimentary record shows marl–limestone alternations stacked in depositional sequences that can be correlated from section to section, and from one study area to another (Pittet and Strasser 1998a, 1998b). In southern Germany, these depositional sequences are expressed by recurrent changes from condensed to noncondensed sediments. Condensation is indicated by increased glauconite content, enrichment in cephalopods, enhanced bioturbation, and generally more marly intervals (Pittet and Strasser 1998a). The biostratigraphic and chronostratigraphic framework is well established for the studied sections (Schweigert 1995a, 1995b; Pittet and Strasser 1998a, 1998b). Dividing the duration of the sedimentary history suggested by dated tie points by the number of recognized depositional sequences suggests that one such sequence corresponds to the 100 kyr eccentricity cycle of the Earth's orbit. Although the number of marl–limestone alternations is generally constant in one laterally correlated sequence, it varies greatly in different sedimentary episodes. Consequently, an interpretation of marl–limestone alternations as being directly related to the precession cycle (i.e., one marl–limestone couplet corresponding to one precession cycle) is not consistent with the observed sedimentary record.

We propose a model based on a detailed sedimentologic analysis of Middle and Upper Oxfordian sections (Pittet and Strasser 1998a), which allows a better understanding of the formation of marl–limestone alternations recorded in deep-shelf environments. We show that marl–limestone alternations and depositional sequences translate the influences of the superposition of short-term and long-term sea-level changes, of paleoclimatic and paleotectonic conditions, and of shallow-platform carbonate productivity. We suggest that deep and/or distal sedimentary environments are indirectly but strongly influenced by the adjacent shallow-platform environments.

PREVIOUS WORK

Twenty-two sections of four study areas (Fig. 1) from the northwestern margin of the Tethys ocean have been studied (Pittet 1994, 1996; Pittet et al. 1995; Pittet and Gorin 1997; Pittet and Strasser 1998a, 1998b). The main method used is facies analysis with the help of thin sections (about 1100) and marl washings, whereas clay mineralogy and palynofacies add supplementary information on the different depositional environments. All studied sections display facies evolutions that can be described as hierarchically stacked depositional sequences. On each hierarchical level, the

JOURNAL OF SEDIMENTARY RESEARCH, VOL. 70, NO. 2, MARCH, 2000, P. 392–407

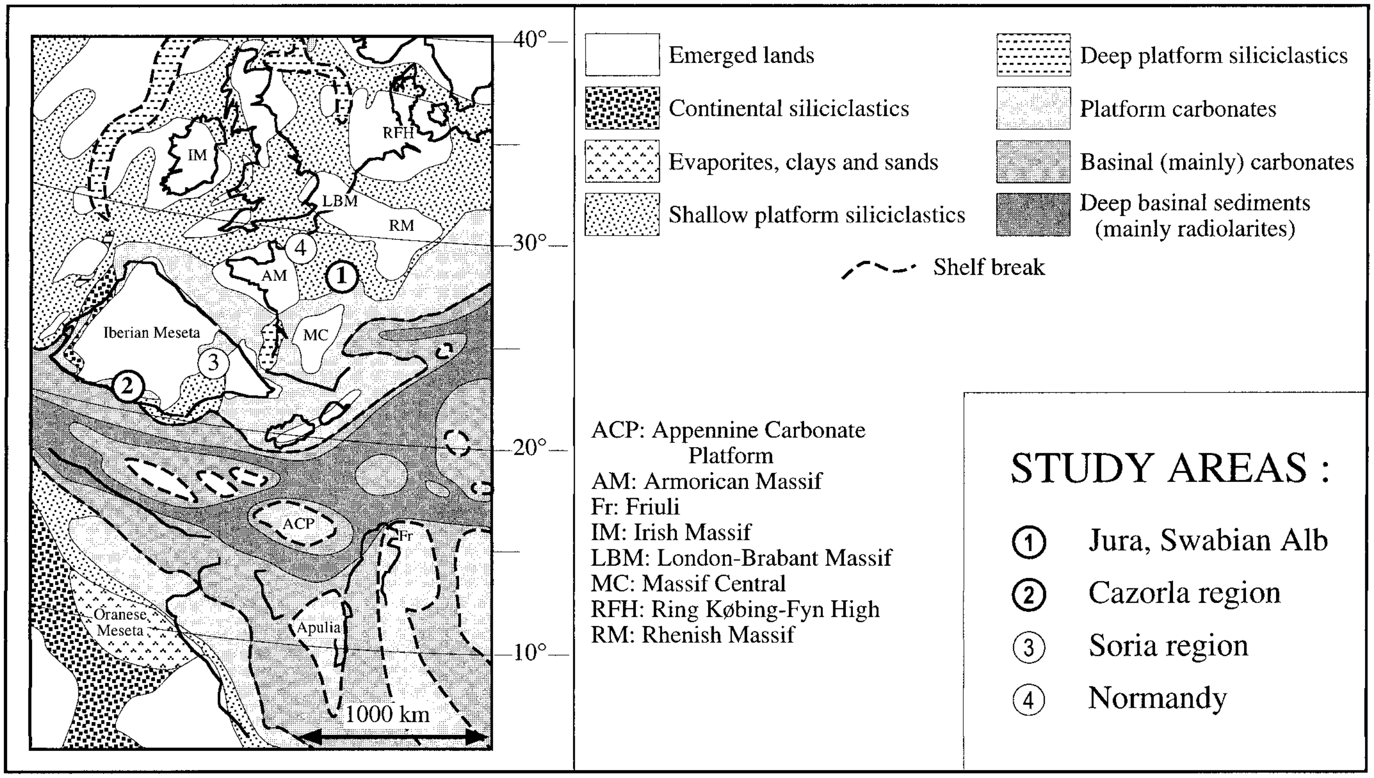


FIG. 1.—Location of the study areas on a paleogeographic map of the western Tethys during the Oxfordian–Kimmeridgian interval; modified from Dercourt et al. (1993). Study areas 1 and 2 are treated in this paper. Study areas 3 and 4 are integrated into the high-resolution sequence-stratigraphic correlations of the sections (see Figure 3 for the result).

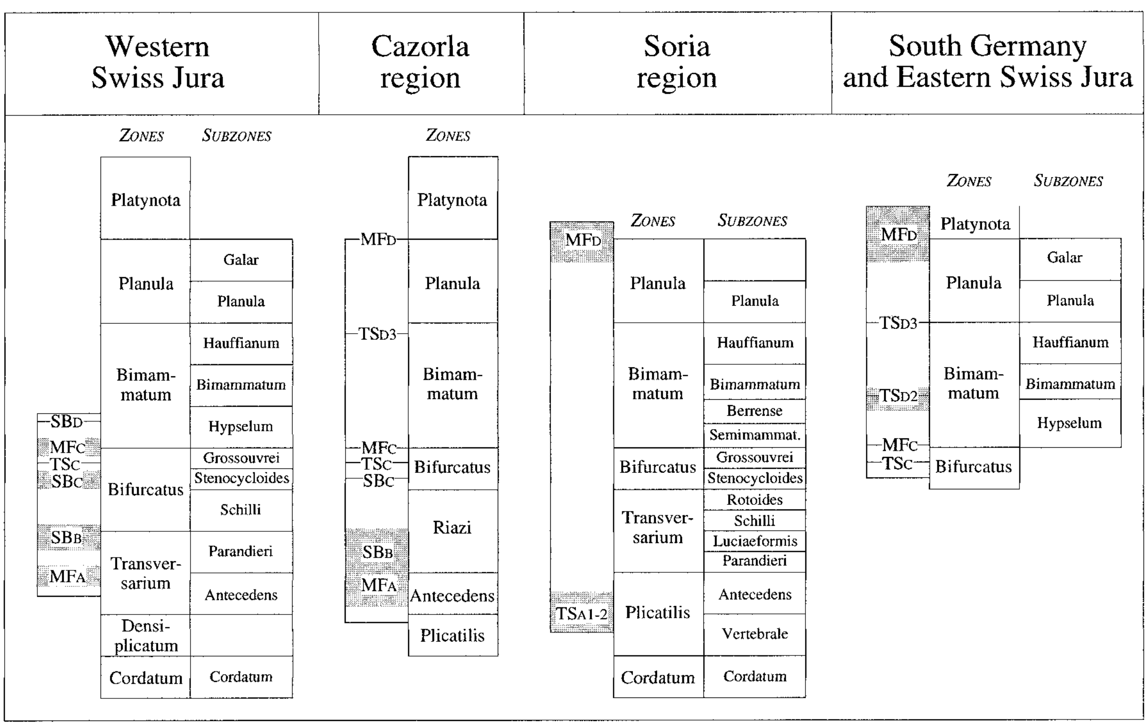


FIG. 2.—Biostratigraphically dated sequence-stratigraphic surfaces or zones (gray intervals) for the two main study areas presented in this paper, and two complementary study areas used to establish the correlation scheme in Figure 3.

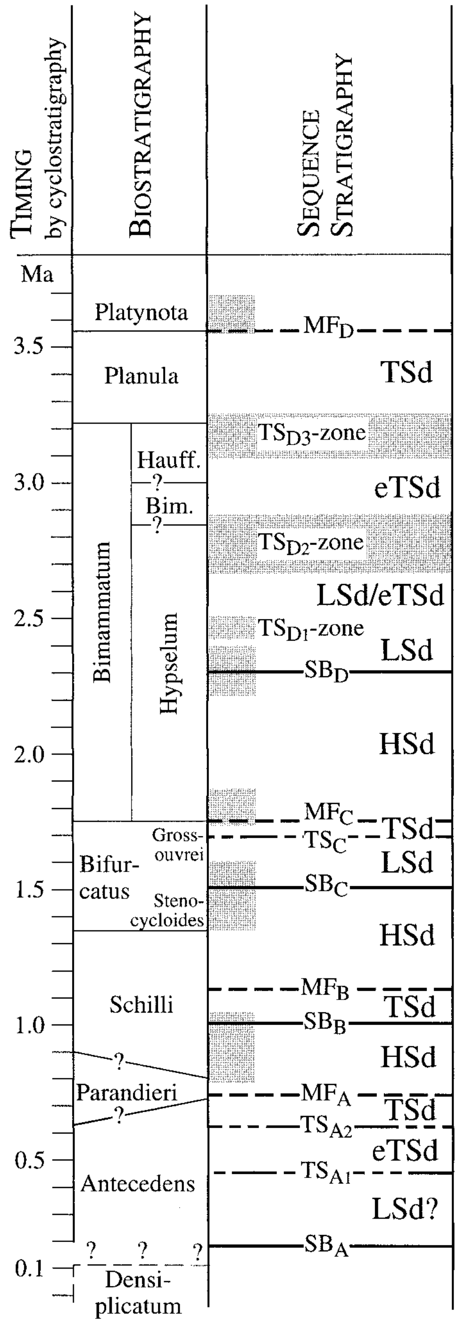


FIG. 3.—Sequence-stratigraphic and cyclostratigraphic interpretation for the Middle and Late Oxfordian based on the correlation of 22 profiles from Switzerland (Swiss Jura), France (Normandy), Spain (Soria and Cazorla regions), and southern Germany (Swabian Alb) (Pittet 1996; Pittet and Strasser 1998a, 1998b; Pittet and Gorin 1997). Biostratigraphy from Gygi and Persoz (1986) and Gygi (1995). SB, sequence boundary; TS, transgressive surface; MF, maximum flooding.

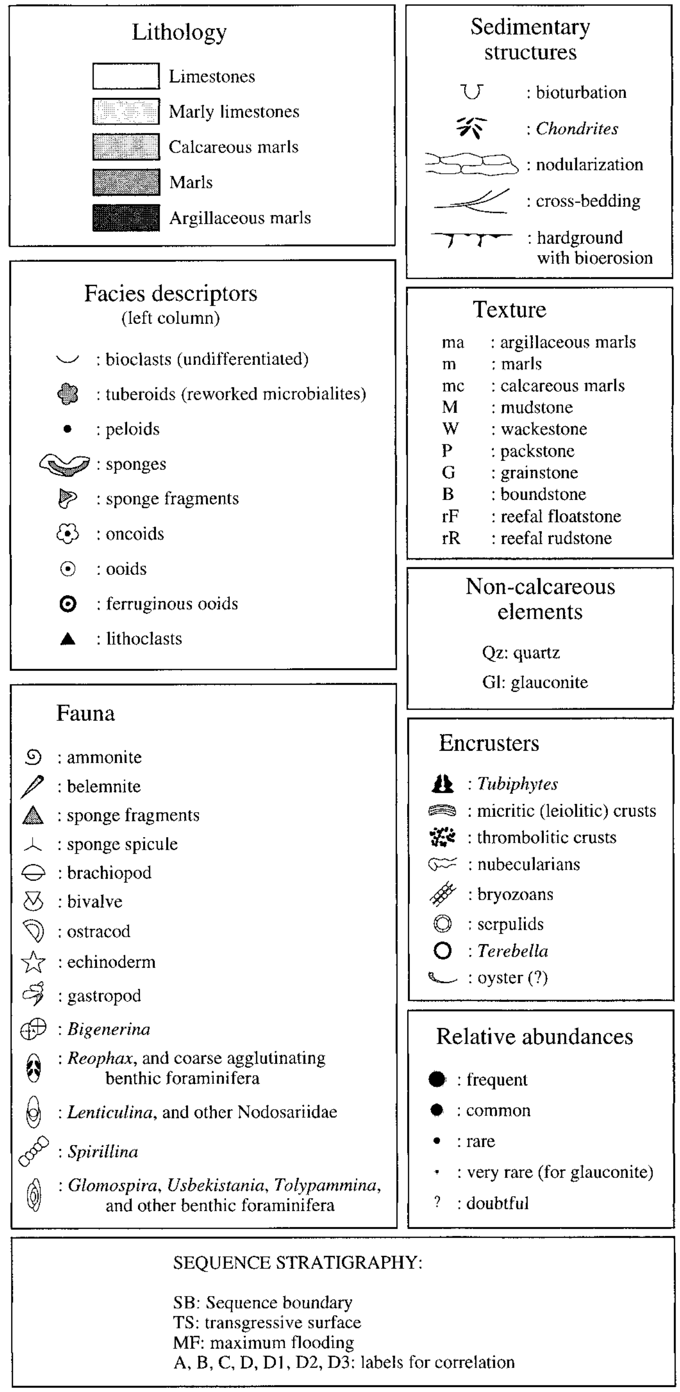


FIG. 4.—Legend for the detailed logs.

generally transgressive–regressive facies trend implies that these sequences formed through relative sea-level fluctuations (e.g., Pittet and Strasser 1998a, 1998b). The largest depositional sequences correspond to long-term changes of relative sea level (''third order''; Vail et al. 1991), and the smaller ones are attributed to sea-level fluctuations in the Milankovitch frequency band. The sections are biostratigraphically and chronostratigraphically well constrained (Fig. 2), thus furnishing guidelines for long-distance sequence-stratigraphic correlations (Fig. 3; Pittet and Strasser 1998a, 1998b) between the Swiss Jura and the western Swabian Alb (study area 1, Fig. 1), the Cazorla region in Spain (study area 2), the Soria region in Spain (study area 3), and Normandy in France (study area 4). Because the studied sections belong to different paleotectonic and paleoclimatic contexts and because most depositional sequences can be correlated between all sections, it is suggested that long-term sea-level variations had an important eustatic component (at least at the scale of western Europe; Pittet and Strasser 1998b).

Short-term sea-level variations were superimposed. They most probably originated from climatic changes in tune with the Earth's orbital cycles,

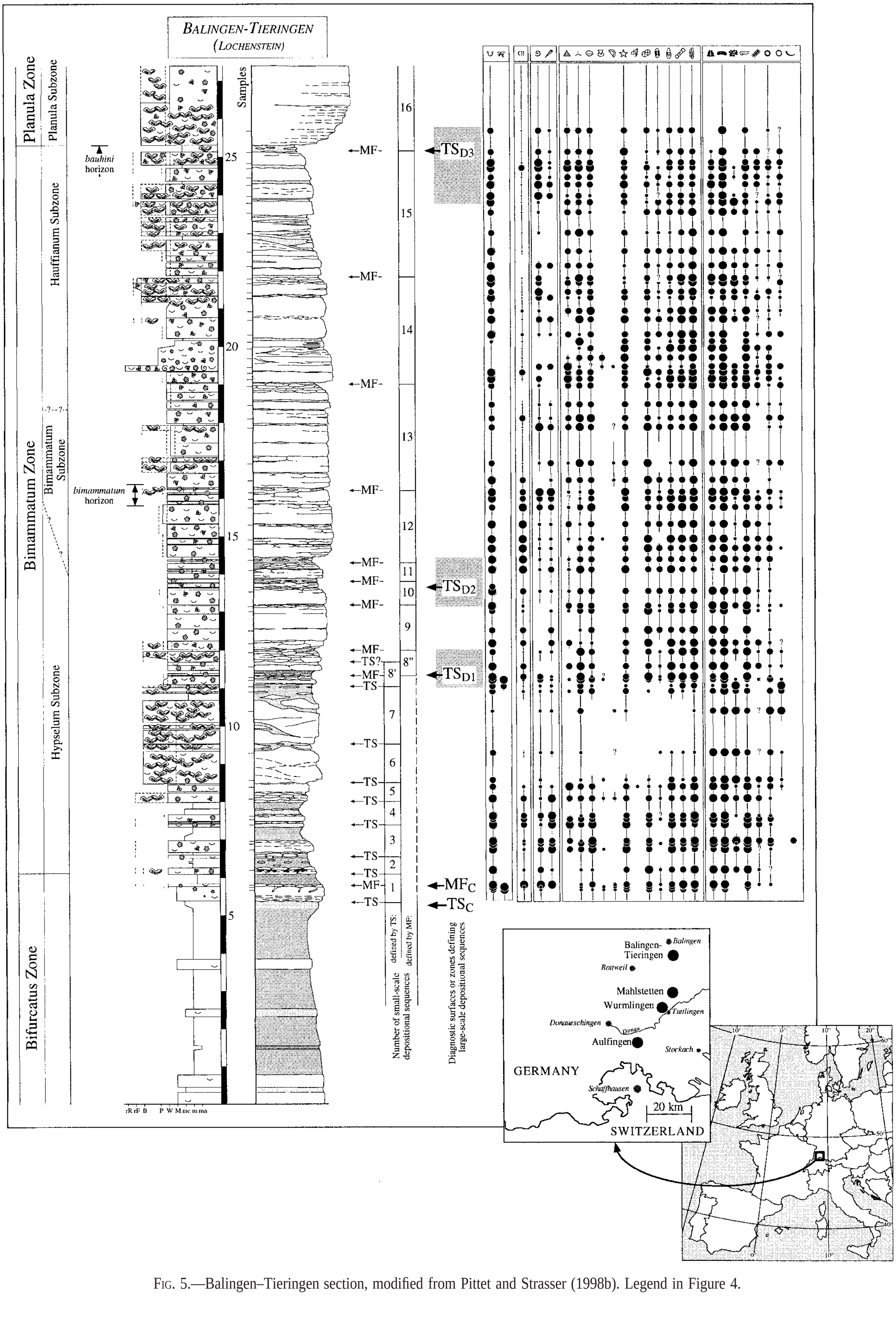
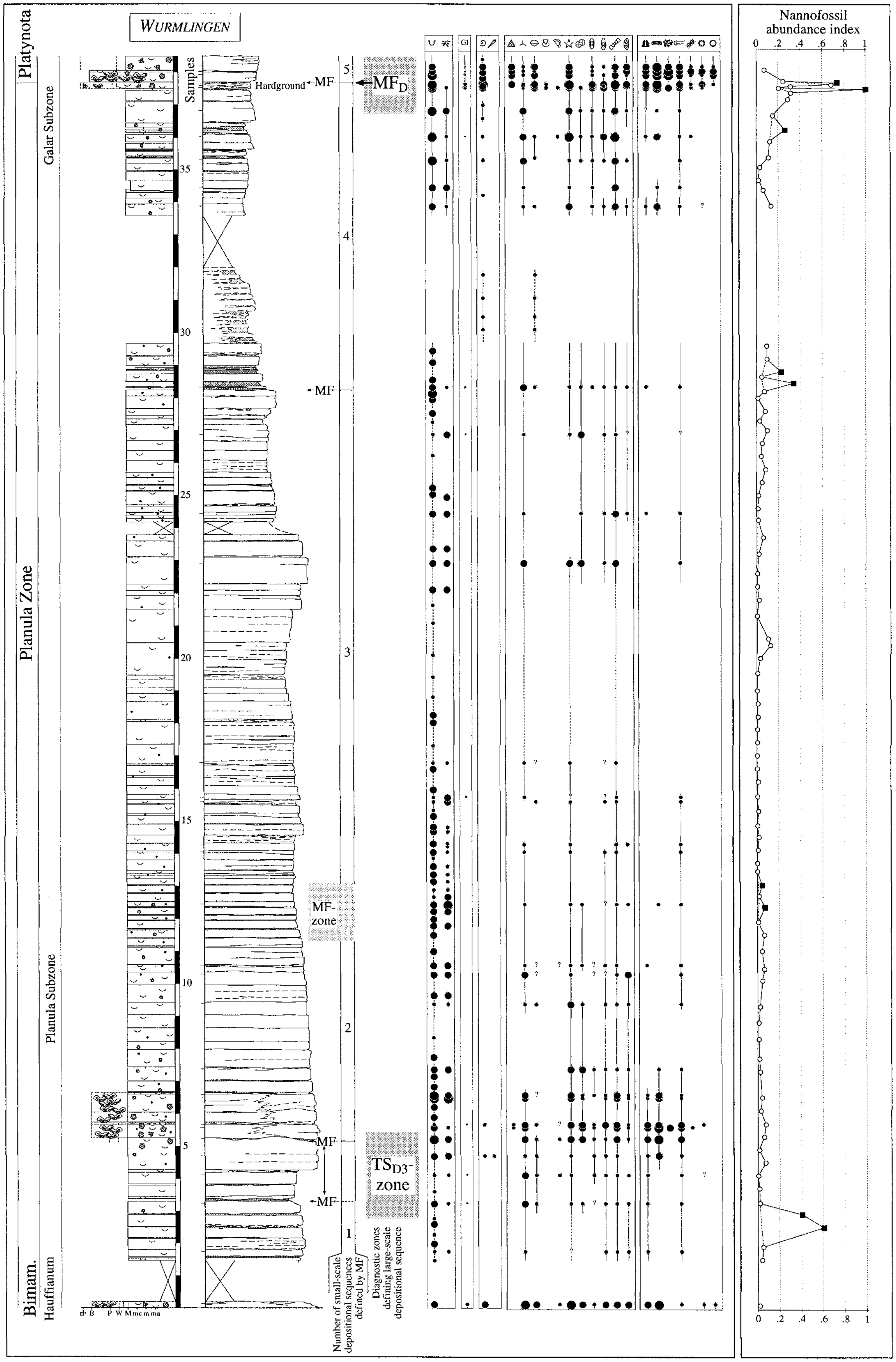


FIG. 5.—Balingen–Tieringen section, modified from Pittet and Strasser (1998b). Legend in Figure 4.


WURMLINGEN
Platynota
Planula Zone
Galar Subzone
Planula Subzone
Bimam.
Hauffianum
Samples
Hardground
MF
MF$_D$
MF-zone
TS$_{D3}$-zone
Number of small-scale depositional sequences defined by MF
Diagnostic zones defining large-scale depositional sequence
Nannofossil abundance index

leading to changes in the volume of ocean water (Gornitz et al. 1982; Schulz and Schäfer-Neth 1998), retention and release of water in aquifers and lakes (Jacobs and Sahagian 1993), and/or waxing and waning of continental ice masses (Fairbridge 1976). A climatic control on the formation of the small-scale sequences is also suggested by changes in distribution through time of indicators such as ooids, corals, or coal in platform areas (Swiss Jura; Pittet et al. 1995; Pittet 1996). Furthermore, comparison between the Swiss Jura and the Soria region (Spain) shows that the distribution of siliciclastics in depositional sequences is dependent on the paleolatitudinal position of the study area: in the Jura, quartz and clays (commonly associated with coal fragments) were flushed from the hinterland because of rainfall during sea-level lowstands, whereas in the Soria region siliciclastics were abundant during highstands (Pittet and Strasser 1998b). Paleolatitudinal changes in humidity may be related to fluctuations of the atmospheric circulation cells driven by orbital insolation cycles (Matthews and Perlmutter 1994) in paleogeographic positions close to the interface of seasonally shifting high-pressure and low-pressure cells (Oschmann 1990).

Counting of small-scale depositional sequences and comparison with the time span available for the studied interval (Gradstein et al. 1995) allows estimation of the durations of the observed sequences. The best-developed small-scale sequences correlated along the northwestern margin of the Tethys are related to the 100 kyr eccentricity cycle (Pittet and Strasser 1998b, 1998a), whereas the 400 kyr eccentricity cycles seem to have been responsible for the most important changes of facies (Pittet 1994, 1996).

The sequence-stratigraphic and cyclostratigraphic correlations of Pittet and Strasser (1998a, 1998b) are shown in Figure 3. They are placed in the biostratigraphic scheme of Gygi and Persoz (1986) and Gygi (1995). The biostratigraphic data for each study area are discussed in detail in Pittet (1996) and Pittet and Strasser (1998a, 1998b).

DESCRIPTION OF SEDIMENTS

In this paper, we focus on two comparable depositional environments: the deep shelves of South Germany (western Swabian Alb) and of the south of Spain (Cazorla region). The German sections have been described and interpreted in Pittet and Strasser (1998a), and the sections of the Cazorla region are presented in Pittet (1996) and Pittet and Strasser (1998b).

In the five sections of the western Swabian Alb (Germany; study area 1, Fig. 1) the sedimentary record is formed mainly of marl–limestone alternations. However, changes in marl–limestone ratios are important in the studied sections (e.g., Balingen–Tieringen and Wurmlingen sections, Figs. 5, 6; legend in Figure 4). Depending on clay content, argillaceous marls, marls, and calcareous marls can be distinguished. The limestones classify as mudstones, wackestones, or packstones. Where sponges were abundant, boundstones and floatstones developed. These deep-shelf deposits contain varying amounts of autochthonous to parautochthonous particles (brachiopods, echinoderms, foraminifera, ammonites, belemnites, sponges and associated encrusters, and scarce bivalves, ostracods, and gastropods). Fragments of reworked microbialites (tuberoids), and glauconite, also occur in variable quantities. Statistical analysis shows that the higher the total percentage of particles is in a sample, the more frequent are glauconite, bioturbation, nodularization, cephalopods, sponges, and microbial crusts (Pittet and Strasser 1998a). Wackestone and packstone samples thus generally correspond to lower sedimentation rates than mudstones, which reflect a high carbonate-mud sedimentation rate. Accumulation rates varied significantly, creating condensed intervals (glauconitization, enrichment in cephalopods, strong bioturbation) and intervals in which autochthonous and parautochthonous elements are strongly diluted with respect to carbonate mud or clays.

In Spain, the two sections of the Cazorla region (study area 2, Fig. 1; logs in Fig. 7) display facies of the Prebetic intermediate platform (Marquez et al. 1991), where material exported from the shallow platform mixed with more distal elements (Pittet and Strasser 1998b). The deep-shelf deposits display marl–limestone alternations. Limestone beds are generally formed by amalgamation of high-energy deposits composed of platform-derived particles (oncoids, peloids, bivalves, echinoderms, ostracods) and parautochthonous particles (globochaetes, cephalopods, brachiopods, benthic foraminifera, sponge spicules, tuberoids, peloids). Storm influence is indicated by tempestites containing abundant echinoderms and oncoids as well as meter-scale hummocky cross-stratification in the more proximal facies. Thinner cross-beds are possibly related to distal tempestites reworked by bottom currents. Marls are deposited during low-energy conditions. Accumulation rates were low, as indicated by common glauconitization of peloids, reworked microbialites, and oncoids, and as suggested by the reduced thickness of the sections: the entire Middle to Upper Oxfordian deposits form a series of only 15 to 25 meters. Ammonitico Rosso facies (reddish ammonite-rich nodular carbonate beds) was deposited on topographic highs, whereas marl deposition prevailed in lows.

MARL–LIMESTONE ALTERNATIONS IN THE DEEP-SHELF SETTING OF THE SWABIAN ALB

Origin of the Carbonate Mud

Calcareous nannofossils have been investigated in the German sections. Nannofossil abundance is low, and marly intervals are richer in nannofossils than the limestone beds. Furthermore, intervals showing condensation features (enrichments in sessile fauna, cephalopods, and glauconite, or nodularization of limestone beds with increasing bioturbation) are enriched in nannofossils. The Wurmlingen section (Fig. 6) contains only rare condensation levels and is dominated by limestone (mudstones) that characterize the Planula Zone. As shown above, this indicates generally high accumulation rates. Nannofossils are rare or absent, except in condensation levels (e.g., Planula–Platynota boundary; Fig. 6). The Balingen–Tieringen section (Fig. 5) contains many condensed horizons and marly intervals, which imply low to moderate accumulation rates. The nannofossil content here is generally higher than in the Wurmlingen section, although the assemblage composition is quite similar. The relative scarcity of nannofossils may be due to three factors: poor preservation, low nannoplankton primary productivity, and/or dilution by carbonate mud.

Visual estimation of nannofossil preservation, based on the observation of etching/overgrowth effects (Roth 1978), allowed us to define five classes of preservation. The samples with the highest abundance of calcareous nannofossils generally display poorly or moderately preserved forms (preservation index 1 or 2) whereas the samples with the best preservation (preservation index 3 or 4) exhibit relatively low abundances of nannofossils (Fig. 8).

The nannofossils are commonly better preserved in marls than in limestones (Noël 1968; Erba 1994). In the Wurmlingen section (Fig. 6), the marly intervals are enriched in nannofossils when compared to limestones. However, the increase in nannofossil abundance at the top of the Oxfordian (top Planula Zone) is observed in both marls and limestones, and coincides

←

FIG. 6.—Wurmlingen section (see Figure 5 for location), modified from Pittet and Strasser (1998b). Legend in Figure 4. The nannofossil abundance index is calculated as the average of counted specimens per field of view under the microscope. The abundance of nannofossils is normalized to the maximum value (sample at 37.8 m in the marly layer above the hardground). White dots, limestone samples; black squares, marl samples. Dashed lines relate the limestone samples only (marl samples are enriched in nannofossils relative to limestones).

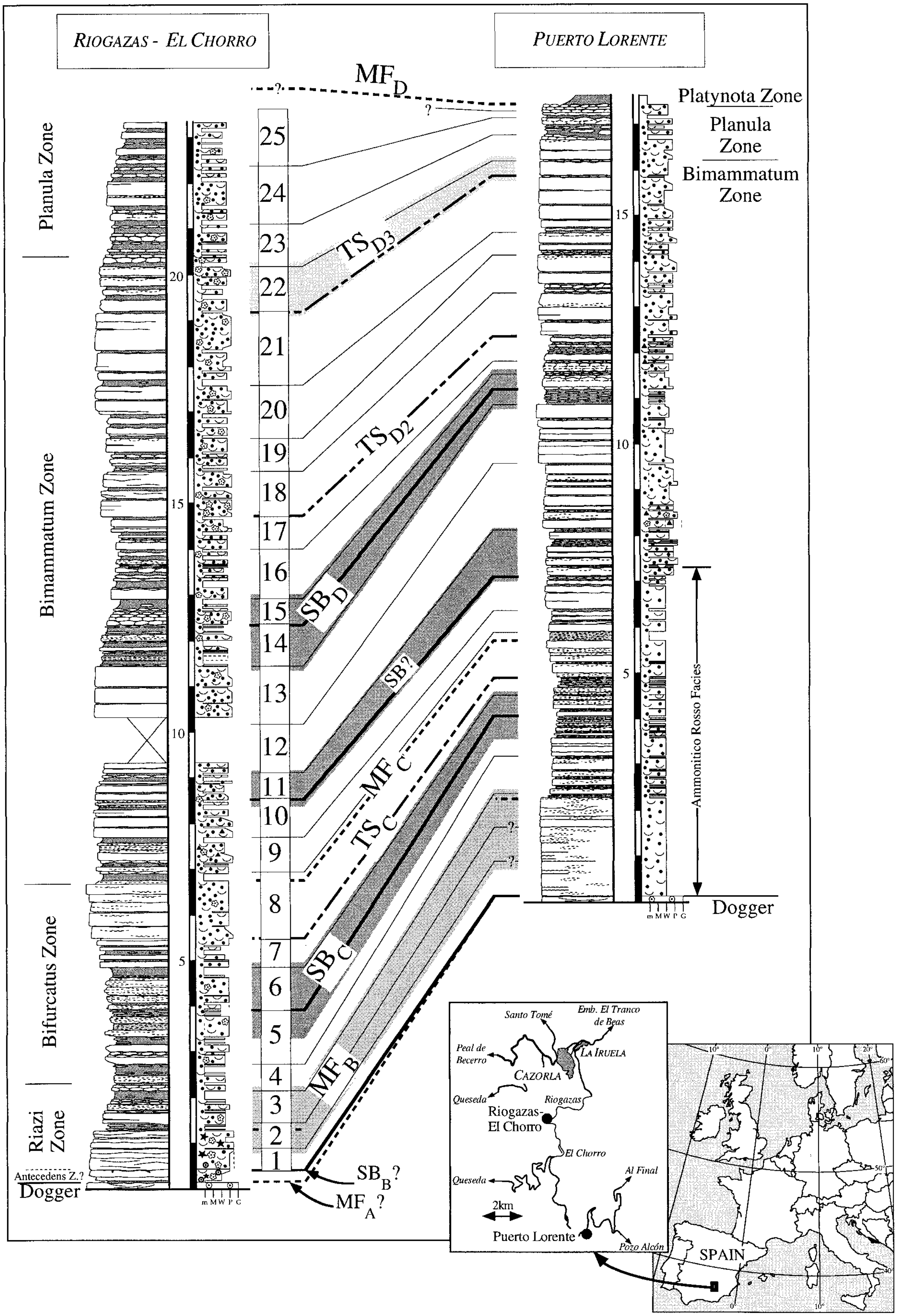


FIG. 7.—Riogazas–El Chorro and Puerto Lorente sections from the Cazorla region (southern Spain). Correlation based on Pittet and Strasser (1998b). Legend in Figure 4.

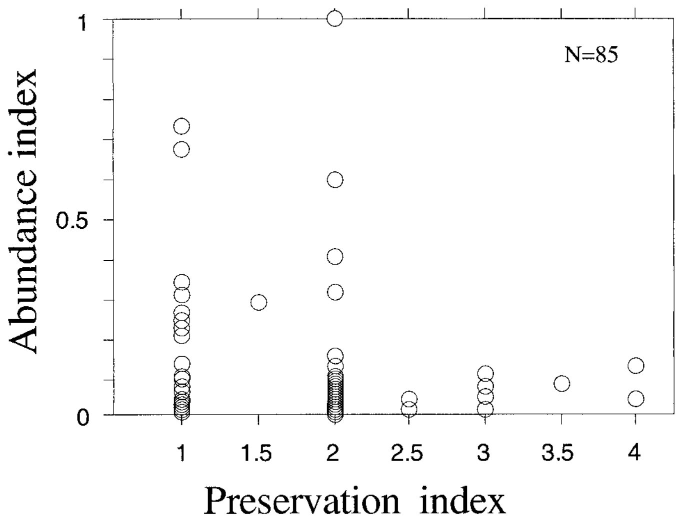


FIG. 8.—Plot of abundance index (normalized to the sample of highest abundance) vs. preservation index. 1, poor preservation; 2, moderate preservation; 3, good preservation; 4, very good preservation.

with lower accumulation rates as indicated by increased intensity of bioturbation and higher abundance of ammonites, sessile fauna, benthic foraminifera, and tuberoids. Enrichment in nannofossil content in the marls may also correspond to lower accumulation rates rather than much better preservation (see also discussion in Pittet and Strasser 1998a).

Therefore, in the Oxfordian of the Swabian Alb, it appears that the higher the sediment accumulation rate, the lower is the nannofossil record. This suggests that the main factor responsible for the generally low nannofossil content is dilution by carbonate mud. Furthermore, the contribution of nannofossils in the formation of pre-Tithonian hemipelagic and pelagic limestones was probably rather low (e.g., Bown 1987).

In coral reefs, bioerosion is responsible for significant production of carbonate mud (e.g., Peyrot-Clausade et al. 1995; Dullo et al. 1996; van Treeck et al. 1996; Vogel et al. 1996). In the studied Oxfordian deep-water settings, however, reefs are composed of siliceous sponges associated with microbialites. Proximal areas are characterized by great amounts of spicules of *Rhaxella,* a siliceous demosponge (Pittet and Strasser 1998a). Bioerosion is rare, and abundant carbonate production related to sponge-reef systems is therefore not likely. Pittet and Strasser (1998a) show statistically that carbonate mud recorded in sponge-reef systems correlates negatively with sponge-reef bioconstructors and related particles such as tuberoids, and with autochthonous and parautochthonous fauna.

Consequently, neither nannofossils nor sponge reefs can be invoked to produce the bulk of the carbonate mud needed to form the observed limestones. We must therefore assume that the carbonate mud was exported from shallow platform areas. Fluctuations in carbonate-mud ratios thus probably are related to fluctuations in carbonate production on the platform, and/or to changes in the dynamics of carbonate export from the platform to the deep shelf. Varying input of carbonate mud into the deeper environments then influences the relative abundance of autochthonous and parautochthonous particulate elements (fauna, tuberoids). The carbonate mud was probably exported from the Jura platform (northern Switzerland, eastern France, and southwestern Germany) situated about 50 to 70 km to the west (Meyer and Schmidt-Kaler 1989; Gygi 1990; Gygi and Persoz 1987).

The terrigenous input is represented by clays and derived from the Hercynian London–Brabant, Rhenish, and Bohemian massifs (Fig. 1; Gygi and Persoz 1986; Ziegler 1988; Dercourt et al. 1993). Especially the Rhenish Massif was a major emergent area during the Oxfordian (Meyer and Schmidt-Kaler 1989). Clay contents in the studied interval (Figs. 5, 6) show that there was a general decrease in the Upper Oxfordian, which probably resulted from a change from generally more humid to generally more arid climates (Gygi 1986; Gygi and Persoz 1986, 1987; Pittet and Strasser 1998b). However, sedimentation rate of carbonate mud is another important factor in defining relative clay content. Common condensation on the tops of limestone beds implies a decrease in sedimentation at the passage from limestone bed to marly bed. Abundant marly beds and thinner carbonate beds generally correspond to a decrease in carbonate sedimentation rates, as shown by enrichment in autochthonous and parauthochthonous particles, cephalopods, sponge reefs, and glauconite. Moreover, many sponges grow in marly layers, whereas sponge reefs commonly die out during carbonate-rich phases. All this suggests that variations in clay input are less important in the formation of small-scale depositional sequences than variations in input of carbonate mud. High-frequency changes in clay input therefore seem to be of lower amplitude than changes in export of carbonate mud from the platform.

Model

Organic productivity of carbonate on the shallow platform is a limiting factor on the amount of carbonate mud recorded on the deep shelf. Carbonate production by benthic organisms depends on environmental conditions such as water depth, water transparency, siliciclastics, nutrients, and oxygenation (Wilson 1975; Hallock and Schlager 1986; Schlager 1991; Oschmann 1990; Leinfelder 1994a, 1994b). Carbonate accumulates if accommodation is created by sea-level rise and subsidence (Handford and Loucks 1993; Strasser 1994). High production of carbonate leads to greater export to the deep shelf, and low production of carbonate on the platform can lead to sediment starvation in the deeper environments (Schlager et al. 1994).

Sea-level variations play an important role in the export of carbonate mud from the platform to the deep shelf (Droxler and Schlager 1985; Schlager et al. 1994). Retrogradation vs. progradation of facies belts may further diminish, or enhance, the record of carbonate mud in distal localities. ''Highstand shedding'' (Schlager et al. 1994) occurs when, during high sea level and within the photic zone, overproduction on the platform is intense and accommodation is decreasing. Fine-grained sediment is stirred up by storms and exported over the platform edge into deeper environments. Milliman et al. (1993) and Robbins et al. (1997) suggest that large amounts of inorganically or microbially precipitated carbonate mud are exported. Rapid flooding can lead to drowning of the platform (Schlager 1989), and rapid changes in environmental conditions stop or diminish production of carbonates (Tipper 1997).

Carbonate productivity on the shallow platform is dependent on the response of the biological system to the dynamics of sea-level change (Fig. 9):

Phase I.—At the beginning of a sea-level rise, accommodation is created but carbonate production still low; this is the ''start-up'' phase of Kendall and Schlager (1981).

Phase II.—When carbonate production picks up on the shallow platform, accommodation continues to be created but the sediment partly fills in the available space; this is the ''transgressive-production phase'', corresponding to the ''catch-up'' and possibly ''keep-up'' phases of Kendall and Schlager (1981).

Phase III.—Rapid sea-level rise may outpace carbonate production; the sediment surface drops below the optimal depth for carbonate production, and the carbonate-producing environments are drowned or shifted towards shallower areas. This phase is here described as the ''drop-down'' phase. It may correspond to the ''give-up'' phase of Neumann and Macintyre (1985). If such a phase is enhanced by environmental conditions unfavorable for carbonate production (e.g., high nutrient levels and dysoxic conditions), drowning can occur (Schlager 1989). Commonly, this phase corresponds to a slowing of carbonate production, and more bioturbated, condensed sediments are observed.

Phase IV.—During slowing sea-level rise in the highstand, carbonate production again becomes intense on the platform. Space created beforehand is rapidly filled, allowing for aggradation or gentle progradation of the sedimentary environments. This again can be compared to the ''catch-up'' and ''keep-up'' phases (Kendall and Schlager 1981).

Phase V.—During late highstand, production of carbonates slows down because water depth is now too shallow for the carbonate-producing organisms, or water volumes are too small to allow formation of inorganically produced grains (ooids) or mud. Progradation is forced, and the surface of the sediment stays close to sea level (''keep-up'' phase of Kendall and Schlager 1981).

Phase VI.—When emersion takes place on the platform and sea level continues to fall, erosion can be prolonged and effective.

Phase VII.—When a relatively long period of exposure occurs, carbonates are commonly cemented on the platform and may undergo chemical dissolution.

The start-up, transgressive-production, and drop-down phases generally cause retrogradation of facies belts. Aggradation commonly occurs during the catch-up phase, and progradation during the keep-up and erosional phases (Fig. 9). However, platform morphology may strongly influence this generalized pattern.

Carbonate produced on the shallow platform is recorded in deep-shelf environments mainly during two times (Fig. 10): the transgressive-production phase (Phase II), and the keep-up and erosional phases (Phases V and VI).

Low export of carbonate occurs during the drop-down phase (Phase III) and the cementation phase (Phase VII). During the drop-down phase, carbonate production slows down on the platform, condensation features develop in deep-shelf sediments, and some marls are deposited. This condensation is enhanced by the more distal position of the deep-shelf environments at that time. During the cementation phase (Phase VII), the shallow platform is exposed and cemented, and carbonate production is possible only at the margin. Consequently, deeper environments are starved and record mainly marls.

All seven phases shown in Figure 9 rarely occur within one sea-level cycle: during a strong long-term transgressive trend, exposure may not occur and/or may be very short, so exposure and cementation phases may be lacking (Fig. 10B); during a long-term regressive trend, short-term sea-level rise is attenuated, and the drop-down phase is absent (Fig. 10C, D); when sea level falls below the platform level, only marginal carbonate production occurs, and the deeper environments exhibit low accumulation rates commonly dominated by marls (Fig. 10D).

High vs. low carbonate sedimentation rates, condensed vs. noncondensed intervals, limestone-dominated vs. marl-dominated sedimentation, and/or intervals rich in autochthonous to parautochthonous elements vs. intervals poor in autochthonous to parautochtonous elements in deeper-water sediments can thus be used as indicators of relative sea-level rises and falls, on the long term as well as on the short term.

On the long-term evolution (a few million years), generally increasing carbonate sedimentation can be related to increasing accommodation space and carbonate productivity on the platform, accompanied by increasing export of carbonate mud to the deep shelf. Intense condensation and marly layers in such limestone-dominated intervals are due to accelerated flooding of the platform, which slow down or stop export of carbonate mud. Accordingly, they correspond to maximum-flooding surfaces. Where such features occur in an interval rather than as discrete surfaces, transgressive zones or maximum-flooding zones can be defined (Montañez and Osleger 1993; Pasquier and Strasser 1997). Marl-dominated intervals are interpreted as lowstand deposits when carbonate production on the platform is reduced and clays bypass the exposed platform. Relatively constant ratios in carbonate and marl are seen as highstand deposits. They form when high-frequency fluctuations of relative sea level allow for moderate carbonate production and export and also for moderate clay transport and deposition.

During long-term transgressive periods, features indicating flooding are enhanced through the addition of short-term sea-level rises to the general transgressive trend (Fig. 10A, B). The short-term maximum-flooding surfaces are therefore the best expressed surfaces during long-term sea-level rises. The sequence boundaries of the short-term sequences correspond to the maximum of carbonate export from the platform to the deep shelf. They are not expressed as discrete surfaces in the deep shelf, but their equivalents lie in carbonate-dominated, noncondensed sediments.

During long-term regressive periods, carbonate is deposited mainly during short-term rising sea level and corresponds to transgressive and (early) highstand deposits of short-term cycles (Fig. 10C, D). The first record of limestones after a relatively important marl deposition thus lies above the short-term transgressive surface. The surface at the top of the most condensed carbonate bed thus corresponds to the maximum-flooding surface of the sequence. Enrichment in marls corresponds to low carbonate productivity on the platform, or to emersions. For this reason, the short-term sequence boundaries in a long-term regressive context are placed into the generally well-developed marly intervals (Fig. 10C, D).

Depositional sequences resulting from one short-term sea-level cycle can thus be expressed by one (Fig. 10B, C) or two (Fig. 10A) marl–limestone couplets with varying clay–carbonate ratios, or can be dominated by marls (Fig. 10D). Small-scale sequence boundaries are hidden inside limestone or marl beds, whereas small-scale transgressive or maximum-flooding surfaces generally are well expressed.

Interpretation of Long-Term Sequences

The sedimentary record shown in Figures 5 and 6 suggests that the transition from the Bifurcatus Zone to the Bimammatum Zone corresponds to a general increase in carbonate export due to a rapid transgressive event affecting shallow platform areas and increasing carbonate productivity. The first pulse of enrichment in carbonates and the following condensed interval in Figure 5 are interpreted as a long-term transgressive surface and a long-term maximum flooding, respectively. These two levels defining a very short transgressive interval have also been recognized in the other study areas (Pittet 1996; Pittet and Strasser 1998b) and named TS_C and MF_C (Fig. 3). After the maximum flooding the sedimentary record shows a relatively constant marl–limestone ratio and is therefore interpreted as a highstand deposit. Two intervals marked by condensation precede increasing carbonate deposition and argue for a general transgressive trend. These condensation features are interpreted as being related to two successive transgressive pulses (TS_{D1} and TS_{D2}). A long-term sequence boundary (Sb_d) was recognized in other study areas (Fig. 3) but can only be inferred in the Balingen–Tieringen section (Fig. 5). It probably corresponds to the sponge development in the lower part of the section, or to the interval between the sponge reefs and the transgressive pulse TS_{D1}.

We have interpreted the transition between the Bimammatum Zone and the Planula Zone as a third transgressive pulse (TS_{D3}) that is overlain by thick limestone deposits (Figs. 5, 6). These mark a strong export of carbonate mud towards the deep shelf and correspond to increased carbonate productivity during the Planula Zone, which is also suggested by thick ooid deposits recorded on the Jura platform (Gygi and Persoz 1986). Change of facies and well-developed condensation features argue for a long-term maximum-flooding zone around the Planula–Platynota boundary (Fig. 6). This MF_D was also recognized in other study areas (Fig. 3).

Definition and Correlation of Small-Scale Depositional Sequences

In the studied sections condensed intervals formed by one or two marl–limestone couplets alternate with less condensed or noncondensed intervals formed by one to six marl–limestone alternations. Thus, a rhythmically structured sedimentary record is created (Figs. 5, 6).

In transgressive intervals on the long-term trend, the condensed intervals

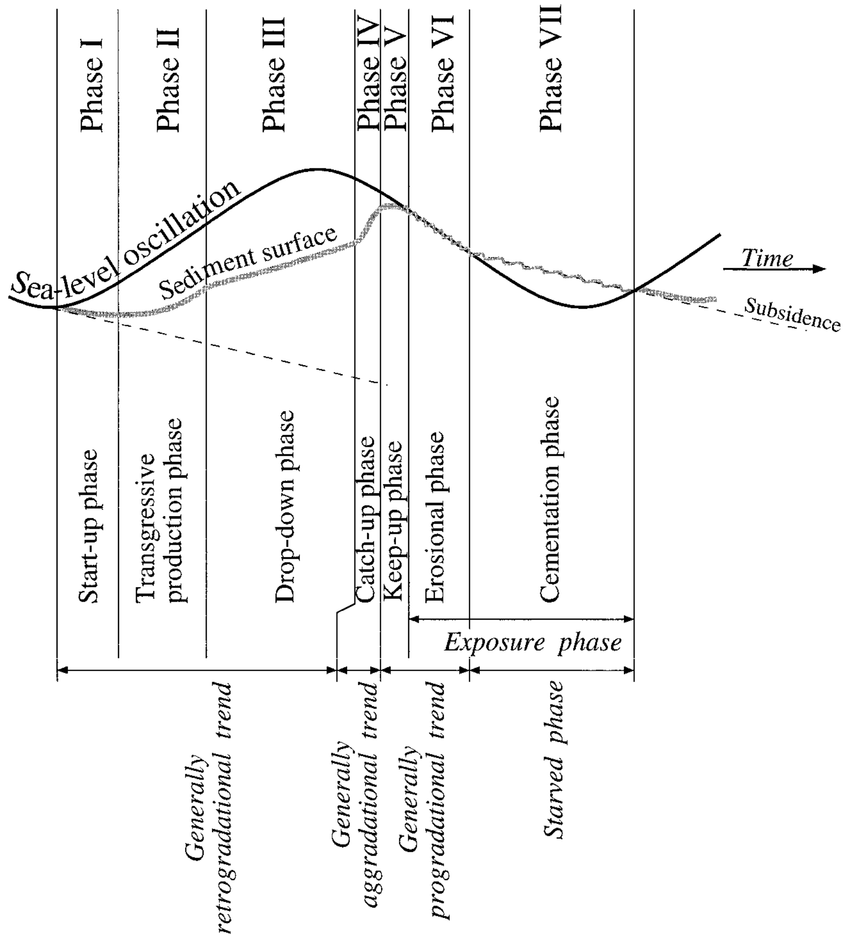


FIG. 9.—Carbonate production/starvation phases as a function of the dynamics of sea-level changes. For explanation refer to text.

(Fig. 5, e.g., 16.2 m or 19 m) are interpreted as being related to short-term maximum-flooding events (Fig. 10A, B): these define a first type of small-scale depositional sequence. During the Planula Zone (Fig. 6), the carbonate-mud sedimentation rate is high. No important sedimentary break is observed, and changes from noncondensed to condensed deposits are not well expressed. Thus, a very precise interpretation of small-scale sequences is difficult. However, increasing marl deposition coexisting with some condensation features permits the identification of relatively thick small-scale sequences.

In highstand intervals on the long-term evolution, the first occurrence of carbonates on the top of decimeter-thick marly layers (e.g., Fig. 5: 6.0 m, 6.5 m, or 7.4 m) is interpreted as a transgressive surface of a short-term cycle (Fig. 10C, D). These transgressive surfaces delimit a second type of small-scale depositional sequence.

The small-scale sequences thus defined, calibrated by ammonites (Schweigert 1995a, 1995b; see Figs. 2, 3), can be correlated with small-scale sequences recorded in other study areas (Pittet and Strasser 1998a, 1998b). A constant number of small-scale depositional sequences in any given ammonite zone or subzone has been recognized in each study area, suggesting that the formation of these sequences was induced by a supra-regional factor. Commonly, four small-scale sequences are stacked into a medium-scale sequence. In many cases medium-scale sequences define lithologic entities: for example, the Wohlgeschichtete Kalke Formation, covering the Planula Zone and the base of the Platynota Zone, is a carbonate-dominated body (mudstones; Fig. 6). In the Balingen section (Fig. 5), sequences 8 to 11 and 12 to 15 form two successive medium-scale sequences bounded by well-defined nodular, intensely bioturbated, and condensed intervals. The hierarchy recognized in the German sections as well as in other areas (see examples in Pittet and Strasser 1998b) suggests that these small-scale and medium-scale depositional sequences were created by cyclical processes. Counting the small-scale sequences and comparing their number with the time interval given by Gradstein et al. (1995) implies that they have an average duration of about 100 kyr and may form in tune with the 100 kyr orbital eccentricity cycle. Accordingly, the medium-scale depositional sequences correspond to the 400 kyr eccentricity cycle.

Superposition of Different Orders of Sea-Level Fluctuations

The simple model presented in Figure 10 can explain the formation of marl–limestone alternations and, roughly, the long-term evolution of the studied section (Figs. 5, 6). However, changes in marl–limestone ratios, as well as number of beds recorded in the small-scale sequences evidenced in Figures 5 and 6, are still not well explained. Consequently, superposition of high-frequency and low-frequency sea-level changes has to be considered.

In the shallow platform environments of the Swiss Jura, Pittet (1994, 1996) could demonstrate that symmetrical sea-level fluctuations related to the 100 kyr orbital eccentricity cycle compose cycles of 400 kyr. The first and last 100 kyr cycles within a 400 kyr cycle induced smaller sea-level changes (1.5–2 m amplitude), whereas the second and third 100 kyr cycles caused stronger sea-level changes (3–5.5 m). These results and the comparison with the insolation changes calculated by Berger (1990) suggest that the orbital forcing was relatively directly translated into sea-level

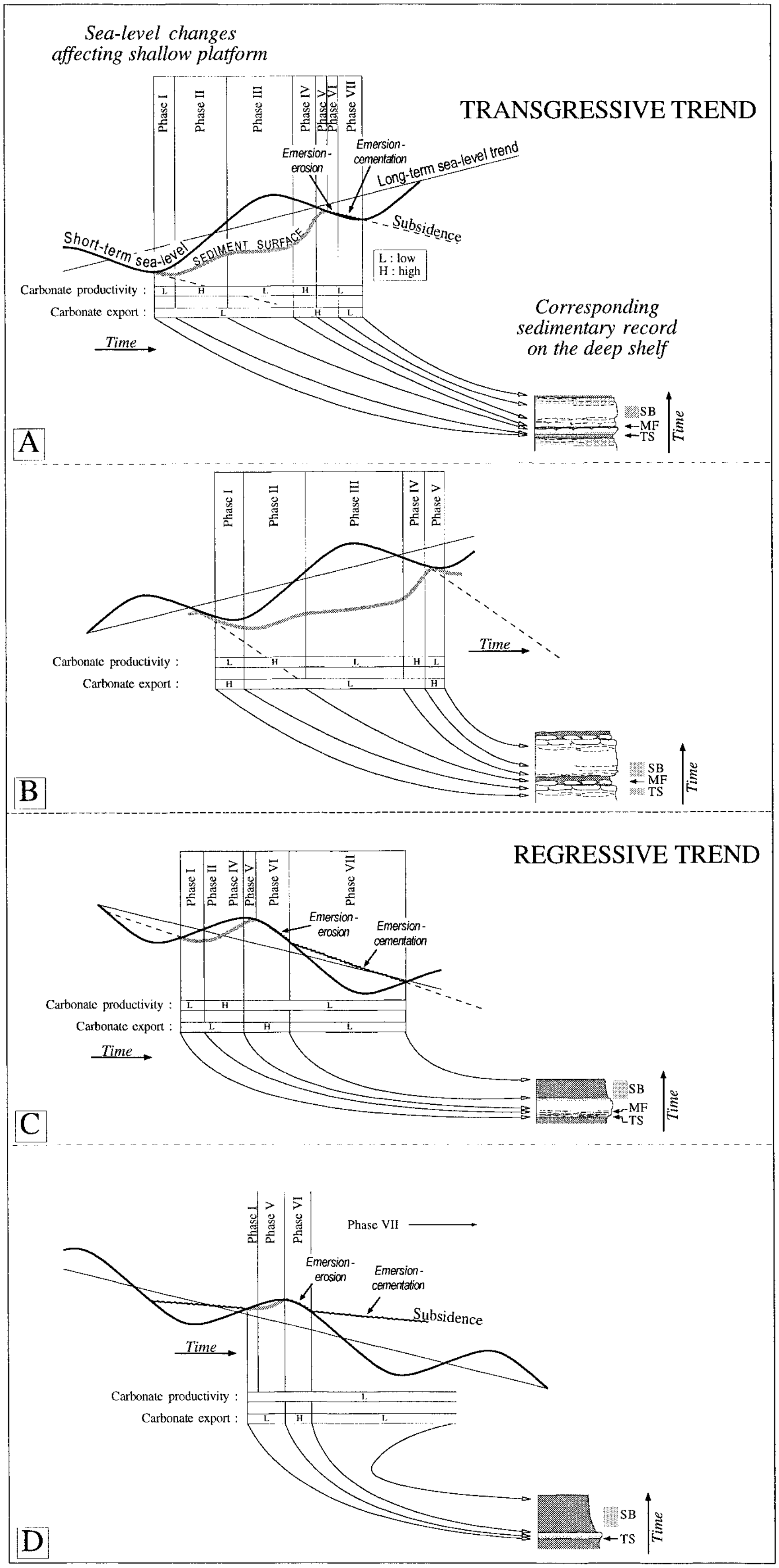


FIG. 10.—Model for the export of carbonate from the shallow platform to the deep shelf driven by long-term and short-term sea-level variations and their associated sedimentary record in deep-shelf environments (modified from Pittet and Strasser 1998a). **A)** Transgressive long-term sea-level trend (general case). **B)** Transgressive long-term sea-level trend, with very short subaerial exposure period on the shallow platform (no cementation), or without subaerial exposure. **C)** Regressive long-term sea-level trend (general case). **D)** Regressive long-term sea-level trend, with the long-term sea level falling below the platform edge. Phases I to VII are defined in Figure 9. SB, sequence boundary; TS, transgressive surface; MF, maximum flooding.

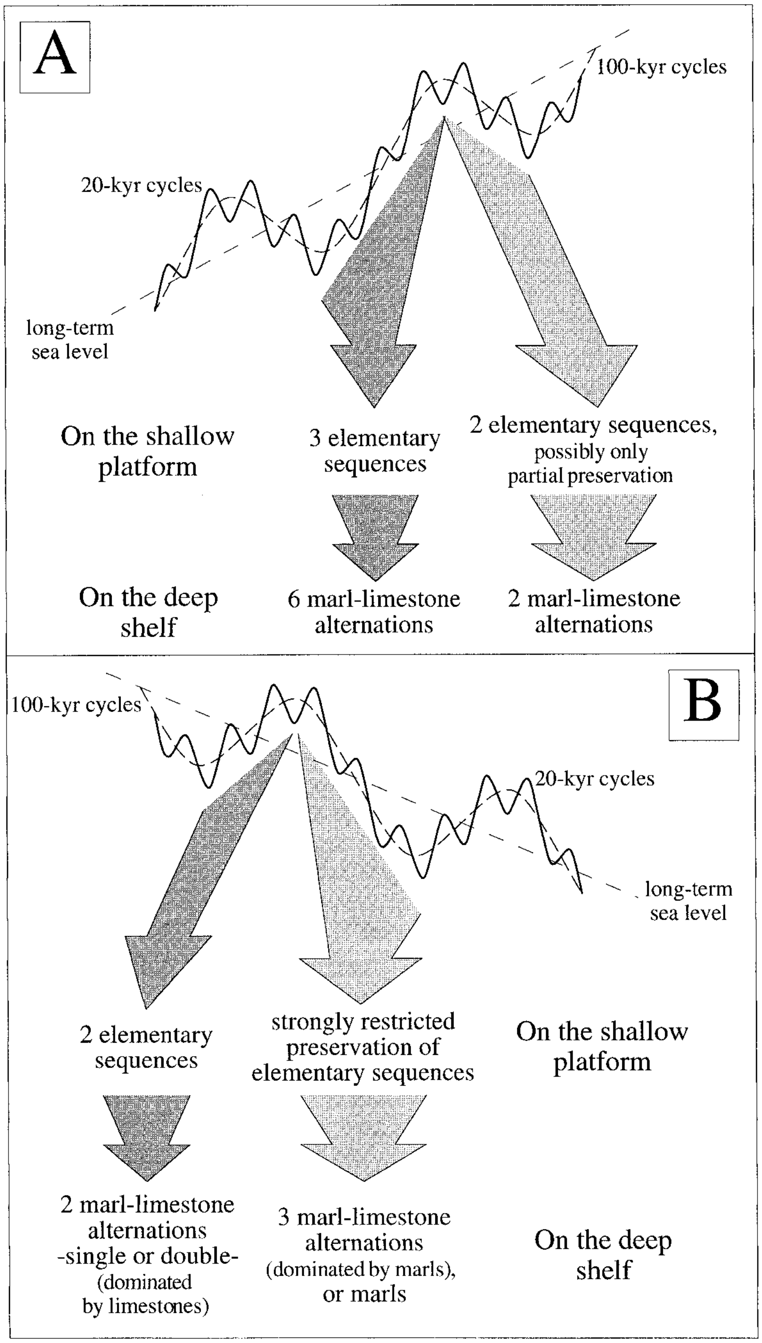


FIG. 11.—Superposition of different frequencies of sea-level variation during **A)** a long-term sea-level rise and **B)** a long-term sea-level fall, and the corresponding sedimentary record of marl–limestone alternations in deep-shelf environments according to the model presented in Figure 10. See text for further explanation.

changes, probably mainly due to thermal expansion of the ocean water (e.g., Gornitz et al. 1982; Revelle 1990; Schulz and Schäfer-Neth 1998).

Figure 11 illustrates the superposition of sea-level cycles created by the orbital eccentricity cycle of 100 kyr and by the cycle of the precession of the equinoxes (about 20 kyr in the Oxfordian; Berger et al. 1989) during a long-term sea-level rise and a long-term sea-level fall.

Long-Term Sea-Level Rise

During a 100 kyr sea-level rise superimposed on a long-term rise, the short-term sea-level fluctuations related to precession show very rapid and important sea-level rises, whereas during a 100 kyr sea-level fall they exhibit small and gentle sea-level rises and falls (Fig. 11A). Therefore, during the transgressive trend at the 100 kyr scale, the deep shelf records two marl–limestone alternations during one single sea-level cycle (Fig. 10A), or one well-defined marl–limestone alternation in which the marl layer corresponds to the maximum flooding (Fig. 10B). During sea-level fall at the 100 kyr scale, each single 20 kyr cycle generates a single marl–limestone alternation (Fig. 10C).

The best-developed small-scale sequences observed in the field that are related to 100 kyr cycles (Figs. 5, 6) would, in such a model case, be composed of seven or eight marl–limestone alternations. Figure 12 illustrates an example from southern Germany where two 100 kyr sequences formed during a long-term sea-level rise are composed of eight marl–limestone alternations each. A similar pattern is also visible in Figure 5 (from 16 to 25 meters). During strong transgression, the sedimentary record is

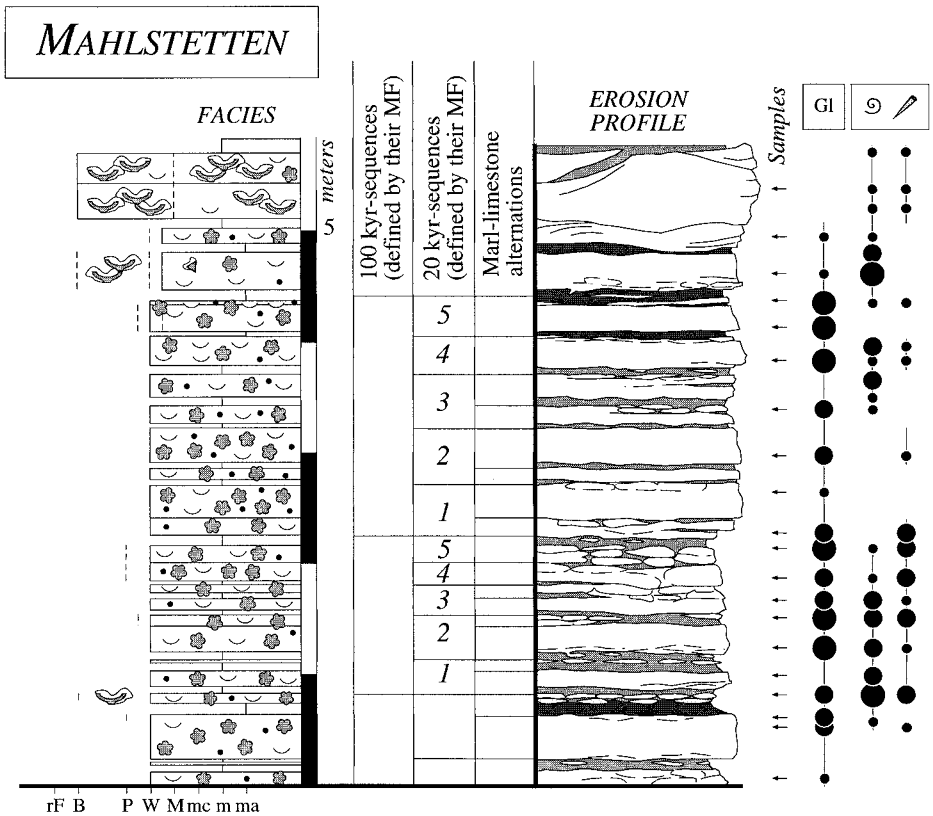


FIG. 12.—Example of sedimentary record of marl–limestone alternations during a long-term transgression in the Mahlstetten section (location in Figure 5; legend in Figure 4). 100 kyr sequences are formed by 8 marl–limestone alternations.

composed of intensely condensed levels with well-marked marl–limestone alternations as suggested by Figure 10B, and visible in Figure 5 in the TS_{D1} and TS_{D2} zones.

Long-Term Sea-Level Fall

During a 100 kyr sea-level rise superimposed on a long-term fall (Fig. 11B), the short-term sea-level fluctuations related to precession exhibit relatively modest rates of sea-level rises and falls. Therefore, a single marl–limestone alternation is expected during one precessional cycle (Fig. 10C). During a 100 kyr sea-level fall, important sea-level falls and very small sea-level rises related to precessional cycles would generate single marl–limestone alternations (Fig. 10C), or a record strongly dominated by marls (Fig. 10D).

Observations in the field show that during long-term highstand periods, the small-scale sequences related to the 100 kyr eccentricity cycle are generally composed of two or three marl–limestone alternations (e.g., Fig. 5 from 5 to 8.5 m). At the base of Figure 5 (first 5 m), the dominantly marly sedimentation is characteristic for lowstand deposits, as suggested by Figure 10D. If no limestone beds are formed, the record of high-frequency cycles may be lost.

COMPARISON OF THE SEDIMENTAREY RECORDS BETWEEN THE CAZORLA REGION AND SOUTHERN GERMANY

Importance of Subsidence Rate

In considering the two sections of southern Spain (Fig. 7), we suggest that deep-shelf morphology is an important controlling factor for the sedimentary record of marl–limestone alternations: in Puerto Lorente, the scarce record of marl layers suggests a position on a morphological high, whereas in Riogazas–El Chorro enrichment in marls and a greater sediment thickness for the same time interval are interpreted as the result of a morphological low (Marquez et al. 1991; Pittet and Strasser 1998b). The generally low accumulation rate in the Prebetic realm of the Cazorla region (Fig. 13) is attributed to relatively slow subsidence on the platform (Pittet and Strasser 1998b). Carbonate production and accommodation on the platform and export towards the deep-shelf environments were smaller than in the southern Germany area. A long distance from the carbonate and clay sources to the deep shelf also contributed to the generally reduced depositional rates.

Figure 7 shows the sedimentary record during the Oxfordian in the Cazorla region. Even though facies are somewhat different from those in Germany, we apply the model developed for the German sections: the most marly intervals are interpreted as late highstand or lowstand deposits, and the more carbonate-rich intervals as transgressive and early highstand deposits. Small-scale sequences commonly display four or five marl–limestone alternations per 100 kyr sequence (Pittet and Strasser 1998b). This suggests that, in the case of the Spanish sections, one marl–limestone alternation generally corresponds to one precession cycle. Only rare doubled marl–limestone alternations per precession cycle are recognized in the long-term transgressive intervals, as is the case in the German sections. This observation thus suggests a different relationship between platform and deeper environments than in southern Germany, and that reduced accommodation on the platform did not allow for two phases of carbonate export per precession cycle.

While sedimentation was generally slow in the Cazorla region, the deep shelf of southern Germany had high depositional rates. This suggests relatively important subsidence of the adjacent shallow-marine Jura platform, which is confirmed by the analysis of the corresponding shallow-water sediments (Pittet 1994, 1996).

Climatic Influences

Climatic conditions are paramount for carbonate productivity in shallow-water environments (e.g., Lees 1975; Isern et al. 1996; Riding 1996; Home-

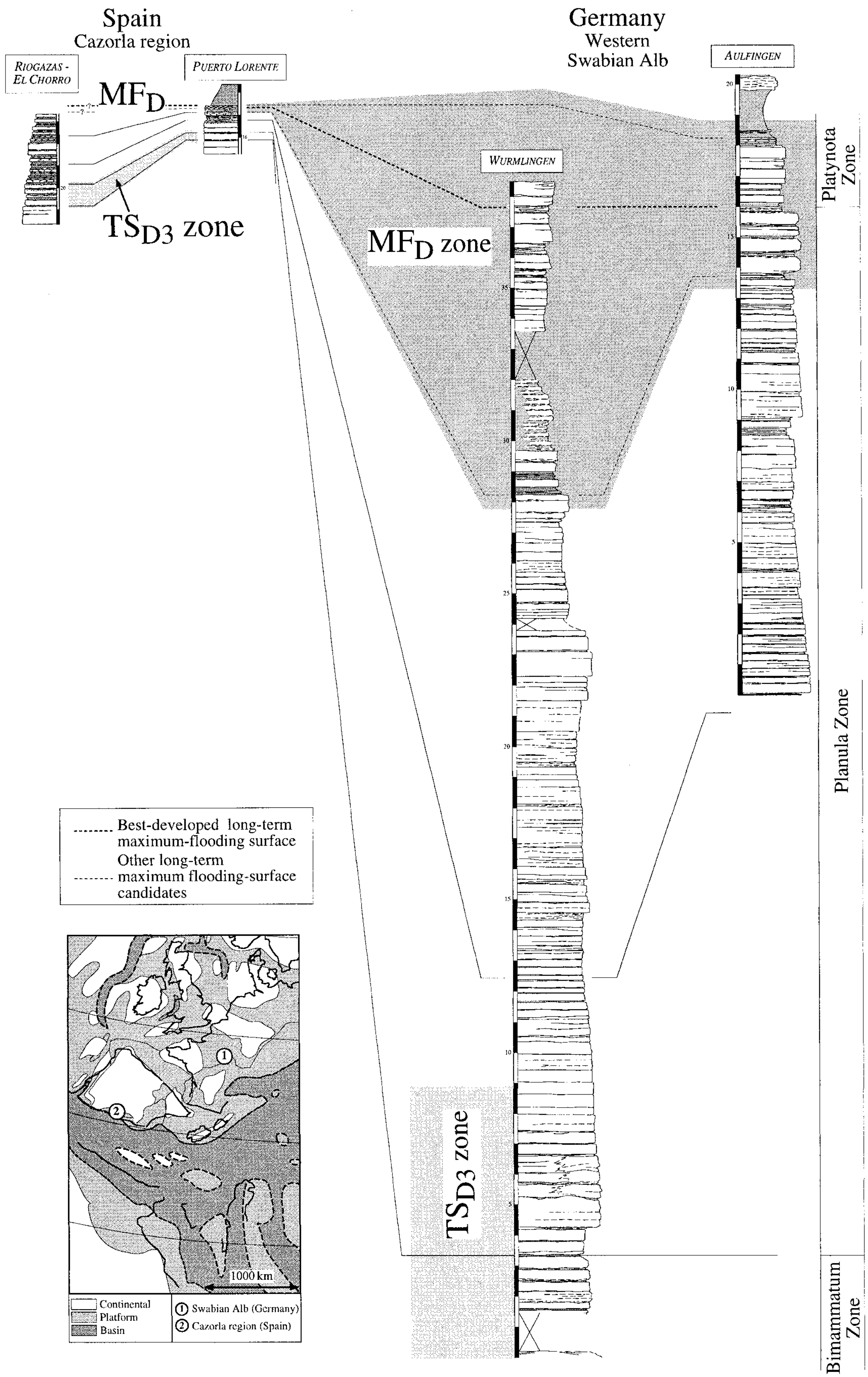


FIG. 13.—Correlation of depositional sequences in the uppermost Bimammatum and Planula Zones between the Spanish sections (Riogazas–El Chorro and Puerto Lorente) and the German sections (Wurmlingen and Aulfingen). Compare the change in thicknesses and carbonate contents. See text for further explanation.

wood 1996). During the Planula Zone, arid and/or oligotrophic conditions and an important transgression induced high carbonate production in the Jura Mountains (30–45 m of ooid bars; Gygi and Persoz 1986) and other connected shallow platform areas, and thus contributed to an important export of carbonate mud towards the deep shelf of southern Germany (Figs. 6, 13). These conditions prevailed during the entire Planula Zone. Therefore, no major depositional breaks occurred in distal areas. Only increasing marl deposition indicates periods of lower sedimentation rates, and/or increasing distality during maximum flooding related to 100 kyr cycles.

In Spain, where more humid conditions prevailed (Pittet and Strasser 1998b), the Planula Zone corresponds to a period of strongly decreasing deposition of carbonates and condensed sedimentation (drowning of the platform during the transgression). This led to pure marl deposition at the beginning of the Platynota Zone (Figs. 7, 13, Puerto Lorente section). The record of pure marls in the Aulfingen section in the Platynota Zone suggests that a drowning event also occurred in southern Germany (Fig. 13), but that it began later than in southern Spain.

The more humid conditions during transgression and early highstand recognized in Spain at the level of the small-scale sequences as well as at the scale of ''third order'' sequences (Pittet and Strasser 1998b) possibly diminished the carbonate productivity during rising sea level. Therefore, export of carbonates during this phase was low, and during sea-level rises related to precession cycles only reduced carbonate export occurred. The recorded limestone beds correspond to the falling stage of short-term sea-level variations when more arid conditions prevailed. This can explain the rare formation of two marl–limestone alternations per precession cycle during long-term sea-level rise. The limestone beds in the Spanish sections may thus correspond to high-frequency highstand shedding and/or lowstand flushing of carbonates (Schlager et al. 1994).

CONCLUSIONS

Sedimentation in deep-shelf areas during the Oxfordian of southern Germany and southern Spain was strongly linked to carbonate production in shallow platform areas and to export of carbonates from the platform to more distal environments. The sedimentary record in deeper environments reflects the interaction of sea-level variations induced by short-term climatic changes related to the precession and eccentricity cycles of the Earth's orbit, and by longer-term climatic, eustatic, and tectonic changes.

The stacking pattern of marl–limestone alternations composing small-scale depositional sequences related to the 100 kyr eccentricity cycles depends on the combined effects of eustatic sea-level changes and subsidence conditions in the study area:

- when relative sea-level rises on the long term are strong, each precession cycle generates two marl–limestone alternations;
- when relative sea-level falls on the long term are strong, precession cycles are no longer recognized, and only marls are deposited;
- when relative sea-level rises and falls are modest, one precessional cycle is represented by one marl–limestone couplet.

Climatic conditions expressed by humid–arid changes at the Milankovitch-cycle scale and also on the longer-term scale are dependent on the paleolatitude of the study areas. They may be important enough to generate different stacking patterns of small-scale sequences. Carbonate production in shallow platform areas depends mainly on accommodation and humid versus arid conditions. If arid conditions occur contemporaneously with creation of accommodation by subsidence and/or sea-level rise, great amounts of carbonate can be produced on the shallow platform and, potentially, be exported towards deeper areas. On the other hand, if humid conditions prevail during a relative sea-level rise, carbonate production is damped, and export towards deeper environments is reduced.

The model presented here explains the formation of stacked depositional sequences during long-term sea-level changes in deep-shelf environments. It demonstrates that different types of marl–limestone alternations can develop, and that their expression and numbers per depositional sequence may vary as a function of tectonic and climatic conditions. One marl–limestone alternation does not always correspond to one climatic cycle, even though its formation is related to this climatic cycle. It must be stressed, however, that each type of marl–limestone alternation and each type of depositional sequence must be studied in detail before any conclusions can be drawn.

ACKNOWLEDGMENTS

Günther Schweigert is gratefully acknowledged for having led us in the field, for having continuously furnished biostratigraphic data, and for many discussions. Wolfgang Riegraf shared his information on the Balingen–Tieringen section. Reinhold Leinfelder kindly hosted B. Pittet at the Geological–Paleontological Institute in Stuttgart. With their careful and constructive reviews, David Osleger and Wolfgang Oschmann greatly improved the manuscript. This study would not have been possible without the financial support of the Swiss National Science Foundation (Projects No 21-32185.92 and 20-41888.94), as well as the Young Researcher Grant and the confidence of the Fribourg Research Commission, which awarded this grant to B. Pittet.

REFERENCES

Berger, A., 1990, Paleo-insolation at the Plio-Pleistocene boundary: Paléobiologie Continentale, v. 17, p. 1–24.

Berger, A., Loutre, M.F., and Dehant, V., 1989, Astronomical frequencies for pre-Quaternary palaeoclimate studies: Terra Nova, v. 1, p. 474–479.

Bown, P.R., 1987, Taxonomy, evolution, and biostratigraphy of Late Triassic–Early Jurassic calcareous nannofossils: The Palaeontological Association, Special Papers in Palaeontology, v. 38, 118 p.

Brachert, T.C., 1992, Sequence stratigraphy and paleo-oceanography of an open-marine mixed carbonate/siliciclastic succession (Late Jurassic, Southern Germany): Facies, v. 27, p. 191–216.

Davaud, E., and Lombard, A., 1973, Statistical approach to the problem of alternating beds of limestone and marl (Upper Oxfordian of the French Jura): Eclogae Geologicae Helvetiae, v. 68, p. 491–509.

Dercourt, J., Ricou, L.E., and Vrielynck, B., eds, 1993, Atlas: Tethys Palaeoenvironmental maps: Paris, Gauthier-Villars, 307 p., 14 maps, 1 plate.

Droxler, A.W., and Schlager, W., 1985, Glacial versus interglacial sedimentation rates and turbidite frequency in the Bahamas: Geology, v. 13, p. 799–802.

Dullo, W.-C., Reijmer, J.J.G., Schuhmacher, H., Eisenhauer, A., Hassan, M., and Heiss, G.A., 1996, Holocene reef growth and recent carbonate production in the Red Sea, *in* Reitner, J., Neuweiler, F., and Gunkel F., eds., Global and Regional Controls on Biogenic Sedimentation. I. Reef Evolution—Research Reports: Göttinger Arbeiten zur Geologie und Paläontologie, v. Sb2, p. 13–17.

Einsele, G., and Ricken, W., 1991, Limestone-marl alternations—an overview, *in* Einsele, G., Ricken, W., and Seilacher, A., eds, Cycles and Events in Stratigraphy: Berlin, Springer-Verlag, p. 23–47.

Erba, E., 1994, Nannofossils and superplumes: The early Aptian ''nannofossil crisis'': Paleoceanography, v. 9, p. 483–501.

Fairbridge, R.W., 1976, Convergence of evidence on climatic change and ice ages: New York Academy of Sciences, Annals, v. 91, p. 542–579.

Fischer, A.G., 1991, Orbital cyclicity in Mesozoic strata, *in* Einsele, G., Ricken, W., and Seilacher, A., eds, Cycles and Events in Stratigraphy: Berlin, Springer-Verlag, p. 48–62.

Gaillard, C., 1983, Les biohermes à spongiaires et leur environnement dans l'Oxfordien du Jura méridional: Laboratoire Géologique de Lyon, Documents, v. 90, 515 p.

Gaillard, C., Atrops, F., Marchand, D., Hanzo, M., Lathuilière, B., Bodeur, Y., Ruget, C., Nicollin, J.P., and, Werner, W., 1996, Description stratigraphique préliminaire des faisceaux alternants de l'Oxfordien moyen dans le bassin dauphinois (Sud-Est de la France). Géologie de la France, v. 1, p. 17–24.

Giraud, F., Beaufort, L., and Cotillon, P., 1995, Contrôle astronomique de la sédimentation carbonatée dans le Crétacé inférieur du Bassin vocontien (SE France): Société Géologique de France, Bulletin, v. 166, p. 409–421.

Gortnitz, V., Lebedeff, S., and Hansen, J., 1982, Global sea level trend in the past century: Science, v. 215, p. 1611–1614.

Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J., van Veen, P. Thierry, J., and Hang, Z., 1995, A Triassic, Jurassic, and Cretaceous time scale, *in* Berggren, W.A., Kent, D.V., Aubry, M.P., and Hardenbol, J., eds, Geochronology, Time Scales, and Global Stratigraphic Correlation: SEPM, Special Publication 54, p. 95–126.

Gygi, R.A., 1986, Eustatic sea level changes of the Oxfordian (Late Jurassic) and their effect documented in sediments and fossil assemblages of an epicontinental sea: Eclogae Geologicae Helvetiae, v. 79, p. 455–491.

Gygi, R.A., 1990, Die Paläogeographie im Oxfordium und frühesten Kimmeridgium in der Nordschweiz: Geologisches Landesamt Baden-Württemberg, Jahrgangsheft, v. 32, p. 207–222.

Gygi, R.A., 1995, Datierung von Seichtwassersedimenten des Späten Jura in der Nordwestschweiz mit Ammoniten: Eclogae Geologicae Helvetiae, v. 88, p. 1–58.

Gygi, R.A., and Persoz, F., 1986, Mineralostratigraphy, litho- and biostratigraphy combined

in correlation of the Oxfordian (Late Jurassic) formations of the Swiss Jura range: Eclogae Geologicae Helvetiae, v. 79, p. 385–454.
GYGI, R.A., AND PERSOZ, F., 1987, The epicontinental sea of Swabia (southern Germany) in the Late Jurassic—factors controlling sedimentation: Geologische Paläontologische Abhandlungen, Neues Jahresband, v. 176, p. 49–65.
HALLOCK, P., AND SCHLAGER, W., 1986, Nutrient excess and the demise of coral reefs and carbonate platforms: Palaios, v. 1, p. 389–398.
HANDFORD, C.R., AND LOUCKS, R.G., 1993, Carbonate depositional sequences and systems tracts—Responses of carbonate platforms to relative sea-level changes, *in* Loucks, R.G., and Sarg, J.F., eds, Carbonate Sequence Stratigraphy, Recent Developments and Applications: American Association of Petroleum Geologists, Memoir 57, p. 3–41.
HOMEWOOD, P.W., 1996, The carbonate feedback system: interaction between stratigraphic accommodation, ecological succession and the carbonate factory: Société Géologique de France, Bulletin, v. 167, p. 701–715.
ISERN, A.R., MCKENZIE, J.A., AND FEARY, D.A., 1996, The role of sea-surface temperature as a control on carbonate platform development in the western Coral Sea: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 124, p. 247–272.
JACOBS, D.K., AND SAHAGIAN, D.L. 1993, Climate induced fluctuations in sea level during non-glacial times: Nature, v. 361, p. 710–712.
KENDALL, C.G.ST.C, AND SCHLAGER, W., 1981, Carbonates and relative changes in sea level: Marine Geology, v. 44, p. 181–212.
LEES, A., 1975, Possible influences of salinity and temperature on modern shelf carbonate sedimentation: Marine Geology, v. 19, p. 159–198.
LEINFELDER, R.R., 1994a, Distribution of Jurassic reef types: a mirror of structural and environmental changes during breakup of Pangea, *in* Embry, A.F., Beauchamp, B., and Glass, D.J., eds, Pangea: Global Environments and Resources: Canadian Society of Petroleum Geologists, Memoir 17, p. 677–700.
LEINFELDER, R.R., 1994b, The origin of Jurassic reefs. Current research developments and results: Facies, v. 31, p. 1–56.
MARQUEZ, B., OLÓRIZ, F., AND RODRIGUEZ-TOVAR, F.J., 1991, Interactions between tectonics and eustasy during the Upper Jurassic and lowermost Cretaceous. Examples from the south of Iberia: Société Géologique de France, Bulletin, v. 162, p. 1109–1124.
MATTHEWS, M.D., AND PERLMUTTER, M.A., 1994, Global cyclostratigraphy: an application to the Eocene Green River Basin, *in* de Boer, P.L., and Smith, D.G., eds, Orbital Forcing and Cyclic Sequences: International Association of Sedimentologists, Special Publication 19, p. 459–481.
MEYER, R.K.F., AND SCHMIDT-KALER, H., 1989, Paläogeographischer Atlas des süddeutschen Oberjura (Malm): Geologisches Jahrbuch, v. A115, p. 3–77.
MILLIMAN, J.D., FREILE, D., STEINEN, R.P., AND WILBER, R.J., 1993, Great Bahama Bank aragonitic muds: mostly inorganically precipitated, mostly exported: Journal of Sedimentary Petrology, v. 63, p. 589–595.
MONTAÑEZ, I.A., AND OSLEGER, D.A., 1993, Parasequence stacking patterns, third-order accommodation events, and sequence stratigraphy of Middle to Upper Cambrian platform carbonates, Bonanza King Formation, Southern Great Basin, *in* Loucks, R.G., and Sarg, J.F, eds, Carbonate Sequence Stratigraphy—Recent Developments and Applications: American Association of Petroleum Geologists, Memoir 57, p. 305–326.
NEUMANN, A.C., AND MACINTYRE, I., 1985, Reef response to sea level rise: keep-up, catch-up, give-up: 5th International Coral Reef Congress, Tahiti, Proceedings, v. 3, p. 105–110.
NOËL, D., 1968, Nature et genèse des alternances de marnes et de calcaires du Barrémien supérieur d'Angles (Fosse vocontienne, Basses Alpes). Académie des Sciences [Paris], Compte Rendus, v. D266, p. 1223–1225.
OSCHMANN, W., 1990, Environmental cycles in the late Jurassic northwest European epeiric basin: interaction with atmospheric and hydrospheric circulations: Sedimentary Geology, v. 69, p. 313–332.
PASQUIER, J.B., AND STRASSER, A., 1997, Platform-to-basin correlation by high-resolution sequence stratigraphy and cyclostratigraphy (Berriasian, Switzerland and France): Sedimentology, v. 44, p. 1071–1092.
PEYROT-CLAUSADE, M., LE CAMPION-ALSUMARD, T., HARMELIN-VIVIEN, M., ROMANO, J.-C., CHAZOTTES, V., PARI, N., AND LE CAMPION, J., 1995, La bioérosion dans le cycle des carbonates: essais de quantification des processus en Polynésie française: Société Géologique de France, Bulletin, v. 166, p. 85–94.
PITTET, B., 1994, Modèle d'estimation de la subsidence et des variations du niveau marin: Un exemple de l'Oxfordien du Jura suisse: Eclogae Geologicae Helvetiae, v. 87, p. 513–543.
PITTET, B., 1996, Contrôles climatiques, eustatiques et tectoniques sur des systèmes mixtes carbonates–siliciclastiques de plate-forme: exemples de l'Oxfordien (Jura suisse, Normandie, Espagne) [unpublished Ph.D. thesis]: Université de Fribourg, Switzerland, 258 p.
PITTET, B., AND GORIN, G.E., 1997, Distribution of sedimentary organic matter in a carbonate–siliciclastic platform environment: Oxfordian of the Swiss Jura mountains: Sedimentology, v. 44, p. 915–937.
PITTET, B., AND STRASSER, A., 1998a, Depositional sequences in deep-shelf environments formed through carbonate mud import from the shallow platform (Late Oxfordian, German Swabian Alb and eastern Swiss Jura): Eclogae Geologicae Helvetiae, v. 91, p. 149–169.
PITTET, B., AND STRASSER, A., 1998b, Long-distance correlations by sequence stratigraphy and cyclostratigraphy: examples and implications (Oxfordian from the Swiss Jura, Spain, and Normandy): Geologische Rundschau, v. 86, p. 852–874.
PITTET, B., STRASSER, A., AND DUPRAZ, C., 1995, Palaeoecology, palaeoclimatology and cyclostratigraphy of shallow-water carbonate–siliciclastic transitions in the Oxfordian of the Swiss Jura: International Association of Sedimentologists, 16th Regional Meeting of Sedimentology, Field Trip Guide Book, Association Sédimentologues Français (ASF) Publication, Paris, v. 23, p. 225–254.
REVELLE, R., 1990, Sea Level Change: Washington D.C., National Research Council, National Academy Press, Studies in Geophysics, 234 p.
RIDING, R., 1996, Long-term changes in marine $CaCO_3$ precipitation: Société Géologique de France, Mémoires, v. 169 n.s., p. 157–166.
ROBBINS, L.L., TAO, Y., AND EVANS, C.A., 1997, Temporal and spatial distribution of whitings on Great Bahma Bank and a new lime budget: Geology, v. 25, p. 947–950.
ROTH, P.H., 1978, Cretaceous nannoplankton biostratigraphy and oceanography of the northwestern Atlantic Ocean: Initial Reports of the Deep Sea Drilling Project, v. 44, p. 731–760.
SCHLAGER, W., 1989, Drowning unconformities on carbonate platforms, *in* Crevello, P.D., Wilson, J.L., Sarg, J.F., and Read, J.F., eds, Controls on Carbonate Platform and Basin Development: SEPM, Special Publication 44, p. 15–26.
SCHLAGER, W., 1991, Depositional bias and environmental change—important factors in sequence stratigraphy: Sedimentary Geology, v. 70, p. 109–130.
SCHLAGER, W., REIJMER, J.J.G., AND DROXLER, A., 1994, Highstand shedding of carbonate platforms: Journal of Sedimentary Research, v. B64, p. 270–281.
SCHULZ, M., AND SCHÄFER-NETH, C., 1998, Translating Milankovitch climate forcing into eustatic fluctuations via thermal deep water expansion: a conceptual link: Terra Nova, v. 9, p. 228–231.
SCHWEIGERT, G., 1995a, *Amoebopeltoceras* n.g., eine neue Ammonitengattung aus dem Oberjura (Ober-Oxfordium bis Unter-Kimmeridgium) von Südwestdeutschland und Spanien: Stuttgarter Beiträge zur Naturkunde, Serie B, v. 227, p. 1–12.
SCHWEIGERT, G., 1995b, Zum Auftreten der Ammonitenarten *Amoeboceras bauhini* (Oppel) und *Amoeboceras schulginae* Mesetzhnikov im Oberjura der Schwäbischen Alb: Gesellschaft Naturkunde Württemberg, Jahrgangsheft, v. 151, p. 171–184.
STRASSER, A., 1994, Milankovitch cyclicity and high-resolution sequence stratigraphy in lagoonal–peritidal carbonates (Upper Tithonian–Lower Berriasian, French Jura Mountains), *in* de Boer, P.L., and Smith, D.G., eds., Orbital Forcing and Cyclic Sequences: International Association of Sedimentologists, Special Publication 19, p. 285–301.
TIPPER, J.C., 1997, Modeling carbonate platform sedimentation—lag comes naturally: Geology, v. 25, p. 495–498.
VAIL, P.R., AUDEMARD, F., BOWMAN, S.A., EISNER, P.N., AND PEREZ-CRUZ, C., 1991, The stratigraphic signatures of tectonics, eustasy and sedimentology—an overview, *in* Einsele, G., Ricken, W., and Seilacher A., eds., Cycles and Events in Stratigraphy: Berlin, Springer-Verlag, p. 617–659.
VAN TREECK, P., SCHUHMACHER, H., AND PASTER, M., 1996, Grazing and bioerosion by herbivorous fishes—Key processes structuring coral reef communities, *in* Reitner, J., Neuweiler, F., and Gunkel F., eds, Global and Regional Controls on Biogenic Sedimentation. I. Reef Evolution—Research Reports: Göttinger Arbeiten zur Geologie und Paläontologie, v. Sb2, p. 133–137.
VOGEL, K., KIENE, W., GEKTIDIS, AND RADTKE, G., 1996: Scientific results from investigations of microbial borers and bioerosion in reef environments, *in* Reitner, J., Neuweiler, F., and Gunkel, F., eds., Global and Regional Controls on Biogenic Sedimentation. I. Reef Evolution—Research Reports: Göttinger Arbeiten zur Geologie und Paläontologie, v. Sb2, p. 139–143.
WILSON, J.L., 1975, Carbonate Facies in Geological History: Berlin, Springer-Verlag, 471 p.
ZIEGLER, P.A., 1988, Evolution of the Arctic–North Atlantic and the Western Tethys: American Association of Petroleum Geologists, Memoir 43, 198 p., 30 plates.

Received 9 December 1997; accepted 3 August 1999.