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MODELING CARBONATE MICROFACIES IN THE CONTEXT OF HIGH-FREQUENCY DYNAMIC RELATIVE SEA-LEVEL AND ENVIRONMENTAL CHANGES

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ABSTRACT: **Sequence stratigraphic models are used to interpret stratal architecture and key stratal bounding surfaces in ancient carbonate platforms within the context of changing accommodation space during third-order relative sea-level cycles. However, individual systems tracts are still described using standard microfacies that give a snapshot of limestone composition, but they do not take into account gradual changes in the marine environment resulting from variations in water depth during the cycle of relative sea-level change. Water depth is the single most significant collective control on a wide range of environmental gradients affecting carbonate sediment composition. During dynamic relative sea-level fluctuations stratigraphic changes in carbonate sediment composition are characterized by systematic shifts in the relative importance of different limestone component grain types, forming temporal continuums or relays. Relays are detected using computer-optimized Jaccard's similarity coefficient matrices to analyze presence/absence compositional data. Individual relays between grain types may link together samples that are generically unrelated to one another but are nevertheless genetically related to deposition during the same unidirectional dynamic environmental gradient.**

A stratigraphic relay identified within the basal beds of the mid-Cretaceous Urgonian carbonate platform succession of SE France records unidirectional environmental gradients linked to changing water depth, characteristic of a transgressive systems tract. Periods of static water depth, such as the keep-up phase of a late highstand systems tract at the top of the Urgonian carbonate platform succession, are characterized by fixed compositional assemblages. Stratigraphic breaks between individual compositional relays and assemblages occur at inflections in changing water depth, marking the boundaries between individual systems tracts and sequences, currently identified using stratal geometries and key stratal surfaces.

The use of relays to model microfacies and identify individual system tracts and sequence boundaries has several advantages over existing methods. This approach can be used where key stratal surfaces are difficult to distinguish, such as in planar and concordantly bedded, inner platform settings and in arid depositional environments where physical evidence of subaerial platform exposure such as karstification is poorly developed. The technique can also be used to determine the genetic significance of unconformities preserved in outcrop or core within a sequence stratigraphic context by differentiating unconformities formed at the extremes of relative sea-level cycles from those formed by other abrupt acyclical environmental changes.

INTRODUCTION

Sequence Stratigraphic and Standard Microfacies Models

It is now widely known that there have been numerous high-frequency, dynamic environmental and relative sea-level changes in the geologic past and that these greatly influenced the evolution of individual carbonate platforms. Sequence stratigraphic models are routinely applied to interpret ancient carbonate platforms using stratal architecture and the distribution of key stratal surfaces and facies description within depositional units. Key stratal surfaces represent depositional hiatuses formed during major episodes of subaerial exposure or maximum marine flooding at the extremes of sea-level cycles (Vail et al. 1987; Vail et al. 1991; Galloway 1989). Successions are divided up into sequences and their constituent systems tracts that characterize the different phases of deposition during third-order relative sea-level cycles (1–10 My). However, there has been little consideration of the way that microfacies within these stratigraphic units vary in response to the effects of gradual environmental shifts caused by the relative sea-level changes. Variation in water depth is the single most significant collective control on a wide range of environmental factors including hydrodynamic energy, water turbulence, light penetration, siliciclastic contamination, and nutrient supply (Fig. 1). Thus, a reappraisal of the conceptual approaches used to model limestone microfacies is suggested, which will help recognize such environmental changes.

Carbonate microfacies are most widely interpreted using standard microfacies models (e.g., Flügel 1982; Wilson 1975). However, the rate at which environmental changes occurred, especially fluctuations in relative sea level, were thought to have been much slower then we now know them to have been. Consequently the effects of systematic, high-frequency, dynamic environmental changes on the microfacies of individual platforms were ignored in these models.

Standard microfacies models characterize paleogeographic and stratigraphic changes in carbonate sediment using a series of discrete, unrelated fixed compositional populations or assemblages based on the apparently discontinuous distribution of carbonate grains (Fig. 2A). Carbonate subenvironments represented by individual microfacies assemblages are defined relative to fixed paleogeographic positions within the platform and static paleobathymetries. However, against a background of dynamic relative sea-level changes neither paleogeographic position nor paleobathymetry remain constant. The spatial arrangement and composition of microfacies within a carbonate platform will be affected by changes in the type of carbonate generated by the carbonate factory and carbonate factory size, related in large part to the position of sea level and the nature of any change. Thus, different microfacies can exist at similar locations and depths on a platform at different times within a cycle of relative sea-level change.

Moreover, the effects of the continuous and gradational nature of environmental change on carbonate production and sedimentary processes during similar phases of changing water depth (i.e., parasequences and/or systems tracts) within a third-order sea-level cycle mean that stratigraphic changes in sediment composition are unlikely to occur in a series of abrupt, step-like jumps between fixed compositional assemblages, but rather as continuous systematic shifts in the relative importance of individual grains forming temporal continuums (Fig. 2B). Spatial or temporal systematic shifts in the relative importance of component grains are termed *relays* (Hennebert and Lees 1985). By studying the sequential arrangement of individual grains in a stratigraphic relay, it is possible to determine the nature of underlying dynamic environmental changes.

In many cases, the existence of compositional relays is not immediately apparent in limestones. Not every component present in a limestone may be involved in the underlying relay; this reflects contrasts in the environmental sensitivities of different types of bioclast and the polygenetic modes of formation of many abiogenic grains. In addition, the most volumetrically abundant components, which are given strong emphasis in purely generic classifications of limestones, are not necessarily of greatest environmental

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JOURNAL OF SEDIMENTARY RESEARCH, VOL. 69, NO. 4, JULY, 1999, P. 947–961
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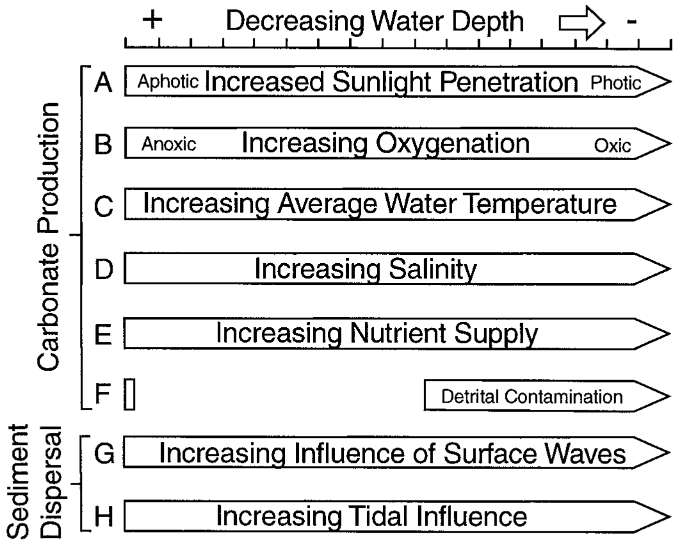

FIG. 1.—The collective control that changes in water depth exert on a range of environmental gradients in carbonate systems illustrated for a single shallowing-up cycle. With decreasing water depth all factors A through H increase in their effect. With regard to nutrients (E), the supply may increase in nearshore waters as phosphate and nitrate leachates drain from the hinterland and from the post-mortem decay of marine organisms. Thermal upwelling may enhance nutrient supply in shallower surface waters. Factors A to F primarily effect carbonate production and G and H influence sediment dispersal.

significance. These factors may disguise any systematic stratigraphic change in sediment composition unless the correct analytical tools are applied.

Most analytical techniques used in carbonate microfacies analysis, such as graphical triangular diagrams, cluster analysis, or factor analysis (e.g., Davis 1986), are geared to identifying groupings between sedimentary components, or samples. These techniques may unwittingly break down compositional relays into a series of static temporal ''pin-points'' or spatial ''snapshots'' which appear to conform to the standard microfacies paradigm. However, the ''boundaries'' between these individual microfacies ''assemblages'' are purely artifacts of the assumptions inherent in the conceptual approach and may hold no intrinsic genetic significance. Interpreting stratigraphic changes in limestones characterized by compositional relays using standard microfacies models may result in the identification of an exceedingly large number of generically unrelated microfacies assemblages, each corresponding to sediment composition at a static instant within a continuum. Conversely, the temptation to expand continually the definitions of individual microfacies assemblages, so as to encompass apparently small compositional differences between individual samples, reflecting progression along a relay, may cause the definitions of individual assemblages to become so broad and vague as to be of little practical use.

The limitations inherent in the traditional standard microfacies approach to modeling limestones in the context of high-frequency environmental changes are demonstrated for a single shallowing-upward parasequence (Fig. 3). Shallowing-upward parasequences deposited during fourth-order (0.1–1 My) to fifth-order (0.01–0.1 My) relative sea-level cycles form the fundamental building blocks of sequence stratigraphy. Four samples (C1 to C4) were collected at regular stratigraphic intervals from the base (C1) to top (C4) of a mid-Cretaceous (Barremian) limestone shallowing-upward parasequence. Modal compositional data from these samples were analyzed using graphical triangular diagrams. The latter are a comparatively rudimentary, but by far the most frequently used, method of identifying microfacies assemblages. Different combinations of parameters are used to identify populations in limestones (e.g., Dunham 1962, Steinhauff and Walker 1995), and three examples are plotted in Figure 3.

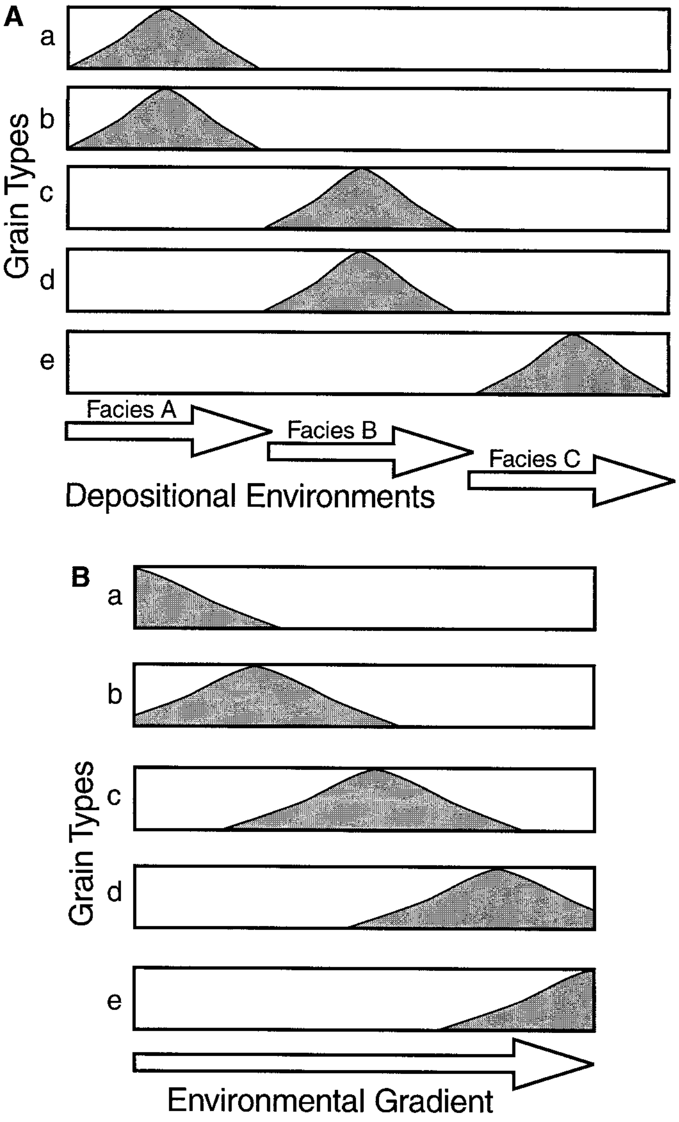

FIG. 2.— **A)** Schematic illustration of traditional standard microfacies divisions of depositional environments into discrete populations (either in space or time), based on the discontinuous distribution of grain-type abundance. **B)** Schematic illustration of the distribution and relative abundance of grain types either spatially or stratigraphically as a relay formed in response to a unidirectional environmental gradient (after Hennebert and Lees 1991). Although samples taken from different geographic or stratigraphic positions may share no grain types in common, they are genetically related to one another as part of the same unbroken dynamic continuum (see text for discussion).

The apparent disparate scatter pattern of samples when plotted using textural parameters, i.e., grains, micrite, and sparite (Fig. 3i), can be conventionally interpreted as indicating that the samples are generically unrelated to one another and that four separate genetic populations are present. However, when modal abundances of micrite, peloids, and mollusca are used to plot samples (Fig. 3ii), the resulting scatter of points is divided into two widely separated clusters. Each cluster defines a separate, generically unrelated assemblage. In this way, samples C1 and C2 appear to belong to the same microfacies assemblage, and C3 and C4 define a second microfacies population. The spatial arrangement of samples when plotted using benthic foraminifera, echinoderms, and mollusca as the three component parameters (Fig. 3iii) again appears to identify the presence of two separate unrelated microfacies assemblages. However, in this case samples C1 and

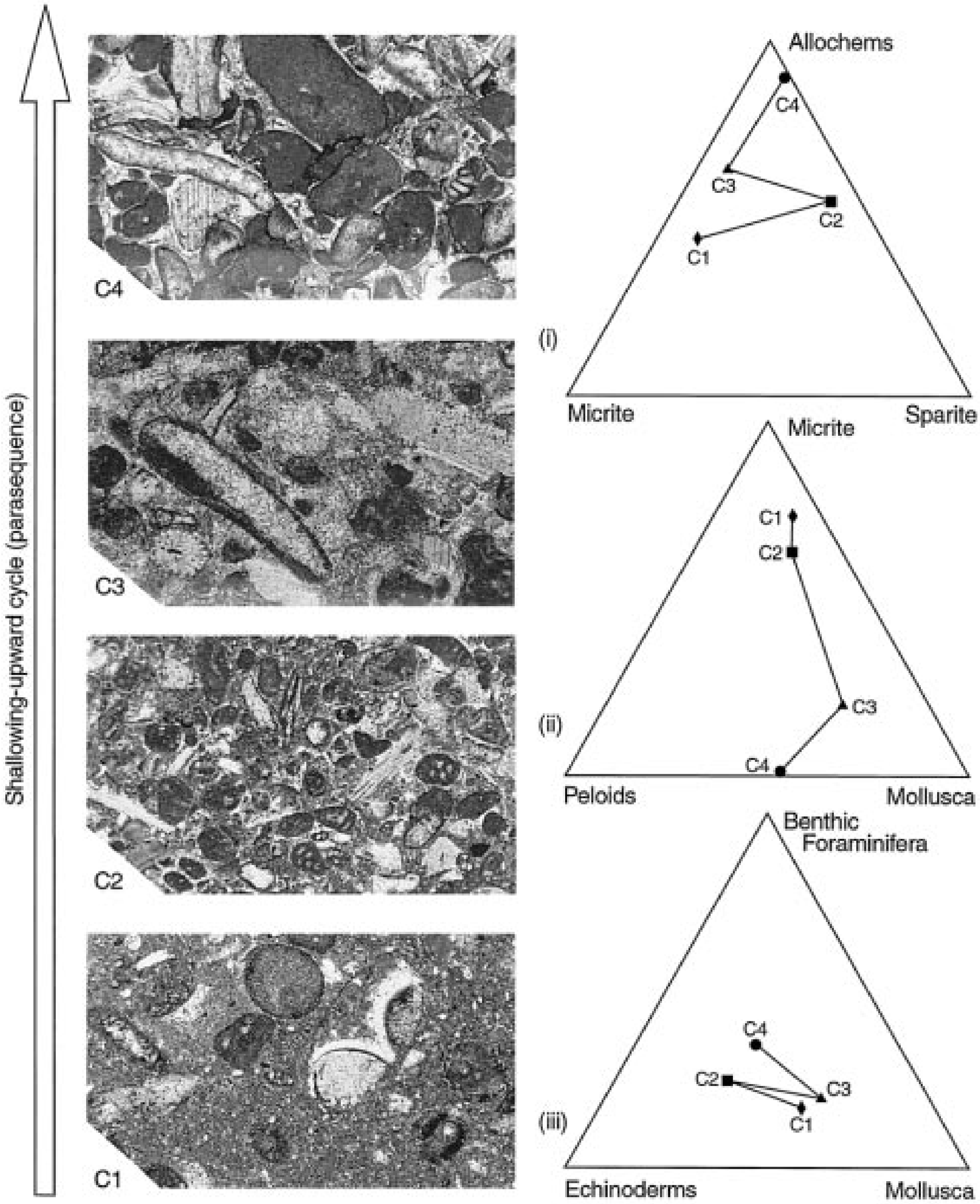

FIG. 3.—Illustration of the shortcomings of the traditional approach to defining carbonate microfacies by attempting to identify compositional populations during high-frequency dynamic environmental changes. Photomicrographs C1 to C4 are of samples taken at regular intervals through a Barremian shallowing-upward cycle (parasequence); C1 from the base; C4 from the top. (i), (ii), and (iii) show graphical triangular plots of modal abundances of grains for samples C1 to C4. Sample plots are linked in stratigraphic order to trace changes. Traditional interpretation would suggest that up to four separate *unrelated* microfacies assemblages are present, but the ''boundaries'' between these microfacies are entirely artificial. Samples C1 to C4 are *genetically related* to one another, representing snapshots of sediment composition during an otherwise continuous shift in sediment composition in response to the same *dynamic* environmental gradient (in this case relative sea-level fall). Key to symbols: ♦, mudstone; ■, wackestone; ▲, packstone; ●, grainstone. Each photomicrograph has a field of view of 4 mm × 3 mm.

C3 plot in positions similar to one another, defining one microfacies population, and they are separated by a greater distance from samples C2 and C4, which plot closer together and appear to belong to another microfacies association.

Attempting to identify generic populations in a shallowing-upward parasequence using different combinations of component parameters thus results in conflicting and contradictory groupings between samples being identified. Depending upon which of these interpretations is followed, stratigraphic boundaries between microfacies assemblages may be placed in different stratal positions. These contradictions reflect the arbitrary way that fixed microfacies assemblages attempt to break up stratigraphic compositional relays. Relationships between individual component parameters within the data set may vary from one to another, and samples taken from different temporal positions within the relay may have few or no components in common. However, samples C1 to C4 are *genetically* related to one another; they represent frozen *generic* snapshots at different temporal positions within the *same* compositional relay formed in response to dynamic environmental changes, collectively controlled by the *same* episode of gradually decreasing water depth. Attempting to identify stratigraphic compositional relays offers a holistic method of describing continuous systematic changes in limestone composition that are of use in identifying high-frequency dynamic environmental changes related to relative sea-level cycles.

Relative Sea-Level Changes and Stratigraphic Compositional Relays

Changes in relative sea level resulting in changes in water depth during carbonate deposition may be preserved in the stratigraphic record as compositional relays. The smallest stratigraphic scale at which compositional relays are likely to occur are individual parasequences formed by fourth-order to fifth-order relative sea-level cycles. However, underlying third-order relative sea-level rises or falls represented by parasequence sets and systems tracts may also form stratigraphic relays. Figure 4 schematically illustrates the predicted stratigraphic occurrence of different environmentally sensitive grain types in response to dynamic changes in water depth during deposition caused by fourth-order to fifth-order relative sea-level cycles superimposed upon an underlying unidirectional third-order relative sea-level fall (Fig. 4A) or rise (Fig. 4B).

During periods of third-order marine regression the beginning of each successive fourth-order to fifth-order shallowing-upward parasequence is marked by a deeper-water environment than occurred at the end of the immediately preceding shallowing-upward parasequence, but is shallower compared to the initial water depth that existed at the onset of the underlying third-order relative sea-level fall (Fig. 4A). Hence, during each separate fourth-order to fifth-order relative sea-level cycle grain types with deeper-water affinities are systematically replaced by those with shallower-water affinities, forming a distinct shallowing-upwards stratigraphic relay (Fig. 4A). However, the underlying third-order relative sea-level fall represented by the parasequence set or lowstand systems tract may be characterized by a different single stratigraphic relay composed of grain types with progressively shallower-water affinities (Fig. 4A).

During episodes of third-order marine transgression the beginning of each successive fourth-order to fifth-order shallowing-upward parasequence is marked by a deeper-water environment than existed at the end of the immediately preceding shallowing-upward parasequence, and is also deeper relative to the initial water depth that existed at the beginning of the underlying third-order relative sea-level rise. Hence, during each separate fourth-order to fifth-order relative sea-level cycle, grain types with deeper-water affinities are systematically replaced by those with shallower-water affinities forming individual shallowing-upwards stratigraphic relays (Fig. 4B). However, the underlying third-order relative sea-level rise may be characterized by a different single stratigraphic relay composed of grain types exhibiting progressively deeper-water affinities, but it may not include all the grain types present in each of the individual fourth-order to fifth-order shallowing-upwards stratigraphic relays (Fig. 4B).

Hence, individual fourth-order to fifth-order parasequences may be recorded stratigraphically by distinct shallowing-upwards compositional relays, but at the scale of a parasequence set or lowstand or transgressive systems tract the underlying third-order relative sea-level fall or rise might be characterized by a single diagnostic stratigraphic compositional relay. Stratigraphic relays potentially therefore can be used as genetic ''fingerprints'' to interpret both small- and large-amplitude relative sea-level changes in limestone successions.

In this study, optimized similarity matrices were used to identify stratigraphic compositional relays at the systems-tract scale in the mid-Cretaceous Urgonian carbonate platform exposed in southeast France, and these can be correlated to dynamic environmental gradients controlled by changing water depth during third-order relative sea-level cycles. Stratigraphic changes in microfacies identified using optimized similarity matrices were integrated with stratal architecture to assist the sequence stratigraphic interpretation of the platform. The microfacies of these same limestone successions were also analyzed using graphical triangular diagrams to identify fixed microfacies assemblages as envisaged by the standard microfacies paradigm. The results of these two different conceptual approaches to modeling limestone microfacies are compared and contrasted.

DETECTING COMPOSITIONAL RELAYS

Spatial or stratigraphic relays in limestone composition can be detected using ordination statistical techniques. Such statistical methods involve calculating coefficients that assign a scaled value of similarity in sample composition or grain distribution relative to all the other samples and/or grains present in the data set. Values of similarity coefficient are then optimized, i.e., systematically ranked according to value so that trends in changes in sample composition or grain distribution may become apparent.

There exist several different similarity coefficients (e.g., Hennebert and Lees 1985) and methods of ordination (e.g., Hennebert and Lees 1991). In this study the method of optimization of a matrix of Jaccard's similarity coefficients was chosen for modeling stratigraphic changes in limestones. The basic procedure involved is briefly outlined below.

Values of Jaccard's similarity coefficients of community (Jaccard 1908) are calculated using binary nonparametric presence/absence criteria. The value of Jaccard's coefficient ($S_{ja,b}$) between any two grains ''a'' and ''b'' in a data set is calculated by the algorithm

$$S_{(ja,b)} = \frac{A}{A + B}$$

where ''A'' is defined as the number of co-occurrences of grains ''a'' and ''b'' in the suite of samples, and ''B'' is defined as the number of individual occurrences of ''a'' and ''b'' only in the suite of samples. Jaccard's similarity coefficients may have a range of decimal values between 0 and 1. A value of Jaccard's similarity coefficient of 0 indicates that ''a'' and ''b'' never occur together, and a value of 1 means that they always occur together. The higher the intermediate values of Jaccard's coefficient within this range, the greater is the probability that both grains will occur in a single sample. Jaccard's similarity coefficients ignore the occurrence of double absences of components between samples, i.e., two grains both being absent from compared samples, which can otherwise spuriously inflate apparent values of similarity coefficients. Jaccard's similarity coefficients are calculated between all parameters present in a data set and are presented in a matrix. The matrix is then optimized so that grains are arranged immediately adjacent to those with which they share greatest similarity in terms of co-distribution. Optimization is achieved by repeatedly reordering the rows and columns of the matrix until the greatest number of high values of similarity coefficients situated nearest to the central diagonal traced through the matrix from top left to bottom right cannot be improved upon.

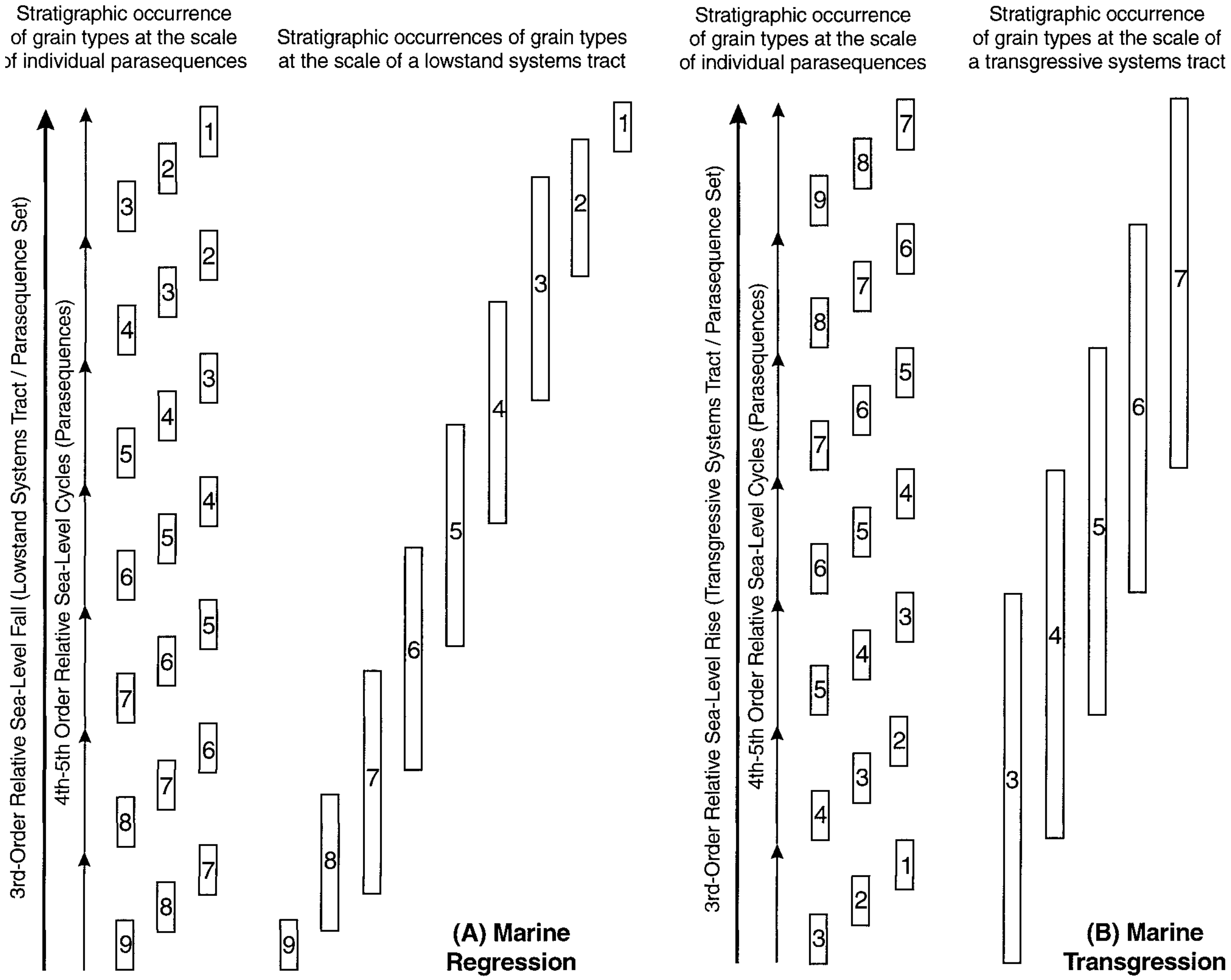

FIG. 4.—Cartoons illustrating the predicted stratigraphic occurrence of different environmentally sensitive grain types resulting from changes in water depth due to 4th/5th-order relative sea-level (RSL) cycles superimposed upon an underlying unidirectional 3rd-order RSL fall **(A)** or rise **(B).** Different grain types are numbered 1 through 9, with 1 the shallowest through to 9 the deepest. **A)** Periods of marine regression: during each 4th/5th-order RSL cycle, grain types with deeper-water affinities are systematically replaced by those with shallower-water affinities, forming individual shallowing-upwards stratigraphic relays. However, the underlying 3rd-order RSL fall is characterized by a single stratigraphic relay composed of grain types with progressively shallower-water affinities. The stratigraphic relay recording the underlying 3rd-order marine regression combines all the different grain types present in each of the individual 4th/5th-order shallowing-upwards stratigraphic relays. **B)** Periods of marine transgression: during each 4th/5th-order RSL cycle, grain types with deeper-water affinities are systematically replaced by those with shallower-water affinities, forming individual shallowing-up stratigraphic relays. However, the underlying 3rd-order RSL rise is characterized by a single stratigraphic relay composed of grain types exhibiting progressively deeper-water affinities. The stratigraphic relay recording the underlying 3rd-order marine transgression does not include all the grain types present in each of the individual 4th/5th-order shallowing-up stratigraphic relays. The base of the deepening-up third-order relay is marked by grain types with the deepest-water affinity present in the basal 4th/5th-order stratigraphic relay (i.e., grain type 3), and the top of the third-order stratigraphic relay is marked by grain types with the shallowest-water affinities occurring in the uppermost 4th/5th-order shallowing-up stratigraphic relay (i.e., grain type 7). Grain types recording upwards shallowing in the basal 4th/5th-order stratigraphic relay (i.e., grain types 2 and 1) and grain types with deeper-water affinities in the uppermost 4th/5th-order shallowing-up stratigraphic relay (i.e., grain types 9 and 8) are not included in the underlying 3rd-order deepening-up transgressive stratigraphic relay.

The analytical algorithm of Beum and Brundage (1950) is used to optimize the matrix. The procedure of calculating Jaccard's similarity coefficients between grains and optimizing the resultant matrix was carried out by computer using software developed by Hennebert and Lees (1985).

To aid interpretation of optimized similarity matrices between grains, individual values of Jaccard's coefficient are represented by vertical scale bars that are linked laterally for each individual grain so as to define a similarity envelope relative to all other grains in the stratigraphic data set.

Optimized matrices of Jaccard's similarity coefficients can detect the presence of relays or populations on the basis of the configuration of the final optimized matrix. If a relay is present, it is indicated by a marked concentration of all the highest values of Jaccard's coefficients near the central diagonal, and then a systematic decrease in value as traced along the rows and columns of the optimized matrix. However, if no relay is present, but the data set is instead characterized by one or more fixed compositional populations, then each population appears as a triangular cluster of uniformly high values of Jaccard's coefficients along and/or parallel to the diagonal traced through the center of the optimized matrix.

THE MID-CRETACEOUS URGONIAN CARBONATE PLATFORM

Geologic Setting and Rival Stratigraphic Models

The mid-Cretaceous Urgonian carbonate platform was deposited on the passive margin of the European continental plate, which at that time formed

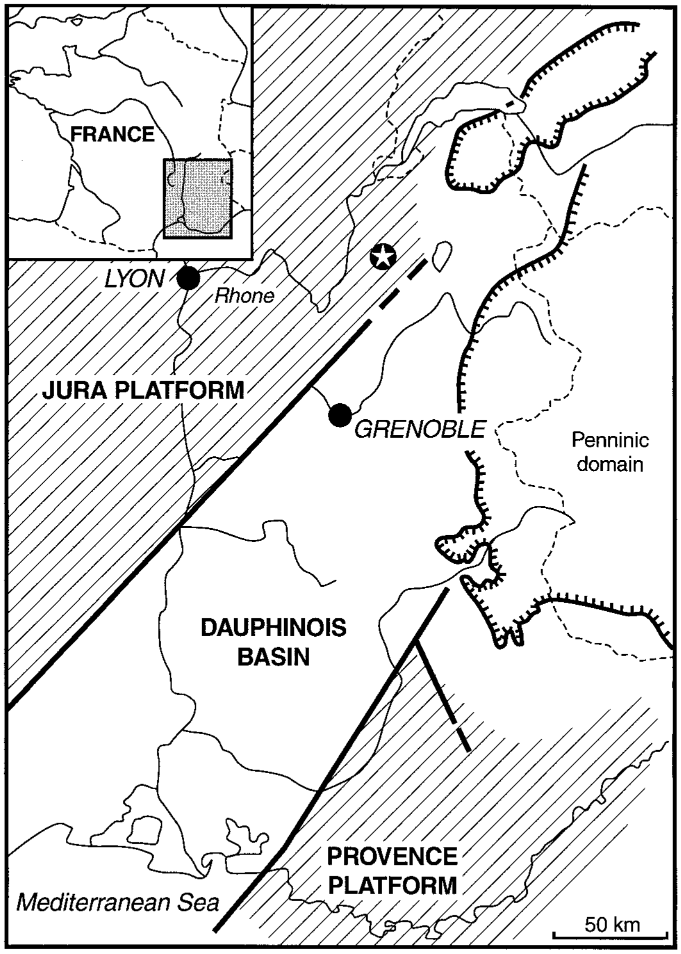

FIG. 5.—Paleogeography of the mid-Cretaceous European passive margin of Ligurian Tethys. The paleogeographic position of the present-day Borne region, SE France, is highlighted by a star-in-circle symbol. (After Arnaud-Vanneau and Arnaud 1991.)

the northern shore of the Ligurian Tethys ocean. This ancient carbonate platform is exposed in the Jura and Subalpine mountain chains of southeastern France and western Switzerland. They were formed by the Alpine orogeny, which closed Ligurian Tethys during the collision between the European and African continental plates in the Late Cretaceous to early Tertiary (Lemoine et al. 1986; Lemoine and Trumpy 1987; Coward and Dietrich 1989). During the mid-Cretaceous, tectonically more stable platforms and more subsident basins developed on the passive margin. To the northwest of the passive margin there existed a relatively more tectonically stable area, the Jura platform, whereas to the southeast a tectonically unstable, more strongly subsident area developed, the Dauphinois basin (Fig. 5).

The significance of the interaction between the irregular passive-margin topography and relative sea-level fluctuations on the stratigraphic evolution of the Urgonian carbonate platform is a source of major controversy. Two quite different stratigraphic models for the evolution of the Urgonian carbonate platform have developed simultaneously. These two models were based on conflicting interpretations of paleontologically derived ages using ammonites and benthic foraminifera for the Urgonian carbonate succession. A source of major disagreement is whether or not a significant paleostratigraphic age gap occurs at the base of the Urgonian carbonate platform in the Jura as proposed by Arnaud-Vanneau and Arnaud (1990).

The more traditional of the two stratigraphic models interprets the mid-Cretaceous Urgonian carbonate succession as representing a period of continuous marine sedimentation across the entire passive margin (Clavel et al. 1987; Clavel and Charollais 1989; Clavel et al. 1992; Clavel et al. 1994a; Clavel et al. 1994b; Clavel et al. 1995; Busnardo et al. 1991; Busnardo et al. 1994; Schroeder 1994). According to this interpretation the Urgonian carbonate platform was emplaced by gradual southeastwards progradation from the Jura platform towards the Dauphinois basin. The basal boundary of the Urgonian platform in this model is interpreted as being conformable with the underlying strata.

An alternative, sequence stratigraphic model for the evolution of the Urgonian platform suggests that relative sea-level fluctuations combined with the irregular topography on the passive margin to cause episodic breaks in marine sedimentation (Arnaud-Vanneau and Arnaud 1990, 1991). Thus, during lowstands of relative sea level the more stable Jura platform became subaerially exposed to produce depositional hiatuses penecontemporaneous with continued marine sedimentation at the still submergent margin within the Dauphinois basin. The Urgonian carbonate platform has thereby been divided into several depositional sequences and their component systems tracts. According to this model the Urgonian carbonate platform was installed by aggradation, and the basal (sequence) boundary of the Urgonian carbonate platform in the Jura corresponds to a major subaerial exposure surface.

The uppermost boundary of the Urgonian carbonate platform is marked by an undisputed karstic surface. This karst developed following a major relative sea-level fall that terminated carbonate deposition and was followed by a return to detrital sedimentation during a subsequent major marine transgression (Arnaud-Vanneau et al. 1987; Charollais et al. 1994; Delamette 1994).

These two conflicting stratigraphic interpretations based on disagreements about the stratigraphic occurrence and diagnostic ages of benthic foraminifera used for dating the succession require different ages for the deposition of the Urgonian limestone, from the Late Hauterivian to the Middle Bedoulian (Clavel et al. 1995), or, alternatively, from the Barremian until the Aptian (Arnaud-Vanneau and Arnaud 1990).

Since these two different stratigraphic models were originally proposed, numerous sedimentologists have applied sequence stratigraphic criteria and standard microfacies models to elucidate the evolutionary history of the Urgonian carbonate platform in this region. However, no clear consensus has emerged in favor of either of the original stratigraphic models, with different interpretations continuing to provide some support for each of the models (e.g., Arnaud-Vanneau and Arnaud 1992; Everts et al. 1992; Everts et al. 1995; Jacquin et al. 1991; Spence and Tucker 1999).

The Inner Urgonian Carbonate Platform of the Borne Region of SE France

The mid-Cretaceous Urgonian carbonate platform exposed in the Borne region of southeast France corresponds paleogeographically to the inner carbonate platform deposited on the tectonically more stable Jura platform (Fig. 5). The inner platform succession in the Borne area is approximately 200 meters thick.

The lowermost part of the inner Urgonian platform succession immediately above the basal stratigraphic boundary, and the top of the inner Urgonian succession immediately below the upper stratigraphic boundary of the platform, were both logged and sampled. Because of the very fine-grained nature of the limestone succession it was difficult to recognize significant changes in limestone composition in the field. Samples were collected at regular intervals between the base and the top of successive parasequences within the sections. Petrographic compositional data were determined from detailed microscopic examination of 5 cm by 5.5 cm thin sections prepared from these samples. Compositional data characterizing stratigraphic changes in sediment composition during earliest and latest Urgonian platform deposition were analyzed using both traditional standard

FIG. 6.—View of the inner-platform succession of the mid-Cretaceous Urgonian Platform at Montagne-sous-Dine, Borne region, SE France. The base of the Urgonian Platform is marked by an abrupt contact (arrowed) with the underlying deeper-marine ''Hauterivian'' calcareous basinal sediments. However, the nature of this stratigraphic boundary is the subject of a major controversy (see text for discussion).

microfacies techniques and optimized matrices of Jaccard's similarity coefficients between component parameters.

In the cliff-face exposure at Montagne-sous-Dine the disputed basal boundary between the characteristically gray-weathered shallow-marine limestones of the Urgonian carbonate platform and the underlying, brown-weathered deeper-marine micritic limestone is marked by an apparently sharp, planar, concordantly bedded transition (Fig. 6). The basal 45 m of the Urgonian succession above this stratigraphic boundary, accessible in Col du Landron, were logged and sampled.

The top stratigraphic boundary of the inner Urgonian platform is marked by a paleokarstic surface formed during a considerable period of subaerial exposure and is unconformably overlain by greensand. Access to the upper Urgonian carbonate platform succession at Montagne-sous-Dine is difficult, so the uppermost 50 m of the Urgonian carbonate succession exposed nearby at Les Combes were logged instead and sampled to within a few meters of the upper boundary of the Urgonian carbonate platform.

RESULTS

Microfacies of the Basal Platform Succession

Compositional presence/absence data between syndepositional biogenic and abiogenic limestone components plus accessory detrital quartz and glauconite identified in the stratigraphic data set of 32 samples collected from the basal platform succession were used to calculate an optimized matrix of Jaccard's coefficients between parameters (Fig. 7). In total, 18 different types of component parameters were included in the optimized similarity matrix. Modal abundance data of selected parameters in the data suite were also plotted as graphical triangular diagrams in an attempt to identify sample populations as envisaged by standard microfacies models (Fig. 8).

Interpretation of Optimized Matrix of Jaccard's Similarity Coefficients Between Parameters

Figure 7 shows the graphic representation of the optimized similarity matrix of Jaccard's coefficients calculated between component parameters. The arrangement of values of Jaccard's similarity coefficient in the optimized matrix indicates the presence of a relay. The order in which the components occur in the relay as traced from bottom right to top left is interpreted below in terms of changes in depositional environment linked directly to changes in relative sea level.

The first components encountered in the relay as traced in sequence from the bottom right are sponge spicules, glauconite, ooids, and quartz. Ostracods may occupy a wide range of habitats but tend to be especially abundant in shallow hypersaline or brackish environments and are interpreted as indicating a low-energy restricted or peritidal environment. Sponge spicules may occur in both shallow-marine inner platform and deep basinal and foreslope environments. Small sponge spicules have been found to be one of the more common bioclasts in the otherwise micrite-dominated deep-water basinal limestones (Spence and Tucker, unpublished work). Sponge spicules may also have been reworked from the underlying strata. Early diagenetic glauconite forms exclusively in marine environments, and thin (5–10 cm) horizons rich in glauconite formed in the basinal limestones during depositional hiatuses. The rounded morphology of the glauconite grains and their low concentration may therefore indicate that they are again derived by reworking of the underlying strata. Ooids indicate an increase in hydrodynamic energy probably linked to increasing tidal influence and/or shallow-marine currents as increased water depth reestablished open-marine conditions during marine transgression. In this context the positioning of quartz in the relay can be interpreted as indicating reworking of detrital sediment originally deposited in the subaerially exposed inner part of the platform as the platform became progressively reflooded. The bottom-left part of the relay is therefore interpreted as reflecting reworking of the underlying strata during the initial stages of marine transgression that led to the formation of a low-energy, very shallow restricted hypersaline environment, possibly in lagoons formed in minor topographic depressions, that progressively developed into an open shallow-marine high-energy, current-agitated environment as relative sea-level rise reflooded the platform.

The relay is continued sequentially by micrite, peloids, echinoderms, benthic miliolid foraminifera, bryozoans, and gastropods, which are interpreted as reflecting the transition to open-marine euphotic medium-to-high-energy, current-agitated, relatively shallow conditions on the platform as water depth continued to increase during relative sea-level rise.

The top-left part of the relay is completed by corals, green algae, rudist bivalves, Orbitolinidae foraminifera, and *Lithocodium–Bacinella*, which are interpreted as reflecting a shallow, open-marine high-energy external platform environment within the photic zone. *Lithocodium–Bacinella* may occur in shallow back-reef environments. The presence of corals suggests an oligotrophic environment from which corals were gradually displaced by the appearance of colony-building rudist bivalves.

The effects of progressive environmental changes in salinity, hydrodynamic energy, and nutrient supply on sedimentary processes, which govern the arrangement of the component parameters in the relay, can be linked to gradually increasing water depth during a relative sea-level rise. Overall, the relay can be interpreted within a sequence stratigraphic context as representing deposition during progressive reflooding of a previously subaerially exposed part of the Jura platform, i.e., a transgressive systems tract. This interpretation is consistent with the basal boundary of the inner Urgonian carbonate platform being marked by an unconformity as proposed in the stratigraphic model of Arnaud-Vanneau and Arnaud (1990, 1991).

Interpretation of Graphical Triangular Plots

Figure 8 shows graphical triangular plots of samples collected from the basal stratigraphic succession of the Urgonian platform using modal abundances of selected component parameters. Comparisons with modal estimate charts were used to determine modal abundances of the various component parameters. Three different combinations of component parameters commonly used to identify populations in limestones are plotted (Fig. 8). When using graphical triangular diagrams the degree of differentiation between different types of component parameter is reduced. Thus rudist bivalves, other bivalves, and gastropods are combined as ''mollusca'' to form a single parameter and orbitolinid and miliolid foraminifera are grouped together as ''benthic'' foraminifera (Fig. 8).

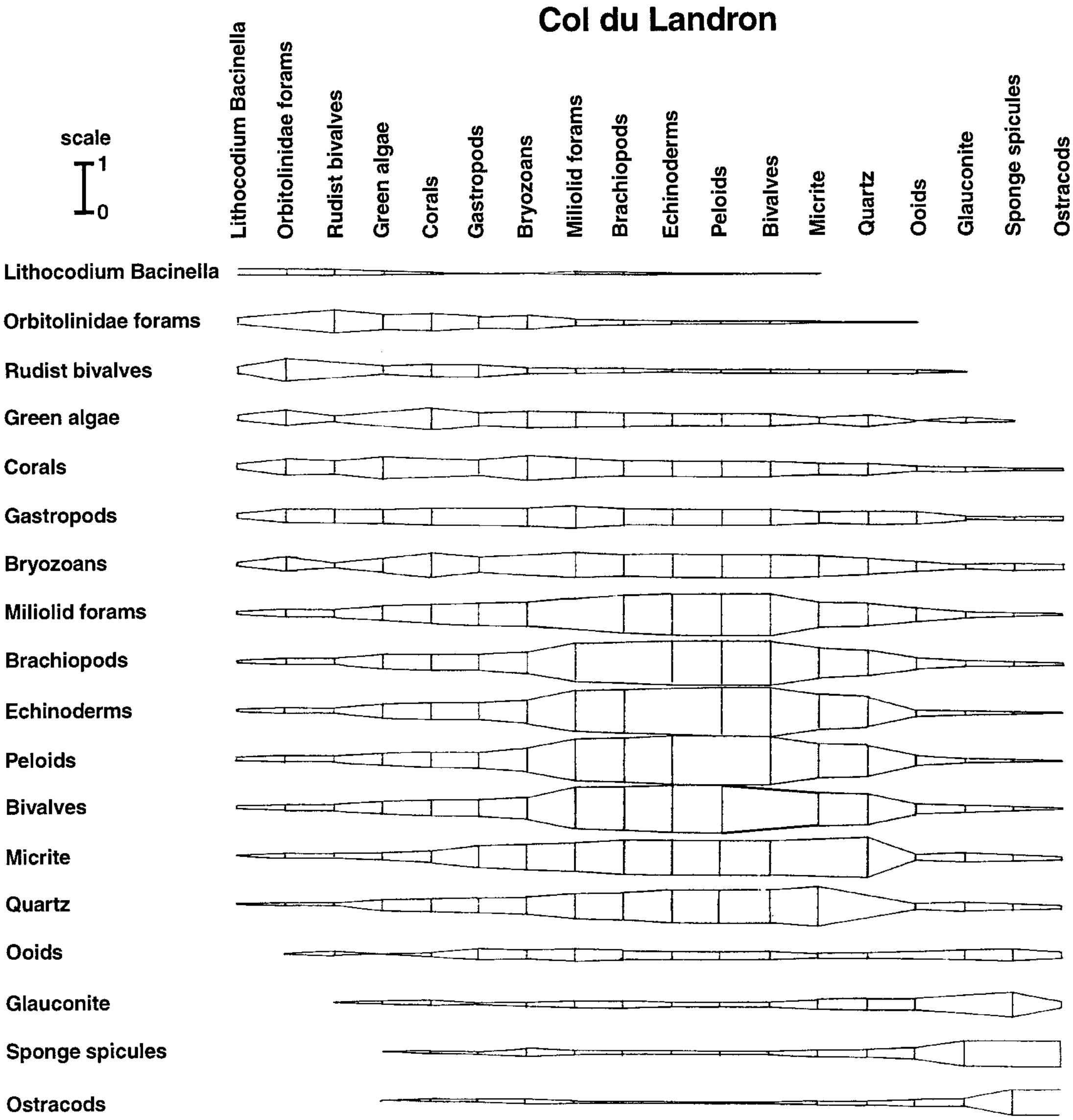

FIG. 7.—Optimized matrix of Jaccard's similarity coefficients between grains for the basal Urgonian succession at Col du Landron begun immediately above the underlying basinal sediments. Individual values of Jaccard's similarity coefficient are represented as vertical scale bars whose length is in direct proportion to their magnitude between 0 and 1 (see scale). Individual scale bars are linked horizontally for each individual parameter, defining similarity envelopes relative to the other parameters in the data set. Grains are positioned next to those with which they have greatest similarity. The symmetrical configuration of Jaccard's coefficient around the central diagonal (top left to bottom right) identifies a compositional *relay.* This relay is interpreted as reflecting the environmental gradient during a RSL rise characterizing a TST (see text for discussion).

Figure 8iA shows a broad continuous scatter of sample plots ranging between micrite and allochems as the most abundant sample components, with sparite remaining a relatively minor constituent.

Figure 8iiA shows a more dispersed scatter of sample plots, with all three parameters influencing the distribution of sample plots. The sample scatter patterns produced in Figure 8iiA can be subdivided into three populations on the basis of the distribution of samples sharing similar sedimentary fabric into distinct groups. These assemblages can be classified as: (a) peloidal/molluscan grainstone microfacies; (b) peloidal/molluscan packstone microfacies; and (c) wackestone microfacies.

Figure 8iiiA produces a scatter pattern of samples with a broad range in abundance of echinoderms or mollusca but with the abundances of benthic foraminifera remaining at low, comparatively uniform values. During the Cretaceous, echinoderms were most common in shallow-marine environments agitated by marine currents that provided steady feeding for the crinoid animals (Arnaud-Vanneau et al. 1987). The high abundance of echinoderms and low content of benthic foraminifera indicates a shallow-marine depositional setting. It is not possible to differentiate individual populations in this plot.

To investigate whether the spread of samples in these triangular plots reflects a stratigraphic systematic gradational shift in modal composition linked to an underlying dynamic environmental control, as suggested by the interpretation of the optimized matrix above, the samples were numbered in ascending stratigraphic order from a1 to a32 (Fig. 8B). To aid rapid visual identification of the presence or absence of a systematic stratigraphic trend, or trends, in modal abundances, individual sample plots were linked together in stratigraphic order to form a continuous ribbon (Fig. 8C). If a unidirectional stratigraphic trend in modal composition is present, individual samples might be expected to be linked by the ribbon to their nearest neighbor, and in this way the ribbon traverses, in small steps, from

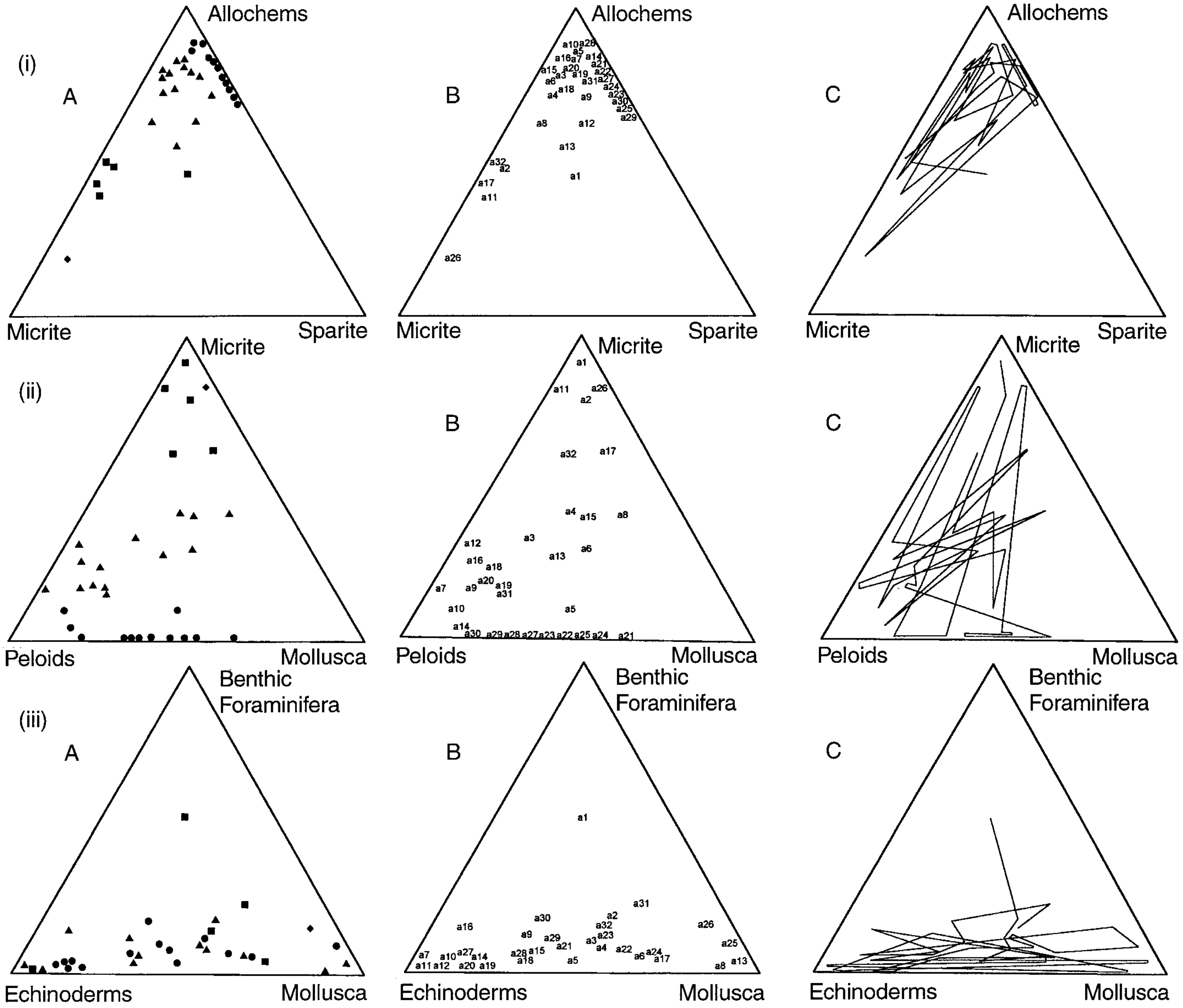

FIG. 8.—Triangular plots of compositional modal abundances of samples from the basal Urgonian at Col du Landron. Plots (i), (ii), and (iii) use grains commonly used to interpret Cretaceous carbonates. **A)** Samples plotted highlighting sedimentary texture (Key to symbols: ◆, mudstone; ■, wackestone ▲, packstone; ●, grainstone.). **B)** Samples numbered in ascending stratigraphic order from a1 (base) to a32 (top). **C)** Sample plots linked in ascending stratigraphic order by a continuous ribbon to trace stratigraphic variations in grain abundance (see text for discussion).

one extreme of the sample scatter to the other. If more than one unidirectional stratigraphic trend is present, the ribbon develops in a constant mean ''direction'' in small steps and then abruptly changes direction before continuing to develop in small steps in the new direction. In this scenario each ''leg'' of the ribbon identifies a different stratigraphic trend. If a distinct pattern is repeatedly traced out by the ribbon, this indicates repetition of the same stratigraphic trend, e.g., an individual shallowing-upward parasequence. If there is no systematic stratigraphic trend in modal compositional changes between limestone components, then the ribbon may link widely disparate samples, producing a random overwriting zigzag.

The irregular zigzag patterns of the stratigraphic ribbons in Figures 8iC and 8iiC indicate that there is no systematic stratigraphic trend in changes of modal abundance between these parameters. However, the repetitive switch between echinoderms or mollusca being the dominant modal constituents of samples identified by the ribbon's pattern in Figure 8iiiC may reflect cyclical environmental changes during deposition of individual shallowing-upward parasequences.

The interpretation of graphical triangular plots fails to identify the systematic and gradational nature of stratigraphic change in carbonate sedimentation in response to marine transgression indicated by the interpretation of the optimized matrix of Jaccard's similarity coefficients between parameters. Instead the data set can be differentiated into three generic populations suggesting the existence of three different discrete depositional environments.

Microfacies of the Uppermost Platform Succession

Figure 9 shows the graphic representation of the optimized similarity matrix between component parameters identified in the data set of 24 samples collected from the uppermost part of the Urgonian stratigraphic suc-

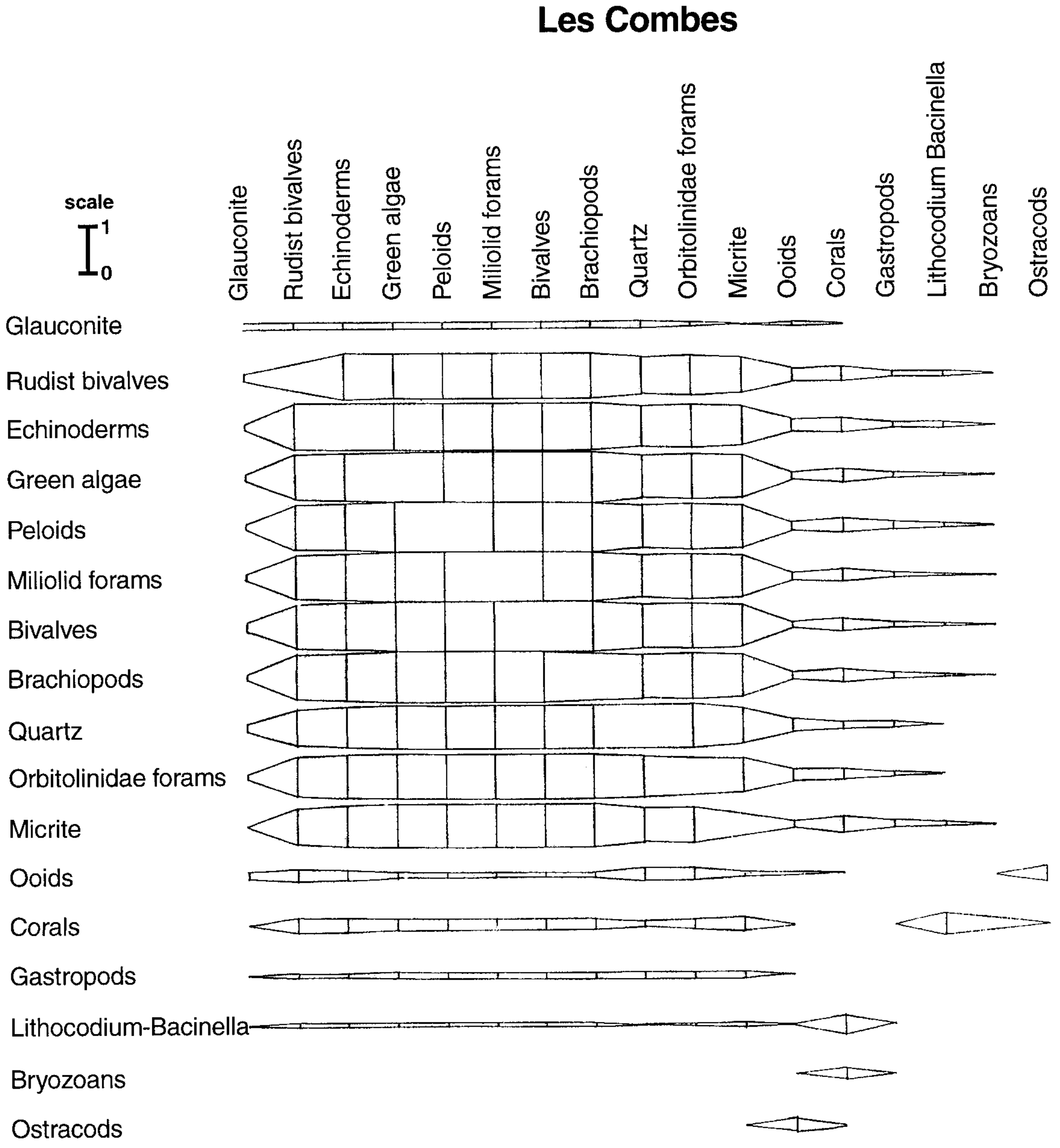

FIG. 9.—Optimized matrix of Jaccard's similarity coefficients between grains for the top Urgonian carbonates at Les Combes. The clustering of components with uniformly high values of Jaccard's similarity coefficient in the top left corner, indicating that these components share strong environmental affinities with one another, is interpreted as reflecting a single fixed compositional assemblage. See caption of Figure 7 and text for detailed discussion.

cession. In total, 17 different types of component parameter were included in the optimized similarity matrix (the same components as used for the basal succession minus sponge spicules). Graphical triangular plots using modal abundance data of selected grains are shown in Figure 10.

Interpretation of Optimized Matrix of Jaccard's Similarity Coefficients between Parameters

Figure 9 shows the graphic representation of the optimized matrix of Jaccard's similarity coefficients calculated between component parameters. The optimized matrix of Jaccard's similarity coefficients between parameters identifies a distinct cluster of components towards the top left of the matrix, with uniformly very high values of similarity coefficients indicating that these components have strong environmental affinities with one another. All the remaining parameters in the optimized similarity matrix display very low (or no) similarity to any other. The cluster is interpreted as indicating the presence of a single population or microfacies assemblage, rather than the existence of a relay. This population, characterized by micrite, orbitolinid foraminifera, quartz, brachiopods, bivalves, miliolid foraminifera, peloids, green algae, echinoderms, and rudist bivalves, is interpreted as representing deposition in a constantly shallow-marine moderate-energy inner-platform setting that experienced comparatively little temporal variation in environmental factors. Ooids, corals, gastropods, *Lithocodium–Bacinella,* bryozoans, and ostracods are present only as anomalous grain types and have no link to the other parameters. These parameters may have been reworked from the platform interior and margin by occasional storms.

The depositional environment therefore appears to have been comparatively stable and unchanging during the deposition of the latest Urgonian limestones. Depositional environment is most stable when water depth re-

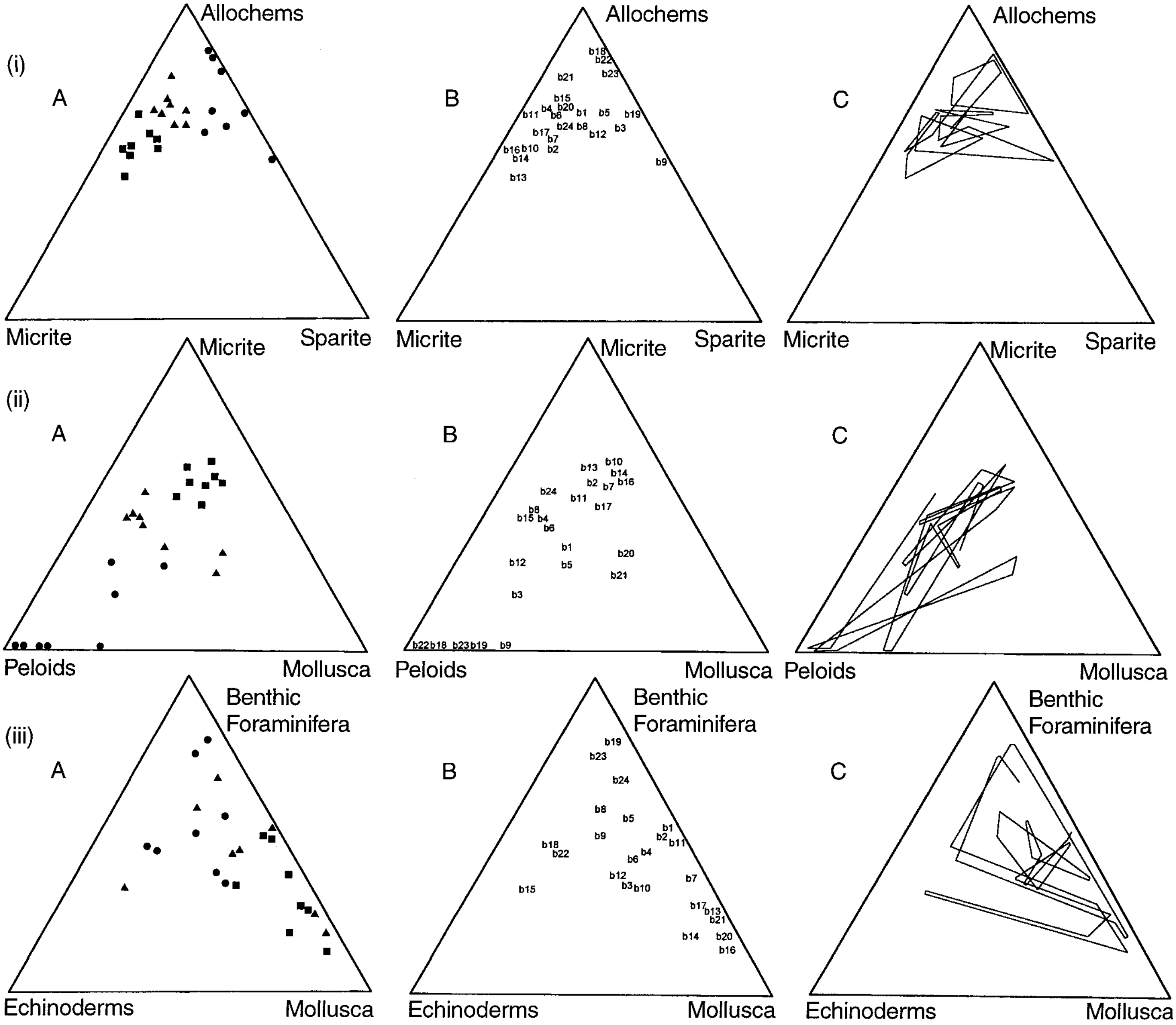

FIG. 10.—Triangular plots of compositional modal abundances of samples from the upper Urgonian carbonates at Les Combes. See caption to Figure 8 and text for interpretation and discussion.

mains static. Environmental quiescence causing uniform sedimentation represented by a single stratigraphic microfacies population can be interpreted within a sequence stratigraphic context as defining the late stage of a highstand systems tract. As the rate of relative sea-level rise begins to decelerate in the late highstand, sediment accumulation on the platform top is able to keep pace with the relative sea-level rise, resulting in a stillstand in sea level characterized by more-or-less constant water depth (Sarg 1988). The single stratigraphic shallow-marine microfacies association identified by the optimized similarity matrix is therefore interpreted as being indicative of deposition during the late highstand of a third-order relative sea-level cycle. This interpretation is consistent with the upper boundary of the inner Urgonian platform being marked by a karst surface unconformably overlain by detrital transgressive deposits.

Interpretation of Graphical Triangular Plots

Figure 10 shows graphical triangular plots of modal abundance between parameters characterizing 24 samples collected from the uppermost stratigraphic succession of the Urgonian carbonate platform. The same three sets of parameters plotted for the basal succession are used.

The scatter of samples produced using textural parameters in Figure 10iA is less dispersed than that from the basal Urgonian section. Figure 10iA shows grains to be by far the most abundant sample component, with both micrite and sparite occurring in comparatively low abundances with a similar narrow range.

The sample scatter in Figure 10ii can be differentiated into three separate populations on the basis of the grouping of samples sharing the same sedimentary fabrics. These groups can be classified as: (a) peloidal grainstone microfacies; (b) peloidal/molluscan packstone microfacies; and (c) bioclastic wackestone microfacies. These assemblages are not greatly different from those identified using similar parameters from the basal succession (compare with Figures 8i and 8ii), although the depositional environment towards the top of the succession within a sequence stratigraphic context should be significantly different from that of the lower platform.

However, in Figure 10iiiA there is a broad range in sample distribution between benthic foraminifera and mollusca, with the abundance of echinoderms tending to be of a lower order with a smaller range. This contrasts markedly with the lower Urgonian platform succession, where echinoderms and molluscans are modally dominant and benthic foraminifera are almost absent (Fig. 8iii). Comparing Figures 8iii and 10iii plotted between biogenic components provides a better indication of the contrasts in depositional environment between the basal and upper platform succession. The comparatively low abundance of echinoderms and high abundance of benthic foraminifera in the upper platform succession is interpreted as indicating a shallower-marine environment in comparison to the moderate water depth during deposition of the basal platform. It is not possible to differentiate assemblages in Fig. 10iiiA.

Interpretation of the stratigraphic distribution of the sample scatters in all these plots, using the method described above, indicates that no stratigraphic trend exists in the modal abundances between these parameters (Fig. 10B and 10C).

The selective interpretation of graphical triangular plots appears to identify three separate generic populations characterizing different subenvironments in the upper inner Urgonian platform succession. This interpretation conflicts with that of the optimized matrix between parameters above, which indicates comparatively stable environmental conditions and uniform sedimentation during latest Urgonian time. In this case triangular plots appear to overexaggerate the genetic significance of generic contrasts between samples, obscuring the quiescent nature of late Urgonian deposition.

DISCUSSION

Compositional Relays versus Standard Microfacies Assemblages

Compositional relays identified using ordination statistical techniques have previously been used to interpret limestone microfacies (e.g., Hennebert and Lees 1985, 1991). However, sample data sets from thick stratigraphic limestone successions likely to contain several sequences have tended to be used to calculate a single similarity matrix. Any relay identified is thus a polyglot of all the undifferentiated environmental signatures caused by opposing senses of relative sea level change, limiting the relay's interpretive usefulness. In order to use ordination methods to analyze limestone successions, data from each different phase of changing water depth must be used to calculate a separate matrix. When preserved, ''candidate'' key stratal surfaces can be used to help subdivide the succession, as in this study.

The relay identified in this study suggests that carbonate successions can be characterized by a series of individual relays arranged stratigraphically head-to-tail at the scale of systems tracts (Fig. 11). Boundaries between individual stratigraphic compositional relays correspond to abrupt environmental shifts caused by inflections in changing water depth and coincide with subaerial exposure surfaces or marine flooding surfaces.

Fixed compositional microfacies assemblages form only in relatively stable depositional environments and may stratigraphically characterize a late highstand systems tract or stillstand. During a third-order stillstand, paleogeographic changes in microfacies are controlled by the effect of sea-floor topography on lateral changes in water depth. If the sea-floor profile is regular, causing water depth to increase gradually basinwards, transitional geographic changes in microfacies can be characterized by a single compositional relay developed along dip. If, however, sea-floor topography is irregular then abrupt geographic changes in water depth dictate the lateral distribution of individual microfacies populations.

The standard microfacies paradigm can therefore be considered valid only during a short period of deposition in the course of any third-order relative sea-level cycle and spatially subject only to the additional control of antecedent sea-floor topography on changes in water depth. An idealized model of the likely temporal distribution of environmentally sensitive grain types characterizing different phases of changing water depth at the scale of individual systems tracts during a third-order cycle is shown in Figure 11.

However, as demonstrated in this study, it is almost inevitable that assemblages will be identified when using triangular plots, or conceptually similar statistical methods, by either broadening (e.g., Figs 8iA and 8iiA) or tightening (e.g., Figs 10iA and 10iiA) the generic criteria that are used to define each population. This is reflected in the deliberately vague descriptions used for many microfacies assemblages, e.g., ''*Some* samples *may* contain'' (Grötsch 1996), and sweeping classifications of component grains, e.g., ''*bioclastic debris*'' (Grötsch 1996) and ''*all other fossils*'' (Steinhauff and Walker 1995). Phantom stratigraphic boundaries imposed between facies assemblages may confuse, rather than aid, sequence stratigraphic interpretations, as shown for the base of the Urgonian platform (compare Figures 7 and 8).

Using optimized similarity matrices to analyze presence/absence compositional data of a large number of different types of sample component appears to be more sensitive in identifying gradational trends than the analysis of variations in modal abundance of a small number of parameters (e.g., compare Figures 7 and 8). Changes in composition, rather than in compositional abundances, are more significant in characterizing microfacies in the context of high-frequency relative sea-level changes.

Using Relays for the Microfacies Analysis of Limestones

The stratigraphic division of limestone successions into a series of individual compositional relays each recording progressive environmental changes linked to similar phases of dynamic changes in water depth (i.e., systems tracts) during third-order relative sea-level cycles can assist sequence stratigraphic interpretations when key stratal surfaces are poorly constrained. Boundaries between individual standard microfacies assemblages defined using simple generic criteria may have no intrinsic genetic significance. In contrast, boundaries identified between individual relays correspond to flooding and subaerial-exposure surfaces formed during third-order relative sea-level cycles, and they can be used to identify directly sequence boundaries and boundaries between systems tracts.

The strong emphasis placed on identifying key stratal surfaces for sequence stratigraphic interpretations reflects sequence stratigraphy's origins in seismic stratigraphy (e.g., Vail et al. 1977). Angular unconformities at ancient carbonate platform margins form good seismic reflectors that are easily traced laterally into the inner platform at the resolutions commonly attained on seismic sections. However, in limestone outcrops physical evidence for such stratal surfaces is often poorly developed or absent, making these surfaces difficult to identify and trace out laterally. This is especially so in the inner platform, where stratal architecture is planar and concordantly bedded, making it difficult to differentiate bedding surfaces from environmentally significant depositional unconformities that define the boundaries of individual sequences and systems tracts (e.g., Fig. 6). For inner platform settings interpretation of stratal stacking patterns is often the only way to identify sequences and systems tracts (e.g., Goldhammer et al. 1990; Goldhammer et al. 1993), but this approach remains controversial (e.g., Drummond and Wilkinson 1993a, 1993b). Physical evidence recording subaerial platform exposure, such as karstification, is especially scant for limestones originally deposited in arid climates (e.g., Handford and Loucks 1993). Environmental factors operating out of phase with relative sea level may in some cases also form depositional hiatuses that resemble those produced by relative sea-level changes (e.g., Glynn 1991; Mullins et al. 1987; Pinet and Popenoe 1985; Schlager 1991; Voght 1989). By using optimized similarity matrices to characterize stratigraphic changes in microfacies above and/or below disputed stratal surfaces observed in outcrop, it is possible to determine the genetic significance of such surfaces within a sequence stratigraphic context.

In this study of the Urgonian carbonate platform, a broad range of different types of component parameter was deliberately chosen for analysis

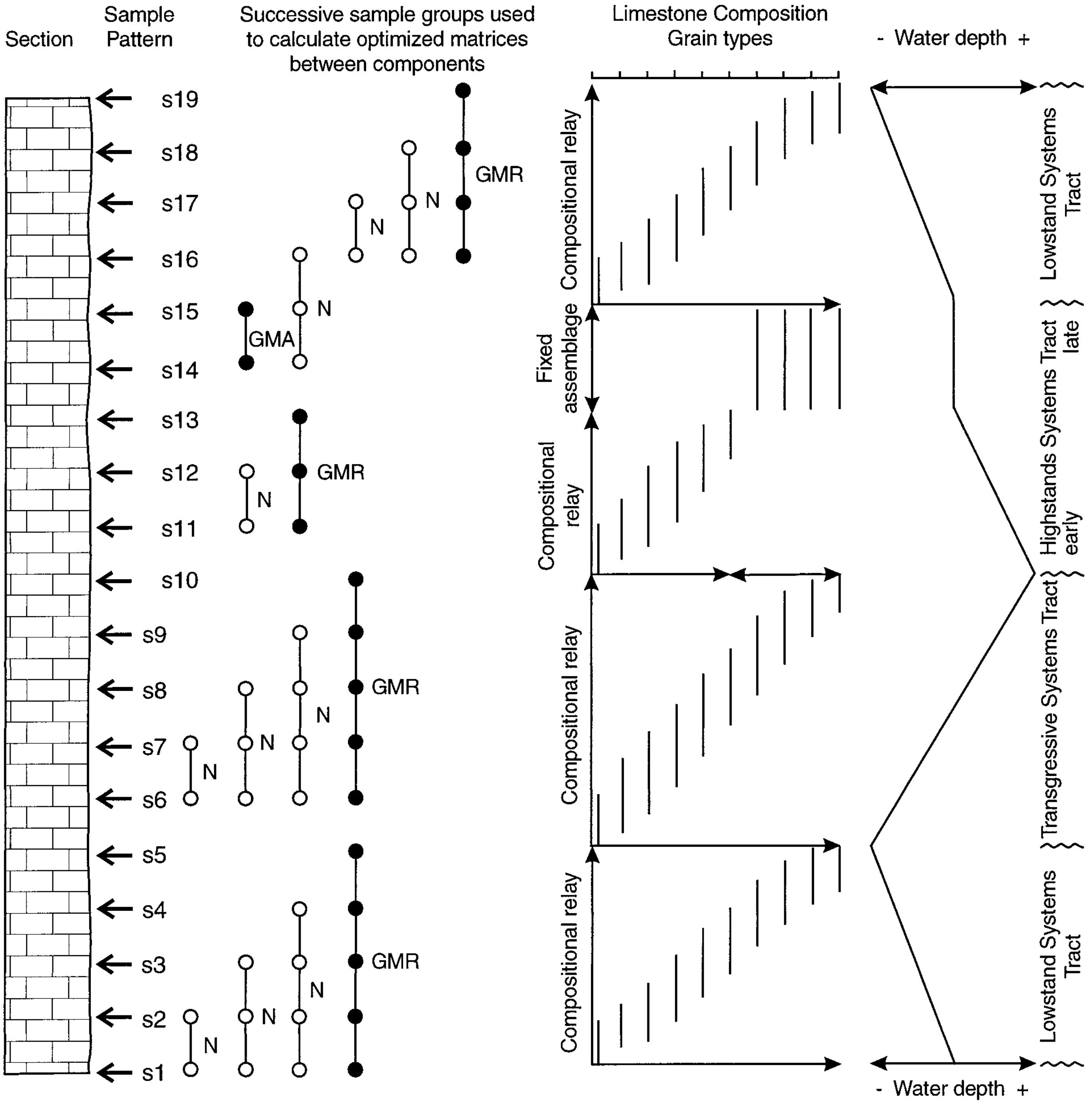

FIG. 11.—Schematic illustration of the likely stratigraphic distribution of environmentally sensitive limestone components characterizing changes in microfacies during different phases of a complete 3rd-order RSL cycle and the base of the following cycle. The microfacies of the LST, TST, and early HST can be characterized by separate stratigraphic compositional relays caused by environmental gradients resulting from continuous changes in water depth. The late HST can be characterized by a compositional assemblage reflecting comparatively stable environmental conditions as water depth remained constant. Boundaries between individual compositional relays and assemblages record abrupt environmental shifts caused by inflections at peaks and troughs in changing water depth and coincide with marine flooding and subaerial exposure surfaces (right of figure).

In order to recognize such microfacies changes using ordination statistical techniques, the succession must be subdivided into different phases of changing water depth within the 3rd-order RSL cycle. Compositional data from each phase must be used to calculate a separate optimized matrix. An incremental approach of calculating matrices to detect each stratigraphic compositional relay and assemblage (systems tracts) is illustrated on the right.

Starting at the base of the succession, optimized similarity matrices are repeatedly calculated between sample *components* progressively increasing the number of stratigraphic *samples* in the data set (open circles) until a good match between an optimized similarity matrix calculated from the succession is achieved with one held in a database of environmentally diagnostic relay and assemblage templates. The part of the stratigraphic column containing samples used to calculate the good-match optimized similarity matrix (closed circles) is classified according to the interpretation held by the diagnostic template in the database. The procedure is then repeated starting with the next two samples in the succession. N = no good match between calculated optimized similarity matrix and environmental template database; GMR = good match between compositional relay in the succession and environmental template database; GMA = good match between compositional assemblage in the succession and environmental template database. This same approach could equally well be used to identify all compositional relays and assemblages in a succession without making comparisons to an environmental template database.

using optimized similarity matrices to demonstrate the collective control exerted by dynamic changes in water depth on ecology, sedimentary processes including reworking, and early marine diagenesis. However, by choosing a more selective range of limestone components, it is possible to identify stratigraphic compositional relays that are diagnostic of different types of depositional systems tracts of comparable geologic age, deposited in similar latitudes (climates) and sea-floor topographies, which can be used as standard environmental ''templates'' or genetic environmental ''fingerprints'' to classify other successions. This technique has applications when key surfaces are poorly developed. Stratigraphic relays between different types of benthic foraminifera have been detected using optimized similarity matrices to back-model well-constrained Cretaceous transgressive and highstand systems tracts (Spence et al. 1996). Limestone successions can be differentiated into their component systems tracts and sequences by progressively calculating matrices between components as traced up stratigraphy until a diagnostic relay or assemblages is identified, and then repeating the process (Fig. 11). In the future this procedure could be carried out automatically by computer software, and is a subject of continuing research.

CONCLUSIONS

There is a conceptual discrepancy between standard microfacies models used to interpret changes in sediment composition and sequence stratigraphic models used to interpret stratal architecture of ancient carbonate platforms. Sequence stratigraphic models interpret stratal architecture and key stratal surfaces representing depositional hiatuses within the context of changing accommodation space during high-frequency relative sea-level changes. However, standard microfacies models are poor at characterizing gradational changes in sediment composition caused by variations in water depth during the different phases of high-frequency relative sea-level cycles.

Stratigraphic changes in limestone composition during different episodes of dynamic change in water depth (i.e., systems tracts) within a third-order relative sea-level cycle have been shown to be characterized by compositional relays linked to gradational environmental changes, rather than by abrupt shifts between a series of fixed compositional assemblages. The only period when microfacies may be stratigraphically characterized by fixed compositional assemblages is during the late highstand of a third-order relative sea-level cycle, when water depth may have remained constant. During a third-order stillstand in relative sea level, the influence of sea-floor topography on paleogeographic changes in water depth is the main control on whether spatial changes in microfacies are characterized by a compositional relay or by a series of individual microfacies assemblages.

Consequently, the standard microfacies paradigm may at best be stratigraphically representative only of a short period of deposition in the course of any third-order relative sea-level cycle, is valid only intermittently for a typical limestone succession composed of several sequences, and may characterize paleogeographic changes in microfacies only during a late highstand subject to the additional control of antecedent sea-floor topography on lateral changes in water depth.

Calculating similarity matrices between grains can identify compositional relays or assemblages resulting from relative sea-level changes and allows carbonate sequence stratigraphic models and microfacies models to be properly integrated. The benefits of this approach have been demonstrated in helping determine the unconformable nature of the previously disputed basal sequence boundary of the mid-Cretaceous Urgonian platform.

ACKNOWLEDGMENTS

The authors thank Alan Lees for providing computer software used to calculate optimized matrices of Jaccard's coefficients. The manuscript was reviewed for JSR by Rick Sarg, Toni Simo, and Wolfgang Schlager. This paper is dedicated to Joan V. Spence, Malcolm A. Spence, Gary M. Spence, and Tracey A. Clayton.

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Received 31 March 1997; accepted 31 October 1998.