ARCHITECTURE OF A BENCH-TYPE CARBONATE LAKE MARGIN AND ITS RELATION TO FLUVIALLY DOMINATED DELTAS, LAS MINAS BASIN, UPPER MIocene, SPAIN

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ABSTRACT: The Upper Miocene stratigraphic succession of the Las Minas Basin, located at the external zone of the Betic Chain in SE Spain, preserves several examples of lake carbonate bench deposits. Excellent exposures of the carbonate benches allow detailed observation of the architecture of these sediments and provide new insights for the "steep-gradient bench margin-low energy" model proposed by Platt and Wright (1991). The lake carbonate benches developed in close association with fluviually dominated shallow deltas that exhibit typical Gilbert-type profiles. The delta sequences comprise bottomset prodelta marl facies, distal to proximal foreset facies, deposited mainly in a delta-front environment, and topset facies, the latter reflecting both subaqueous delta-front and subaerial delta-plains environments. The development of the carbonate benches was constrained by the convex-upward morphology of the deltaic deposits, which led to the available accommodation space for the growth of the steep-gradient platforms. The benches display a progradational pattern characterized by sigmoid-oblique internal geometries and offlap upper boundary relationships, which suggests that the carbonate benches developed under slow though continuous lake-level rise. Both the dimensions of the benches and the dominant carbonate components (i.e., encrusted charophyte stems and calcified cyanobacterial remain), allow comparisons with the progradational marl benches recognized in modern temperate hard-water lakes. Accordingly, the case study presented here provides a good analog sedimentary analog for low-energy lake carbonate benches. Moreover, the evolutionary trend inferred from the fossil example offers new insights into the depositional conditions of this type of sediment and allows recognition of the transitional pattern from bench to ramp carbonate lake margins.

INTRODUCTION

Facies models for recent and ancient carbonate lake systems have been refined considerably in the last two decades. The increasing available documentation on this topic allowed Platt and Wright (1991) to propose a two-fold classification scheme for marginal lacustrine carbonate facies that is based on the morphology and on the wave energy conditions under which marginal facies accumulate. Accordingly, Platt and Wright (1991) subdivided carbonate lake margins into four types: (1) low-energy bench; (2) high-energy, wave-dominated bench; (3) low-energy ramp; and (4) high-energy, wave-dominated ramp. Examples of the four types of carbonate lake margins have been documented from both modern lakes and the fossil record. However, although some of the resulting facies models have been supported by abundant case studies, for example, the low-energy ramp type (Brown and Wilkinson 1981; Freydet and Plaziat 1982; Wells 1983; Freydet 1984; Cabrera et al. 1985; Alonso-Zarza et al. 1992; Platt and Wright 1992; Armenteros et al. 1997), documentation of the other types of lake margin is less common. In particular, models of the low-energy bench type are based on a few examples of modern North American lakes, i.e., Lake Littlefield (Murphy and Wilkinson 1980) and Sucker Lake (Treece and Wilkinson 1982), and from a single large-scale ancient example, the Lower Cretaceous Peterson Limestone of Wyoming and Idaho (Glass and Wilkinson 1980). This paper attempts to refine the facies model for the low-energy-bench type of carbonate lake margin by presenting a detailed study of Upper Miocene lacustrine carbonates in southeastern Spain. The excellent exposures of these carbonates allow the investigation of some aspects that are critical in evaluating the sedimentary model: (1) the relative depths of the lake floor ("basinal") and rimmed platform deposits; (2) the progradational pattern of the carbonate lake platform; (3) the distribution of carbonate facies within the bench lake margin, and, importantly, (4) the sedimentological and geomorphologic factors accounting for the initial development and further growth of the carbonate benches. The case study is relevant in demonstrating that the architecture of the benches was controlled largely by the depositional pattern of terrigenous systems with which the carbonates are associated. This observation may aid further analysis of this type of carbonate lake margins elsewhere.

GEOLOGICAL AND SEDIMENTOLOGICAL CONTEXT

The lake carbonate bench deposits form the uppermost part of an approximately 500-m-thick succession of lacustrine sediments that accumulated in the Las Minas Basin throughout the Upper Vallesian and Turolian (Middle Tortonian and Messinian in the marine chronostratigraphic scale). The basin is located in the so-called Prebetic Zone of the Betic Chain, a major structural feature of southeastern Spain (Fig. 1A). The Las Minas Basin is the largest (ca. 160 km²) of several basins that formed in the area as a result of distensional tectonics during the Late Miocene (Bellanca et al. 1989; Calvo et al. 1998). The lacustrine Miocene deposits unconformably overlie Mesozoic terrigenous and carbonate formations, as well as Middle Miocene marine carbonate strata that either constitute the basin margins or are present as separate outcrops in inner parts of the basin (Fig. 1B).

The lowermost Tertiary continental deposits that crop out in the Las Minas Basin comprise turbidites related to reseddimentation from shallow lake carbonate platforms (Elizaga 1994), which are followed by a rather monotonous succession of 2–3 m thick marlstone–carbonate cycles. At the top of lower third of the total section (Fig. 2), an episode of lake lowstand is marked by evaporite deposits, mainly gypsum and diagenetically formed sulfur (Calvo and Elizaga 1994). The evaporite beds are overlain by a thick package of alternating laminated carbonates and marls that are widespread in the northern part of the basin. The deepest lacustrine facies, composed of laminated marls containing abundant planktonic diatoms and siliceous sponge spicules, are found in that part of the basin, suggesting that it behaved as an asymmetrical trough at least during the final stages of the lake (Calvo and Elizaga 1994). Lamproitic volcanic rocks, dated at 5.7 ± 0.3 Ma by Bellon et al. (1980), are present as small isolated outcrops in the central part of the basin (Fig. 1B). Seismic activity associated with the volcanism caused breakdown of the older lacustrine platforms (Calvo and Elizaga 1987), resulting in the formation of scars and slumps at several scales. A slump deposit formed of a set, up to 40 m thick, of contorted and fractured marl and limestone beds (Fig. 2) can be traced across most of the basin. The reseddimented deposits are covered by a monotonous succession of alternating diatomaceous marlstone and limestone deposited at moderate depth in open lake areas (Elizaga 1994). The Miocene section is capped by a mixed silicilastic–carbonate stratigraphic unit that is restricted to the northern part of the basin, along the footwall of a major fault bounding the Sierra de los Donceles (Fig. 1B).

The mixed silicilastic–carbonate unit is formed of mudstone, sandstone, and lacustrine carbonate deposits that are especially well exposed along the Rambla del Saltador (Fig. 3), a 4-km-long creek incised parallel to the strike of the Miocene beds. Several smaller creeks cut these beds normal to strike so that the outcrops allow partial three-dimensional observation of the silicilastic and carbonate se-
Fig. 1.—Location map for the study area. A) Structural framework of the Betic Range in SE Spain with the location of the Las Minas Basin (rectangle); B) Geological sketch map of the Las Minas Basin. The Rambla del Saltador area lies at the upper right side of the map.
Fig. 2.—Simplified summary stratigraphic column of the Upper Miocene lacustrine deposits of the Las Minas Basin showing the stratigraphic position of a main episode of slump formation (see text) and location of the lake carbonate benches described in this study.

Figures. The total thickness of the siliciclastic–carbonate unit reaches 150 m. The lower part of the succession, which is not exposed in the eastern side of the area, comprises brownish sandy mudstones in which three main tabular white marlstone and limestone beds are intercalated. The uppermost part of the succession, exposed along the Rambla del Saltador, consists of two superposed packages of sandstone bodies with associated brownish mudstone that are covered by carbonate beds whose geometries are clearly influenced by those of the sandstones. The total thickness of these two sediment packages is about 25 m. The upper package, which is the focus of this study, is overlain by broadly tabular carbonate beds with intervening organic-rich layers. These extend both north and south of the creek and are, in turn, covered by reddish mudstone containing sandfill channels. The top of the Miocene succession is capped unconformably by Pliocene fluvial gravels.

This paper deals mainly with the terrigenous and carbonate deposits that are located toward the upper part of the Rambla del Saltador section. Elizaga (1994) was
the first to recognize the complex geometric relationships between the sandstone bodies, which he interpreted as Gilbert-type delta deposits, and the associated lacustrine limestones. Bellanca et al. (1995) provided a sedimentological and geochemical approach for differentiating lacustrine and palustrine carbonates in the area. They described a lower member composed of carbonate beds deposited in a platform bench-margin lake environment and an upper member formed of carbonates interbedded with organic-rich marlstones that they interpreted as palustrine deposits. The recognition of the bench-margin lake carbonate facies by Bellanca et al. (1995) served as the starting point for the analysis of their characteristics and pattern of formation that we present in this paper.

**FACIES DISTRIBUTION**

An east-west cross section (Fig. 4A, B) was studied in the eastern part of the Rambla del Saltador (Fig. 3) in order to examine the distribution and stratigraphic relationships between the terrigenous and the carbonate deposits. The section (Fig. 3), which is 400 m long, is traced perpendicular to the main direction of the terrigenous depositional system as deduced from paleocurrent measurements in the sandstones. Paleocurrent directions were measured on both the dip planes of foresets (Figs. 5, 6) and using current ripples (see facies description below). Both indicate clearly that the direction of flow was south to north in this part of the basin. The easternmost side of the section (Fig. 4A) shows carbonate beds that dip up to 28° toward the east (Fig. 7). The thickness of these carbonate beds is seen to decrease in proximity to the sandstone bodies. Both the sandstones and the mudstones display a complex arrangement of cross-bedded units and channelized forms that can be followed laterally all along the lower part of the section. These in turn are capped by crudely tabular carbonate beds. The westernmost side of the section (Fig. 4B) also includes sloping carbonate beds similar to those observed on the eastern side, but with an opposite dip direction.

Bearing in mind the south-to-north direction of the flow, which is almost perpendicular to the two-dimensional section, the carbonate beds form benches that developed laterally to the main direction of terrigenous supply. Moreover, northward-dipping carbonate beds can be recognized just in front of the outcrop described, which provides evidence that the carbonate benches developed as a halo surrounding the terrigenous system. Other examples of these stratigraphic and depositional relationships between the terrigenous and carbonate deposits have been recognized in several places throughout the Rambla del Saltador area (Fig. 3); they will be grouped with the example described in order to present a general sedimentary model for these deposits.

**FACIES DESCRIPTION AND INTERPRETATION**

The main sedimentary features of the terrigenous and carbonate deposits present in the Rambla del Saltador are summarized in Table 1. The clastic units show typical bottomset, foreset, and topset depositional geometries of lake-margin deltas as documented in the classical model of Gilbert (1885). Sedimentary logs that show the vertical and lateral relationships of these lithofacies are presented in Figure 6.

**Bottomset Deposits**

Description.—These deposits crop out with a thickness of 1 m at the base of the section. They consist of massive to crudely laminated, grayish-green marlstone beds with varied carbonate content. Stratification of the marls results mainly from differences in color, although it is locally marked by a higher abundance of gastropod shells and bioturbation traces. The degree of bioturbation is high in some beds. Thin carbonate and siliciclastic silty layers with normal grading are locally interbedded with the marlstone.

Interpretation.—The marlstone with intercalated silty layers is interpreted to result from slow deposition of suspended sediment under the influence of an active delta leading to the formation of deltaic bottomset deposits transitional to basinal sediments (prodelta environment). The bottomset silty layers may represent deposition by low-density turbidity currents (cf. Lowe 1982). Bioturbation of the bottomset beds indicates reworking of the sediment by organisms during periods of low sediment discharge.

**Foreset Deposits**

Description.—This facies association comprises both sandstone and silty mudstone that form steeply inclined (30°–35°), accretionary beds (Fig. 5) that dip toward the lake area. These beds are up to 4 m thick (Fig. 6). Individual foreset beds show typical downslope fining and decreasing dip along the foreset slope. Some foreset beds have a sigmoidal geometry. Two distinct lithofacies can be recognized in the foreset deposits: (1) The updip part of the foreset beds, up to 2 m thick, consists of very well-sorted, fine-to medium-grained sandstones with planar lamination and climbing ripples; individual sandstone beds usually exhibit normal grading, although inverse grading is present locally; cross-bedding, scour-and-fill structures, ripple marks, and erosional surfaces between the beds are also present. (2) The downdip part of the foreset beds, with an average dip of 24°, comprises dip-oriented climbing-rippled sandstone intercalated within yellow-brown, horizontally laminated silty mudstone; this laminated mudstone, up 0.7 m thick, typically forms superposed graded layers, 2.5–3 cm thick, whose basal part is locally formed of very fine-
Fig. 4.—Cross section showing deltaic deposits (central part of the photograph) and associated lake carbonate benches (at both left and right sides of the photograph) in the eastern part of the Rambla del Saltador (see Figure 3 for location). Above, photomontage of the outcrop cross section split in two segments, A and B; below, line drawing showing facies distribution. Profiles marked in line drawing segment A correspond to sedimentary logs shown in Figure 6. Photographs were taken from the north, nearly coincident with the main axis of the deltaic body as determined by paleocurrent measurement.
LAKE CARBONATE BENCHES, LAS MINAS BASIN, SPAIN

Fig. 4.—Continued.

| Carbonate palustrine beds | Carbonate lacustrine beds | Topset deltaic beds (Delta plain / bay) | Topset deltaic beds (Delta front - bar crest) | Foreset distal beds (Delta front - Prodelta) |

0  10 m
grained sandstone. Intercalations of white, more calcareous beds are present within the yellow-brown mudstone deposits. Composite foreset sequences are formed of numerous imbricated foresets that are separated by unconformities or reactivation surfaces. These surfaces are usually draped by thin silt and/or clay bottomset deposits that pinch out landward. Packages of delta foreset beds are separated by large curved scour surfaces.

Interpretation.—The planar cross-stratified sandstones are interpreted as steep avalanche sets, characteristic of proximal foresets. Changes in location of foreset building are marked by large curved scour surfaces that separate packages of foreset beds. These sediments represent the slumping, lakeward margin (bar front) of an advancing subaerial delta-front environment (Orton and Reading 1993). In this setting, progradation is controlled by bedload deposition from turbidity currents flowing down the avalanche slope during episodic flood events. In contrast, the climbing-rippled sandstone and the silty mudstone beds are interpreted as distal foreset deposits in which climbing ripples and graded silt layers represent waning-flow sequences. Distally, the silty mudstone beds intertongue with the bottomset deposits. Interbedding of silty mudstone and carbonate may indicate episodic stabilization of the clastic input and further precipitation of the lake carbonate directly on the delta-front sediments.

Topset Deposits

Description.—The topset deposits comprise two distinctive facies associations reaching 3.3 m in maximum thickness (Fig. 6). The lower part of the topset deposits consists of a 2.5-m-thick package of multistory, moderately sorted, coarse- to medium-grained sandstone beds with intervening erosional contacts. The internal structure of the sandstone beds is characterized by planar and trough cross-stratification, some beds showing microconglomerate lags where phytoseams and mud chips are prominent constituents. Where not incised by the overlying sandstone, the beds are topped by ripple-laminated finer-grained sandstone, locally with wave ripples. These lower topset deposits are separated from the foreset beds by subhorizontal erosional surfaces. Although the slope break the topset beds conformally overlie the dipping foresets.

The upper part of the topset deposits is predominantly finer grained and consists of sandy silt, silty marlstone, and calcareous marlstone containing abundant gastro- pod remains. Several facies associations are recognized within these deposits:

Channel-Fill Sediments: The paleochannels are 2–3 m thick and 8–10 m wide. The steep channel sides are symmetrical, and the base cuts sharply into the under-lying sediments. Sediment fill consists of coarse to fine, even silty sand that grades upward into silty mudstone. The lower part of the channel fill is formed of a microconglomeratic lag containing abundant phytoseams and carbonized wood fragments. Two main sand-filled channels are present in the section (Fig. 4A, B). The channel at the west side of the section shows a lower microconglomerate lag overlain by trough cross-bedded, coarse-grained sandstone that passes upward into thinner sets of finer-grained ripple cross-laminated sandstone. The total thickness of the channel fill is 3.1 m. The channel at the east side of the section shows a different infill sequence dominated by finer-grained sediments. The overall internal structure of the channel is markedly concave upward, with a total thickness of 3.8 m. The lower part of the infill consists of silt-poor, cross-bedded sandstone that grades upward into silty sand displaying small-scale cross-bedding. Most of the channel fill (2.1 m) consists of laminated to massive silty marlstone beds, some of which extend laterally away from the channelized body.

Levee Sediments: These deposits form clastic wedges with a characteristic triangular cross section. They are up to 3.7 m thick adjacent to the channels, and can be followed for about 20 m, thinning rapidly away from the channel. The sediments consist of well-bedded, horizontally laminated to ripple cross-laminated silts and marls with intervening sandstone beds displaying small-scale cross-bedding and local, microscale ripples. The sediment is locally reddened and contains root traces and scattered plant debris. The levee deposits downlap the upper topset beds and grade laterally into the deposits that accumulated in interdistributary troughs.

Interdistributary Trough/Open Bay Sediments: These deposits, up to 1 m thick, consist of massive to horizontally laminated silty sandstone interlayered with fine-grained sandstone, sandy siltstone, and argillaceous marlstone. The sandstone units typically display a lenticular geometry, and reach up to 30 cm in height and 2–3 m in length. The internal structure of the sandstone bodies is characterized by cross-bedding that grades laterally into finer-grained deposits. The geometric relationship of these deposits with other lithofacies associations of the topset deposits shows that the interdistributary trough sediments grade laterally into the adjacent levee sediments, but in the vicinity of the distributary mouths (open bays) they grade downward into channels in the lake and into wave-ripple bedding that are common in the fine-grained sandstone and siltstone beds.

Interpretation.—The topset deposits comprise a complex lithofacies association with significant changes from bottom to top. The lower sediment package (~2.5 m thick), comprising multistory, erosional sandstone beds with planar and trough cross-stratification, is interpreted as upper delta-front deposits which accumulated mainly under the influence of fluvial discharge and which represent the subsequaeus part of the topset deposits (Colesan and Gagliano 1965). As a whole, the lower part of the topset deposits and underlying foreset and bottomset deposits constitute a river-mouth bar showing a Gilbert-type profile that was deposited in a delta-front environment (Wright 1977). As observed in recent deltaic environments, the narrow river-mouth bars typically show a lunette shape in plan view (bar crests), and their deposition is related to inertia-dominated effluent diffusion (Wright 1977). The upper part of the topset deposits, composed of channel-fill sediments, levee deposits, and finer-grained sediments that accumulated in interdistributary troughs and open bay settings, represent a delta plain environment (Fisk 1961; Colesan and Gagliano 1965; Donaldson et al. 1970; Gould 1970). The channel deposits are interpreted as the products of straight and stable distributaries whose energy decreased progressively, resulting in infill of the channels with fining-upward sequences. The dominant sand-fill observed in one of the channels is indicative of active filling related to decreasing flow upstream, probably due to progressive abandonment of the channel. On the other hand, the predominance of finer-grained sandstone and mudstone in the other channel suggests that the channel was actively incised but suddenly abandoned, the channel course being filled later by overbank flows from adjacent channels. Thus, the resulting fill sequence is one that could be expected from passive superposition of clay plugs. These channels are similar to those described as type C feeder systems by Postma (1985), although they could also represent an intermediate case between his type C and type D feeder systems. The channel architecture reflects moderate-gradient sandy alluvial systems of closely spaced, but relatively stable, channels acting as a line source characterized by fixed points of sediment supply. Orton and Reading (1993) described similar channels in sandy, mixed-load delta plains that were incised by straight and meandering channels with clay-consolidated channel banks.

The levee sediments were deposited subaerially when flood waters escaped from the channels onto overbank areas. A zonation of coarser-grained accumulations close to the channels and finer-grained sediment deposited farther out in the interdistributary troughs is recognized. In the latter subenvironment, fine-grained sandstone accumulated as shallow-water distributary crevasse deposits that incised the levees in episodic floods. Most sediment settled from suspension, so that the most distal deposits are finer-grained and covered the floor of the interdistributary troughs and bays.

Carbonate Bench Deposits

Description.—At both the eastern and western sides of the cross section (Fig. 4), the deltaic terrigenous facies are covered by carbonate sediments that display an internal stratigraphic pattern consisting of inclined, laterally prograding carbonate beds (i.e., clinoforms; Fig. 7). Three clinoform sets, outlined by changes in inclination of the sloping beds, are recognized throughout the carbonate bench deposits. The resulting picture is that of a sigmoid-oblique progradational pattern of carbonate stratification (Bobesuini 1984), where horizontal to gently dipping, tabular platform carbonate beds pass laterally into sloping carbonate beds whose inclination decreases progressively.
toward the toe of slope. The lower clinoform set directly overlies topset marlstone deposits. The geometry of the clinoform set is slightly sigmoidal, with a maximum observed thickness of 3 m. The internal structure of this set is characterized by decimeter-thick, marly carbonate beds, whose dip angles decrease gently from bottom to top. The convex-upward morphology of the set of carbonate strata is marked by a relatively rapid change in slope from 7° to 19° (Fig. 7). The upper boundary of this clinoform set displays slight truncations at the ends of the carbonate beds, whereas the lower boundary is characterized by the flattening out of the beds. The second clinoform set has a better defined sigmoidal geometry. The maximum thickness of this set is 1.3 m, thinning toward both the platform and the lower slope.

Fig. 6.—Sedimentary logs of deltaic lithofacies and overlying lacustrine and palustrine deposits. See location of the sections in Figure 4A.
Fig. 7.—Photomontage and line drawing of the carbonate bench deposits of Rambla del Saltador. The outcrop corresponds to the easternmost part of the cross section shown in Figure 4. Note sigmoid-oblique pattern defined by the geometric relationships of three main clinoform sets (bench slope carbonate strata) and their correlative tabular platform carbonate beds, which resulted from the progradation (from right to left) of the lake carbonate bench. Note also the onlap relationship of the carbonate wedge developed in front of the bench (left side of the photograph). The softer bed with negative relief in the middle part of the outcrop is clayey marlstone. Horizontal beds at the upper part of the photograph are mainly palustrine carbonates with thin marlstone interbeds. Inset at the left of the photomontage corresponds to that observed in Figure 8. Person is 1.70 m tall.
The height of the outcrop is 5.30 m.

The angle of the clinoforms downslope conform broadly to those determined in the underlying clinoforms, while the carbonate beds at the edge of the sigmoid dip at up to 23°. The third clinoform set has a similar geometry and a maximum thickness of 1.8 m. The well-bedded platform carbonate beds that are related laterally to these clinoforms conformably overlie those of the second clinoform set. Carbonate beds at the edge of the sigmoid dip at up to 28°.

The outer surface of the third clinoform set is covered by onlapping tabular carbonate beds (Fig. 8) that pass progressively upward into tangential beds draping the upper part of the clinoform surface and conformably overlie older platform carbonates. The upper surface of the carbonate deposits is veneered by a light green, clayey marlstone bed that is seen to cover the carbonate irregularly (Figs. 7, 8). The clayey marlstone bed dips at approximately 11°. It is overlain, in turn, by a wedge of carbonate beds that thicken in the same direction as the complete package of clinoforms. A 2-m-thick package of palustrine carbonates, comprising tabular, commonly root-biorthusted carbonate beds, carbonate mounds, oncoid- and intracleast-filled channels, and phytoclast shoals (Bellanca et al. 1995), overlies the section. These carbonates are horizontally stratified, in contrast to the underlying bench carbonate deposits.

The total thickness of the bench platform and slope carbonate deposits in the measured outcrop is up to 5.5 m and the length of the section is ~70 m (Fig. 4). There is a variation in thickness from 2.6 m of tabular, platform carbonate beds superimposed on the deltaic facies to maximum vertical thickness of 5.5 m in the part of the section where the progradational carbonate sigmoid forms are present. The thickness of the platform carbonate beds, where they directly overlie the core of river-dominated delta deposits, is reduced to 1 m. The carbonate beds at these sites display channel geometries and abundant erosional surfaces.

The bench platform deposits consist of weakly laminated, white, soft to indurated beds of biomicrite (mainly wackestone) in which calcified cyanobacterial clusters, encrusted charophyte stems and gyrogonites, gastropods, and ostracods that are the dominant components included in the lime mud. Calcified cyanobacterial clusters are seen as a network of irregularly to radially distributed micritic filaments (Fig. 9A). The individual filaments consist of a central tubular void, up to 10 μm in diameter, and an external coating of micrite (1 μm) crystals. The bench slope deposits are formed of well-defined, decimeter-thick, soft to indurated carbonate beds formed mainly of biomicrite (packstone and wackestone) in which the skeletal components, basically the same types observed within the platform carbonate beds, are oriented parallel to the bed surfaces. Fragments of calcified cyanobacterial clusters are clearly defined within the micrite groundmass (Fig. 9B). Thinner biomicrite laminae are locally recognized as a veneer on the single clinoform carbonate beds. The toe-of-slope carbonate beds exhibit fabrics that are similar to those observed in the slope beds. Carbonate forming a wedge at the side of the progradational bench also consists of packstone and wackestone containing charophyte stems and calcified cyanobacterial remains.

The mineralogy of the carbonate is only low-magnesium calcite (MgCO₃ < 2 mol%), with Mg/Ca and Sr/Ca ratios lower than 0.019 and 0.0020, respectively (Bellanca et al. 1995). δ¹³C values from eight samples of the carbonate range from −5.6 to −3.6‰, whereas δ¹⁸O values range from −6.9 to −4.9‰ (Bellanca et al. 1995).

Interpretation.—The carbonate textures with dominant micrite and variable amounts of skeletal components typical of freshwater conditions indicate deposition in a protected, low-energy lacustrine environment. The freshwater nature of the lake carbonate is also supported by mineralogy and geochemical data determined from the carbonates (Bellanca et al. 1995). Carbonate production was mostly biogenic, driven by extensive growth of charophytes on both the platform and the slope of the bench (cf. Murphy and Wilkinson 1980; Treese and Wilkinson 1982) and a significant population of cyanobacteria. The accumulation of carbonate in the horizontal bench platform resulted mainly from the breakdown of carbonate-encrusted stems of charophytes together with calcified cyanobacterial clusters, whereas in situ accumulation, followed by episodic resedimentation of these carbonate contributors, was the most effective mechanism of deposition in the bench slope. The origin of the micrite groundmass has not been investigated in detail, although our observations of the micrite under SEM suggest that most of the fine-grained carbonate could have been derived from disintegration of both encrusted charophyte stems (Dean 1981) and calcified cyanobacterial sheaths (Merz 1992).

The homogeneity of the carbonate textures across the bench shows that depositional conditions, both in terms of depth and energy under which carbonate accumulated, probably did not undergo significant changes. The internal pattern of carbonate strata in the bench indicates successive episodes of progradation of the carbonate platform basinward. The progradation took place throughout a generalized lake highstand, as evidenced by the aggradational and progradational geometries of the bench carbonates. The first clinoform set shows the lowest dip angles and covers

**Table 1.** Summary of sedimentary facies descriptions and depositional systems of the lake carbonate benches and associated deltas in Rambla del Saltador.

<table>
<thead>
<tr>
<th>Lithofacies Association</th>
<th>Sedimentary Features</th>
<th>Depositional System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massive marlstone with intercalated thin siltstone beds</td>
<td>Structureless to irregular laminar defined by changes in color, degree of bioturbation, and abundance of gastropod shells. Interbedded siltstone (turbidites) shows normal grading.</td>
<td>Prodelta—bottomset deposits.</td>
</tr>
<tr>
<td>Fine- to medium-grained sandstone and laminated silty mudstone</td>
<td>Well-sorted foreset sandstone beds exhibiting planar and climbing-rippled laminations with normal grading. Local scour-and-fill and erosional surfaces. Laminated mudstone formed of stacked cm-thick, normally graded siltstone layers.</td>
<td>Subaqueous delta front—proximal to distal forest deposits.</td>
</tr>
<tr>
<td>Coarse- to medium-grained sandstone and microlaminated carbonate beds</td>
<td>Multistory planar and trough cross-stratified sandstone with microlaminated carbonate layers. Mud chips and phytoclasts. Abundant erosional surfaces.</td>
<td>Upper delta front—subaqueous bench deposits.</td>
</tr>
<tr>
<td>Coarse- to very fine-grained sandstone and silty mudstone</td>
<td>Microconglomerate. Trough cross-stratification and ripple cross-stratification. Typical fining-upward channel-fill sequences.</td>
<td>Delta plain—active and/or abandoned channels.</td>
</tr>
<tr>
<td>Silstone and mudstone with interbedded sandstone</td>
<td>Well-beded, horizontally to ripple cross-laminated siltstone and marlstone. Sandstone shows cross-bedding and occasional climbing ripples. Root traces</td>
<td>Delta plain— levee deposits.</td>
</tr>
<tr>
<td>Silty marlstone with interbedded sandstone and silty sand</td>
<td>Cross-beded sandstone bodies with lens-like geometries. Massive to flat-laminated silty marlstone</td>
<td>Delta plain—deposited in interdistributary troughs and bays.</td>
</tr>
<tr>
<td>Skeletal to micrite-rich limestone (mud lake sediments)</td>
<td>Tabular, flat to gently dipping limestone beds. Wackestone formed mainly of encrusted charophyte stems and calcified cyanobacterial clusters.</td>
<td>Lake bench platform.</td>
</tr>
<tr>
<td>Calcareous marlstone</td>
<td>Dipping limestone beds (clinoforms) with angles ranging from 7° to 28°. Wackestone and packstone formed mainly of reworked skeletal fragments.</td>
<td>Lake bench slope.</td>
</tr>
<tr>
<td>Limestone, organic-rich marlstone, and sandfill channels.</td>
<td>Well-beded tabular marlstone. Wackestone to mudstone with scattered ostracod shells and gastropods. Diatom frustules within the groundmass.</td>
<td>Basinal lake deposits.</td>
</tr>
</tbody>
</table>

Carbonate shallow lake undergoing periodic lake-level fluctuation (palustrine conditions). Marshes.
250

bonate bench deposits: A) Detailed view of cyanobacterial micrite filaments from micritic that forms platform carbonate facies. The calcite crystals lie on the cyanobacterial sheaths. Both longitudinal and transverse sections of the calcified sheaths are illustrated. B) Cyanobacterial clusters forming a main component of the bench slope carbonate. The clusters exhibit a very porous, spongy internal structure with vague, irregular lamination. Some micrite tubes are locally recognizable. In bench slope carbonate. The clusters exhibit a very porous, spongy internal structure with vaguely shallow depth on the lake floor, as shown by moderate preservation of lamination and presence of minor bioturbation traces. The depth estimated for the depression of the basinal sediments ranges from 5 to 10 m. Under these conditions, permanent stratification of lake waters is improbable. Varve sedimentation, which is recognizable in other lake deposits of the basin (Calvo and Elizaga 1987; Calvo et al. 1998), is absent in the basinal deposits of the Rambla del Saltador area, also supporting the hypothesis that the lake water was not deep during development of the platform benches.

Palustrine Carbonates and Marsh Deposits

Description.—This facies association caps the lacustrine and deltaic deposits in the Rambla del Saltador area. The measured thickness of palustrine carbonates and marsh deposits is up to 15 m. The association comprises mainly indurated carbonate beds, organic-rich marlstone, and sand-filled channels, the latter being restricted to troughs between adjacent carbonate benches. The palustrine carbonates comprise: (1) tabular, commonly root-bioturbated beds, ranging from a few centimeters to 70 cm thick, formed of pelmicrite and micritic with abundant charophyte stems and gastropods, ostracods, and calcified cyanobacterial clusters; (2) strongly root-bioturbated micritic mounds; (3) oncoidal- and intraclast-filled channels; and (4) thin (10–20 cm thick) tabular micritic beds consisting of a dense accumulation of encrusted charophyte stems. The interbedded dark, organic-rich marlstone deposits contain abundant gastropod shells (Planorbis, Hydrobia, Helix) and include some horizons of hydromorphic soils and thin layers formed of root mats. Irregularly distributed patches of reddened marlstone, interpreted to be a result of spontaneous burning of the organic-rich deposits, are locally observed. Sand-filled channels, ranging from 5 to 30 m in width and up to 1.4 deep, show lateral accretion and abundant reactivation surfaces. The channel fills are fine- to medium-grained litharenites with abundant phytoclasts and some oncoids.

Interpretation.—Both carbonate and organic-rich marsh carbonates are characteristic of a palustrine environment, i.e., shallow lake areas subjected to episodic or periodic fluctuation of water level, where areas of carbonate deposition are coeval and/or succeed marshes with rapid stratification of organic matter. These depositional features fit well the “low-gradient ramp–low energy” model of Platt and Wright (1991, 1992). In the Rambla del Saltador, evidence of subaerial exposure of carbonate sediments is shown mainly by extensive root bioturbation leading to the development of prismatic structures and carbonate mounds (Freytet 1984; Calvo et al. 1985; Alonso-Zarza et al. 1992). Carbonate production was related mainly to extensive growth of charophytes and cyanobacteria, as well as gastropod and ostracod benthic faunas living in freshwater. Pedogenic modification linked to lowstand periods is also recorded in the organic-rich marlstone in the form of hydromorphic soils. The presence of sand-filled channels in troughs between adjacent carbonate benches suggests that these depressed areas were favorable sites for meandering fluvial streams to reach the margins of the shallow lake environment.

SEDIMENTARY MODEL

In this section we present an integrated model for the development of lake carbonate deposits and associated terrigenous sediments in the Rambla del Saltador area. From the selected example described above, a close relationship between the emplacement of a fluvially dominated delta and the growth of a lake carbonate bench can be deduced. The same relationship can be also observed at several other locations throughout the study area (Fig. 3).

Development and Characteristics of the Fluvially Dominated Delta

The alternating terrigenous and carbonate deposits exposed along the Rambla del Saltador are a part of a thicker (up to 150 m) sedimentary complex restricted to the northern part of the Las Minas Basin (Fig. 1B). The position of this terrigenous–carbonate stratigraphic unit suggests that during the later stages of basin infill (Upper Turonian) the northern part of the basin behaved as a rapidly subsiding trough related to fault reactivation of the basin margin. In this setting, a fluvial system flowing

FIG. 9.—Photomicrographs showing specific microfacies aspects of the lake carbonate bench deposits: A) Detailed view of cyanobacterial micrite filaments from micrite that forms platform carbonate facies. The calcite crystals lie on the cyanobacterial sheaths. Both longitudinal and transverse sections of the calcified sheaths are illustrated. B) Cyanobacterial clusters forming a main component of the bench slope carbonate. The clusters exhibit a very porous, spongy internal structure with vague, irregular lamination. Some micrite tubes are locally recognizable. In bench slope carbonate. The clusters exhibit a very porous, spongy internal structure with vaguely shallow depth on the lake floor, as shown by moderate preservation of lamination and presence of minor bioturbation traces. The depth estimated for the depression of the basinal sediments ranges from 5 to 10 m. Under these conditions, permanent stratification of lake waters is improbable. Varve sedimentation, which is recognizable in other lake deposits of the basin (Calvo and Elizaga 1987; Calvo et al. 1998), is absent in the basinal deposits of the Rambla del Saltador area, also supporting the hypothesis that the lake water was not deep during development of the platform benches.

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LAKE CARBONATE BENCHES, LAS MINAS BASIN, SPAIN

Fig. 10.—Idealized paleogeographic sketches showing evolution of fluvially dominated deltas and associated carbonate platforms in the Rambla del Saltador area. A) Development of the fluvially dominated shallow deltas according to a “birdfoot” pattern; estimated depth of lake floor is 3–5 m as deduced from thickness of Gilbert-type foreset units. B) Development of freshwater lake carbonate benches fringing the deltas; estimated depth of lake floor is <8 m. C) Final stage showing generalized flooding of the area by lake waters and development of a low-gradient (ramp) carbonate lake system overlaying the carbonate benches. The scale in the drawing is approximate and indicative of the size of the deltas and associated carbonate benches; it does not reflect distance between the deltaic bodies.

from the south (and southeast?) toward the north and northwest discharged in the Rambla del Saltador area through several distributaries, forming a “birdfoot” delta plain (type D feeder system of Postma 1995). The spatial distribution of the main sandstone deposits that mark the locations of the distributary mouth bars and/or delta-front deposits delineates a digitate geometry (Fig. 10A), with streams flowing predominantly toward the north and northwest. Distinction between north-flowing distributaries and those discharging more to the west, toward more open lake areas, is significant because the carbonate benches that developed on the delta fingers display some differences in depositional features (see comments below).

The deltaic deposits show typical Gilbert-type profiles (Gilbert 1885; Flores 1990) formed of (i) bottomset, marly and silty horizontal beds that accumulated in a pro-delta environment, (ii) steeply inclined foreset beds (delta-front environment), and (iii) overlying topset beds. The overall geometry of these deposits is probably the result of progradational streams of the delta-plain distributary channels formed at the points where these channels intersected the lake margin. As observed in some sections, episodic drops in lake level could have resulted in the incision of proximal foreset deposits by the progradational channels. The thickness of the foreset units can be used as a good indicator of the depth of the lake basin (Smoot and Lowenstein 1991; Postma 1995). In the Rambla del Saltador deltas, the measured thicknesses of the foresets hardly exceed 3 m, which clearly indicates the relatively shallow character of the lake at the time the deltas were formed. This interpretation is compatible with the category of shallow-water deltas (water depths of the order of some tens of meters) with wider-spaced, highly stable channels proposed by Postma (1990, 1995). This type of delta is characterized by a low ratio of bedload to total load, which fits well with the localized accumulations of medium- to coarse-grained sandstone and the widespread distribution of mudstone in the Rambla del Saltador area.

Growth of the Lake Carbonate Benches

Development of the carbonate benches started when terrigenous deltaic deposition at the lake margin became progressively reduced as a result of relative rise of lake
level and flooding of the delta topset surface. Under these conditions of reduced terrigenous input and increase of the available accommodation space adjacent to the delta bodies, high productivity by shallow-water benthic plants and cyanobacteria resulted in buildup of the shore zone and its progradation into the lake (Platt and Wright 1991). Lateral to the deltas, the carbonate deposits rapidly thickened, providing evidence of the existence of the "continental shelf" (Murphy and Wilkinson 1980) and in both cases the carbonate facies model for this type of lake sedimentation. Despite the strong similarities both in the geometry and composition of their deposits, the lake carbonate benches of Rambla del Saldor can be regarded as typical products of sedimentation in temperate hard-water (waters saturated with respect to CaCO₃) lakes where assimilation of CO₂ by photosynthesis is the most important mechanism of CaCO₃ precipitation (Dean 1981). In this setting, the rate of CaCO₃ accumulation is greater in the littoral zones than in the deeper ones. The Rambla del Saldor deposits, which developed in a lake located at 38°-39° latitude (similar to the present day: Smith 1996), and surrounded by a limestone watershed, are a good example of the differential growth rate of highly productive, littoral lake zones leading to the building of carbonate benches in a marl lake setting. However, specific constrains, notably the pattern of lake-level evolution and the topographic control exerted by preexisting sediment bodies, on the development of the carbonate benches introduce some variations that could be used for refining the current facies model for this type of lake sedimentation.

**DISCUSSION**

**Comparison with Modern Examples of Lake Carbonate Benches**

The facies model for carbonate lakes with high-gradient, bench type margins developed under low-energy conditions (the steep-gradient "bench" margins—low energy model of Platt and Wright 1991) was proposed following observations of the depositional pattern exhibited by progradational marl benches in several small temperate lakes in Michigan (Murphy and Wilkinson 1980; Treese and Wilkinson 1982). This facies model for carbonate lakes has been supplemented by a large-scale example from the temperate lakes in Michigan (Murphy and Wilkinson 1980; Treese and Wilkinson 1982). Nevertheless, detailed observation of the geometries of the Upper Miocene deposits of Rambla del Saltador reveals a distinct regressive pattern in the progradation of the carbonate benches. In contrast with the regular progradation of the benches described from modern marl lakes, the clinoforms of Rambla del Saltador show marked discontinuous variations in slope angles throughout the stepwise progradation of the platform. Moreover, the carbonate beds display offshore relationships. Both features reflect growth of the bench as a response to slow, episodic lake-level rise in the absence of significant terrigenous supply. Accordingly, the discontinuous upbuilding and outbuilding pattern shown by the carbonate benches described in this study could be considered a reference for the evaluation of other ancient, and perhaps modern, lacustrine carbonates.

**Contribution to the Carbonate Bench Lake-Margin Facies Model**

Despite the strong similarities between the lake carbonate bench deposits of Rambla del Saldor and those documented from several modern North American lakes, some differences in growth pattern can be outlined (Fig. 11). The first relevant point is that the installation of the carbonate benches of Rambla del Saldor was closely related to the convex-upward growth of the deltaic deposits that had previously accumulated at the lake margin. This picture is notably different from that described from modern marl lakes, where bench development does not seem to have been constrained by any geomorphic feature. Interpretation of lake carbonate benches in other ancient or modern settings should consider this aspect.

A second point concerns the progradational pattern observed in the Rambla del Saldor carbonate benches. In contrast with the regular progradation of the benches described in modern marl lakes, the clinoforms of Rambla del Saldor show marked discontinuous variations in slope angles throughout the stepwise progradation of the platform. Moreover, the carbonate beds display offshore relationships. Both features reflect growth of the bench as a response to slow, episodic lake-level rise in the absence of significant terrigenous supply. Accordingly, the discontinuous upbuilding and outbuilding pattern shown by the carbonate benches described in this study could be considered a reference for the evaluation of other ancient, and perhaps modern, lacustrine carbonates.
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Lake carbonate deposits in the Upper Miocene succession of the Las Minas Basin provide new insights into the development of low-energy, steep-gradient carbonate lake margins previously modeled from modern temperate marl lakes. In our case study, the lake carbonate benches are closely associated with fluvially dominated deltas that exhibit Gilbert-type profiles. The association of the two depositional systems clearly indicates that the initiation of the carbonate benches was favored by the convex-up delta morphologies as enough accommodation space was created adjacent to the delta bodies. Moreover, the lake carbonate bench deposits display a discontinuous progradational pattern outlined by offlap relationships of the slope and platform carbonate beds forming the bench. This progradational pattern is inferred to be related to a relatively slow but continuous lake-level rise. Carbonate production on the bench platform was due mainly to the development of meadows of charophytes and cyanobacterial mats with some contribution from gastropod and ostracod shells. The bench slope beds consist mainly of reworked carbonate fragments, although a significant contribution of in situ carbonate producers is also envisaged. The carbonate components of the Rambla del Saltador benches show strong similarities to those forming marl benches in modern temperate lakes. In addition, the Upper Miocene carbonate benches are of similar size to their modern counterparts, such that depositional conditions, i.e., water depths on the platform and at toes of the benches, can be related to those of the ancient sediments. However, despite the observed similarities, some significant differences arise when the ancient example is compared to the modern ones. The main differences concern the discontinuous progradational pattern of the carbonate benches and, importantly, the evolutionary trend that leads to cessation of bench development and further sedimentary infilling of the lake basin. In this respect, the Rambla del Saltador deposits provide a very good illustration of the transition from a bench-type to a ramp-type carbonate lake margin, which contributes to a wider view of how carbonate lake margins can develop under different geological conditions.

CONCLUSIONS

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FIG. 11.—Comparison with the carbonate bench facies model derived from recent marl lakes (Murphy and Wilkinson 1980; Treese and Wilkinson 1982); A) Figure modified from Platt and Wright (1991) and B) the case study of carbonate benches from Rambla del Saltador. Main differences between the two models relate to the continuous vs. discontinuous progradational pattern of the bench, the evolution from bench to ramp, and the topographic control of previous depositional systems on the development of the carbonate benches.


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