# Reservoir-Scale Heterogeneity in Depositional Packages and Diagenetic Patterns on a Reef-Rimmed Platform, Upper Miocene, Mallorca, Spain[1]

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## ABSTRACT

Predictive models for interwell-scale variations in heterogeneous carbonate rock are best made from outcrop studies of well-exposed limestone and dolomite, such as the upper Miocene reef complex that crops out in the sea cliffs of Mallorca, Spain. The sea-cliff sections reveal highly complex lithofacies stacking patterns that could lead to ambiguous lateral correlations of coeval units. The stratigraphic complexity and distribution of primary and secondary porosity are the result of a sea-level-driven hierarchical stacking of different magnitudes of accretional units.

Thickest sections of porous and permeable rocks are in the aggradational portions of the reef, upper slope, and outer lagoon units. The relative volume of the various accretional units and heterogeneity in the lithofacies architecture were dependent on the amount of carbonate production, which was related to (1) accommodation changes controlled by sea-level fluctuations and (2) depositional profile.

Moldic porosity, mostly from the dissolution of aragonitic constituents, is the predominant porosity type, and its heterogeneous distribution is related to the lateral and vertical distribution of lithofacies. The secondary porosity in much of this reef complex was produced mainly during early dolomitization. Dolomite patterns are complicated, apparently mainly related to shallow flooding of the platform during third- or fourth-order sea level highs and to geographic location of permeable pathways for brine reflux, probably primarily through fourth-order aggradational reef units.

Many of these stratigraphic complexities and diagenetic patterns are below the resolution of seismic and well analyses; thus models based on outcrop data such as this can enhance reservoir development in certain shallow-water carbonate rocks.

## INTRODUCTION

Analyses of reservoir rocks composed of shallow-water limestone or dolostone commonly are plagued by considerable uncertainties resulting from the complexities of stratigraphic packaging and distribution of diagenetic facies. Even within the distance of the common spacing of field wells, an average of about 330 m, many shallow-shelf carbonate rocks show substantial lateral and vertical variations in stratigraphic architecture and in the amount and distribution of porosity and permeability. Ascertaining and predicting these heterogeneities within carbonate reservoirs are strategic to field development and optimum production. With current subsurface methods, however, most of the smaller-scale stratigraphic architecture and diagenetic facies are difficult to define. Predictive models for interwell-scale variations in bodies of heterogeneous carbonate rock are best made from outcrop studies (e.g., Kerans et al., 1994, 1995; Barnaby and Ward, 1995). In this paper we describe insights into small-scale heterogeneity gained from detailed outcrop studies of the well-exposed upper Miocene reef complex of Mallorca, Spain (Pomar, 1991; Pomar and Ward, 1994, 1995; Pomar et al., 1996). In these carbonate rocks, stratigraphic complexity and distribution of primary porosity are the result of a sea-level–driven hierarchical stacking of different magnitudes of accretional units. Considerable secondary porosity was produced during early dolomitization by dissolution of aragonitic components. The patterns of this early,

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pre–deep-burial diagenesis are worth considering because they may predict trends of deep-burial porosity and permeability. Even though much of the lithologic complexity of the Llucmajor platform is beyond the resolution of current subsurface methods, the causal relationship between processes and products illustrated in this paper is relevant to predicting and analyzing the heterogeneous distribution of rock properties in reef-complex reservoirs.

## UPPER MIOCENE REEF COMPLEX, LLUCMAJOR PLATFORM

On Mallorca island during the late Miocene, reef complexes built up on shallow-marine shelves adjacent to basins (Figure 1). The most extensive accumulation of these progradational reefal carbonates was on the Llucmajor platform, a 20-km-wide carbonate platform on the southeastern side of the Palma basin (Figure 1). The 16 km of continuous sea-cliff outcrops around the southwestern Llucmajor platform (Figures 1, 2) allow us to trace stratigraphic surfaces and document stratal geometries and to discern details of the lithofacies and diagenetic facies. In addition, subsurface data from 69 water wells (100–150 m deep) allow us to reconstruct the three-dimensional architecture of the whole Llucmajor platform (Figure 3).

Subsidence during deposition is thought to have been minor, and most of this flat-lying platform has been buried no more than several tens of meters (some much less). The platform was only slightly deformed by Pliocene–Pleistocene uplift, faulting, and gentle flexure. Minor burial compaction and scarcity of pervasive cementation has preserved much of the primary porosity. These characteristics make the Llucmajor platform an extraordinary example for analyzing pre–deep-burial stratigraphic and diagenetic heterogeneities on a Neogene progradational carbonate platform. The heterogeneous Llucmajor platform also can serve as a model for analyzing older Phanerozoic progradational platforms (when applied, of course, within the context of the different biota and settings), especially those built up during glacioeustatic sea-level fluctuations.

### Correlation Problems

During the late Tortonian and early Messinian, reefal complexes prograded rapidly across the Llucmajor platform. These carbonate buildups consisted of shelf-margin tracts of coral reefs with fore-reef slopes and back-reef lagoons (Figures 2, 3). Progradation of these reef systems produced a fairly simple vertical sequence of lithofacies, which characterizes the outcrop and well sections on the Llucmajor platform. The open-shelf (shallow-basin) lithofacies is overlain by fore-reef-slope lithofacies, which is overlain by reef core, which, in turn, is overlain by lagoon lithofacies. The lateral relationships of chronostratigraphic units, however, are far from straightforward. Analysis of the sea-cliff sections reveals highly complex lithofacies stacking patterns that could lead to ambiguous lateral correlation of coeval units in a setting with limited data or exposure. As an example, using just two stratigraphic sections as analogous to using data from two cores, Figures 4 and 5 show plausible, but incorrect, correlations between the closely spaced outcrop sections vs. correlations traced in the field. If a simple layercake lithostratigraphic model were constructed instead of the accurate lithostratigraphic model, the fluid flow in the reservoir could be misrepresented. This realization emphasizes the need for analyzing exceptional exposures such as these when building reservoir analog models.

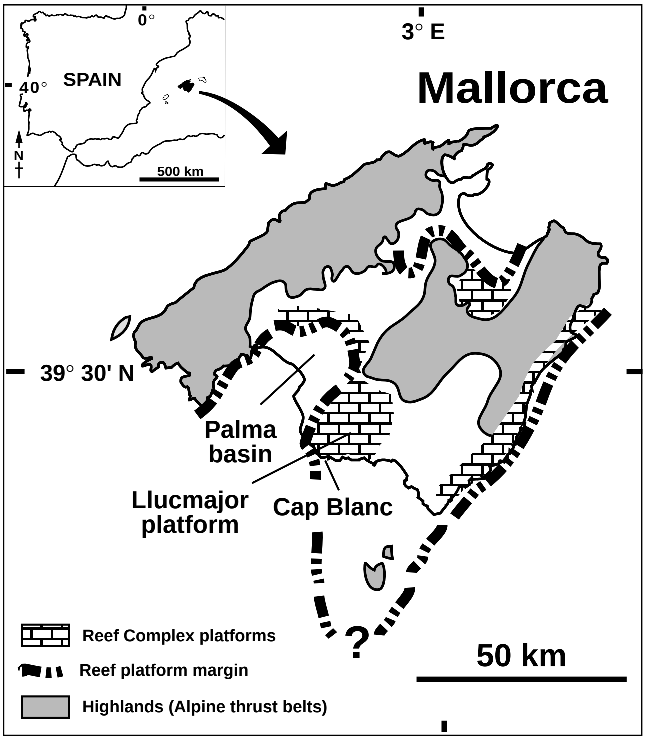

**Figure 1—Map showing location of Llucmajor platform on the central-southern part of Mallorca island in the western Mediterranean Sea.**

### Stratigraphic Heterogeneity

The progradational upper Miocene reef complex on the Llucmajor platform may be considered to have built up during a third-order sea-level

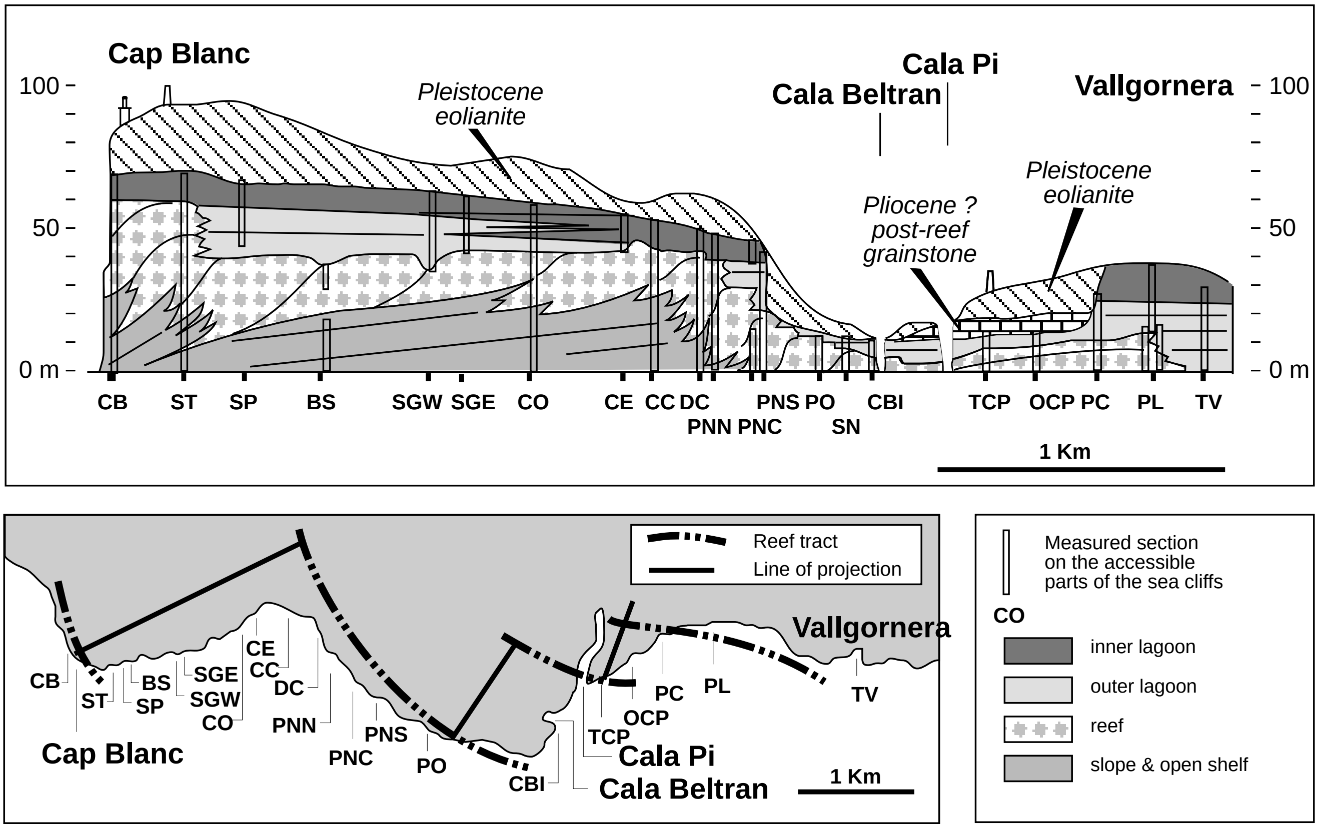

**Figure 2—Projected cross section showing major lithofacies of the upper Miocene reef complex on the southern margin of the Llucmajor platform. Lower left map shows lines of projection aligned parallel to the line of reef-tract progradation. Cross section constructed from continuous near-vertical sea-cliff outcrops and based on (1) measured sections, (2) walking out surfaces where possible, and (3) tracing surfaces on photographs. Letters (e.g., CB) designate localities of measured sections shown in cross section.**

highstand (e.g., Pomar and Ward, 1994). The basic accretional unit or building block of this prograding platform is the "sigmoid" (Pomar, 1991). Sigmoids stack into progressively larger-scale accretional units of sets, cosets, and megasets of sigmoids, which reflect hierarchical orders of sea level cycles. Estimated amplitudes of these cycles are less than 15 m, 20–30 m, 60–70 m, and about 100 m, respectively, and are thought to be glacioeustatic in origin (Pomar, 1991). All these accretional units, which represent high-frequency depositional sequences (seventh to fourth order), have similar characteristics in stratal geometries, bounding surfaces, and facies architecture (Figure 6). All of these units are composed of horizontal lagoonal beds passing basinward into reef-core lithofacies with sigmoidal bedding, then into fore-reef-slope clinobeds, and then into flat-lying open-shelf (or shallow-basin) beds. For the lagoonal and reef-core units, boundaries are erosion surfaces (submarine and subaerial), which pass basinward into correlative conformities.

The Llucmajor platform exemplifies how sea-level change determines not only the relative hierarchy of the accretional units but also their relative positions and the facies belts developed within them. Up to four bundles (or systems tracts), which are related to specific parts of the sea level cycle, can be defined from characteristic changes in the hierarchical stacking patterns among these accretional units (Figure 6). The lowstand systems tract (LST) formed during the initial sea-level rise, after the lowest point of the sea-level cycle. The LST consists mainly of prograding reef core with thin fore-reef-slope and open-shelf lithofacies without significant lagoonal beds. The aggrading systems tract (AST) corresponds to the most rapidly rising part of the sealevel curve, and it is volumetrically the most important. The AST is characterized by well-developed barrier reefs and thick aggradation without backstepping in all depositional systems, from the lagoon to the open shelf (shallow basin). The AST lagoonal lithofacies overlies the LST and consists of landward-onlapping strata.

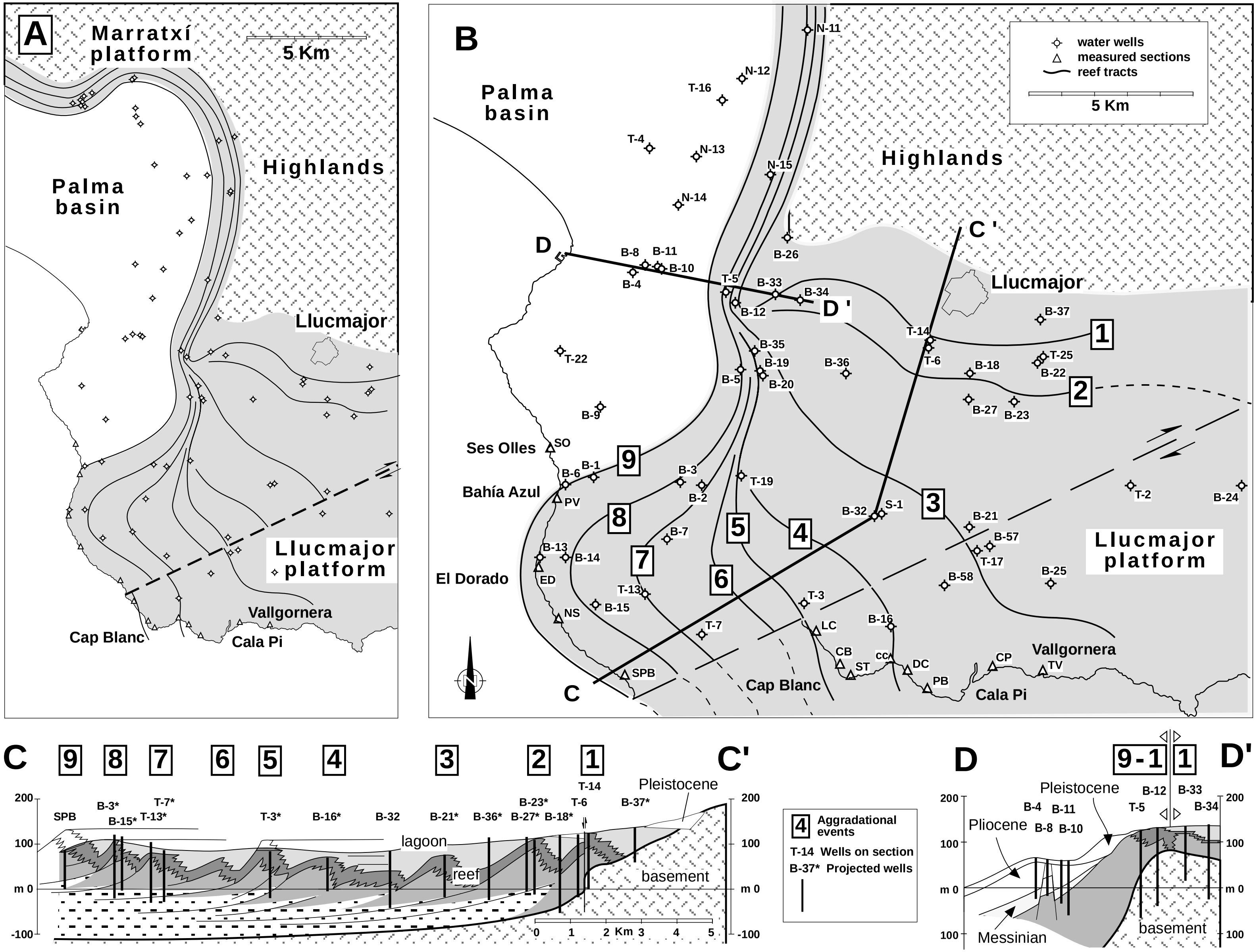

Figure 3—(A) Postulated trends of major upper Miocene reef tracts on the Llucmajor platform and margins of the Palma basin. Reef tracts show offset by postulated right-lateral fault (dashed line). (B) Postulated traces on nine major reef tracts on Llucmajor platform. Map shows water-well control (lithologic logs and some cores) used in reconstruction of reef trends. Lines CC′ and DD′ show location of cross sections.

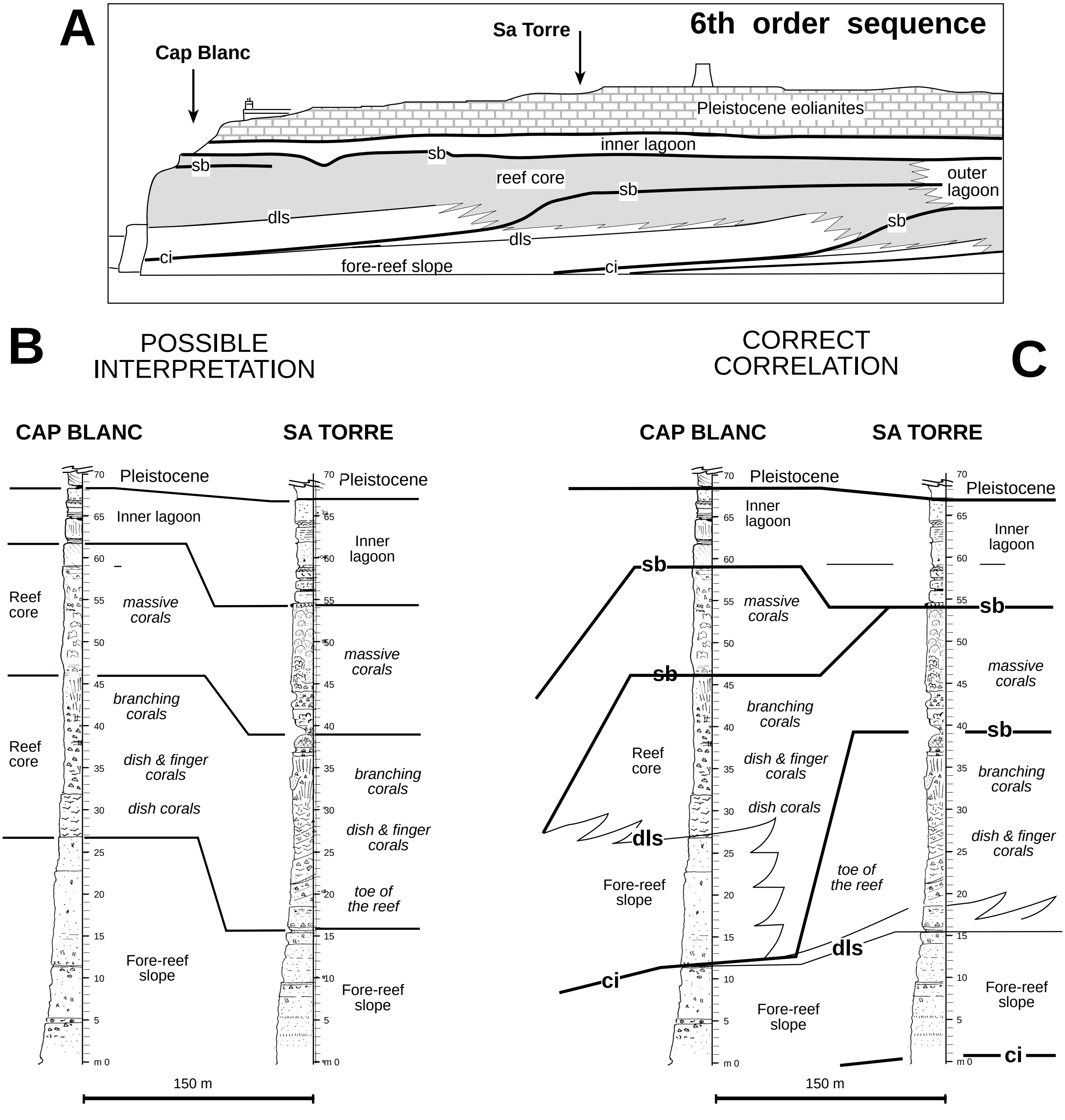

**Figure 4—(A) Cross section through closely spaced measured sections at Cap Blanc and Sa Torre (CB and ST, respectively, on Figure 2); sb = sequence boundary, dls = downlap surface, ci = condensed interval. (B) Plausible correlation of lithologic units. (C) Definition of chronostratigraphic units based on tracing surfaces on outcrop. The interpretation shown in (B) would lead to an incorrect model of fluid flow because of erroneous connection of noncontiguous porous and permeable reef-rock units.**

The highstand systems tract (HST) is related to the highest part of the sea-level cycle and consists of prograding reef core with fore-reef-slope lithofacies wedging out basinward and volumetrically condensed open-shelf lithofacies. Lagoonal beds commonly are absent (because of nondeposition or

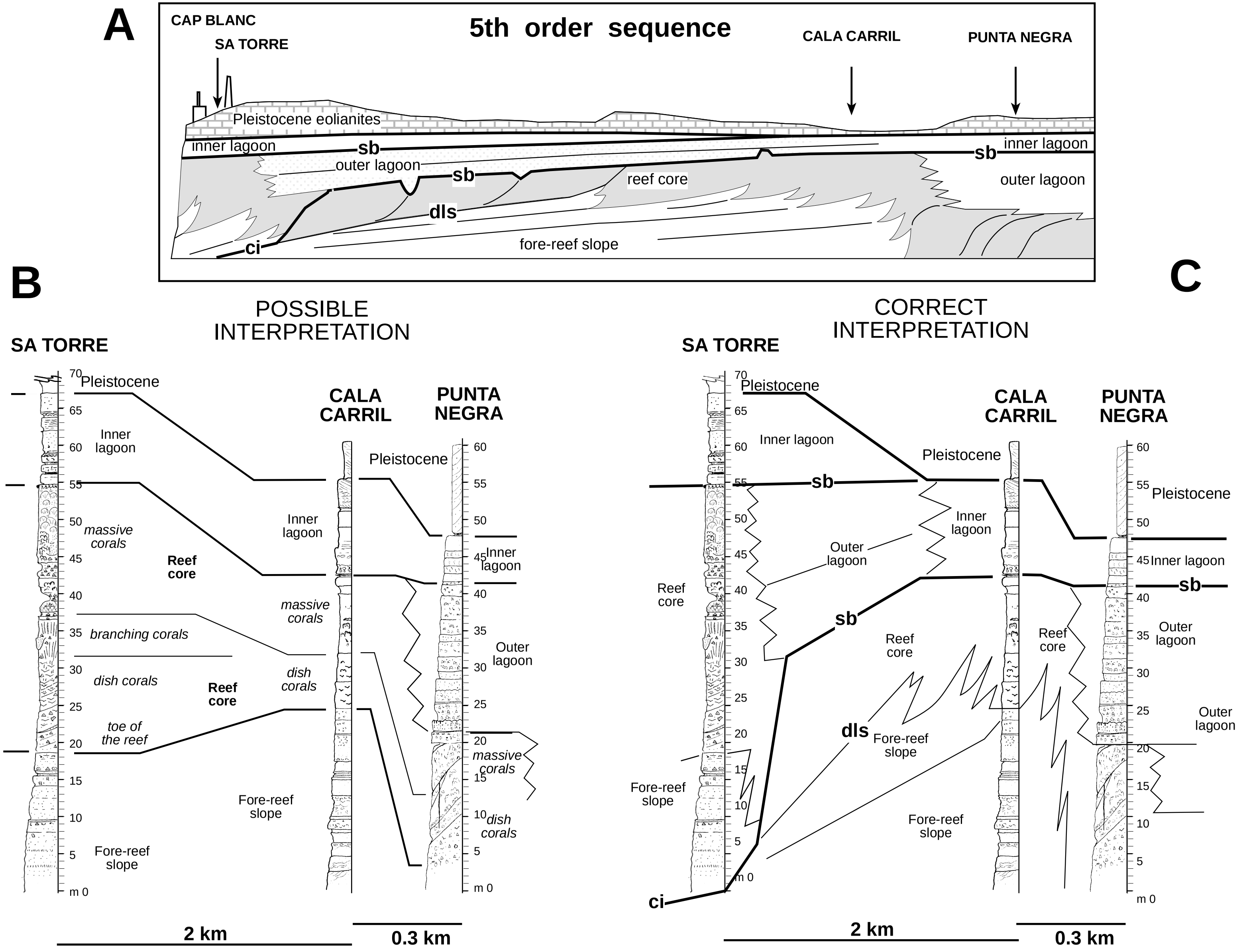

**Figure 5**—(A) Cross section through measured sections at Sa Torre, Cala Carril, and Punta Negra (ST, CC, and PNN, respectively, on Figure 2); sb = sequence boundary, dls = downlap surface, ci = condensed interval. (B) Plausible correlation of lithologic units. (C) Definition of chronostratigraphic units based on tracing surfaces on outcrop. The interpretation shown in (B) would lead to an incorrect model of fluid flow because of erroneous connection of noncontiguous porous and permeable reef-rock units.

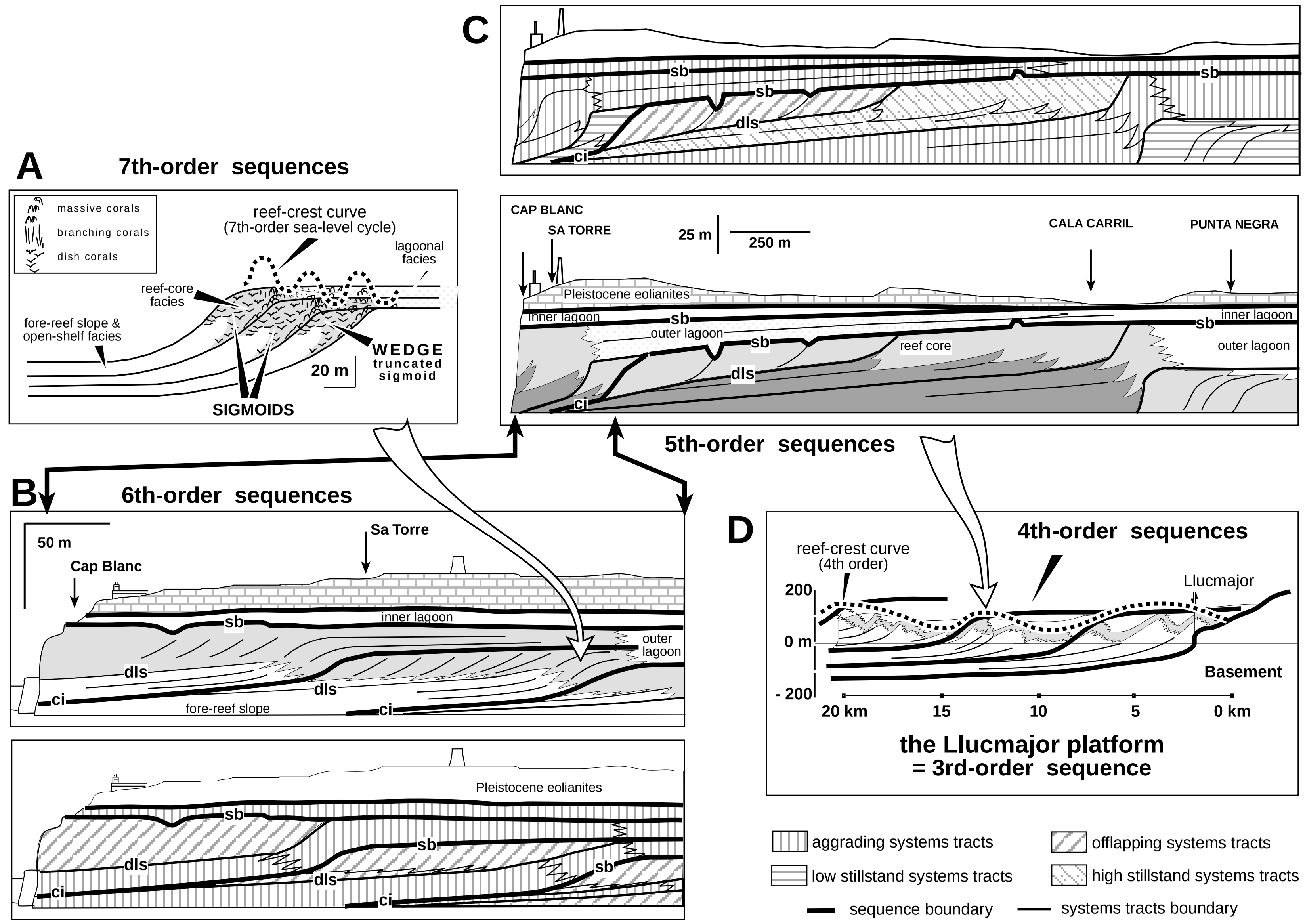

Figure 6—Chronostratigraphic units defined within upper Miocene reef complex of Mallorca. (A) Basic unit, the sigmoid, presumably seventh-order sequences; (B) sixth-order sequences composed of packages of seventh-order sequences (location of Cap Blanc and Sa Torre shown as CB and ST, respectively, on Figure 2); sb = sequence boundary, dls = downlap surface; (C) fifth-order sequences composed of sixth-order units (location of Sa Torre, Cala Carril, and Punta Negra shown as ST, CC, and PNN, respectively, on Figure 2; and (D) fourth-order sequences composed of fifth-order units (cross section same as CC′ in Figure 3).

erosion during subsequent fall of sea level). The offlapping systems tract (OST) formed during falling sea level. The OST consists of prograding and downstepping reef lithofacies (fringing reefs without significant fore-reef-slope lithofacies), which downlaps onto the distal-slope and open-shelf lithofacies of the previous HST. There is no lagoonal lithofacies, and the open-shelf lithofacies is volumetrically condensed.

### *Carbonate Production*

The relative volume of these high-frequency depositional sequences was basically dependent on the amount of carbonate production and sedimentation (Figure 7), which was directly related to accommodation changes controlled by sea-level fluctuations. The depositional profile was another important factor in controlling carbonate production. Areal extension of the lagoon was dependent on the previous floor morphology and on the changes of relative sea level. Maximum lagoonal extension took place behind barrier reefs during rises of sea level on gently inclined surfaces (Figure 3 CC′); areas with steeper inclined surfaces had narrower lagoons (Figure 3 DD′). Fringing reefs with little or no lagoons predominated in all areas during falls of sea level when coral reefs shifted downward and basinward as a result of the decrease in accommodation (Figures 3, 7). Steepness of the fore-reef slope was dependent mainly on the paleobathymetry and depositional profile of the basin floor, rather than on changes in accommodation. Volume of the fore-reef-slope sediments, however, was directly related to the extent of the existing lagoons. Maximum progradation rates occurred across gently inclined areas (Figure 3) not only because accommodation was less, but also because carbonate production was greater; consequently, the progradational geometry and the facies and stratal architecture in this platform were controlled by the high-frequency changes both in accommodation and in carbonate production in the absence of significant compaction and subsidence. Carbonate production was not an independent factor with respect to changes in accommodation; production varied according to changes in relative sea level and to the depositional profile of the basin floor.

During sea-level lowstands, carbonate production in shallow-basin settings was significant over a large area (Figure 7). Only coarse sediment rich in red algae remained on the shallow open shelf because wave action winnowed finer material and transported it to the deeper open platform. During the lowest stands of sea level, scattered corals grew on the open platform (Figure 7A). The red-algal biostromes of this setting interfingered with the fore-reef slope of the LST on the shallower shelf (Figure 3CC′). The red-algal deposits were not produced where the basin floor was too deep to allow sufficient light penetration (Figure 3DD′).

When sea level rose, most of the production of sediment shifted to the shallower shelf (Figure 7), where extensive lagoons developed behind reefs. We inferred from the stratigraphic architecture that during a rise of sea level, deposition on the open shelf primarily was the result of shedding of fine sediment from the shallow-shelf lagoons, although we are unable to specifically identify lagoonal sediment in the open-platform deposits. This interpretation agrees with that of other workers who show that carbonate-sediment shedding is volumetrically important when platform tops are flooded (Driscoll et al., 1991; Glaser and Droxler, 1991; Grammer, 1991; Boschler, 1992; Grammer and Ginsburg, 1992; Schlager, 1992; Schlager et al., 1994).

Proximal and distal open-shelf settings differed mainly in the volume of material shed from the shallower shelf. The thicker proximal deposits thinned out basinward, where amalgamated rhodalgal biostromes accumulated over time. Downslope shedding decreased during sea-level highstands and virtually ceased during falls and lowstands. On the shallower shelf, the changes in accommodation were reflected in the up-and-down shifts of the reef lithofacies and truncation of the upper AST/HST reef and lagoon lithofacies. In the lagoons, buildup was related to rising sea level and erosion to falling sea level.

In summary, heterogeneity in the lithofacies architecture in this type of prograding platform reflects changes in carbonate production, which depends on changes in accommodation and on basin-floor morphology.

### *Primary Porosity*

Primary porosity is related to distribution and proportion of lithofacies, which vary with systems tracts. For example, framework megapores of the reef lithofacies (Pomar et al., 1996) are preserved in the AST of fifth-order sequences because the framework is better preserved during increases in accommodation. Intergranular primary porosity is best in grainstones of the outer and middle lagoon and in some upper-slope layers. These lithofacies are thickest in the AST.

## Diagenetic Heterogeneity

Diagenetic products in these upper Miocene carbonate rocks can be characterized as early or pre–deep-burial; nevertheless, the early diagenetic heterogeneity in this carbonate complex is important

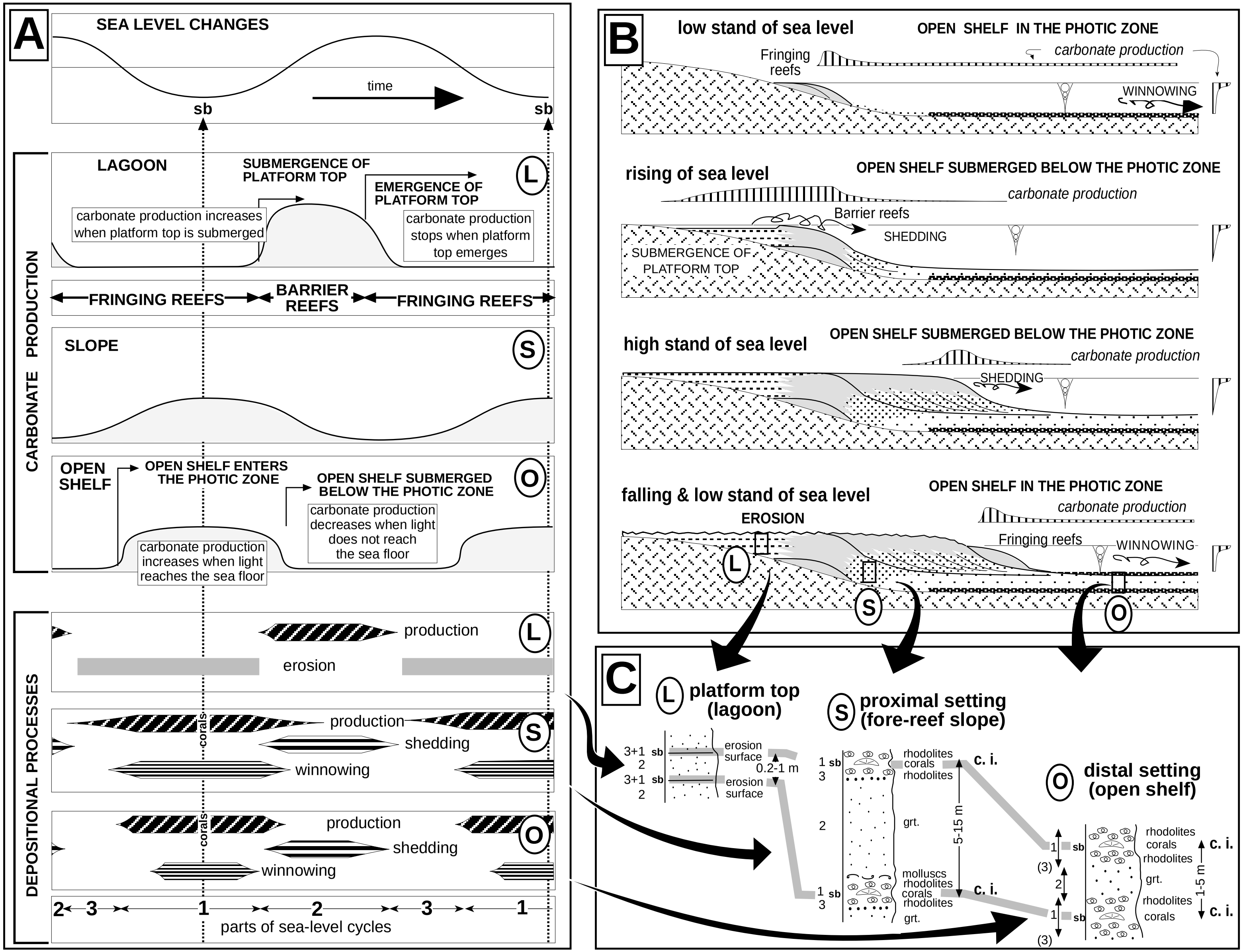

Figure 7—(A) Diagram showing relationships among sea level fluctuations, carbonate production, and depositional processes on three parts of a reef-rimmed carbonate platform. (B) Cross sections showing accretion of reef-rimmed platform as a function of carbonate production and erosion during various stands of a fluctuating sea. (C) Stratigraphic sections built up in lagoons, fore-reef slopes, and open shelves in response to the depositional processes during sea-level fluctuations illustrated in (A) and (B).

to consider because it sets the stage for heterogeneity of deeper-burial diagenesis.

Original porosity and permeability, which were closely related to depositional facies, were altered mostly by (1) dolomitization of much of the complex and (2) dissolution of aragonitic components. Other diagenetic features are (1) syndepositional marine cements in some reef and lagoon units, (2) various stages of phreatic and vadose calcite cement unevenly distributed through the complex, (3) minor calcite replacement of aragonitic components, and (4) thin subaerial crusts and microkarst in some lagoon units.

We concentrate on two major products of the diagenesis in these rocks: secondary porosity and dolomite. In this paper, we seek to illustrate that although there is a heterogeneous distribution of diagenetic features within this reservoir-scale shallow-platform carbonate buildup, some patterns of diagenesis may be predicted based on the knowledge of system-tract geometries, facies distribution, and sea-level history.

### *Secondary Porosity*

Present-day porosity is the result of both deposition and diagenesis. Figure 8 shows estimated porosities among the various lithofacies of the Llucmajor platform. Moldic porosity, mostly from dissolution of aragonitic bioclasts, is the predominant porosity type in nearly all the rocks. In dolomitic rocks, this secondary porosity was produced early, during dolomitization. Aragonitic constituents also are dissolved from the nondolomitized lithofacies. In both dolomitic and nondolomitic rocks there generally are only thin crusts of cement in the moldic pores or in intergranular pores. Coarse, later-stage calcite is abundant in some pores in reef rock and in a few lagoon rocks, but rarely is porosity totally occluded; therefore, nearly all the rocks of this upper Miocene reef complex are highly porous.

Because secondary porosity is characteristic of these rocks, total porosity and pore size is a function of original mineralogy, as well as of original grain size and sorting. For the most part, lithofacies that had abundant aragonitic components have the most secondary porosity. Lithofacies that included large aragonitic constituents, such as in reef and proximal-slope rocks, were left with megapores lined with only thin crusts of dolomite or calcite cement. Secondary porosity is less abundant in many inner lagoon rocks, which are composed largely of benthic foraminifers, or in middle and outer lagoon rocks that are composed mostly of red algae and echinoids because these calcitic fossils are more resistant to dissolution than aragonitic components. Many dolomitized distal-slope rocks have high porosity because both aragonitic and calcitic fossils are leached out.

Probably because of the arid climate just after this reef complex accumulated (Sun and Esteban, 1994), dissolution porosity related to high-frequency oscillations of sea level is not conspicuous. There is microkarst in some lagoon layers associated with sea level falls of probably fifth- and sixth-order cyclicity, but the effects of this dissolution are only local. Apparently, most secondary porosity on the margins of the Llucmajor platform is related to major dolomitization, which presumably was associated with a third-order oscillation of sea level. More core data are needed to evaluate the relationship between depositional cyclicity and secondary porosity in the calcitic rocks on the interior platform.

### *Dolomite*

In much of this reef complex, both replacement dolomite and dolomite cement are the earliest diagenetic components. In the pervasively dolomitized rocks, we found no evidence that dolomitization was preceded by precipitation of diagenetic calcite other than syndepositional marine cements. Most replacement dolomite is microcrystalline (1–5 µm); thus original fabrics generally are well preserved. Nearly all dolomitized rocks also have euhedral to subhedral dolomite cements (0.02–0.15 mm) precipitated in original pores and in secondary pores. For the most part, pore-lining cements are one crystal wide; in a few places some pores are occluded by dolomite cement. Furthermore, many dolomitized rocks still remain free of calcite cement. Transmission electron microscopy study of the microstructure of replacement and cement dolomite crystals from the reef at Cap Blanc (Figure 2) shows that the dolomite crystals are constructed of original growth structures with no evidence of recrystallization (Ward and Reeder, 1993).

Cathodoluminescent patterns in dolomitized corals show that the first stages of dolomite cement (commonly polyhedral) precipitated in intracoral pores before wholesale dissolution of the aragonite skeleton (Ward et al., 1993; Pomar et al., 1996). Later stages of dolomite cement (generally rhombic) precipitated over the early cement and in moldic pores, following wholesale dissolution of aragonite skeletons (Pomar et al., 1996). In general, the rhombic phase is volumetrically most abundant. The final crystal habit of dolomite (cement and replacement) coarser than 0.015 mm can be divided into six categories, based on plane-light petrography: (1) rhombic, (2) rhombic with polyhedral core, (3) rhombic with dissolved or calcite-replaced rhombic core, (4) rhombic with dissolved

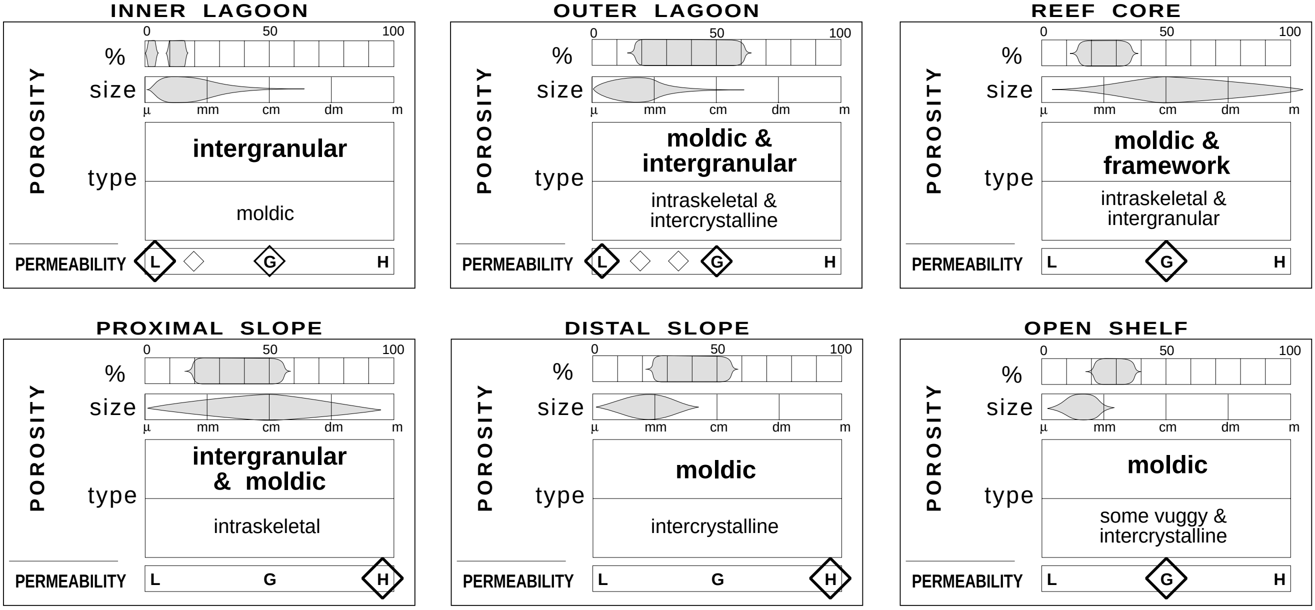

**Figure 8—Estimated percentages and types of porosity of major lithofacies of the upper Miocene reef complex and estimated range of pore sizes. "Type" indicates porosity type; bold lettering designates predominant porosity types for each lithofacies. Rough estimates of permeability: L = low, G = good, H = high. Modified from Pomar et al. (1996).**

or calcite-replaced polyhedral core, (5) polyhedral, and (6) polyhedral with dissolved or calcite-replaced polyhedral core. Presumably, polyhedral dolomite is the product of relatively rapid crystal growth from relatively more-saturated waters, and rhombic dolomite precipitates from relatively less-saturated waters (Sunagawa, 1984).

Whole-rock analyses of oxygen and carbon stable isotopes yield mean values of $\delta^{18}$O = +4.65‰ PDB (Oswald, 1992) and +4.3‰ PDB (Green, 1993), and mean $\delta^{13}$C = +2.01‰ PDB (Oswald, 1992) and +1.7‰ PDB (Green, 1993). These isotopic values, as well as concentrations of Na (489–1995 ppm), Cl (<90–856 ppm), and $SO_4$ (887–5968 ppm) (Staudt et al., 1993), are characteristic of dolomite precipitated from brines derived from evaporated sea water.

### *Stratigraphic and Areal Distribution of Dolomite*

A composite cross section drawn parallel to the direction of reef progradation (Figure 9) shows that the general distribution of dolomite along the southern coast of the Llucmajor platform changes from patchy or absent in the Vallgornera outcrops (older part of the exposed reef complex) to pervasive in the Cap Blanc area (younger part of this segment of the exposed reef complex). The coral-reef mounds on the Vallgornera coast are partly dolomitized. The overlying lagoon units in this area are mostly calcite, except for thin dolomitic layers apparently associated with subaerial exposure surfaces. Reefs and overlying outer-lagoon rocks along the Els Bancals coast (PO-CBI area, Figure 9) are pervasively dolomitized. In the vicinity of localities PNN and DC (Figure 9), proximal-slope, reef, and lagoon units are only partly dolomitized in contrast to lateral equivalents along depositional strike (CC and PNS, Figure 9). This distribution of dolomitized and nondolomitized rock suggests that there was some vertical and lateral heterogeneity (fracture control?) to the movement of early-diagenetic fluids, even in the same lithofacies belts. From the vicinity of this vertical zone of poorly dolomitized proximal-slope and reef rocks to Cap Blanc, the slope beds, reefs, and most lagoon units are pervasively dolomitized, with the exception of some inner-lagoon beds and layers below an unconformity.

Outcrops and sparse well control indicate that along the southern and western margins of the Llucmajor platform, the reef and slope lithofacies are pervasively dolomitized. An exception to this are the nondolomitic distal-slope and deeper-platform lithofacies cropping out at Ses Olles on the southwestern coast (Figure 3B). Considering only the southwestern one-half of the Llucmajor platform, it appears that dolomitization generally decreases toward the platform interior away from the Palma basin; however, the upper Miocene reef complex on the northeastern one-half of the Llucmajor platform also is pervasively dolomitized

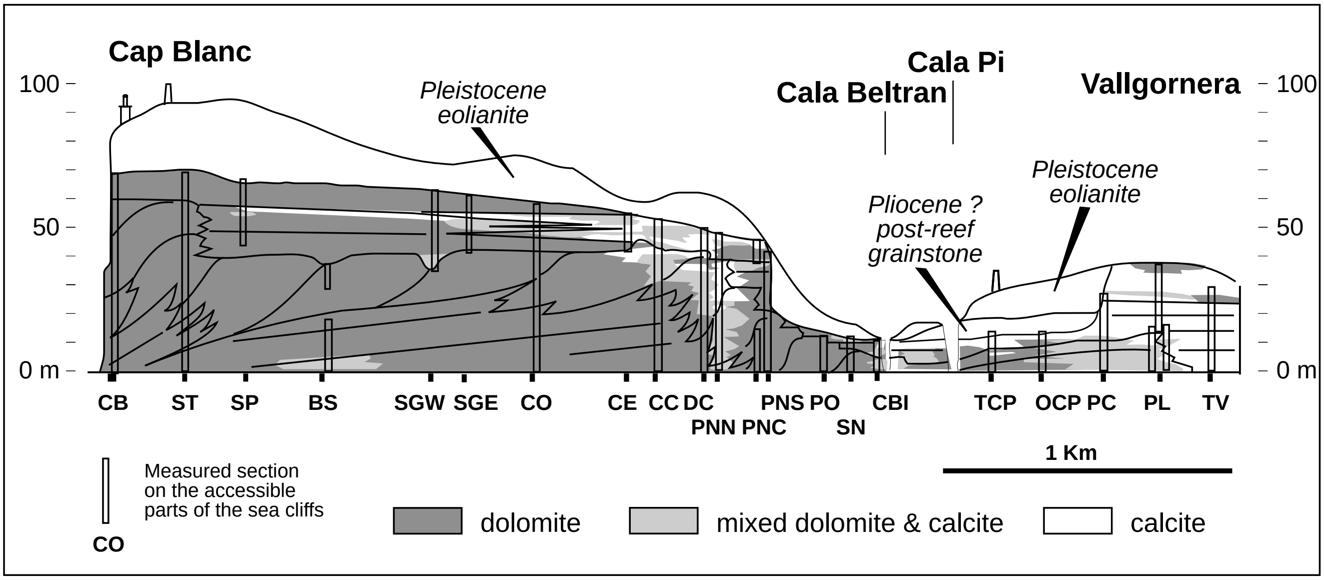

**Figure 9—Distribution of dolomite in sea-cliff outcrops. Cross section is the same as that in Figure 2.**

in the reef lithofacies and most of the slope lithofacies. The lagoon lithofacies is eroded away over the northwestern two-thirds of this area (because of gentle southeastward structural tilt of the Llucmajor platform during the Pliocene–Pleistocene); however, over most of the southeastern part of the platform, the lagoon units contain both calcitic and dolomitic beds.

The predominant dolomite crystal habits in the reef lithofacies across the Llucmajor platform vary greatly, making patterns of distribution difficult to discern. There is an apparent association of abundant polyhedral crystals with the platform margins, but subsurface control is limited. Preliminary results may indicate that precipitation of much of the polyhedral dolomite cement was related to brines from restricted basins, such as the Palma basin, where evaporites were deposited during the Messinian.

### *Relationship of Dolomitization to Depositional Cycles*

Within the Llucmajor platform, dolomite distribution is related to larger-scale stratigraphic position, as well as to geographic location, as has been discussed. Pervasive dolomite overprints stratigraphic boundaries higher than third and fourth order. Most of the dolomitization described here, therefore, is related to large-scale depositional cycles (presumably third- and fourth-order cycles).

Stratigraphic constraints and geographic patterns of dolomitization indicate that dolomitization took place soon after buildup of the reef complex. Figure 10 is based on detailed sampling of the sea-cliff outcrops and limited sampling of water-well cores. This model shows preferential dolomitization of fourth-order aggradational reef/upper-slope units, with less dolomitization both toward the interior of the shallow platforms and toward the distal slopes. Recall that the geochemistry of the dolomites shows the necessity for the platform to have been flooded with brines derived from evaporated sea water during dolomitization (Oswald, 1992; Staudt et al., 1993). One hypothesis based on this model (Figure 10) is that three periods of dolomitization were related to fourth-order sea-level highs following buildup of the aggradational tracts. Such an interpretation, however, is inconsistent with the sea-level history recorded in the stratigraphic sequences. The aggradation of the reef complex was followed by lowering of sea level, which would have given no opportunity for flooding of the platform and reflux dolomitization from saline lagoons before the deposition of the next fourth-order unit began. Another working hypothesis is that the main dolomitization occurred following deposition of the whole complex and during a sea level high that flooded the Llucmajor platform. One period of major dolomitization during the latest Miocene or early Pliocene is consistent with other western Mediterranean studies showing post-reef dolomitization, following a short period of evaporite deposition in several basins of this region (Oswald et al., 1991; Braga and Martin, 1992; Rouchy and Saint Martin, 1992; Calvet et al., 1996; Esteban, 1996; Meyers et al., 1997). Under this scenario the good porosity and permeability of the

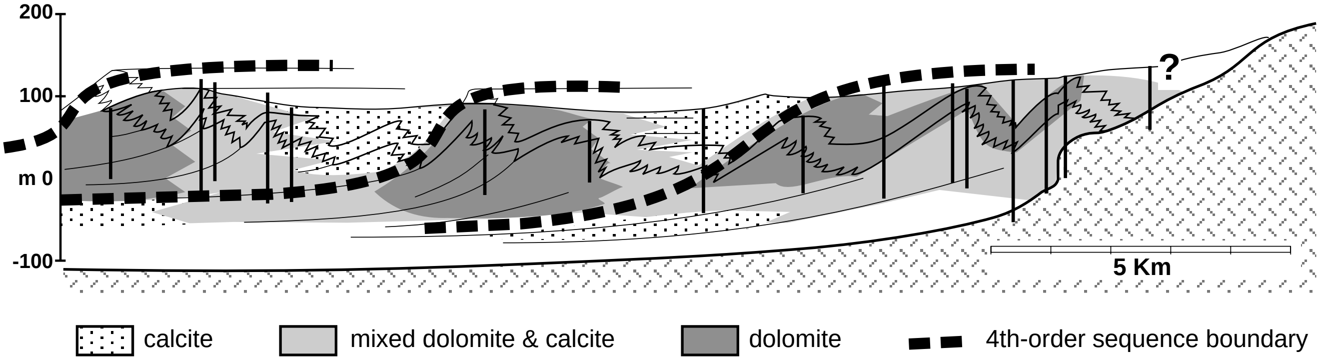

**Figure 10—Cross section showing model for dolomite distribution on the Llucmajor platform. Cross section same as CC′ in Figure 3 and D in Figure 6.**

aggradational reef/upper-slope/outer lagoon units controlled migration of dolomitizing fluids. In areas where reef rock was exposed to the surface or overlain by only thin lagoon units, brines could most easily reflux through this carbonate complex. Vertical and lateral migration of dolomitizing fluids was retarded by lower permeability in finer-grained distal-slope units and by the several lower-permeability zones associated with discontinuities in areas covered by thicker inner-lagoon deposits. (An ongoing study is attempting to test these hypotheses and to consider the hypothesis that patterns of major dolomitization and distribution of dolomite crystal types on both Mallorca and Menorca are related to brines produced in local basins.)

Minor zones of dolomite are associated with boundaries of higher-frequency cycles. For example, where the outcropping reef complex is mostly calcitic (Vallgornera/Cala Pi area, Figure 9), thin dolomite zones are at the top of probable fifth-order sequence boundaries. These zones apparently are associated with initial flooding of the platform interior after a fifth-order drop in sea level. At those boundaries thin layers of calichified lagoonal rock are partly dolomitic. Dolomitizing fluids may have been produced by evaporation in those areas of restricted circulation during initial flooding. The finely crystalline dolomite at these lagoonal boundaries is indistinguishable petrographically from fine dolomite elsewhere in the complex. Furthermore, any syndepositional dolomite at fifth-order boundaries in other parts of the exposed reef complex is obscured by the later dolomitization.

## DISCUSSION

Predicting flow paths and volumes of fluid within reservoirs of shallow-water carbonate rocks commonly will require a model based on studies of well-exposed carbonate complexes, such as the Llucmajor reef complex. Most of the detailed stratigraphic heterogeneities described here are below the resolution of seismic and well-log analyses; thus the outcrop and core studies described here could aid in constructing realistic models for distribution, geometry, and volume of porous and permeable units of some shallow-water carbonate reservoirs, as well as models for fluid flow. Some intermediate- and larger-scale features of the Llucmajor platform were used by Villéger (1996) to analyze facies distribution, sediment geometry, and reef morphology of fourth-order reef units within a third-order highstand systems tract of the subsurface Upper Devonian Nisku Formation of Alberta, Canada.

The most continuous and traceable seismic reflectors within this carbonate complex are likely to be the flat-lying erosional boundaries truncating reef to lagoon beds at the top of fourth- and fifth-order units. These horizontal surfaces, together with the basinward inclination of the sigmoidal reef and upper-slope beds of the lower-order sequences, also might be seismic reflectors that could be used to interpret the stratigraphic architecture of similar reef systems in the subsurface (Pomar, 1993).

The early diagenetic patterns described here indicate that the flow of early subsurface fluids was heterogeneous and was related to the porosity and permeability of depositional units and the stratigraphic architecture. This porosity and permeability are functions not only of depositional textures but also of original mineralogy. Reef, upper-slope, and outer-lagoon units of the aggradational packages contain the thickest sections of permeable and porous rocks. The patterns of early diagenesis in these “preburial” carbonate rocks reflect the flow path of shallow-subsurface fluids soon after deposition. The zones of porosity and permeability that controlled this flow probably will continue to be main pathways of fluid migration after deeper burial. If so, the zones of fluid migration on a reservoir scale will be heterogeneous and compartmentalized. Their evaluation will require a well-founded model of the stacking of lithofacies and porosity-permeability distribution.

## CONCLUSIONS

(1) Stratigraphic analysis from outcrop and shallow-subsurface studies of the upper Miocene reef complex of Mallorca give insight into subreservoir-scale heterogeneities and problems of correlations in shallow-water carbonate rocks.

(2) Both stratigraphic and diagenetic heterogeneities in these rocks derive from the complex hierarchical stacking patterns of accretional units. This stratigraphic architecture and the distribution of lithofacies, primary porosity, and potential for secondary porosity, all are related to the control of carbonate production, accumulation, and preservation by high-frequency sea-level fluctuations.

(3) This carbonate complex also was overprinted by complex patterns of dolomite and secondary porosity that are related to probable third- and fourth-order sea-level fluctuations.

(4) Stratigraphic and diagenetic heterogeneity is inherent in this type of prograding reef-rimmed carbonate platform as a consequence of the direct relationship between sediment input (carbonate production) and changes in accommodation (changes in relative sea level and basin-floor morphology). Because of this inherent heterogeneity, carbonate complexes such as described here should be considered in models for development of reservoirs in rimmed-shelf carbonate rocks, especially where subsurface data are insufficient to define the details of heterogeneity.

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