TOPOGRAPHIC CONTROLS ON PRODUCTION AND DEPOSITION OF TIDAL COOL-WATER CARBONATES, UZÈS BASIN, SE FRANCE

JEAN-YVES REYNAUD, ROBERT W. DALRYMPLE, EMMANUELLE VENNIN, OLIVIER PARIZE, DAVID BESSON, JEAN-LOUP RUBINO

1 Museum National d’Histoire Naturelle, Department Histoire de la Terre, 43 rue Buffon, F-75905 Paris, France
2 Queen’s University, Department of Geological Sciences and Geological Engineering, Kingston, Ontario K7L 3N6, Canada
3 École Nationale Supérieure des Mines de Paris, 35 rue Saint Honoré, F-77305 Fontainebleau, France
4 Total, CSTJF, F-64018 Pau, France

ABSTRACT: We document an example of a cool-water carbonate deposit interpreted as a flood-tidal delta formed during sea-level fall in the Uzès basin (French Miocene foreland basin). In the Miocene it was a peripheral basin connected to the open sea by a narrow, 15-km-long seaway. The studied Uzès Formation is a 50-m-thick tidal bioclastic carbonate body, formed at the junction between the Uzès basin and the seaway. It is composed dominantly of rhodalgal packstones that are interpreted to have been produced inside the basin. However, most of the deposit was built out by bidirectional hydraulic dunes, suggesting that accumulation of carbonate grains was not controlled by production but rather by tidal currents. The deposit is thickest and coarsest grained, and exhibits the larger dunes at the inlet toward the basin; that is interpreted as a result of a decrease of current velocity due to flow expansion. The main deposit exhibits a general upward increase in thickness and grain size of cross-beds, together with a decrease of faunal diversity (from bivalve-rich to rhodalgal facies), consistent with progressive tidal flow acceleration in the seaway resulting from sea-level fall. Lime mud is pervasive in the matrix of even the highest-energy facies. This suggests that one cannot draw any average correlation between permeability and architecture of the deposit. Also, this could favor the observed early marine diagenesis of the deposit and give it a high preservation potential in the stratigraphic record.

INTRODUCTION

Cool-water carbonates may form large accumulations of clastic deposits (Nelson 1988b). In contrast to tropical carbonates, which are generally pervasively cemented by lime mud, cool-water carbonates are mostly skeletal in origin, sorted and accumulated by currents, so that the related deposits are expected to have good reservoir qualities (permeability, porosity). Ecology and taphonomy of cool-water carbonate producers have been studied extensively for 20 years (Lees and Buller 1972; Carannante and Simone 1988; Nelson et al. 1988b; Scoffin 1988; Boreen and James 1993; Gallagher et al. 1999; Sefian et al. 1998; among many others). Some contributions show the behavior of cool-water carbonates as clastics under currents (Anastas et al. 1997; André et al. 2003). Many comparisons are possible with the sedimentary dynamics of terrigenous clastics because grainy cool-water carbonates and large sand bodies might develop in the same high-energy shelf environments.

Tide-dominated deposits are probably among the best targets, because they occur in coastal areas, where carbonates have the highest diversity of producers. Benthic associations of species can be used to assess bedload transport paths by tidal currents over large areas (Reynaud et al. 1999a), as well as to determine the maturation of a current-swept deposit (Wilson 1988). A wide span of grain sizes is present in tidal deposits, reflecting contrasted current settings. Special attention must be paid to muds, which are produced abundantly in cool-water carbonate systems (Simone and Carannante 1988), because they may control much of the internal geometries and diagenetic evolution of the related coarser-grained sediment bodies. Also, the generally admitted increase of carbonate production during sea-level rise, at the same time as tide-dominated systems are reported to have their widest extent on shelves, suggests that tidal carbonates should be among the best targets for reservoir geology.

The scope of this paper is to explore the relationships between carbonate producers and tidal dynamics based on the example of a large cross-bedded carbonate body deposited in an enclosed, coastal basin without significant terrigenous supply.

BASIN OUTLINE

The study area is on the French side of the foreland basin of the western European alpine chain (Fig. 1). The evolution of this basin is well constrained, on the basis of geophysical (Guillev et al. 1990; Roure and Colletta 1996) and geological (Clauzon et al. 1989; Rubino and Clauzon 1996; Sissingh 2001) data. From the Aquitanian to the early Tortonian, the foreland basin was an open sea under the influence of large tides (Homewood and Allen 1981; Allen et al. 1985; Lesueur et al. 1990; Martel et al. 1994; Sztano 1995). This was particularly the case for the southern part of the “Rhodanian” Basin (named from the Rhône River), which has been studied extensively (Cumbaluzier 1932; Demarcq 1970). Miocene deposits have been correlated to high-order eustatic cycles and related sequences mapped throughout this area (Rubino et al. 1990; Besson 2005). The southern part of this basin, far from the alpine thrust belt and thus from siliciclastic sources (Fig. 1), was filled by almost only cool-water carbonates, the coarsest successions of which have been demonstrated to be tidal estuarine to offshore bars and dunes (Lesueur et al. 1990; Rubino et al. 1994; Dexpert 2001; Parize et al. 2001). Most of these deposits have been interpreted as incised-valley fills (Parize et al. 2001; Besson et al. 2002). To the southeast, tectonic subsidence was high, leading to a complex stratigraphy (Besson 2005). To the southwest, at the outer margin of the foreland, the interplay between sea-level change, carbonate production, and basin morphology is easier to unravel. In this area, the foreland basin ends in several marginal basins, the largest of which is the Uzès basin (Fig. 1).

The Uzès basin is a 15-km-wide depression that occupies a syncline of Cretaceous strata (Fig. 1). The folding was mostly achieved before the onset of deposition, and the present-day limits of the basin correspond mostly to the hightstand Miocene shoreline (Toussaint 2000). Minor
reactivation may have occurred during the middle and late Miocene (Besson et al. 2002; Séranne et al. 2002), leading to a southward tilting of the area less than 4°. The Uzès basin is connected to the east with the main Rhodanian Basin by a narrow sill in the Cretaceous basement, which acted as a seaway in the Miocene (Fig. 1). Facies and paleocurrent data suggest that any other connection to the sea would have been absent or minor (Toussaint 2000).

The Uzès basin succession comprises three lithostratigraphic formations. These consist of (from base to top): glauconitic sandstones (here named the Greenish Sandstones), offshore marls (here named the Grey Marls), and bioclastic carbonates. These formations do not crop out farther east in the seaway, but they have been found below younger Miocene strata where the seaway meets the Rhodanian Basin, in the Pont-du-Gard area (Fig. 1). In this paper, we describe the bioclastic carbonates, which we named the Uzès Formation, because they are present mainly in the southern part of Uzès basin, around the town of Uzès and near the connection with the seaway.

The three formations in Uzès basin have been attributed to the Burdigalian for a long time (Demarcq 1970). New identifications of benthic foraminifers (E. Bicchi, personal communication) and nannofloras (S. Gardin, personal communication) suggest a Late Burdigalian age for the Grey Marls and also for mudstones layers found inside the Uzès Formation. However, recent reassessment of stratigraphic sequences in the Rhodanian area have highlighted the importance of reworking by transgressive ravinement (Besson 2005). Therefore, it is also possible that Uzès Formation, as other bioclastic deposits delivering typical Burdigalian faunas in the Rhodanian Basin, could be Langhian or Serravalian.

DESCRIPTION OF THE UZÈS FORMATION

The description of the deposit synthesizes three types of data at different scales: (i) petrography and taphonomy from thin sections, (ii) outcrop panels for bedding and paleocurrents, and (iii) mapping and boreholes for large-scale geometry (km).

Outer Geometry

The Uzès Formation forms a 7-km-wide plateau resting on the Grey Marls in the north and west (Fig. 1). The limits in map of the Uzès Formation are erosional, because of fluvial incision by the Alzon and Seynes rivers during the Quaternary (Fig. 2). The top of the plateau has a morphology that is controlled in detail by Quaternary fluvial terracing (Fig. 2). It has an average slope of 4° to the south, which is consistent with the general dip of Miocene strata as measured in the Grey Marls below the Uzès Formation. Major bedding boundaries inside the deposit also appear to dip in that direction, so that the top of the Uzès Formation appears to be conformable with the general bedding throughout the area.

The cliffs related to fluvial incision allow examination of the contact at the base of the Uzès Formation. At the map scale, the Uzès Formation is underlain by the Grey Marls. The contact is erosional, showing that the Uzès Formation is incised about 20 m lower in the east than in the west, depicting a large-scale incision of the Uzès Formation inside the Grey Marls (Fig. 3D, E). Above this contact, the easternmost part of the Uzès Formation ends abruptly against the Cretaceous border of the basin by stratal onlap, without facies variation inside the Uzès Formation near the border. The Cretaceous limestone at the contact exhibits numerous borings, mostly by echinids. At the outcrop scale, the contact with the Grey Marls is not obvious, and the deposit below the Uzès Formation is a more specific mudstone (Table 1). White and chalky in aspect, this mudstone contains sparse planktonic foraminifers and calcareous nannofossils, the latter being difficult to identify because of strong dissolution, and possibly mechanical abrasion. A few decimeters below the Uzès Formation, the mudstone exhibits grainy laminae of shell fragments (mainly small bivalves) that are locally shaped into ripples. The contact itself locally exhibits meter-scale interfingering or mixing of Uzès Formation deposits with underlying mudstone.

Facies

The Uzès Formation consists of more than 70% skeletal carbonate. These are of “bryomol” type (Nelson et al. 1988b), ranging from...
Massive Beds.—These beds, which occur only at the base of the Uzès Formation, are mostly characteristic in the south (Fig. 5). Near the contact with the underlying mudstones, they are dominated by a bivalve-rich packstone with abundant floating mudstone clasts and gravel (Table 1, Fig. 5). The massive beds are 0.5 to 1.2 m thick, and locally exhibit subtle internal simple cross-bedding (Fig. 5). The contact with the mudstone consists of a 0.5-m-thick layer in which the bivalve-rich packstone is mottled, mixed with the underlying mudstone, with numerous Glossifungites burrows (Fig. 5). This mixed layer contains rounded and flat blocks, 0.1 to 2 m in diameter, composed of well cemented, laminated bivalve-rich mudstone, interconnected by Ophionomorpha and encrusted by serpulids on their upper side (Fig. 5). The bivalve-rich packstone grades upward to a rhodalgal packstone, which may be very coarse-grained where the base of the Uzès Formation is the least elevated (Fig. 6).

Shelly Beds.—This facies occurs from the lamina scale to large cross-beds, interfingered with the white mudstones at the base of the Uzès Formation, in the north and east (Fig. 6). It is dominated by a bivalve-rich grainstone (Table 1) with abundant clusters of reworked, entire shells. Burrows (Diplocraterion) are common. The thicker beds are also coarser grained and commonly exhibit discrete inclined beds, demarcated by mudstone laminae (Fig. 4).

Bioturbated Beds.—This facies dominates in the outer, western part of the Uzès Formation, where the deposits are thinner. The bioturbated beds consist of amalgamated lens-shaped, flat-bedded to flaky mottled rhodalgal packstone to mud-rich floatstone (Table 1, Fig. 7). The floatstone exhibits angular aragonitic bioclasts mixed together with abraded, rounded calcitic ones. The lenses are about 0.5 m thick and 15 m in lateral extent. The recessive intervals between the beds have a more muddy matrix and are finer grained. In the outer part of the Uzès Formation, the bedding is overall blurred by intense bioturbation. Toward the center of the Uzès Formation, bioturbation in these beds decreases and the beds locally exhibit a more detailed internal structure. There, the lens-shape beds have a flat base, a convex-up top, and an increase of mud in the matrix toward the edges of the lens (Fig. 4). They show a parallel to low angle downlapping internal lamination with local ripples superimposed at the toesets of the beds (Fig. 4).

Heterolithic Cross-Beds.—This facies is observed at the base in the north of the Uzès Formation, mostly above shelly beds. The main part of this facies consists of trough cross-bedded bivalve-rich packstone–grainstone, interbedded with up to 0.1 m thick mudstone (Table 1, Fig. 8). The mudstone is located in the troughs, which are up to 0.5 m in depth and 5 m in extent (Fig. 4). It contains low-angle grainstone laminae that downlap onto the trough base and are traceable updip into the packstone–grainstone cross-beds (Fig. 8). This heterolithic lamination in the mudstone beds commonly forms bundles of 8 to 13 mudstone–grainstone couplets, showing a progressive thickening and thinning of grainstone laminae within the bundles (Fig. 8, detail). The thicker grainstone laminae exhibit preserved ripple formsets. The heterolithic cross-beds are grouped in successions of amalgamated trough cross-beds, which define tabular master beds dipping dominantly to the north at 5–10° (Fig. 4).

Coarse-Grained Cross-Beds.—This is the main facies, forming the central, eastern, and southern part of the Uzès Formation. It is composed dominantly of rhodalgal packstone and floatstone (Table 1), well sorted and with relatively low faunal diversity (particularly with respect to bryozoan species). Some Thalassinoides burrows are present at the bases of the thicker beds, but otherwise this facies is unburrowed. The 0.2–1 m
thick cross-beds are composed of sets of planar to trough laminae (Fig. 4). In simple cross-beds, laminae are mostly parallel to bed boundaries, and the dip of beds reaches 25°. In compound cross-beds, laminae are oblique to bed boundaries, which dip generally less than 15°. Very commonly, laminae in compound cross-beds dip obliquely up the slope of the beds. The dip direction of laminae may also vary from one bed to another, more rarely inside the same bed. Inclined, tabular to arcuate cross-beds form coarsening-upward cross-bedded successions, 2–12 m thick and about 100 m in extent (Fig. 4). The bases of cross-bedded successions are composed of 0.1–1 m thick bioturbated mudstone. They correspond to the amalgamation of bottomsets of the cross-beds (Fig. 4). The coarser-grained top of cross-bedded successions is generally composed of trough cross-beds (Figs. 4, 9). The thickest cross-bedded successions are observed in the south (Fig. 9). They comprise arcuate cross-beds up to 8 m in height. The toesets of these beds are composed of mud-rich floatstone, and the upper part of the foresets is dominated by rudstone. This deposit contains the largest rhodoliths, and exhibits the highest biodiversity in bryozoan species.

**Large-Scale Architecture**

**Facies Successions.**—Larger-scale bedding within cross-bed successions define < 10 thick units (U) overall parallel to the regional dip and to the plateau surface, that are stacked or incised on each other (Fig. 3B, C, D, E). Units are bounded by abrupt facies changes, namely coarse lags of rhodoliths and bryozoans (base of U3, Fig. 6) or major recessive intervals (bioturbated mudstone at the base of U4).

Unit 1 is preserved in the eastern and southern part of the Uzès Formation (Fig. 10). It is composed of dominantly shelly or massive beds, passing into each other, infilling the lower parts of incision at the base of the formation (Fig. 3A, B, F, G). Bed successions in this unit commonly have a fining-upward trend (Fig. 6).

Units 2 to 4 form the main part of the deposit in the center and the north of the Uzès Formation (Fig. 10). They are composed of coarse-grained cross-beds, passing laterally into bioturbated beds toward the west and heterolithic beds toward the north (Fig. 3D, E). In unit 3, the coarse-grained cross-bedded successions are overall thickening and coarsening up, the upper successions also showing large-scale complex cut-and-fill patterns (Fig. 6). Laterally, the bioturbated beds record an upward increase of bed amalgamation (decrease of occurrence of recessive interbeds) together with an increase of mud in the matrix (rhodalgal packstones passing upward to mud-rich floatstones). Unit 4 is composed almost entirely of coarse-grained cross-beds, overlapping bioturbated beds of unit 3 in the western part of the formation (Fig. 3D, E). At the top, corresponding mostly to the ground surface of the Uzès plateau, the lows in the formsets of the cross-bedded successions
### Table 1. Summary of petrography of the main lithologies composing Uzès Formation bioclastic carbonates.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Skeletal grains (by decreasing abundance)</th>
<th>Skeletal grain size in mm (mean-max)</th>
<th>Non skeletal grains (Qz quartz and lithic)</th>
<th>Matrix and cement</th>
<th>Microstructures</th>
<th>Outcrop bedding (by decreasing occurrence)</th>
<th>Dominant location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mudstone</td>
<td>Planktonic and benthic foraminifers, sponge spicules, ostracods, bivalves, radiolaria, bryozoan and red algae debris (in packstone laminae only)</td>
<td>&lt; 0.01–2</td>
<td>Abundance and grain size</td>
<td>Micrite: lime mud, poorly cemented</td>
<td>Sparse laminae, sharp based, disrupted by bioturbation (commonly &lt; 1 mm thick)</td>
<td>Heterolithic trough cross-beds</td>
<td>Base in the north (U1–2)</td>
</tr>
<tr>
<td>Bivalve-rich packstone to grainstone</td>
<td>Bivalves, echinoderms, bryozoans, foraminifers (mostly miolildae, rare planktonic), gastropods, serpulids, ostracods, corals, red algae, sponge spicules</td>
<td>0.5–10</td>
<td>Abundance and grain size</td>
<td>Primary matrix of finer-grained bivalve-rich wackestone to packstone. Where cemented, micrite in clusters or in umbrella porosity. Syndauxial to fibrous cement coating the grains laminite locally disrupted by bioturbation</td>
<td>Matrix-filled perforations on big bioclasts</td>
<td>Shell beds, massive beds, heterolithic trough cross-beds</td>
<td>Base (U1–2)</td>
</tr>
<tr>
<td>Rhodalgal packstone–floatstone</td>
<td>Mutually encrusting bryozoans and red algae (rhodolites), bivalves, echinoderms, ostracods, arthropods, serpulids</td>
<td>2–50 (for rhodolites)</td>
<td>Abundance and grain size</td>
<td>Patcstone-rudstone: locally syntaxial, fibrous and drusy cements</td>
<td>Floatstone: common heterolithic lamination (= calcarenite laminae with top encrusted by red algae, overlain by mudstone drapes), bioturbation disrupting lamination</td>
<td>Shell beds, massive beds, bioturbated beds</td>
<td>Main part (U2–U5)</td>
</tr>
<tr>
<td>Rhodalgal grainstone–packstone to calcarenite</td>
<td>Coarser-grained facies (grainstone dominant): bryozoans, bivalves, foraminifers, gastropods, red algae, echinoderms (dominant in calcarenite).</td>
<td>0.5–15</td>
<td>Abundance and grain size</td>
<td>Micrite coating the grains. Fibrous to drusy cement</td>
<td>Overall very bioturbated</td>
<td>Simple cross-beds, bioturbated beds, coarse-grained massive beds, coarse-grained laminae in mudstone</td>
<td>South (U1–U5)</td>
</tr>
</tbody>
</table>

are “filled” by muddier and more bioturbated floatstones, which also may overlie the topsets (Fig. 3D, E). The cross-beded succession and unit boundaries within U2–U4 dip overall toward the basin at < 10° (to the north on N–S sections, to the west on E–W sections; Fig. 3).

Unit 5, restricted to the southern part of the formation, is the only one with strong erosion at its base, onto which the deposits pinch out northwards (Fig. 3A, B, F, G). The erosional unit base gets flatter and rises to the north, where it pinches out above the base of unit 4 (Figs. 3A, B, 6). Unit 5 comprises the coarsest-grained and largest cross-beds of the whole Uzès Formation, the vertical succession of which is overall thinning and coarsening upward (Fig. 9). The topmost beds are flat trough cross-beds of calcarenite with a large amount of lithic gravels and shell lags.

**Paleocurrents.**—Cross-bed dips were analyzed for paleocurrent reconstruction. Ripple-scale bedforms, as well as large compound cross-beds, are not taken into account because they generally are not in equilibrium with the flows that built them, especially in tidal, coastal settings, because their lag time is much less or much more than a single tidal cycle (Dalrymple and Rhodes 1995). Thus, simple cross-beds 0.2–
2 m in height were used to define mean bedload transport directions (Fig. 11). The results are not corrected for postdepositional tilting because the latter accounts for less than 2–4° of the strata dip, whereas the measured foreset beds dip approximately 20°.

The cross-bed dip directions show a large dispersion, probably because of (i) the local influence of seafloor relief (e.g., flow constrained by channel paths, or deflected over larger bedforms) and (ii) the heterogeneity of dip measurement over the foresets of 3D cross-beds. However, two stratigraphically distinct direction groups are identified (Fig. 11). The first group corresponds to measurements obtained at the base of the Uzès Formation, mostly in unit 1, and the lower part of unit 2, but also from the lowermost part of unit 3 where it forms the base of the formation. The mean flow directions in this group are toward the northeast and southwest, the latter direction being a little more commonly measured. The second group includes the measurements from all of the upper units. It is characterized by a strong predominance of northwest directions.

**INTERPRETATION**

The various lithologies of carbonates in the Uzès Formation are typical of cool-water to temperate-water coastal seas, with bathymetric ranges that largely overlap each other. The coarser-grained floatstones, with many large rhodoliths, may occur from the shoreface down to 50 m below sea level (Gallagher et al. 1999; “facies à pralines” of Pérès and Picard 1964). However, the petrography of the carbonates may help to unravel sediment dynamics. The Uzès Formation depositional model is deduced largely from bedding and lithology, because most of the deposit is cross-bedded, which is controlled by currents. Understanding this carbonate body is therefore the understanding of changing energy in space and time, which has some feedback on petrography and reservoir properties. Unit boundaries are interpreted as time lines, because they are widespread at the scale of the deposit and because they reflect sharp changes in depositional energy. Inside units, lateral facies changes are
gradational, at all scales, suggesting they are controlled mostly by basin morphology.

**Flood Tidal Deposition**

The cross-bedded facies that form the bulk of the Uzès Formation are shaped by currents that are bidirectional, although over a wide span (Fig. 11). Although pure bidirectional “herringbone” cross-bedding has not been observed, this is a major hint that the whole deposit should be tide-dominated, as is the case for all other clastic lower to middle Miocene formations in the Rhodanian Basin (Lesueur et al. 1990; Besson 2005). The bundling of marly–sandy laminae observed in the bottomsets of heterolithic cross-beds correspond to the lenticular bedding of muddy tidal flats, which is a classical signature of tidal environments in which deposition at slack water is marked by thick mud drapes (Fig. 8).

**Fig. 6.—Synthetic logs of the Uzès Formation from cliffs and quarry outcrops east of Uzès, with the proposed correlation (see Figs. 2 and 3 for location). Triangles represent grain-size trends (base = coarsest). Mb, massive beds; Sb, shelly beds; Cc, coarse-grained cross-beds.**

**Fig. 7.—Bioturbated beds in A) the west and B) the north of the Uzès Formation (see Figs. 2 and 3 for location). Bioturbation is higher in the west. The recessive intervals are more marly. In part A, the contact with the mudstones underlying the Uzès Formation is at the level of the road on the right side of the picture. The thickening-up pattern of the beds is perceptible. The coarse-grained cross-beds are about 2 m higher in the series. In part B, which is stratigraphically higher, the internal bedding is still apparent. Note in part B also the slightly convex-up formsets at the decameter scale (see Figs. 4 for synthesis).**
The bedforms at the origin of most cross-bedded successions in the Uzès Formation are therefore interpreted as subaqueous small to very large/giant tidal dunes (Ashley 1990). The cross-beds correspond to the dune foresets, their geometrical variations being related to the shape of the dunes (2D versus 3D), the presence of superimposed bedforms, and the rate of sediment transfer to the seabed (Rubin 1987). The laminae represent superimposed smaller dunes migrating obliquely either toward the crests or the troughs of the large dunes (Allen 1980). The mudstone between the cross-beded successions or in the troughs of heterolithic cross-beds would correspond to the bottomsets of the dunes. The trough cross-beds commonly topping the cross-beded successions could represent "repair structures," composed of small to medium 3D dunes reworking the crests of the large dunes (Dalrymple 1984). The largest cross-beds in the south are interpreted as giant 3D dunes. The "chevron" interbedding displayed in Figure 9 is interpreted as the structure of saddles separating the scour pits of the giant dunes. The troughs in that outcrop are incised over 3 m below the massive beds in Figure 5 (see also Fig. 3F, G). The increasing content of lime mud in the matrix of sediment from the upper (rudstone) to the lower part (mud-rich floatstone) of the cross-beds would express the spatial deceleration of currents from the crests to the feet of the dunes.

Large to very large tidal dunes are observed in offshore shelf areas, either as isolated individual dunes (Berné et al. 1989) or as part of very large sand bars (Reynaud et al. 1999b). Similar tidal dunes have been reported from the Rhodanian Basin (Lesueur et al. 1990; Parize 1996; Besson 2005) and other ancient cool-water carbonate shelves (Allen and Homewood 1984; Nelson et al. 1988a; Anastas et al. 1997; André et al. 2003).

Most of paleocurrents recorded in the main part of the cross-beded facies of the Uzès Formation are to the north (Fig. 11). Assuming that the Uzès basin was connected to the sea by the southern seaway only (Fig. 10), this suggests that the Uzès Formation is flood dominated.
Large-Scale Channels at the Base

The cross-bedded successions dominate where the Uzès Formation is most deeply incised (Fig. 3), suggesting that tidal currents may have been responsible for incision at the base of the formation as well as for infilling the incision. Lateral facies evolution points to an increase of muddiness toward the basin. This would be recorded by the passing from coarse-grained cross-beds to (i) bioturbated beds to the west of the incised area and (ii) heterolithic cross-beds to the north, thus downstream of the flood-dominated system (Fig. 10). The increase of muddiness is not scaled to maximum current velocity (the coarsest-grained floatstone in unit 5, which implies strong currents at the sea floor, is mud-rich) but rather to the duration of slack water in the tidal cycle.

Large-scale channels are suspected at the base of unit 1 (Fig. 6). The massive beds forming most of this unit in the lows have some characteristics of channel deposits. The mudstone blocks at their base (Fig. 5) have the same lithology as the eroded mudstone below the Uzès Formation, which suggests that they slid and were rafted from firm muddy cliffs. The Glossifungites burrows underly the blocks are typical of firmgrounds (MacEachern et al. 1992; Gingras et al. 2001). Another hint that the lower contact of these beds would represent a channel floor is the low sedimentation rate and strong bypass suggested by the network of Ophiomorpha burrows and by the occurrence of serpulids encrusting the upper sides (only) of the rafted blocks (Fig. 5). The lenses of shelly beds in unit 1 are likely to correspond to lag accumulations commonly occurring at channel floors. Their interbedding with the mudstones (Fig. 6) suggests an episodic supply and strong current threshold, which are consistent with tidal-channel settings.

The bioturbated beds at the western margin of the channelized area are interpreted as low-relief bedforms (Fig. 7). The ripples preserved at their foot suggest that these bedforms were originated by currents or at least that currents were temporarily present at the time of deposition. The higher mud content in the troughs between the bedforms (Fig. 4), similarly to what is observed in dune systems, argues in favor of current segregation of grains and is probably a feedback of the bedform influence on current velocity. However, the pervasive, intense bioturbation and the high amount of mud in this facies suggest that currents were below the threshold of motion of the mean grain size most of the time. This is consistent with the low relief of the bedforms and the presence of well preserved fragile bioclasts (aragonite).

Progradational Architecture

The vertical facies evolution from thin heterolithic cross-beds to thick, coarse-grained compound cross-beds in the northern part of the deposit (Fig. 3B, C) suggests a progressive increase of current strength in that area. The same evolution is recorded on the western side of the formerly channelized area, where coarse-grained cross-beds overlap bioturbated beds (Fig. 3D, E). The upward increase of amalgamation and lithic content of the bioturbated beds in that area (Fig. 7A) is consistent with...
a progressive increase of frequency and duration of current surges above the threshold of motion of the mean grain size.

The overall geometry of deposition inside units 2–4 is therefore progradational, with higher-energy facies migrating basinwards above lower-energy ones. At the unit scale, master beds commonly dip to the north or northwest (Fig. 3), which is toward the basin. This expresses the same progradational pattern. As well, facies successions that build up the units show a general coarsening- and thickening-upward trend (Fig. 6) that is consistent with an overall (punctuated) progradation of the deposit.

The increase of tidal energy (in both current speed and duration) that is expressed by this vertical facies evolution is also recorded to the south of the Uze basin, where the coarsest and thickest cross-beds of unit 5 are incised down to the Grey Marls (Fig. 3A, B, F, G).

**A Flood-Tidal Delta**

The maximum incision of unit 5 is located in the southernmost part of the Uze basin, where the Uze basin is narrowest and meets the seaway connecting it to the main Rhodanian Basin (Fig. 3A, B). Tides must come from there, as demonstrated by the higher position of the interfluves elsewhere around the basin (Toussaint 2000). The increase of tidal energy in that direction suggests that the whole deposit was controlled by tidal flow acceleration in that seaway, which may have acted as a tidal pass. The main clastic deposit in the Uze Formation would thus correspond to a flood-tidal delta, built up where the tidal flood current expands from the tidal pass to the basin (Hayes 1975; Dalrymple et al. 1992). The forward-decreasing energy and the progradational pattern are two major hints in favor of such an interpretation, on the basis of study of modern examples (Boersma 1991; Murakoshi and Masuda 1991; Davis et al. 2003). The erosional surface below unit 5 would correspond to the tidal inlet, floored by a tidal ravinement surface, which would partly explain the sharp base of the tide-dominated deposit (Willis and Gabel 2001). This surface, which rises to the north up to the base of unit 4, would be the “source diastem” (Thorne and Swift 1991) of most of the deposits in units 2–4. The presence of large rhodoliths in the floatstones of the giant dunes infilling the tidal inlet suggest significant bypass and averaged low sedimentation rates over the tidal ravinement surface (Hottinger 1983).

In classical flood-tidal deltas, which belong to wave-dominated estuarine depositional systems, the barrier behind the deposit does emerge. One cannot demonstrate the subaerial position of the Cretaceous highs surrounding the basin during deposition of the Uze Formation, because of the absence of paleosols or typical meteoric morphological features. The anticlines might have been transgressed during Miocene highstands of sea level in many areas of the Rhodanian Basin, and reworked as wave-cut platforms (Besson 2005). However, connections of the Uze basin with the open marine realm seem to have been weak at the time of deposition of the Uze Formation, as suggested by the scarcity of syndepositional open marine nannoflora and microflora in the Grey Marls (Toussaint 2000; E. Biachi, personal communication) and the relatively high diversity of siliceous microfossils (diatoms, sponge spicules, radiolarian debris; Toussaint 2000). Strong limitations to the development of full, open marine conditions are also indicated by the abundant pyrite grains in the mudstones (P.-J. Giannesini, personal communication), which suggest anoxic conditions at the sea floor (sulfate reduction) and therefore eutrophic conditions consistent with basin restriction. Therefore, not necessarily everywhere above sea level, the basin borders may have acted as a barrier against tidal flows, which would have been concentrated and thus accelerated in the seaway behind the Uze Formation. Similar tidal deposits, controlled by flow expansion across submarine passes, have been reported from offshore areas (Kamp et al. 1988; Newell 2001).

**Sea-Level Changes**

The chronostratigraphic interpretation of the Uze Formation as a flood-tidal delta is synthesized in Figure 12. The deformation of strata in the Uze Formation is postdepositional, as demonstrated by the same general dip as that in the underlying Grey Marls, which is weakly tilted to the south. Folding and faulting of the basin substratum was quite completed at that time (Reynaud et al. 2001), as demonstrated namely by the unchanged dip of the Grey Marls across the Cretaceous anticline axis to the east of the Uze basin (Fig. 1). Therefore, changes in relative sea level recorded in the Uze Formation are eustatic.

The Grey Marls exhibit numerous clasts of small bivalves typical of relatively deep shelf settings (*Corbicula, Lucina, Tapes*; Demarcq 1970). By contrast, most of the ecological associations inside the Uze Formation occur in coastal areas. Given that, the strong increase in tidal energy associated with (i) the development of the Uze Formation tidal deposits above the Grey Marls and (ii) the upward-coarsening trend of facies inside the Uze Formation must have been controlled by a sea-level fall, although in the latter argument one cannot rule out the possible role of rapid sediment accumulation on the progradational pattern, and therefore the acceleration of currents on top of the deposit. Although periods of sea-level fall are not considered as favoring carbonate production on shelves, there are some other, well-described examples of sharp-based clastic carbonates deposited as forced-regression wedges (Pomar and Tropeano 2001).

There is no hint that the Uze Formation was exposed above sea level in the course of this sea-level fall. In that case, the formation would be overscoured by the lag surface at the top of unit 5 (Fig. 6) but subsurface
data would be required to demonstrate it (if so, a fluvial valley cutting the Uzès Formation farther east in the seaway should exist under Quaternary deposits of the Alzon River). Thus, the Uzès Formation would correspond to a falling-stage systems tract (Hunt and Tucker 1992). This situation is likely, because the main Burdigalian lowstand shelf deposits are located farther south near the shellbreak of the Mediterranean margin (Bache 2003). In this respect, the sequence boundary should be placed above unit 5 and not at the base of the Uzès Formation (Fig. 12).

In any case, deposition of the Uzès Formation ended when most of the deposit was still under significant water depth, as demonstrated by the bioturbated beds draping the troughs of the large dunes at the top of unit 4 (Fig. 3D, E). The dunes are not reworked into smaller bedforms, suggesting that this change occurred because of an abrupt cessation of tidal currents. A change of the tidal phase and amplitude inside the basin due to a rise or fall in sea level that could explain such a current cessation would last much more than the lag time of the dunes in unit 4. Therefore, fossilization of these dunes is more likely to correspond to a rapid closure of the tidal inlet, which is expressed by in-place deposition of unit 5. This could happen because of aggradation of the delta, so that flow deceleration in response to increase in friction would exceed its acceleration by constriction above the deposit.

If any transgressive to highstand, finer-grained deposit was deposited at the top of Uzès Formation, as in the classical depositional model of the Rhodanian Basin (Rubino et al. 1990), it has been removed by erosion. Higher-order cycles of sea-level change may be preserved inside the Uzès Formation, which would be marked by the sharp facies shifts at the unit boundaries (Fig. 3). A similar architecture is observed in other flood-dominated deposits in the Rhodanian Basin, as, for example, in the Saumane-Venasque incised-valley fill (Besson et al. 2002; Dalrymple, unpublished observations).

**DISCUSSION**

**Sediment Sources**

The hinterland of the Uzès basin favored the deposition of carbonate sediments instead of siliciclastics because, as interpreted by Brachert et al. (2003) for other basins, the surrounding limestone relief was probably moderate. The petrography of the Uzès Formation shows that most of the bioclasts probably originated inside the basin or were imported from nearby areas. Most of the biota present in the coarse-grained facies was probably derived from rocky or granular substrates swept by currents (cf. James 1997; Cebrian et al. 2000; Smith and Nelson 2003). This is particularly the case for encrusting, spherical forms, the shape of which expresses continuous reworking (the rhodoliths; Bosence 1991). However, even under strong currents, encrusting bryozoans may develop and remain fixed at the sea floor (Bassant 1999; Smith et al. 2001).

Early authors had noticed the general occurrence in the Rhodanian Basin of Miocene bioclastic carbonate formations above or against Cretaceous highs, while marly formations were found in the centers of the sub-basins (Demarçq 1970). More recently, more attention has been paid to the impact of sea-level fall on reworking in incised valleys of carbonate produced on their interfluves during the preceding highstands (Besson et al. 2002). Reworking and importation are obvious in the bioturbated beds of the Uzès Formation, because abraded bioclasts are mixed together with fragile, freshly supplied forms (namely fragile echinids). The coarser rounded clasts as rhodoliths may have been transported over large distances (Piller and Rasser 1986). Thus they also could be supplied from the surrounding areas of the basin experiencing sea-level fall, as well as from the seaway, which would then have been flood-dominated also.

However, most of the species assemblages observed in the Uzès Formation reflect biota that could be adapted to local hydrodynamics and therefore could be produced in situ as well. The facies variations in space are well followed by ecological variations of the bioclast assemblages (Table 1). For instance, not only the coarsest clasts but also those from the most robust bryozoan species are found inside the largest dunes of unit 5. The more quiet, marly peripheral areas, in contrast, contain more delicate branching bryozoans, as well as bivalve- and sponge-rich facies that seem to be adapted to the deeper and/or sheltered areas (Gostin et al. 1988). Similarly, vertical facies successions record changes in depositional environments that suggest the same general story as that interpreted from bedding and lithology. The base of the deposit is dominated by bivalve-rich facies while the upper part mostly consists of rhodalgal facies (Table 1). This change reflects decreasing trophic conditions, which are related to the acceleration of currents. Correlatively, the biodiversity of the deposit decreases upward. This trend has been observed in several Miocene classic carbonate sequences of the whole Rhodanian Basin (Nelly 1978).

**Petrography and Architecture**

Overall, the distribution of all grain sizes in the Uzès Formation is controlled by tidal currents, not by carbonate production, inasmuch as production might occur everywhere. Therefore, the flood-tidal delta has the classical attributes of its siliciclastic counterparts (this is why it is interpreted so). Some morphological specificities, however, are worth noting, as possibly controlled by the carbonate nature of the deposit.

**Petrography.**—The grain size of the coarse clasts are scaled to current speed. This is not the case for mud, because the mudiest facies can also occur inside the largest and coarsest-grained dunes (Table 1). The mud between the grains and in the mud drapes reflects only the muddiness of water, which was therefore quite high in the Uzès basin. Mud is deposited at slack water, and its preservation suggests that long-term tidal drifts were weak or slower than the rate of mud production. The origin of the mud is dominantly from erosion, either bioerrosion or erosion by mechanical abrasion of the coarser skeletal grains reworked by currents (Farrow and Fyfe 1988; Young and Nelson 1988; Brachert and Dullo 2000; Smith and Nelson 2003). Production of lime mud may have occurred within the carbonate factory or by reworking of the Grey Marl. The white mudstone at the base of Uzès Formation, composed mostly of abraded or dissolved microclasts and nannoclasts of lime, could be the partly the result of such reworking and downstream transportation (Blom and Alsop 1988; Carnannante and Simone 1988; Gostin et al. 1988). The occurrence of a large amount of highly “floatable” sponge spicules in the mudstone is consistent with this hypothesis (James and Bone 2000; Gammon and James 2003). The coexistence of very coarse sediment and abundant mud is rare in siliciclastic settings, where sediments are sorted mud farther ahead of the area of deposition. In cross-beded carbonates, the abundance and location of mud as deciphered by tidal dynamics would be an important guideline for assessing diagenetic and reservoir properties of the deposit.

**Architecture.**—The delta was large as it is scaled to the basin. More than 50 m at its thickest, its architecture suggests a high aggradation rate (Fig. 6). Basically, this could be explained by the fact that the delta could not shift sideways, because of the fixed position of the seaway (in contrast to tidal passes cut in sandy barriers). Thus, deposits were accumulated on top of each other. Several other arguments, related to the carbonate nature of the deposit, can be suggested: (i) The high aggradation can be due to the fact that carbonate clasts were supplied continuously from everywhere upstream of the tidal current. (ii) Cool to temperate carbonate ecosystems can produce particles at high rates (Halfair et al. 2001; Smith et al. 2001). (iii) Physical consolidation of the sediment could have taken place during deposition, as suggested by the presence of laminae of encrusting bryozoans and red algae in the toesets
of the large dunes. (iv) Early, marine cementation of the large dunes could have forced the system to aggrade.

On the latter point, the early closure of porosity, either by the lime mud or by cements (Table 1), may be an important condition for preservation of the deposit. This situation contrasts with burial diagenesis as reported from other example of cool-water clastic carbonates (Nelson et al. 1988a).

Vadose cements and calcite replacement of dissolution voids are rare in the Uzès Formation, in spite of a 15 Myr evolution of the rocks at the ground surface above sea level. It seems that most of the meteoric fluids could have circulated at the impermeable, marly boundary of the Uzès Formation, partly explaining the intense dissolution features observed in the mudstones at this level.

CONCLUSIONS

The Uzès Formation is a clastic, cool-water to temperate carbonate body interpreted as a flood-tidal delta deposited in an enclosed marine basin because of a sea-level fall. The sea-level fall would have amplified the tidal wave and constrained tidal currents into a seaway connecting the basin to the open sea. Tidal currents would have been responsible for erosion of formerly deposited highstand marls in the basin, which would have supplied large amounts of lime mud into the tidal system. The tidal deposit is composed of coarse-grained cross-beds in the axis of the paleo-seaflow, passing laterally to bioturbated, muddier beds. The flood-tidal delta architecture was fully controlled by tidal dynamics. It is uncommonly thick (max. 50 m), probably because the tidal inlet could not shift sideways. While the onset of tidal currents could have been progressive, they ceased abruptly, likely because of the closure of the inlet after the rapid aggradation of the delta.

In addition, this study addresses some prospective issues about clastic carbonate systems:

(1) Most tidal systems that are well documented are part of transgressive stratigraphies. This is generally related to the morphology of the shelf area: empty of sediments during sea-level rise, there is space enough to develop a tidal wave; overfilled with highstand deposits at the onset of sea-level fall, there is not enough submarine space to form tidal systems. Basins with carbonate basement, which would supply less terrigenous sediment to the coast than their siliciclastic counterparts, could be privileged targets for regressive tidal systems, as is the case with the Uzès Formation.

(2) In spite of their behavior as clastic grains, which is by nature transportation and sorting by currents, the clastic carbonates in the Uzès Formation are likely to have been produced mostly in situ, because there is a good match between depositional environment as described by paleoecology, on the one hand, and bedding and physical structures, on the other hand. This suggests that specific production and deposition areas could be the same in carbonate, current-dominated systems.

(3) Because sediments were produced everywhere in the Uzès basin, sediment supply can be ruled in the process of unravelling sedimentary dynamics from stratal and facies patterns. The tidal deposit is thus interpreted as a pure interaction between morphology and hydrodynamics. For instance, the pinchout of the flood-delta fringe reflects only the current deceleration due to flow expansion inside the basin. From point 2 above, it comes that production adapts to morphology.

(4) Unlike more classical, grainy cool-water carbonates, the Uzès Formation carbonate system produced lime mud by mechanical abrasion or bioreosion of bioclasts (plus that eroded from the underlying marls) faster than it could be re-suspended and removed by long-term tidal drifts. The lime mud fills most of the primary porosity of the tidal facies of both the highest and lowest energy, which would bring about a high preservation potential of the deposit, but also a low permeability of the related reservoir.

ACKNOWLEDGMENTS

This work was funded by grant FR32 of the French National Research Council (CNRJ-3-Y.R.), by grant #5553-01 from the Natural Sciences and Engineering Council of Canada (R.W.D.), and by the French National Museum for Natural History. We thank Silvia Gandi (CRNRS) and Erica Bicchi (ERADATA) for their micropaleontological analyses. We wish to thank the reviewers, namely Gene Rankey and Toni Simo, and the Editor, Colin North, for pushing the authors to extract the best from their observations. We also thank the Corresponding Editor John Southard for polishing the manuscript.

REFERENCES


Cronin, L.E., ed., Estuarine Research, Vol. II, Geology and

Peryt, T.M., S. J. Glosifungites

M. R. Ome \n
J.-Y. REYNAUD ET AL.

S. P. H. ´erosion polyphase

J.-Y. REYNAUD ET AL.

C. E. W. U. EXCOTE

AVIS

ALRYMPLE

Mioce

A Core Workshop, SEPM, Core Workshop 17, p. 169–198.

G. A. EYNAUD

N. P. ARMART, A. T.

G. E. EYNAUD

G. \n
A. T. MITH

H. ISSINGH

G. A.

S. G.

N. L.

M. LITT

P. B.

E. Y.

D. M.

A. M.

S. G.

L. G.

B.

K.

M.

M. ROPPEANO

O.

R.

A. T.

G. \n
A. P.

D.

R.

S.

A.

W.

T.

M.

A.

S.

J.

B.

K.

P.

R.

T.

P.

P.

K.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.

P.

R.

T.


Received 6 May 2004; accepted 8 May 2005.