DISCONTINUITY SURFACES ON A SHALLOW-MARINE CARBONATE PLATFORM (BERRIASIAN, VALANGINIAN, FRANCE AND SWITZERLAND)

HEIKO HILLGÄRTNER
Institut de Géologie, Université de Fribourg, Pérolles, CH-1700 Fribourg, Switzerland

ABSTRACT: **Discontinuities in sedimentation are commonly expressed as surfaces in outcrop sections and are due to rapid and substantial environmental changes. On shallow-marine carbonate platforms most such surfaces represent hiatuses below biostratigraphic resolution, and detailed analysis is necessary to identify and evaluate the environmental change involved. Surfaces in nine sections of the Lower Cretaceous of the French and Swiss Jura platform are characterized on the basis of eight universally applicable criteria (geometry, lateral extent, morphology, biological activity, mineralization, facies contrast, diagenetic contrast, and biostratigraphy). Nine different surface types are distinguished by their common features and environment of formation. All of them are related to environmental changes in the form of subaqueous erosion, subaerial exposure, subaqueous omission, or changes in texture and facies. The distribution of surface types in the studied sections shows that condensation and exposure-related surfaces tend to occur repetitively in certain intervals. Calibrated by biostratigraphy, these surface zones can be correlated across the platform from proximal to distal positions. In comparison with the global sequence-stratigraphic framework (Hardenbol et al. 1997) most exposure zones correlate with third-order sequence boundaries; condensation zones fall in between. In the studied sections, third-order eustatic sea-level drops appear to be represented rather by zones of small-scale discontinuities than by widespread and well-marked single sequence boundaries. This is explained by the superposition of high-frequency, low-amplitude sea-level fluctuations on a larger-scale sea-level trend under greenhouse conditions. The lateral extent of the surface zones varies through time and indicates important changes in platform morphology. Changes in local subsidence rate indicated by variable thicknesses of the deposits in comparison with second- and third-order sea-level trends suggest an evolution of the French Jura platform from a ramp-type morphology in the late Middle Berriasian to a flat-topped platform in the Late Berriasian. The Early Valanginian again is characterized by increased differential subsidence and well-marked platform morphology.**

This study demonstrates that:

(1) small-scale and short-lived discontinuities can reflect large-scale variations of relative sea level;

(2) on shallow platforms characterized by small topographic variations and lateral facies changes, third-order sequence-stratigraphic surfaces are not necessarily expressed by one widespread single surface, but by zones of surfaces indicating repeated environmental changes; surface zones can serve as an additional tool for correlation and interpretation of platform evolution; and

(3) small-scale discontinuities form an integral part of the stratigraphic record and should receive the same attention as the sedimentary deposits they delimit.

INTRODUCTION

Sedimentation is inherently a discontinuous process (Sadler 1981). Sedimentary depositional systems are controlled by many interrelated and interacting parameters like sea level, subsidence, climate, and sediment production and input, which vary through time with different amplitudes and frequencies (Barrell 1917; Matthews and Perlmutter 1994). A gradual change in environmental conditions may be accompanied by a continuous reaction of the sedimentary system, but any abrupt change or passing of a threshold leads to a discontinuity in sedimentation. This is commonly marked by a sharp level of facies change or by a surface in stratigraphic sections. All surfaces indicating a break in sedimentation are therefore called discontinuity surfaces, a term that was first introduced by Heim (1924, 1934). Following the definition of Clari et al. (1995) and Bates and Jackson (1987), the use of this term is purely descriptive in being independent of the duration of the break and of the process causing the formation of the surface. Consequently, all stratigraphic gaps are included in this definition. Any observable surface, from a millimeter-scale stratification formed by the unsteady and multidirectional nature of currents (Allen 1984, Reineck et al. 1995) through diastems (Barrell 1917; small breaks in sedimentation on the scale of beds commonly marked as bedding planes) to major stratigraphic unconformities marked by prolonged subaerial exposure, is a discontinuity surface. Discontinuity surfaces that are characterized by a drastic environmental change or a time gap evidenced by missing biozones have been the subject of numerous studies and are frequently used as stratigraphic markers and boundaries of lithostratigraphic units, or are interpreted as sequence-stratigraphic bounding surfaces. However, subtle discontinuities on the scale of a bed and below biostratigraphic resolution are the rule in stratigraphic successions. Here, a process-oriented study of all surfaces in a stratigraphic section is necessary to determine their relative importance for the interpretation of the evolution of the sedimentary system. The aim of this work is to propose a systematic characterization and classification of small-scale discontinuities occurring on a shallow-marine carbonate platform. On the basis of the Upper Berriasian and Lower Valanginian of the French and Swiss Jura platform, it will be demonstrated that the distribution patterns of such surfaces furnish additional information for correlation and interpretation of platform evolution.

CHARACTERIZATION OF DISCONTINUITIES

Surfaces in vertical outcrops commonly are difficult to observe and hence often underestimated in their importance. The first step therefore is to define a suite of criteria to distinguish even subtle characteristics of the surface itself and take into account differences between underlying and overlying rock. On the basis of published descriptions (Fürsich 1979; Bain and Foos 1993; Clari et al. 1995; Ghibaudo et al. 1996), classification schemes (Doglioni et al. 1990; Ricken 1991; Clari et al. 1995), and nine sections in the French Jura studied in detail (Fig. 1), eight universally applicable criteria for the characterization of discontinuity surfaces are proposed (Fig. 2).

1. Geometry

Many discontinuity surfaces are marked by an angular relationship between underlying and overlying strata. This is commonly caused by the truncation of primary (sedimentary) and secondary (diagenetic) features or entire stratigraphic units due to erosion. In laterally restricted outcrops angular relationships between depositional structures like onlap and offlap patterns are rarely visible (Clari et al. 1995). Discontinuity surfaces with a non-angular, conformable relationship are difficult to characterize in the field, and petrographic, geochemical, and/or biostratigraphic evidence is needed for their interpretation.

2. Lateral Extent

Observation of the lateral extent of discontinuity surfaces is a criterion strongly dependent on outcrop conditions. Single surfaces with wide lateral

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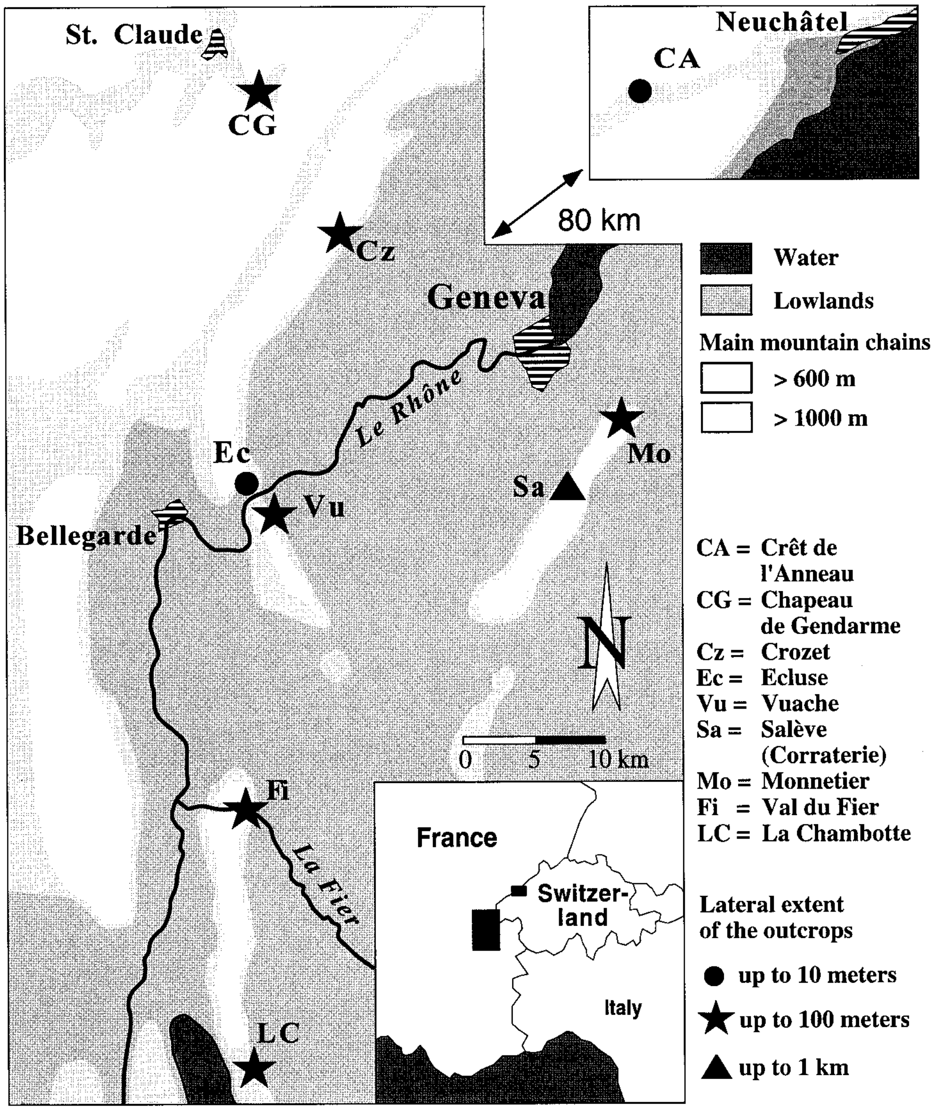


FIG. 1.—Location of studied sections, with indication of the lateral extent of the outcrops.

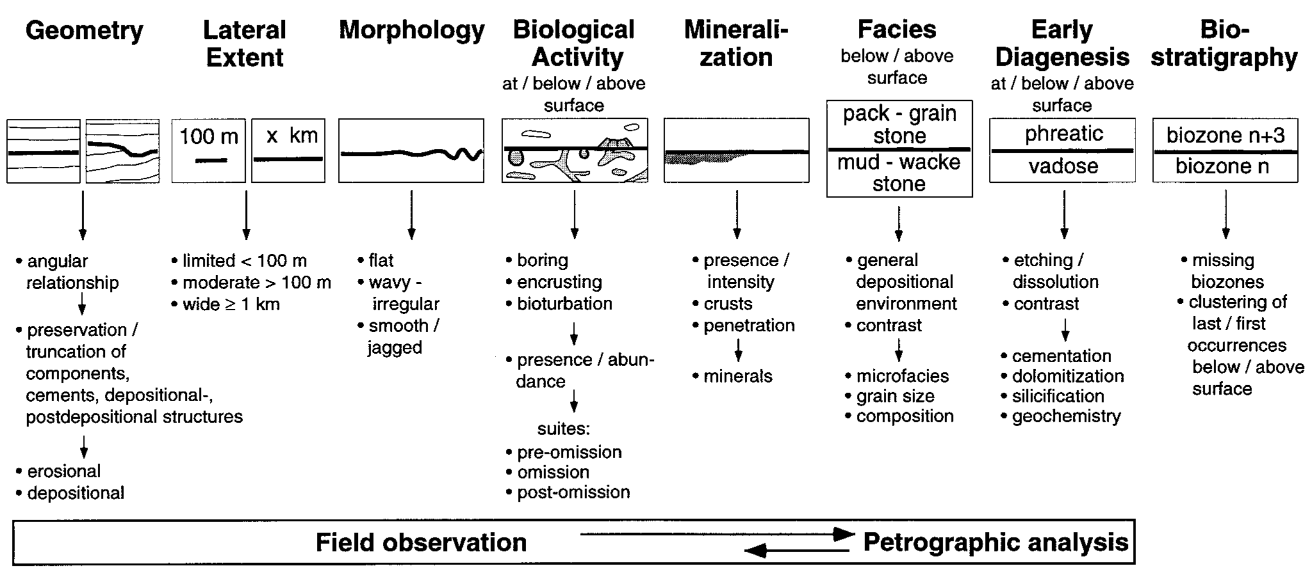


FIG. 2.—Characterization criteria for discontinuity surfaces. Criteria are applied to the surface itself and the rock immediately above and below.

continuity tend to indicate an environmental change of at least regional importance (Walker and Eyles 1991; Meckel and Galloway 1996). Stratification with low lateral continuity (several meters only) is commonly related to a locally restricted depositional process, such as cross-bedding in a subtidal bar. The environmental significance of such surfaces is included in the facies interpretation. In most studied outcrops, surfaces can be traced laterally over 100 m to a maximum of 1 km (Fig. 1). Physical correlation of single surfaces between different outcrops (500 m–3 km) is possible only in cases where prominent surfaces are marked by unequivocal features.

3. Surface Morphology

The morphology of a surface can also be a criterion for the characterization of discontinuities (Jaanusson 1961; Read and Grover 1977; Fürsich 1979), although one of secondary relevance only. An irregular, wavy habit may indicate minor erosion in an otherwise homogeneous sediment without visible sedimentary structures. Biological activity can have a constructive or destructive influence on the surface morphology. Microbial crusts and bioherms create an irregular positive relief, whereas bioturbation and bioerosion cause rough surfaces by destructive modification. On the other hand, very flat, sharply cut surfaces, especially those in a shallow-marine environment, are commonly caused by high-energy abrasion of a homogeneously lithified substrate. Differential compaction may also lead to irregular surfaces, pointing to an often subtle facies change. In other cases, stylolitization superimposed on a pre-existing discontinuity surface may lead to an irregular, commonly jagged surface morphology.

4. Biological Activity

The importance of trace fossils for the genetic interpretation of discontinuity surfaces has already been pointed out by Bromley (1975) and Fürsich (1979). Intensity and type of bioturbation below and above the surface, as well as signs of encrusting and boring organisms at the surface, are used as characterization criteria. A classification into pre-omission, omission, and post-omission suite of trace fossils is used to indicate their relationship with the hiatus (Bromley 1975). Lithification of the discontinuity surface is indicated by an omission suite including boring organisms that cut sharply through the fabric of the underlying rock (Purser 1969; Shinn 1970; Ghibaudo et al. 1996).

5. Mineralization

Sediments that are mineralized by iron and manganese oxides, phosphates, or authigenic minerals such as glauconite are associated with condensation (Föllmi et al. 1991; Carson and Crowley 1993; Gomez and Fernandez-Lopez 1994; Burkhalter 1995). Consequently, discontinuity surfaces showing *in situ* crusts of such a mineral paragenesis indicate a considerable break in sedimentation, commonly in subtidal environments. In contrast, crusts of aluminum–iron oxides and pyrite are found to be the result of paleosol formation (terra rossa) and alteration during subsequent marine flooding (Wright 1994). Penetrative staining of the underlying rock by iron oxides can also point to oxidation due to karstification and paleosol formation.

6. Facies Contrast

Any sharp change in facies across a surface underlines the discontinuous nature of sedimentation. However, when the facies change takes place in the same depositional system, as for example by superposition of lagoonal mudstone onto lagoonal packstone, the relevance of the discontinuity surface is often difficult to assess and an incomplete sedimentary record cannot automatically be inferred. An important break in sedimentation and a drastic environmental change can be inferred only from a superposition of facies contradicting Walther's law (Clari et al. 1995). In this study special attention is given to grain-size changes, being basically a measure for energy variations, changes in composition (siliciclastics vs. carbonates), and changes in carbonate microfacies. Surfaces marking a facies contrast are often enhanced by late diagenetic processes such as pressure solution and stylolitization, which preferentially occur along a contact of rocks with different lithologic properties.

7. Early Diagenetic Contrast

Diagenetic evidence for a discontinuity is given where the underlying rock shows vadose cementation or early diagenetic alteration due to evaporation, meteoric waters, and/or paleosol formation, all indicating subaerial exposure (Videtich and Matthews 1980; Bain and Foos 1993; Wright 1994; Beach 1995). Where erosion has removed other sedimentological evidence, relative enrichment in ^{18}O may point to evaporation during exposure, and ^{13}C depletion can indicate the influence of soil gas (Videtich and Matthews 1980; Joachimski 1994). Different compactional features in underlying and overlying rock can point to different phases of early cementation (Clari et al. 1995). This can also be evidenced by cement stratigraphy, stable isotopes, and trace-element analysis (Goldstein et al. 1991; Plunkett 1997).

8. Biostratigraphy

Biostratigraphic and chronostratigraphic data are the only means for time assessment of a hiatus. They can even be the only way to identify a discontinuity when there is a lack of any other diagnostic features, such as may be the case in basinal settings with rather monotonous sedimentation. The main limitation, however, is time resolution, which commonly is too low for the majority of discontinuity surfaces occurring in the sedimentary record. In a more general sense and with less precision than biostratigraphy and chronostratigraphy other methods can furnish information about the time gap represented by a discontinuity. These include the degree of clustering of first and last occurrences of taxa around discontinuity surfaces and taphonomic characteristics of bioclastic concentrations along a hiatus (Holland 1995; Kidwell 1993). No biostratigraphic evidence indicating prolonged time gaps in the succession was obtained in the present study, which means that all observed discontinuities are below biostratigraphic resolution.

OBSERVED SURFACES AND THEIR INTERPRETATION

Nine sections on the Upper Berriasian to Lower Valanginian carbonate platform in the French and Swiss Jura mountains (Fig. 1) were studied. Sedimentation was dominated by carbonates, except for the top of the Berriasian and the base of the Lower Valanginian, where a siliciclastic influence is observed. Sections were chosen according to continuous outcrop conditions to allow a study of the complete and tectonically undisturbed succession. This was an elementary condition, since the study was to be based on a detailed field examination on a centimeter scale. Samples were taken in the immediate surroundings of each observable bedding surface and where possible from the surface itself. Thin-section analysis of each sample was then carried out to determine depositional facies and early diagenetic alteration. On the basis of field and petrographic evidence, all surfaces were then characterized according to the criteria defined above. Nine major groups of surfaces can be observed in the studied shallow-marine carbonate succession, distinguished by their common features and environment of formation. Their characteristics are summarized in Figure 3 and their detailed interpretation is given below.

1. Subtidal Firmground to Incipient Hardground

Low accumulation rate in a subtidal lagoonal environment favors consolidation and incipient cementation of the sediment at and directly below the water–sediment interface. Intense bioturbation by *Thalassinoides*-pro-

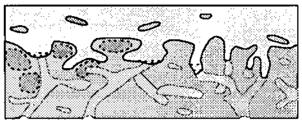
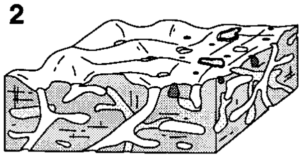
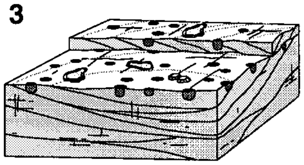
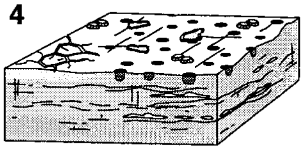
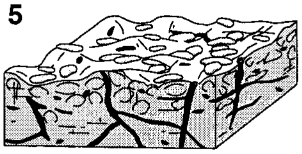
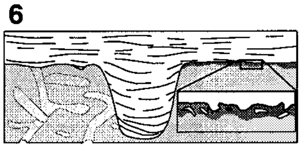
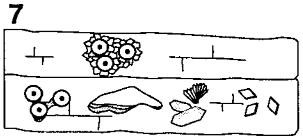
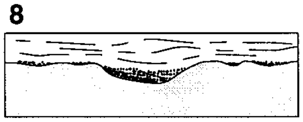
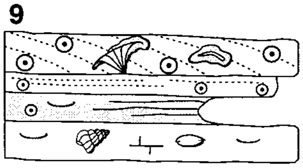
Surface Groups	Characterization: Geometry	Lateral Extension	Morphology	Biological Activity at / below / (above) surface	Minera-lization	Facies and Contrast across surface	Early Diagenesis below surface	Interpretation (for detailed Information see text)
1 	erosional: cutting primary structures	100 m-1 km	irregular: relief often > 5 cm	bioturbation suites: intense preomission, moderate-intense omission: all *Thalassinoides*	weak FeOx	grain size composition microfacies	beginning marine phreatic cementation fibrous aragonite	**firmground to incipient hardground in subtidal environment**
2 	weakly erosional	> 100 m	flat to undulating	bioturbation suites: intense preomission, intense omission, weak-moderate post-omission: all *Thalassinoides* boring, encrusting: *Lithophaga,* Oysters	weak-strong FeOx MnOx possibly phosphates or sulfides	grain size composition microfacies	marine phreatic cementation fibrous aragonite microbial activity	**hardground in subtidal low-energy environment**
3 	weakly erosional	< 1 km	flat	bioturbation suites: occasionally weak omission: *Thalassinoides* boring, encrusting: *Lithophaga,* Oysters	weak FeOx	grain size	marine phreatic cementation fibrous aragonite microbial activity	**hardground in subtidal high-energy environment**
4 	weakly erosional	100 m-1 km	flat	bioturbation suites: weak preomission; (unidentified) boring, encrusting *Lithophaga,* Oysters	weak FeOx	composition	cementation microbial activity calcretization (desiccation) occasionaly relative depletion in ^{13}C and en-richment in ^{18}O	**hardground in inter- supratidal environment**
5 	weakly erosional	> 1 km	undulating often brecciated	bioturbation suites: weak-intense preomission: (unidentified) rhizoturbation: colonization by plants	strong FeOx	grain size composition microfacies	pedogenesis microbial activity dolomitization calcretization silicification relative depletion in ^{13}C and en-richment in ^{18}O	**paleosol commonly super-imposed on subtidal facies**
6 	erosional: cutting primary and secondary structures	> 1 km	flat undulating jagged pitted etched cavities	bioturbation: weak-intense	strong FeOx penetrative staining	grain size composition microfacies	vadose cementation dissolution association with pedogenesis, gravitational ce-ments and sediment infill in cavities	**microkarst / epikarst (karst)**
7 	depo-sitional (erosinal)	< 1 km	flat	bioturbation: weak-moderate		microfacies grain size	cemetation contrast across the surface often vadose cem., dolomitization, silicification below discontinuity	**diagenetic discontinuity**
8 	erosional	< 1 km	undulating irregular	bioturbation: weak-intense		grain size composition microfacies	possible cementa-tion contrast across the surface due to different rock properties	**erosion surface in sub- intertidal environment**
9 	depo-sitional: preserving primary structures	< 1 km	flat undulating	bioturbation: weak-intense		grain size composition microfacies	possible cementa-tion contrast across the surface due to different rock properties	**simple discontinuity surface in sub- intertidal environment**

FIG. 3.—Groups of surfaces and their characteristic features observed in the Lower Cretaceous sections of the French and Swiss Jura.

ducing organisms accompanies this process. Burrows of the omission suite are commonly filled with the same facies found in the overlying rock (Fig. 4A). In rare cases the burrows even preserve a facies not recorded otherwise, indicating recurrent phases of deposition and erosion. Such filling of open burrows can also occur during storms (''tubular tempestites'') and therefore indicate episodic high-energy events (Wanless et al. 1988). When the protective layer of unconsolidated sediment above the layer of incipient cementation is stripped off, weak erosion commonly forms an irregular surface because of the inhomogeneous nature of the lithification.

2. Subtidal Hardground

The characteristics and the setting of this surface group are very similar to the one above, the only distinction being more advanced lithification of the substrate. This allows colonization of the surface by boring and encrusting organisms, which commonly include *Lithophaga*, other boring bivalves (Fig. 4B), sponges, and oysters. These hardgrounds compare well to the ones described by Kennedy and Garrison (1975) and Fürsich (1979). However, the abundance and diversity of both, borers and encrusters, are always low, and no superimposed borings are observed, all pointing to a single omission phase. No evidence of early meteoric or vadose cementation is found and, therefore, an entirely subtidal origin of the lithification can be assumed.

3. High-Energy Hardground

This hardground type also shows encrusting and boring by the same suite of organisms as the subtidal one (Fig. 4C). However, only a few *Thalassinoides* of the pre-omission suite occur. Early cementation is usually restricted to porous subtidal to lower intertidal high-energy carbonates like bioclastic or ooid shoals. The lateral extent of these hardgrounds is rather restricted, commonly reaching not more than a few tens of meters. Their environmental setting and lateral continuity compare well to a recent occurrence of hardgrounds in oolitic shoals on Eleuthera Bank, Bahamas (Dravis 1979). There, they occur in a setting of relative high sedimentation rates and strong agitation by currents. The hydrodynamically active environment causes local winnowing, and the high rate of sea-water percolation and pumping through the porous sediment favors early cementation. Endolithic and chasmolithic algae (Dravis 1979) and other organisms inhabiting empty pore space (such as *Bacinella)* can contribute to the initial stabilization of the sediment (unpublished data).

4. Intertidal to Supratidal Hardground

Shallow intertidal to supratidal environments also favor early lithification. Repeated drying, evaporation, and subsequent wetting lead to complex diagenetic processes. They may be evidenced by desiccation indicators (circum-granular or desiccation cracks), precipitation of evaporites (gypsum), calcretization, and synsedimentary dolomitization. In some cases, the intertidal to supratidal environment of formation is indicated by stromatolitic microbial mats showing sheet cracks or mudstones with birdseyes. A sediment surface thus stabilized and lithified is prone to be rapidly colonized by boring and encrusting endofauna and epifauna during the following marine incursion. It will therefore be difficult in many cases to distinguish from a subtidal hardground, except by facies analysis. Rarely, such surfaces display a very flat, knife-cut nature (Fig. 4D) where only the lower parts of the borings are preserved. They compare to the planar erosion surfaces of tidal origin (Read and Grover 1977) witnessing abrasion on a tidal, probably wave-cut platform.

5. Paleosol

Subaerial exposure of the sediment surface causes colonization by plants and development of a soil. Diagenetic processes associated with pedogenesis destroy primary structures and textures by strong micritization and recrystallization. Dissolution processes and rhizoturbation during exposure, as well as erosion and reworking of the soil during the subsequent marine flooding, cause the commonly brecciated to pebbly appearance of the surface. Roots, root molds, microscopic rhizoliths, and other fabrics of soil development like soil pisoids and calcrete mottles (Bain and Foos 1993; Wright 1994) are evident (Fig. 4E). However, neither a vertical zonation of the soils nor a complete pedogenic transformation of the primary sediment were found, both of which would indicate an advanced stage of soil development (Martin-Chivelet and Giménez 1992; Mack et al. 1993). This points to generally short-lived exposures.

6. Microkarst, Epikarst

Dissolution of carbonate by CO_2-enriched meteoric waters is indicated by sharp-cut and intensely stained surfaces displaying a micro-relief with small cavities (Fig. 4F). Laterally, such a surface can show a relief of up to 15 cm with small paleokarst pits (Vanstone 1998). No caves or larger dissolutional features were observed, though. This can be attributed to a micro-karstification of lithified carbonates and formation of epikarst underneath a soil cover during seasonally humid climates (Wright 1994; Mylroie and Carew 1995) and limited durations of subaerial exposure (D'Argenio et al. 1997). Gravitational infill of cavities by stained and reworked lithoclasts and green, clayey calcisiltites in association with secondary micrite in form of crusts and diffuse patches (Beach 1995) and stalactite cements are also typical features of karst development (D'Argenio et al. 1997).

7. Diagenetic Discontinuity

A sharp change in the style of early diagenesis and cementation (not associated with any other change) commonly causes accentuation of a surface by stylolitization due to differences in rheological properties of the bounding rock layers. All diagenetic discontinuities observed in the studied sections display vadose diagenesis of the underlying rock and contrasting marine phreatic diagenesis in the overlying rock (Fig 4G). This pattern and the absence of any other diagnostic features for subaerial exposure occur only in homogeneous, high-energy skeletal carbonates where sedimentary structures are absent or obliterated by bioturbation and cannot provide evidence for erosion. Vadose zones commonly extend downwards in the strata for a few tens of centimeters only, indicating no major lowering of the base level.

8. Intertidal to Subtidal Erosion Surface

Erosion of underlying strata in intertidal to subtidal settings may be encountered in a large variety of facies, but in all of them it is fundamentally related to an increase of energy in the depositional system. This may be event-related in the case of storms or gravity flows, representing relatively short time spans in which erosion takes place. Long-lasting erosion and condensation can occur during lowering of base level and wave base, causing winnowing, sediment starvation, and erosion of subtidal sediments. The erosion surface itself is rarely indicative of the environment: facies and depositional environment are the keys for interpretation (Fig. 4H).

9. Simple Discontinuity Surface

Surfaces related to an abrupt facies change manifesting neither condensation nor erosion may include changes in texture, sorting, grain size, and mineralogy. Similarly to the intertidal to subtidal erosion surfaces, they rarely contain self-evident features that indicate an environment of formation. A variety of factors influencing a depositional system (see below) cause such discontinuities, and their environmental relevance can be as-

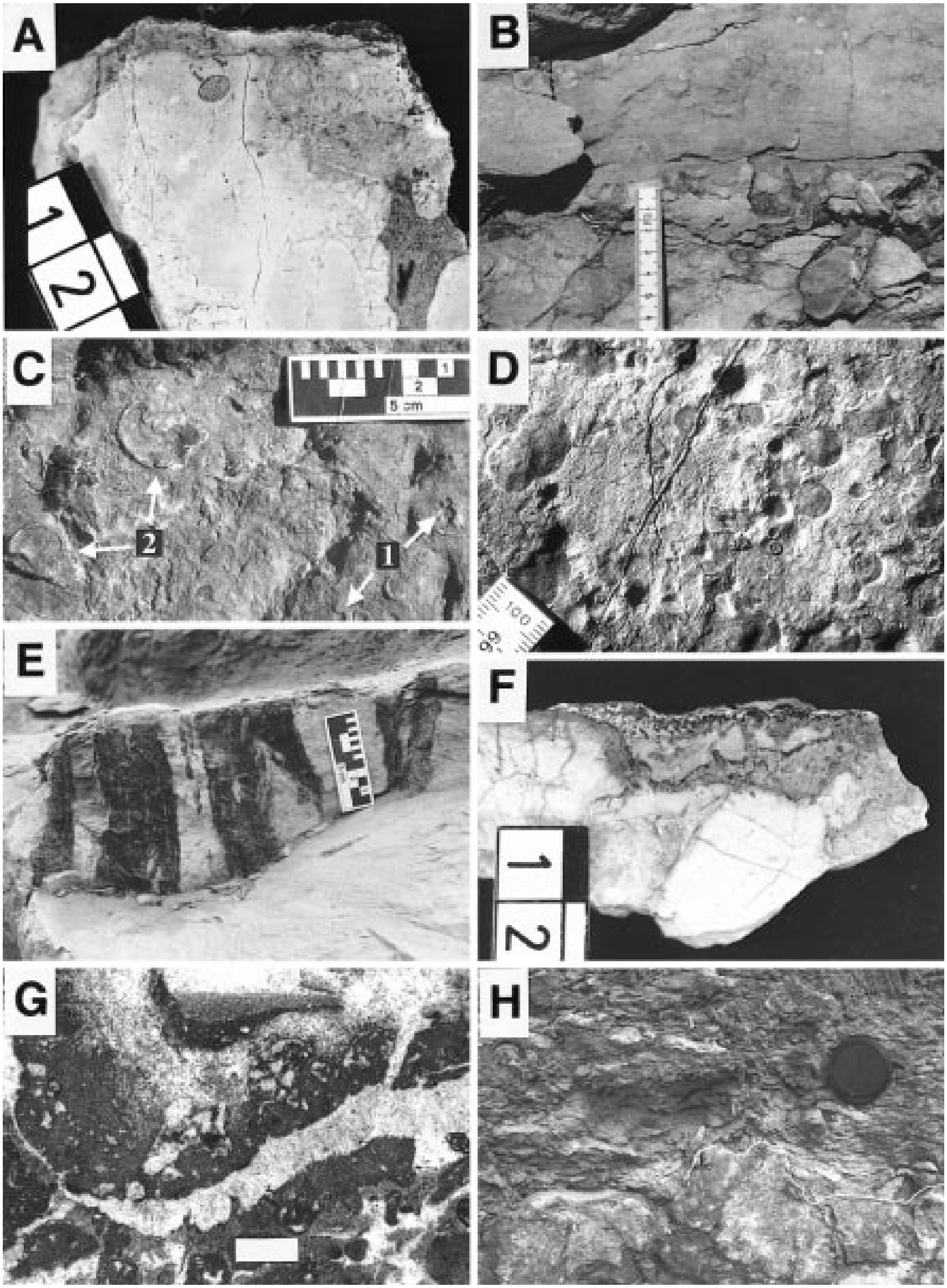


FIG. 4.—**A)** Polished slab of a subtidal firmground to incipient hardground. The sharp borders of the burrows (*Thalassinoides*) and their dark staining indicate early consolidation of the sediment and impregnation by Fe-oxides. Burrows were filled by peloidal packstone to grainstone of the overlying strata (Vuache section; scale in centimeters). **B)** Subtidal hardground with intense bioturbation of the underlying sediment and boring bivalves penetrating the surface (to the left of scale). The surface is marked by an irregular morphology (Salève section). **C)** High-energy hardground on an ooid shoal showing perforation by lithophages (1) and encrusting by oysters (2) (Crozet section). **D)** Hardground on an intertidal laminated mudstone displaying low density and low diversity of borings with rare superpositions. The surface is very flat

sessed only by a detailed facies analysis of the host rock. Many bedding planes and stratification surfaces in the stratigraphic record are of this type.

THE SIGNIFICANCE OF DISCONTINUITIES

Commonly, discontinuities such as those described above are expressed as bedding planes and are responsible for the apparent layering of strata in outcrop and subsurface. The various types of discontinuity surfaces commonly show different morphologic expressions in the field because of differential weathering, which can give a subjective impression about their relative importance. In any case, they reflect changes in the depositional environment at many different scales. The magnitude of the time gap they represent can vary considerably and may represent as much or more time as the sediments between them (Algeo and Wilkinson 1988; Walker and Eyles 1991).

The importance of environmental variations marked by discontinuities is generally evaluated by the time span represented by the corresponding stratigraphic gap and the lateral extent of the discontinuity surface (Salvador 1987; Nummedal and Swift 1987; Doglioni et al. 1990). Major time gaps on the order of several My commonly are related to environmental changes in response to global, long-term processes of tectono-eustatic origin (Sloss 1963). The stratigraphic record between such major unconformities commonly comprises various orders of sequences and stratigraphic units that are bounded by discontinuities progressively representing shorter time intervals and have laterally more restricted importance (Plotnick 1986; Ricken 1991). This hierarchical perception reflects the view of the stratigraphic record as a periodic accumulation of sediment in response to relative sea-level changes of varying magnitude (Vail et al. 1977; Vail et al. 1991; Goodwin and Anderson 1985; Posamentier et al. 1988; Goldhammer et al. 1990; Goldhammer et al. 1991; Mitchum and Van Wagoner 1991; Osleger and Read 1991; D'Argenio et al. 1997).

However, a hierarchical perception of discontinuities based on the duration of the associated time gap (Ricken 1991) and the lateral extent of the surface seems to be inappropriate, at least for shallow marine platforms. Such environments are very sensitive to relative sea-level changes and react in different ways to variations of amplitude and frequency of eustatic sea-level changes associated with different forcing mechanisms. High-amplitude sea-level changes in icehouse worlds lead to well-developed discontinuities because of the longer duration of exposure and a major drop of the ground-water table, causing extensive meteoric alteration of the sediments. Low-amplitude sea-level changes in greenhouse worlds, in contrast, are typically characterized by poorly developed discontinuities reflecting short-lived exposures and sea-level falls not far below the platform surface (Read 1995). This means that the hierarchical ordering of accommodation changes does not necessarily correspond to a hierarchical ordering of bounding discontinuities in the stratigraphic record. In addition, the conditions for the occurrence of laterally extensive single surfaces relating to relative sea-level changes seem to apply only to a very restricted range of environments (Cartwright et al. 1993). Only low-angle platforms with a low morphology where changes in relative sea level lead to coeval environmental reactions over large areas may develop single, laterally extensive surfaces. Even in such environments factors such as amplitudes of relative sea-level change, lateral variability of depositional systems, and variations in sediment supply, accumulation, and redistribution have a significant influence on the lateral extent of individual discontinuities.

In the studied sections of the Lower Cretaceous, no hiatus exceeds the scale of biostratigraphic resolution, which is about 500 ky to 1 My, and single surfaces are rarely correlatable for more than a few kilometers. Therefore, other criteria than duration of the hiatus and lateral extent of the discontinuity surface have to be used to determine the significance of the observed discontinuities.

Environmental Variables

On a shallow-marine carbonate platform, the principal variables controlling sedimentary processes are eustatic sea level, tectonic activity (including subsidence), and climate (Strasser 1991). These variables are interdependent in a complex way and have indirect global or at least regional effects. Variables that have a direct effect on the sedimentary system on a local to regional scale can be reduced to relative sea level, accumulation rate, the type of sediment available for sedimentation, and the energy regime (Fig. 5A). The variations in the type of sediment may be related to changes in autochthonous production or input from external sources, as for example siliciclastics washed in from the hinterland. Any significant and rapid change of any of these four variables causes a specific reaction in the sedimentary system. The reaction is manifested in form of subaqueous erosion, subaerial exposure, subaqueous omission, or changes in texture and facies, which in most, if not all, cases produces a discontinuity surface. The relation of the observed surface groups to these environmental reactions is illustrated in Figure 5A. ''False discontinuities'' or bedding planes caused only by late diagenetic processes (Bathurst 1991) were not encountered in this study.

CLASSIFICATION OF DISCONTINUITIES

On the basis of these expressions of environmental changes in the stratigraphic record, a simple classification is proposed for the observed discontinuities (Fig. 5B). Four surface types have been distinguished taking into account the importance of allogenic forcing of environmental change. The first type includes all surfaces resulting from subaerial exposure, regardless of how they are manifested in the stratigraphic record. In most cases encountered in this study, however, exposures are indicated by an overprinting of subtidal facies. This is an unequivocal sign of a relative lowering of sea level and cannot be caused by progradation or lateral migration of facies belts or changes in sediment supply (Schlager 1993). It is therefore a marker for allogenic forcing of the sedimentary system (Strasser 1991). The second type comprises all discontinuities related to stratigraphic condensation in a subtidal environment. Stratigraphic condensation on shallow-marine platforms is very common and can be caused by local processes such as sediment bypassing or winnowing by locally restricted currents. It is, however, commonly related to relative sea-level changes (Galloway 1989; Kidwell 1993; Gomez and Fernandez-Lopez 1994; Burkhalter 1995). Omission can occur during initial-flooding or maximum-flooding phases causing sediment starvation, or during maximum-regression phases where exposure is not attained but lowered wave base induces winnowing and submarine erosion (Osleger 1991). The third type includes all discontinuities that show evidence of subaqueous erosion. The fourth type describes all surfaces indicating changes of facies and/or texture. In most cases, surfaces indicating small-scale erosion or facies changes are related to locally restricted depositional processes. However, allogenic forcing related to

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and knife-sharp, and only the lower parts of borings are preserved indicating abrasion after colonization on a wave-cut platform (Salève section; scale in millimeters). **E)** Paleosol with massive rhizoliths penetrating the underlying rock (Val du Fier section). **F)** Polished slab of a microkarst showing intense penetrative staining by Fe-oxides and microrelief (Chapeau de Gendarme section; scale in centimeters). **G)** Encrusted bioclast displaying stalactite cements (thin section; scale bar equals 0.5 mm). Such indicators of vadose diagenesis commonly are found in the rock underlying diagenetic discontinuities (Salève section). **H)** Discontinuity surface indicating small-scale erosion and facies change from lagoonal facies to siliciclastically influenced tidal facies (Chapeau de Gendarme section). Scale is 5 cm in diameter.

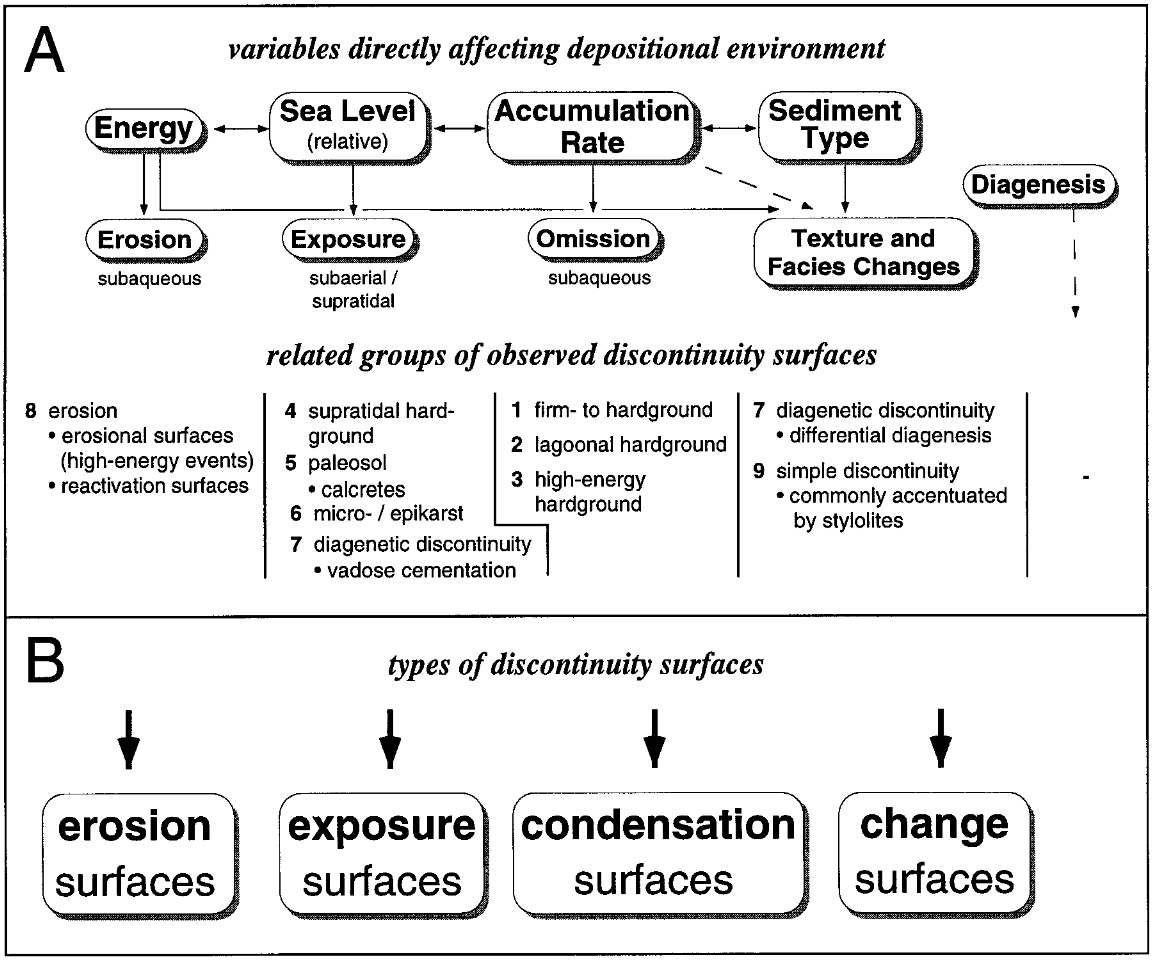

FIG. 5.—Environmental variables directly controlling sedimentation on a shallow-marine carbonate platform. **A)** Variables which for any given position on the platform lead to a specific reaction of the sedimentary system when they change rapidly or by a considerable amount. The observed discontinuity surfaces that are related to these reactions of the sedimentary system are listed below. **B)** Classification of discontinuity surfaces according to the predominant environmental change.

changes of climate and/or relative sea level can for example lead to changes in wave base or energy conditions leading to erosion or to a sudden input of siliciclastics (Strasser and Hillgärtner 1998).

Some surfaces show a combination of subtidal condensation and subsequent exposure (Fig. 6). Hardgrounds that display a vadose overprinting or pedogenic alteration are considered as exposure surfaces because here the latter process is clearly related to allogenic forcing and indicates an environmental change of at least regional importance.

This classification is basically consistent with cyclostratigraphic and sequence-stratigraphic analyses where surfaces indicating exposure or at least a shoaling-up facies evolution capped by supratidal sediments are used to delimit peritidal cycles (Goldhammer et al. 1993) or simple sequences and sequences (Vail et al. 1991). In contrast, well-constrained omission surfaces indicating small-scale submarine erosion and/or marine flooding define subtidal cycles (Osleger 1991; Goldhammer et al. 1993) or parasequences (Mitchum and Van Wagoner 1991; Vail et al. 1991) and typically are interpreted as transgressive and/or maximum-flooding surfaces (Loutit et al. 1988; Brett 1995).

DISTRIBUTION OF DISCONTINUITY SURFACES IN THE LOWER CRETACEOUS SECTIONS

The distribution of the four surface types was established for all studied sections. Figure 6 shows an example of the Monnetier section, illustrating in detail the facies evolution and interpretation of depositional environments and discontinuity surfaces. It can be observed that exposure surfaces and surfaces indicating stratigraphic condensation tend to occur repetitively in certain intervals. They form zones where either exposure or condensation in subtidal environments is predominant. Surfaces indicating facies change or subtidal erosion occur in between and commonly do not form such distinct clusters. The stratigraphic distribution and correlation of these surface zones between study sections is shown in Figure 7. The sections are dated and correlated on the basis of biostratigraphic markers, of which the most abundant are benthic foraminifera (Blanc 1996; Pasquier and Strasser 1997; Pasquier 1995; Darsac 1983; Clavel et al. 1986). Charophyte–ostracod assemblages (Detraz and Mojon 1989) and calpionellids (Blanc 1996; Remane 1985) occur in a few intervals only. The base of most sections is well defined by a regional sequence boundary (Be4) dated as *Privasensis* subzone by ammonites and charophyte–ostracod assemblages (Detraz and Mojon 1989; Strasser 1994; Pasquier 1995). Exposure zones 4 and 5 are well constrained by *Pavlovecina allobrogensis.* Calpionellids and charophyte–ostracod assemblages in the La Chambotte, Salève, and Monnetier sections allow attributing exposure zone 6 to the *Picteti* / *Alpillensis* subzones (Fig. 6; Deville 1991; Blanc 1996). Charophyte–ostracod assemblages indicate a latest Berriasian age for exposure zones 7 and 8 (Deville 1991; Detraz and Mojon 1989) whereas exposure zone 9 and Lower Valanginian surface zones are constrained by benthic foraminifera *(Pfenderina*

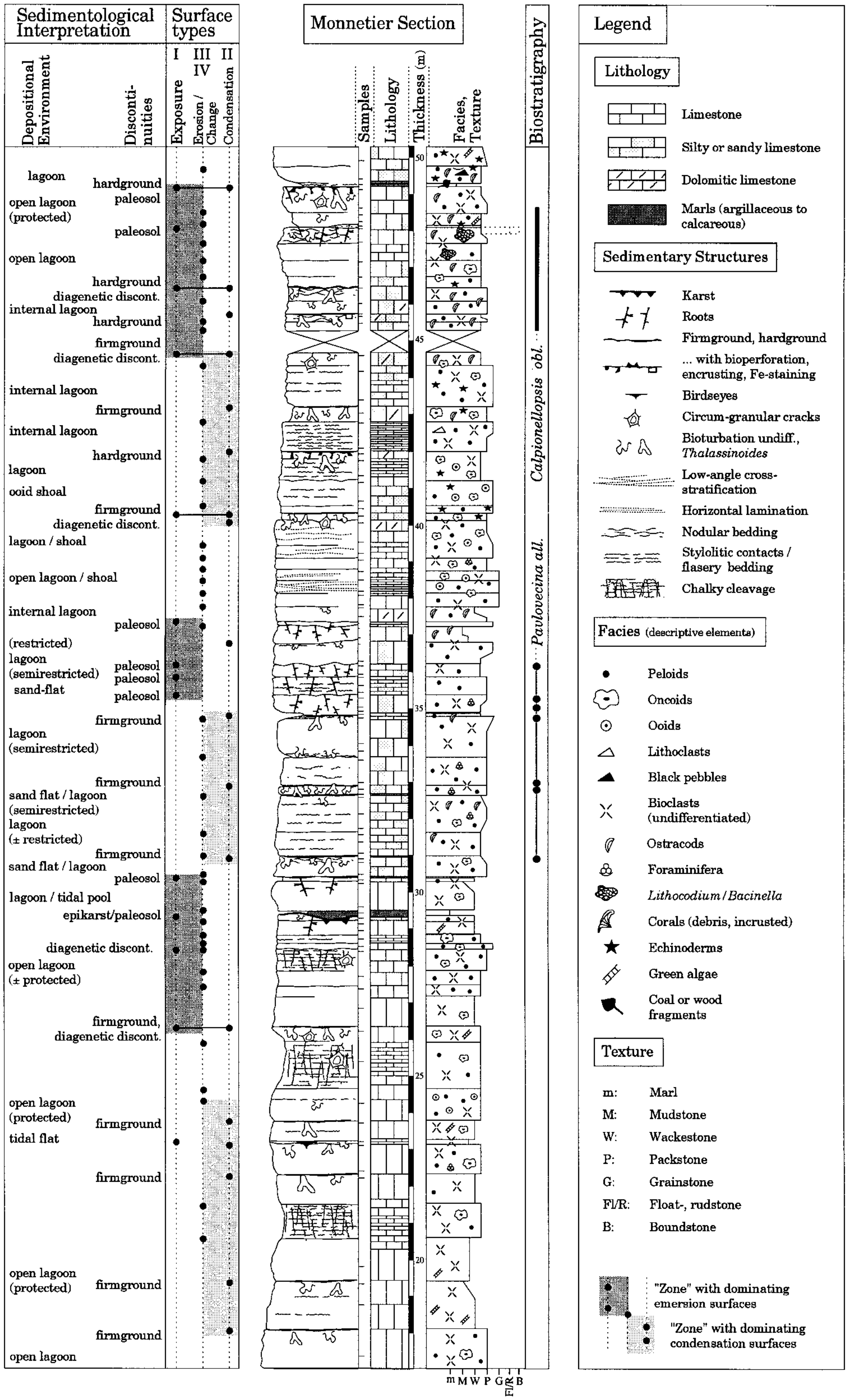

FIG. 6.—Part of Monnetier section with detailed facies evolution and interpretation of depositional environments. Exposure-related and condensation-related discontinuity surfaces form zones of repetitive occurrence.

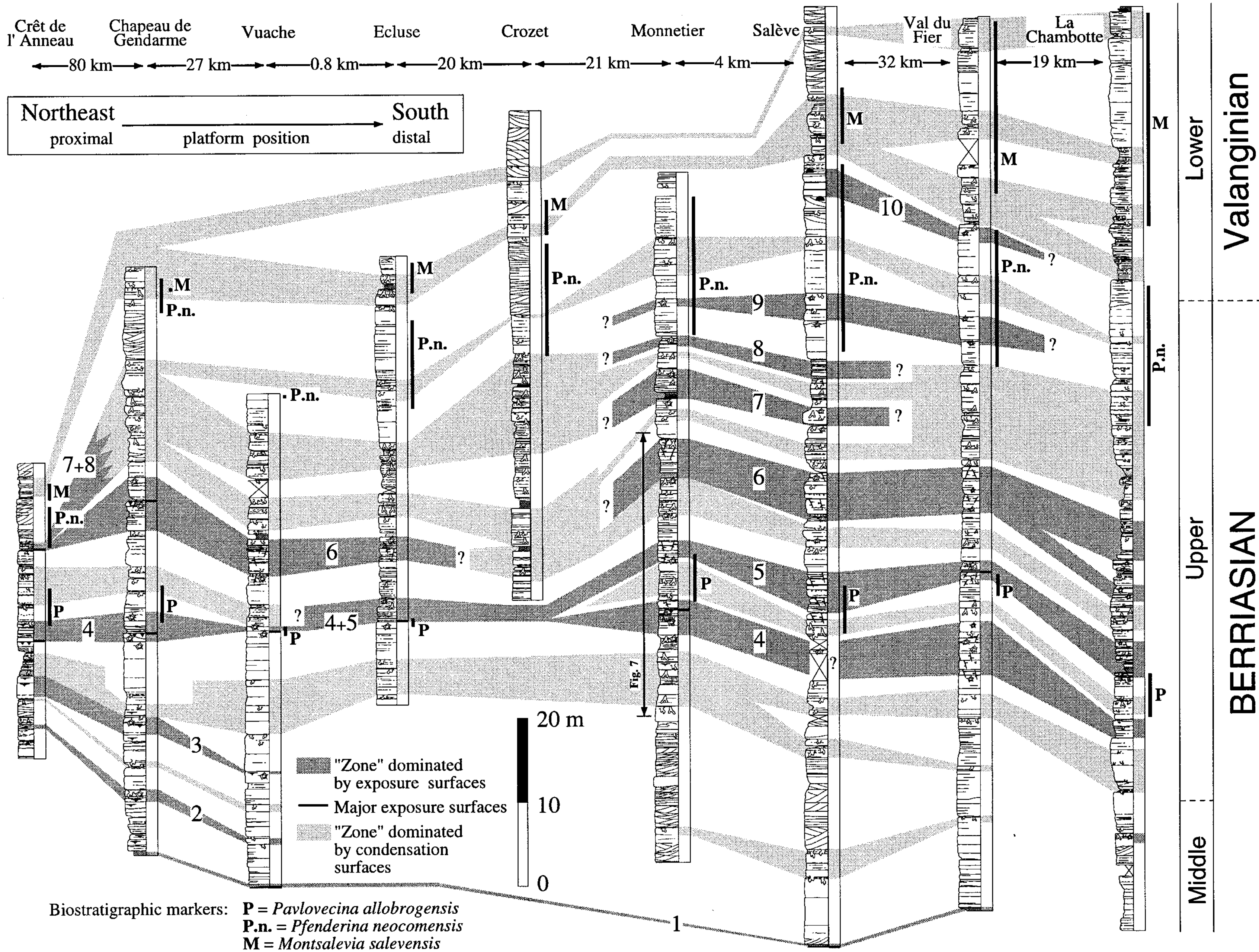

FIG. 7.—Correlation of all studied sections based on the available biostratigraphic framework and different types of discontinuity surfaces. Occurrences of biostratigraphically relevant benthic foraminifera are indicated. ''Zones'' that are dominated by exposure surfaces (numbered 1 to 10) show good lateral correlatability in the lower part of the Upper Berriasian, whereas the Middle Berriasian, the top of the Berriasian, and the Lower Valanginian show locally restricted exposures and widespread condensation.

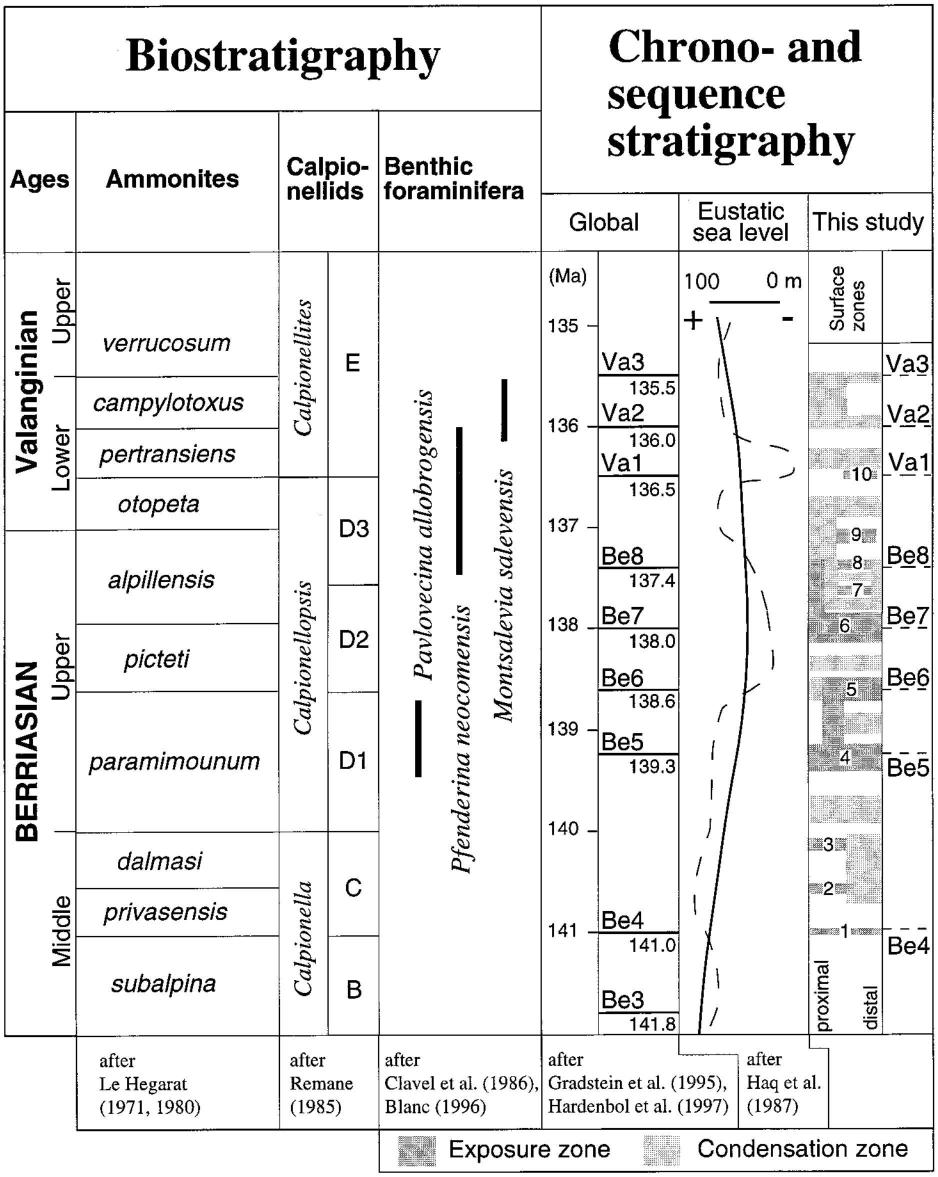

FIG. 8.—Biostratigraphic, chronostratigraphic, and sequence-stratigraphic framework of the studied interval. The positions of the observed zones of discontinuity surfaces and the presumably correlative sequence boundaries are indicated. Exposure zones are numbered and correspond to those indicated in Figure 7. For a detailed interpretation, refer to text.

neocomensis, Montsalevia salevensis). Late first occurrences of *Pfenderina neocomensis* in some sections (Fig. 7) are probably due to unfavorable environmental conditions (restricted facies). Occurrences of the three most important marker foraminifera are noted in the correlation chart (Fig. 7). Within this biostratigraphic framework, a correlation of the surface zones across the platform becomes possible, and the following important trends can be observed:

(1) The upper Middle Berriasian is dominated by widespread condensation, which can be correlated in many cases all across the platform. Exposure occurred only locally, mainly in proximal parts of the platform (exposure zones 2 and 3, Fig. 7).

(2) The lower half of the Upper Berriasian shows alternating zones of exposure and condensation. Exposure, however, prevails and can be correlated throughout the platform from proximal to distal positions (exposure zones 4, 5 and 6). However, exposure zones 5 and 6 correlate with zones indicating condensation and small-scale erosion in proximal platform positions and in Crozet section, respectively. Although facies generally suggest a shallowing trend, no signs of subaerial exposure are detected in these localities. Accommodation increases slightly towards the outer platform during the lower half of the Upper Berriasian.

(3) The top of the Berriasian and the Lower Valanginian are marked by a dominating trend of stratigraphic condensation in subtidal environments. Exposure zones occur repetitively but are restricted to parts of the outer platform (exposure zones 7 to 10). Especially in the Upper Berriasian these exposures correlate laterally with condensation surfaces in the most proximal and most distal parts of the platform (exposure zones 7 and 8). In the Crêt de l'Anneau section, the most proximal locality, the complete Upper Berriasian is condensed and eroded down to a few tens of centimeters of remaining sediment.

INTERPRETATION OF SURFACE ZONES

Comparing the distribution of the surface zones with the ''global'' sequence-stratigraphic framework established by Hardenbol et al. (1997) (Fig. 8), it becomes clear that most zones with dominating exposure correspond to large-scale sequence boundaries. Zones with dominating condensation

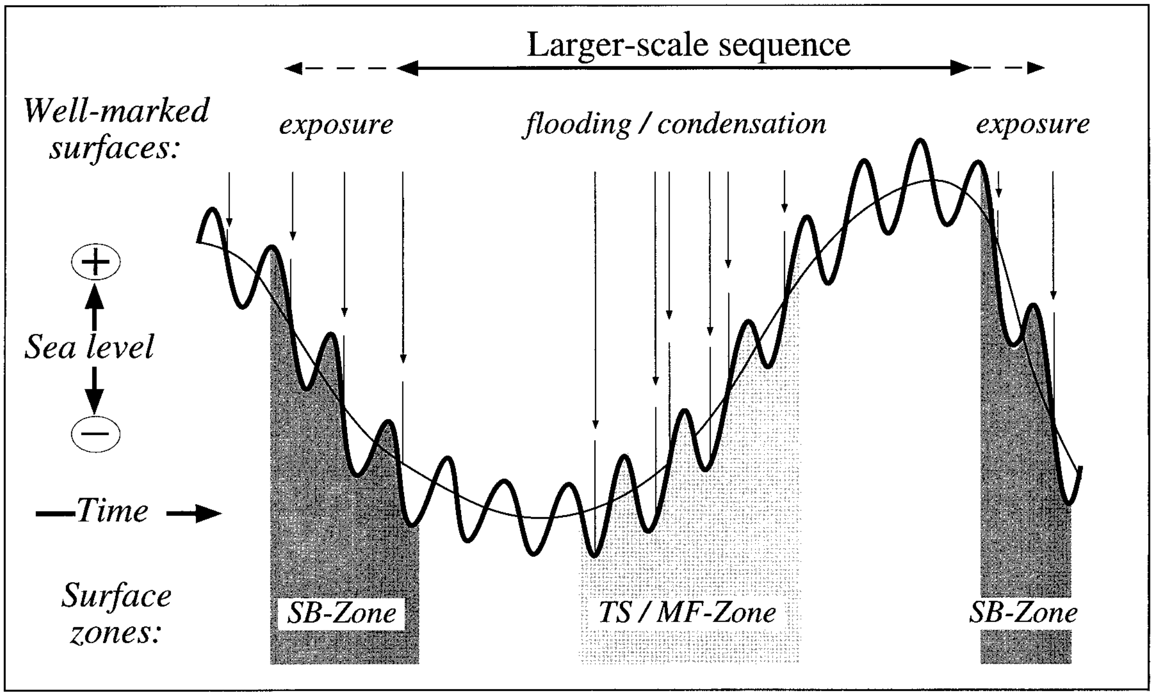

FIG. 9.—Schematic model for the formation of surface zones. Superimposition of high-frequency sea-level fluctuations on longer-term sea-level trends leads to multiplication of diagnostic surfaces. Theoretical position of surfaces is marked with arrows. Longer-term sea-level rises enhance small-scale flooding surfaces that are marked by condensation; longer-term sea-level drops lead to a better expression of small-scale sequence boundaries that show exposure features. Exposure-dominated zones therefore represent sequence-boundary zones on a longer-term sea-level trend, whereas condensation-dominated zones indicate long-term transgression and/or maximum flooding.

fall between sequence boundaries. This implies that the repeated occurrence of specific small-scale discontinuities reflects large-scale (second-order to third-order) eustatic sea-level changes. Exposure-dominated zones between third-order sequence boundaries (exposure zones 7 and 9) may reflect higher-order sea-level fluctuations on the order of several 100 ky, taking into account the relative ages of sequence boundaries (Fig. 8; Hardenbol et al. 1997). A multiplication of diagnostic surfaces forming zones of repetitive short-lived exposure or condensation features rather than distinct single surfaces marked by a long time gap has already been described by Montañez and Osleger (1993), Elrick (1996), and Pasquier and Strasser (1997). This phenomenon can be explained by a superposition of high-frequency sea-level variations on a larger-scale trend of sea-level change (Fig. 9), which creates maximum-flooding or maximum-regression zones on a third-order scale. They are suggestive of a greenhouse climate mode, where small-scale, short-term relative sea-level changes show low amplitudes and tend not to exceed larger-scale, long-term accommodation changes (Read 1995). This does not imply, however, that all discontinuities represent hiatuses of equal and exclusively short-lived duration. Well developed exposure surfaces (karst, exceptionally developed paleosols) with presumably longer durations of subaerial exposure occur locally and in different positions within exposure zones (Fig. 7). This suggests that local factors such as pre-existing morphology and differential subsidence modified allogenic signals. The assumption that all the observed discontinuities reflect high-frequency variations in relative sea level cannot be proven. However, any high-frequency cyclic process, be it autogenically or allogenically controlled, was certainly influenced or even forced by third-order accommodation changes.

The lateral extent of the observed surface zones can be explained with trends of the third-order and second-order eustatic sea-level variations (Haq et al. 1987) (Fig. 8) in combination with subsidence patterns of the platform. Important differential subsidence in late Middle Berriasian times led to a ramp morphology where exposure was restricted to proximal positions. Subsidence in distal platform positions kept pace with, or exceeded, the slowly falling sea level on the second-order and third-order scale, and therefore smaller-scale sea-level drops could not lead to exposure (Fig. 10). In the lower part of the Upper Berriasian, second-order and third-order sea-level falls were superimposed. This induced low accommodation potential all across the platform. The consequence was a rapid platform progradation generating a flat-topped platform morphology. Therefore, short-term sea-level falls caused repetitive, well marked, and laterally extensive exposure features (sequence-boundary zones Be5 to Be7) (Figs. 8, 10) Locally correlative condensation and small-scale erosion surfaces may indicate either restricted topographic lows where subaerial exposure was not attained, or more probably, erosion of all signs attesting for exposure during the following marine flooding (ravinement surface). Exposures are predominantly marked by paleosols indicating, together with siliciclastic input, more humid conditions than in the late Middle Berriasian and Early Valanginian, when exposures commonly show desiccation features (Pasquier 1995). Sequence-boundary zone Be7 marks the end of a large-scale sea-level lowstand that is implied by platform-wide tidal-flat deposits pointing to the most regressive phase in the distal platform positions. During the Latest Berriasian and Early Valanginian, second-order and third-order sea-level changes displayed a rising trend. High accommodation rates here are marked predominantly by low sedimentation rates and laterally continuous condensation during high-frequency sea-level rises. Short-lived rapid sea-level drops led to partial exposure of the platform but affected only areas that were morphologically elevated (sequence-boundary zones Be8 and Va1). Elevated differential subsidence during the Late Berriasian (Detraz and Mojon 1989) is indicated by long-lasting exposure in some proximal platform positions (Crêt de l'Anneau section) and high accommodation in the Crozet section during the same time interval. The lateral correlation of exposure surfaces in more distal positions with condensation surfaces in parts of the platform interior and the outer platform (Fig. 7) suggests the existence of a morphologic barrier. Accommodation in platform positions

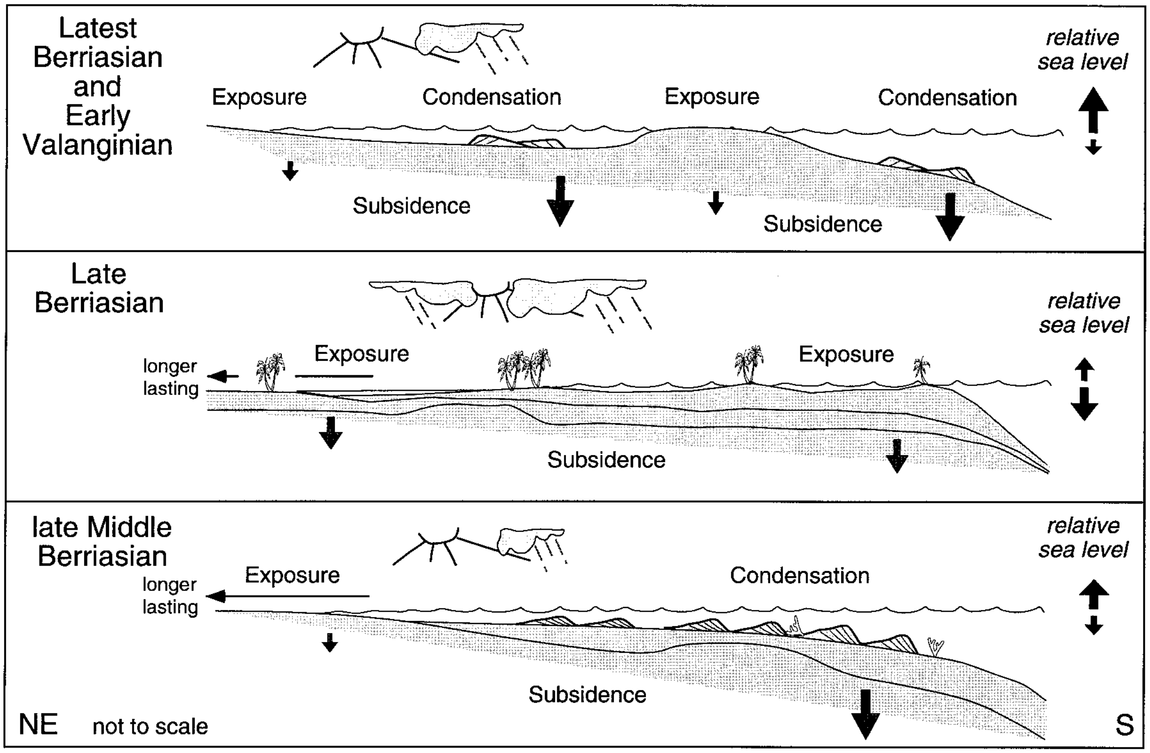

FIG. 10.—Schematic sketch illustrating the evolution of the French Jura platform from the Early Berriasian to the Early Valanginian. For a detailed description, refer to text.

indicating condensation is comparable to accommodation in positions indicating exposure. Therefore a major truncation surface that eroded the whole interval indicating subaerial exposure seems improbable to explain this surface distribution. The short-lived, high-amplitude sea-level drop outlined on the Haq et al. (1987) sea-level curve cannot be corroborated by a major exposure in the present study. The amplitude of this sea-level drop probably was much lower and basically compensated by the elevated subsidence rates in the Early Valanginian. The accommodation potential indicated by sediment thickness excludes a compensation for more than 100 m of sea-level drop in the *Pertransiens* ammonite zone (Fig. 8; Haq et al. 1987) by means of elevated subsidence rates.

EXPECTED DISTRIBUTION OF DISCONTINUITY SURFACES

One important criterion to define sequences and their constituent smaller-scale depositional sequences (independent of scale) are the types of bounding discontinuities (Van Wagoner et al. 1988; Vail et al. 1991; Arnott 1995; Holland et al. 1997). The occurrence and distribution of specific types of discontinuities in cyclic successions, mainly reflecting relative sea-level changes, are a function of the amplitudes and frequencies of superimposed relative sea-level changes and their relative position on this composite sea-level curve (Figs. 9, 11). Therefore, types of small-scale depositional sequences defined by their bounding discontinuities (''parasequences'' bounded by marine flooding and condensation surfaces, ''simple sequences'' bounded by exposure surfaces) and their distribution in the succession vary accordingly (Fig. 11). A different internal facies evolution of such depositional sequences, which is the subject of ongoing studies, may also reflect their relative position on larger-scale sea-level curves (Arnott 1995). On the basis of this case study it can be implied that small-scale depositional sequences defined by exposure surfaces (''simple sequence'' of Vail et al. 1991) occur predominantly when small-scale relative sea-level drops are superimposed on a larger-scale sea-level fall. In contrast, depositional sequences defined by marine flooding, commonly marked by condensation surfaces, occur predominantly when small-scale and large-scale relative sea-level rises are superimposed. The intensity of condensation and exposure should increase towards the strongest rate of sea-level rise and fall on the long-term trend, respectively (Fig. 11). However, superimposition of simple sine waves as shown in Figures 9 and 11 is a rather simplified representation of real composite sea-level curves. As demonstrated in this study, many local factors may interfere and, therefore, the distribution of discontinuity surfaces and types of depositional sequences reflecting complex composite relative sea-level variations cannot be interpreted and are not predictable in a straightforward manner.

CONCLUSIONS

Discontinuity surfaces on shallow-marine carbonate platforms can display a wide variety of characteristic elements. All surfaces (excluded are ''false discontinuities'' of purely late diagenetic origin) reflect reactions of the sedimentary system to rapid and drastic environmental changes. Such surfaces actually record the most important times during platform evolution, namely times of the highest dynamics in environmental change. However, only a detailed and individual investigation of each surface can reveal information on which environmental change caused its formation. Reactions of sedimentary systems to such changes are expressed by subaqueous erosion, exposure (including any erosion in a subaerial setting), subaqueous omission, and facies changes. Changes in energy regime, relative sea level, accumulation rate, and sediment type lead to the formation of such discontinuities. For the interpretation of the evolution of a carbonate platform it is essential to know to what extent allogenic factors such as eustatic sea level, tectonics, and climate controlled the depositional systems. This becomes especially difficult when major unconformities marked by well-constrained single surfaces of platform-wide extent are absent, or when laterally consistent cyclic facies patterns are not present to allow analyses of different hierarchies of accommodation change. This can be the case when amplitudes of high-frequency eustatic sea-level changes are small and de-

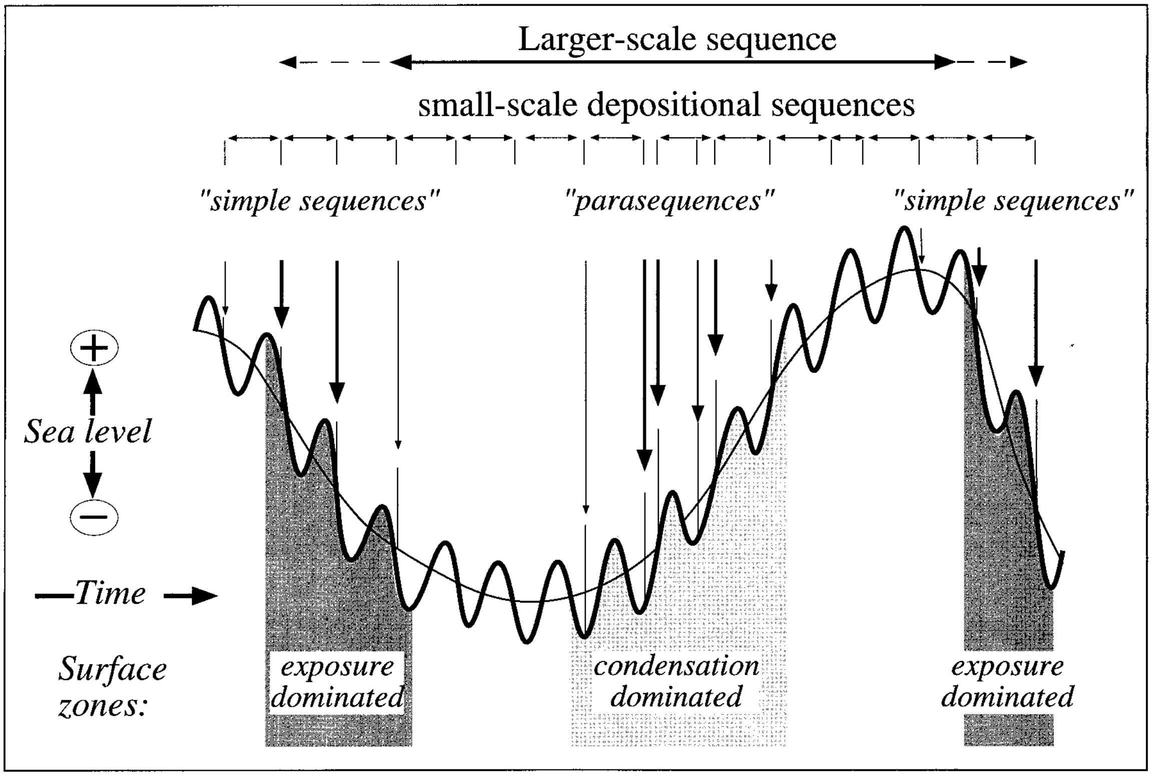

FIG. 11.—Hypothetical distribution of different types of depositional sequences (parasequences, simple sequences) defined by their bounding discontinuities (condensation, exposure) on a composite sea-level curve. The intensity of the inferred condensation or exposure depends on the rate of the larger scale sea-level rise or drop, respectively (thicker arrows indicate higher intensity).

positional systems on carbonate platforms are diverse. Similar effects occur when rapid subsidence buffers high-amplitude sea-level variations.

In the Lower Cretaceous of the French and Swiss Jura, all observed small-scale discontinuities are classified according to the type of environmental change they express: subaerial exposure, subtidal condensation, subtidal erosion, and/or facies changes. Exposure surfaces and condensation surfaces form zones of repetitive occurrence in all sections. The correspondence of exposure zones with the third-order sequence boundaries of Hardenbol et al. (1997) suggests that sedimentation and high-frequency environmental change was controlled by large-scale, low-frequency eustatic sea-level changes. On the basis of a biostratigraphic framework, exposure and condensation zones can be correlated, although single surfaces cannot be traced in the same way. Correlation based on zones of surfaces rather than single surfaces is more realistic in shallow-water settings because such zones span a much larger time interval and therefore are less sensitive to local variations of depositional systems and lateral facies changes. Variation in the lateral continuity of surface zones and the coeval occurrence of exposure and condensation zones can therefore indicate morphological structuring of the platform and areas of differential subsidence.

On the basis of surface and facies analysis, the French and Swiss Jura platform shows evidence for differential subsidence in the late Middle Berriasian, marked by condensation in distal platform positions. Platform morphology was close to that of a distally steepened ramp (Fig. 10; Pasquier 1995, Pasquier and Strasser 1997). The Late Berriasian was marked by platform progradation and slow differential subsidence. Third-order sea-level falls led to widespread exposure, implying a flat-topped platform morphology. From the middle of the Late Berriasian onwards a relative sea-level rise is indicated by surfaces that dominantly indicate condensation, and generally more open-marine and high-energy facies. Elevated differential subsidence and an irregular platform morphology is implied by exposures of local to regional extent.

This study demonstrates that discontinuities can reveal information about depositional processes not necessarily indicated by the sedimentary facies alone, and that they can serve as an additional tool for correlation and interpretation of platform evolution. It serves as a framework for further cyclostratigraphic and sequence-stratigraphic studies, including general facies evolution, geometric analysis of sediment bodies, and quantitative subsidence analyses.

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