
High-frequency carbonate-siliciclastic cycles in the Miocene of the Lorca Basin (Western Mediterranean, SE Spain)

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| ABSTRACT |

The Upper Miocene Parilla Formation, Lorca Basin, Spain, provides an example of stacked high-frequency cycles of mixed carbonates and siliciclastics. Cycles developed on a steep carbonate ramp bordering an alluvial-fan system. Three cycle variants are distinguished: siliciclastic-dominated cycles at the proximal part of the ramp, mid-ramp mixed carbonate – siliciclastic cycles, and carbonate-dominated cycles on the more distal parts of the ramp. The vertical thickness of these stacked simple sequences ranges from 0.7 up to 8 m. High-frequency changes in relative sea level resulted in a dynamic interplay between terrigenous sediment supply and carbonate production rates. During falling stage and lowstands, the alluvial system migrated basinwards and coarse-grained siliciclastics were deposited, whereas rising sea level and highstands provided optimal conditions for the production and accumulation of biogenic carbonates. Coral colonies up to 4 m thick provide a minimum measure of the magnitude of sea-level change involved in the development of the cycles. In contrast to previously documented simple carbonate sequences, this hybrid system of carbonates and siliciclastics preserves a more complete record of cyclic sea-level change, where terrigenous sediment supply compensated for the reduction in carbonate production during periods of falling and low sea level.

KEYWORDS | Mixed carbonates-siliciclastics. Cyclical sedimentation. Sea-level change. Miocene. Spain.

INTRODUCTION

In stratigraphic successions of mixed carbonate – siliciclastic lithofacies, sequence development is often ascribed to reciprocal sedimentation expressed by the alternation of platform carbonates during transgressive and highstand periods, and basinal or “off-platform” lowstand accumulation of siliciclastic material. These types of sequence stratigraphic models are relatively well documented from wide shelves of large-scale carbonate systems interacting with major sources of siliciclastic input (Holmes and Christie-Blick, 1993; López-Blanco, 1993; Southgate et al., 1993; López-Blanco et al., 2000; Mon-

stad, 2000; Tucker, 2003; Campbell, 2005; Wilson, 2005). Another commonly cited type of large-scale mixed system is where the siliciclastic end-member is represented by “default” shale deposition during the lowstand and early transgressive periods of the relative sea-level curve, and a succeeding highstand “catch up” phase of carbonate production (Strasser et al., 1999).

On a smaller scale, high-frequency cycles are a characteristic feature of carbonate platform and ramp depositional systems (Pomar, 1991; Pratt et al., 1992; Braga and Martin, 1996; Wright and Burchette, 1996; Strasser et al., 1999; D’Argenio et al., 2005). Typically, these cycles

form shallowing-upward parasequences bounded by marine flooding surfaces, or simple sequences characterised by bounding surfaces of forced regression (Vail et al., 1991; Schlager, 2005). The sedimentary record of falling sea level and lowstand conditions in these types of small-scale cycles is generally limited and commonly represented by soil development or a hiatus. As a result, deposits of some cyclic carbonate successions may represent no more than ca. 60% of the period of a single sea-level cycle (Hillgärtner and Strasser, 2003). In contrast to the vast literature on purely carbonate cycles and larger-scale mixed successions, comparatively little attention has been directed toward hybrid simple sequences where terrigenous sediments make up a significant proportion of the cycles (Holmes and Christie-Blick, 1993; Rankey et al., 1999; Tucker, 2003). In this paper an example of such a depositional system is documented and it is shown that it provides a setting where more complete records of cyclic sea-level changes can be preserved, terrestrial sediment supply compensating for the reduction in carbonate production during periods of falling and low sea level. These small-scale mixed carbonate – siliciclastic cycles accumulated on a steep ramp bordering an alluvial-fan system where the falling stage and lowstand systems tracts are preserved as coarse-grained siliciclastic deposits, while the transgressive and highstand systems tracts are represented by respectively mixed carbonate – siliciclastic and pure biogenic carbonate facies.

GEOLOGICAL SETTING

The Lorca Basin (Fig. 1A) is an intramontane depression which belongs to a system of interconnected Neogene basins located in the eastern part of the Betic Cordillera in SE Spain. The basin is bounded by NE-SW trending wrench faults at its NW and SE margins, and normal faults at the NE and SW margin. It is considered to represent a pull-apart basin (Montenat et al., 1990; Montenat and Ott d'Estevou, 1999). These fault systems had a significant influence on Neogene sedimentation and were periodically active during the Miocene (Guillén-Mondejar et al., 1995; Montenat and Ott d'Estevou, 1999; Thrana and Talbot, 2005).

Along the southern margin of the basin, which is the focus of this study, Miocene deposits total ca. 130 m and are characterised by lithic heterogeneity and frequent lateral facies changes. The interval of interest here is the Tortonian Parilla Formation of the pre- evaporitic unit (Fig. 1B; Geel, 1976; Dittert et al., 1994; Wrobel and Michalzik, 1999). This formation comprises four units of carbonate ramp sedimentation which interfinger with alluvial conglomerates in proximal areas, and grade distally into basinal marls. The seaward termination of the ramps is however obscure due to faulting and partly covered outcrops. The small-scale cycles described in this paper occur within the uppermost ramp unit of the Parilla Formation which is characterised by a gradual backstep-

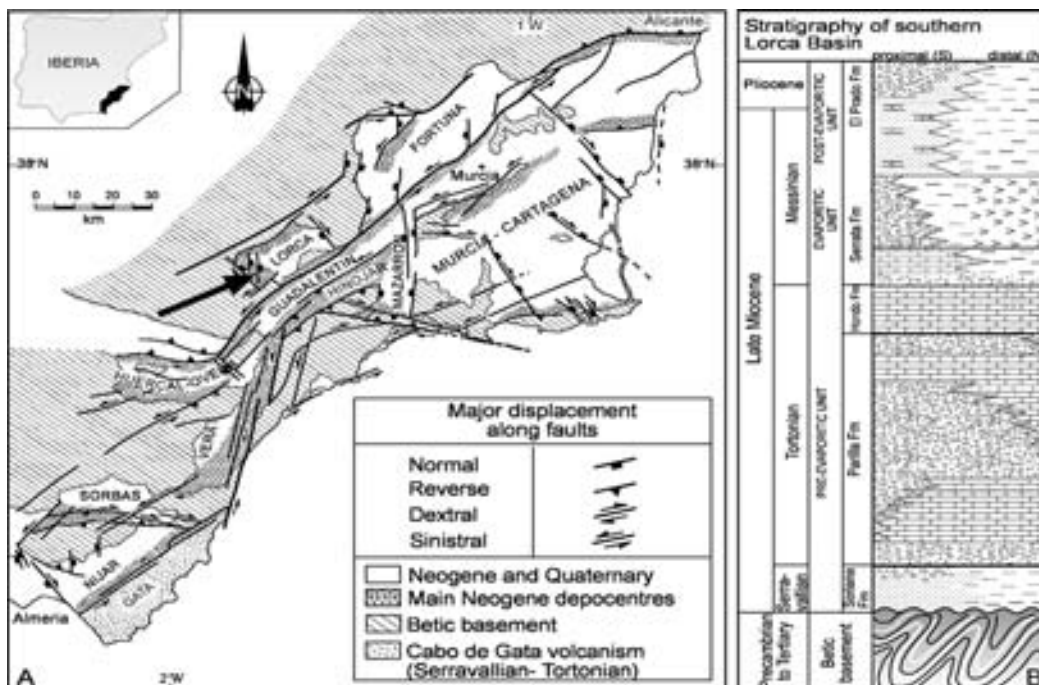


FIGURE 1 | A) Structural framework of the Neogene basins, SE Spain. The study area in the Lorca Basin is arrowed (modified from Montenat and Ott d'Estevou, 1999). B) Stratigraphic column of the southern Lorca Basin (modified from Geel, 1976; Wrobel and Michalzik, 1999; Wrobel, 2000).

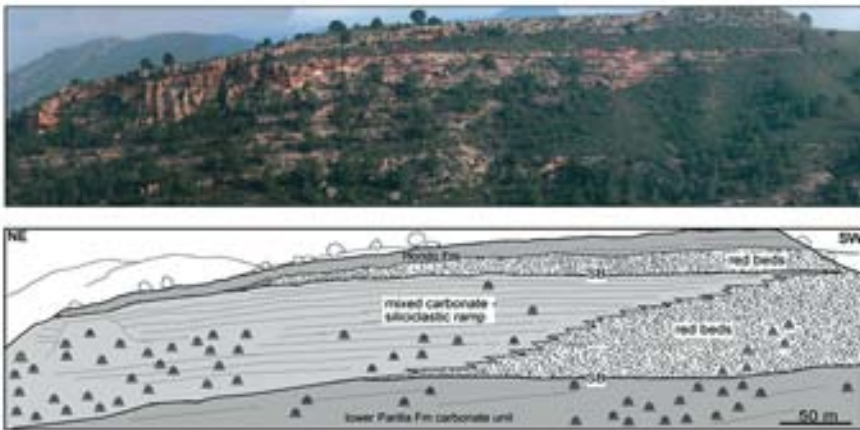


FIGURE 2 | NE-SW oriented section and sketch through the studied succession. The mixed carbonate – siliciclastic ramp shows an overall retrogradational geometry, backstepping into alluvial red beds in a proximal (SW) direction. SB refers to lower frequency sequence boundaries bounding the sedimentary unit of interest. The prominent subparallel stratification represents the bounding surfaces between the cycles, and suggests that the mixed ramp was deposited during a period of relative tectonic quiescence with no syn-sedimentary tilting of the ramp.

ping and shift of facies (Fig. 2). At most 10-12 stacked cycles have been recognised within this succession. Upper Palaeozoic and Mesozoic metasediments of the Betic basement complex which sourced the conglomerates, crop out immediately south of the fault-bounded basin margin.

FACIES ASSOCIATIONS

The mixed carbonate – siliciclastic deposits are characterised by a wide range of facies and considerable lateral and vertical variability (Fig. 3). Three principal facies associations are recognised, representing a basinward transition from continental conditions to a marine ramp.

Alluvial facies association

Alluvial deposits - “red beds”, occur as an up-to 35 m thick wedge along the southernmost part of the study area that grades into and interfingers with the marginal-marine and carbonate ramp facies in a seaward direction. In the most proximal areas the red beds are typically covered by dense vegetation, which makes it difficult to identify stacking patterns and lateral facies relationships. The deposits consist of laterally extensive, poorly sorted conglomerates with subordinate sandstones, red siltstones and paleosols. Texturally immature conglomerates composed of large, angular boulders and cobbles of basement rocks in a pebble-dominated, silty matrix dominate this facies association. The typical thickness of these beds varies from 0.3 to 1.5 m. The conglomerates have tabular and sheet-like geometries, and show no internal organisation. The immature and disorganised fabric is consistent with a mass-flow origin, such as cohesive debris flows (Fig. 4A; Nemeč and Steel, 1984). Vertically and laterally stacked gravel sheets also occur. These clast-supported conglomerates show crude subhorizontal to tabular cross-stratification and have locally erosive bases. These characteristics suggest that they were deposited by sheetfloods

or streams in a braided river system. The debris flow and sheetflood deposits are typically interbedded with paleosols characterised by white to reddish mottled and rubbly texture and concentrations of angular intraclasts in a red and argillaceous matrix. The paleosol facies is also associated with the top of the carbonate beds of facies association 3. Thin sections from these horizons display clotted texture, clay coatings and brecciation of the underlying limestone. These characteristics are diagnostic of early pedogenic processes and the incipient formation of calcrete (Esteban and Klappa, 1983; Wright, 1992). The debris-flow conglomerates, fluvial facies and paleosols have been attributed to an alluvial fan depositional system.

Marginal marine facies association

The marginal-marine facies association includes conglomerates, pebbly sandstones and mixtures of calcarenites and sandstone. These deposits are typically up to 1.5 m thick, they grade into and alternate with the alluvial facies in a proximal direction and the carbonates in down-dip direction. Clast- to matrix-supported conglomerates consist of a moderately to poorly sorted pebble and cobble assemblage mixed with fragmented bioclasts of thick-shelled fossils such as oysters, barnacles and gastropods. The clasts are subrounded to subangular and the deposits typically show few internal sedimentary structures, however tabular and trough cross-stratification does occur. Beds pinch out in a basinward direction over distances of up to 10 m. Apart from the marine bioclasts and the somewhat better sorting at the top of the beds, some of these conglomerates resemble the streamflood deposits of the alluvial fan association. Their fluvial character suggests accumulation in front of the gravely river mouth of a small fan delta (Fig. 4B). Well-sorted, pebbly conglomerates and sandstones showing horizontal or gently seaward dipping stratification are also common in this facies association (Fig. 4C). The clast material is composed of rounded and spherical pebble-sized gravel, however beds with disk and blade-shaped cobbles and pebbles also

occur. Seaward imbrication of clasts is observed within some of the beds. These characteristics are attributed to a beachface setting (Bourgeois and Leithold, 1984; Nemec and Steel, 1984; Bluck, 1999). The different particle shapes can be related to different zones on the beachface (Bluck, 1967; Bourgeois and Leithold, 1984; Bluck, 1999). Due to the relatively high suspension potential of disk-shaped particles, beds dominated by these clast shapes are ascribed to in the swash zone in the upper beachface, whereas spherical clasts will concentrate in the lower positions during backwash, and form lower beachface deposits.

Carbonate-dominated ramp facies association

The carbonate-dominated ramp association includes boundstones, grainstones, packstones and sandy calcarenites rich in coral fragments, foraminifera, bivalves, gastropods, coralline algae and echinoids. The maximum vertical thickness of facies association 3 is 45 m, and the carbonate facies are interbedded with siliciclastics (association 1 and 2) in the landward direction. Seawards the carbonate ramp grades into basal marls. The sandy calcarenites and grainstones within this association show

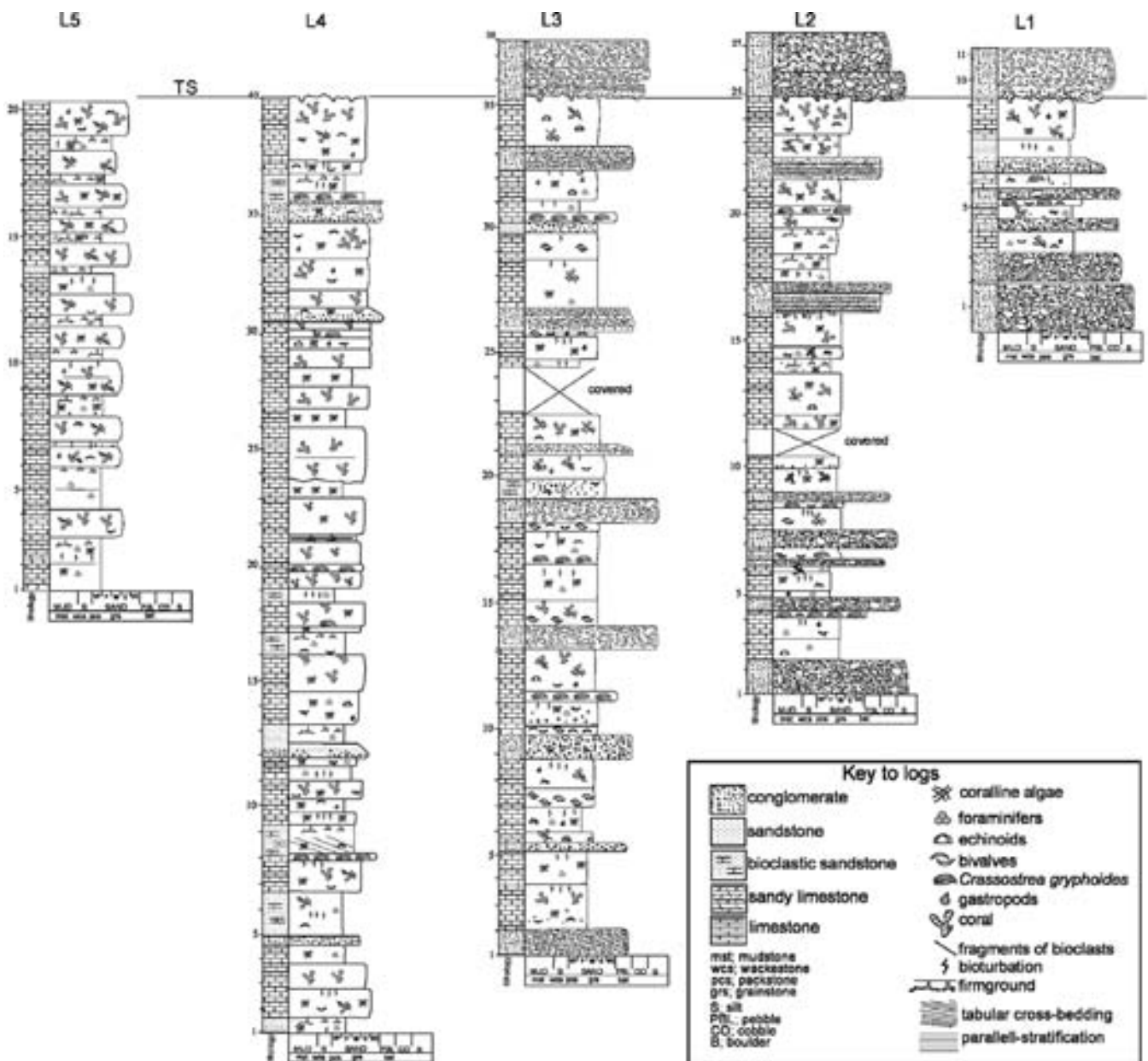


FIGURE 3 | Representative sedimentological logs from the studied succession illustrating vertical facies relationships. See Fig. 6 for location of the vertical sections and Fig. 7 for idealised cycle models corresponding to L1, L2 and L4. Vertical scale in metres.

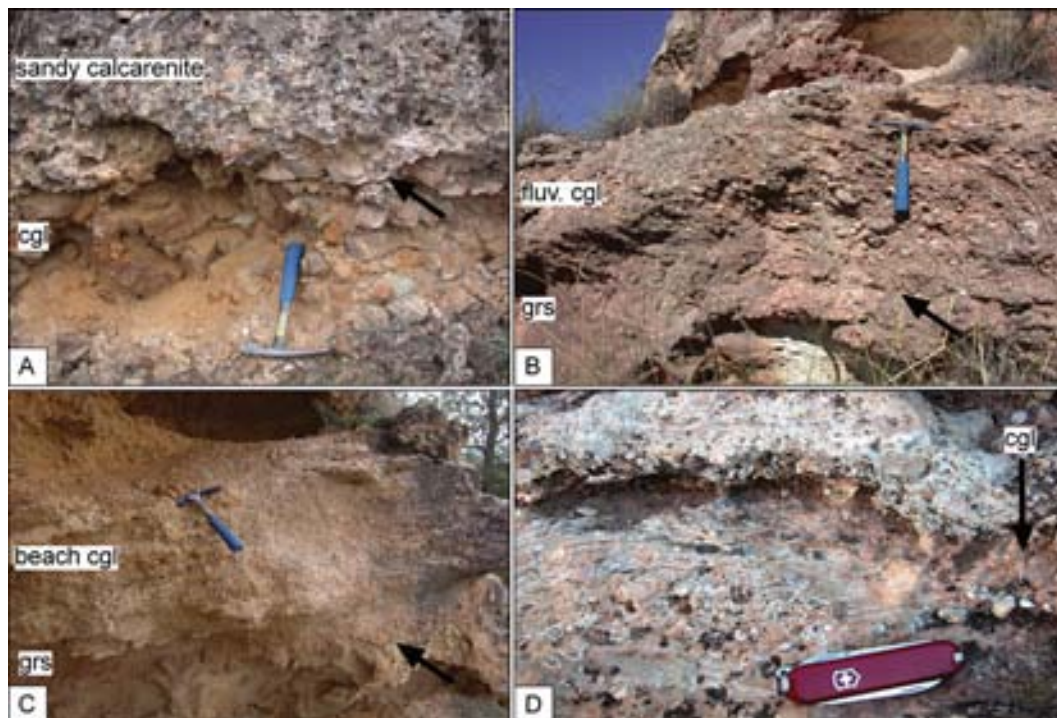


FIGURE 4 | Some characteristic siliciclastic and carbonate facies in the studied sequences. Boundaries between siliciclastic and carbonate beds are marked by arrows. A) Texturally immature debris flow deposits (cgl) succeeded by inner ramp sandy calcarenite. B) Cross-bedded fluvial conglomerates (fluv. cgl) cutting into the underlying medial ramp grainstone (grs). C) Well-sorted beach conglomerate (cgl) showing gently seaward-dipping stratification. The conglomerates show a distinct basal bounding surface cutting grainstone beds (grs). D) Laminated stromatolitic crust capping a proximal calcarenite and abruptly overlain by red-bed conglomerates (cgl).

internal structures such as symmetric ripple cross-lamination and crude parallel-stratification oriented perpendicular to the southern basin margin. These sedimentary structures indicate deposition above fair-weather wave base, and probably represent an inner ramp setting influenced by wave action. Coral boundstones comprising colonies of *Porites* sp. and *Tarbellastrea* sp. constitute an important part of facies association 3. The colonies occur as thin- to thick-branching and columnar forms of *Porites*, up to 150 cm thick and with a lateral extent from 100 cm up to 100 m. These coral carpets and patches developed on a relatively flat substratum of low topographic relief, and may represent biostromes (Vennin et al., 2004). Domed, hemispherical and head-shaped colonies of both *Porites* and *Tarbellastrea* corals are also abundant, and locally occur on top of the biostromes. The size of these colonies varies from 10 cm up to 100 cm thick patches, with a lateral extent of 20 – 150 cm. The coral zonation corresponds to a depth-controlled growth morphology of corals; the branching to columnar varieties may represent intermediate water depths (15 - 5 m), whereas the domed to hemispheric colonies are consistent with shallow-water conditions (less than 5 m) (cf. Martin et al., 1989; Vennin et al., 2004). The coral reefs are thus interpreted to have formed somewhere between storm- and normal wave-base, in an inner to middle ramp environment. An imper-

sistent bed of laminated silt to sand-grade carbonate material and coarser siliciclastics is also observed locally (Fig. 4D). In the absence of additional evidence of pedogenic features associated with this bed, the laminated crust is interpreted to represent stromatolites, probably reflecting nearshore conditions (Tucker and Wright, 1990).

Numerous laterally extensive horizons characterised by colonial clusters and disarticulated valves of the oyster *Ostrea lamellosa* Brocchi and the giant *Crassostrea gryphoides* (Schlotheim) (shells up to 70 cm long and >15 cm thick) associated with a mixed sand and bioclastic matrix, are common in this facies association (Fig. 5A). Many oysters are intensely bored and encrusted by *Entobia*, *Gastrochaenolites* and *Renichnus* isps., which together with their large size and numerous growth bands (>150 in some individuals) suggest benthic colonisation during times of low sediment accumulation rates, with periods of tractional reworking by waves (cf. Jiménez et al., 1991; Parras and Casadío, 2005). Inner to middle ramp deposits grade basinwards into fine-grained to silty bioclastic sandstones, packstones and wackestones rich in foraminifera and rhodalgal material, and basinal marls. These outer ramp, sub-fair-weather wavebase facies are characterised by pervasive bioturbation (*Thalassinoides*, *Ophiomorpha* and *Cylindrichnus* isps.), especially at the

top of beds which formed laterally extensive firmgrounds during prolonged hiatus in sedimentation (Fig. 5B; cf. Ruffell and Wach, 1998; Strasser et al., 1999).

The facies associations of the studied succession represent a threefold environmental subdivision, with gradual to rapid lateral transitions between subenvironments. Measurements of the lateral shift of facies indicate that the maximum seaward extension of alluvial and marginal-marine facies onto the carbonate ramp versus the most landward penetration of marine carbonates into the alluvial system has a maximum range of ca 2 km (Fig. 6). The upward shifts between alluvial, marginal-marine and carbonate ramp deposits are however very abrupt (Fig. 3). Although there is no direct measurement of the ramp slope, these vertical facies transitions may suggest that the ramp had a significant relief during deposition, where only small variations in sea level caused considerable changes in the depositional environment.

HIGH-FREQUENCY CYCLES

In the southern Lorca Basin the three facies associations which characterise the Parilla Fm. form small-scale

cycles (0.7–8.0 m thick). The facies belts and the stacking pattern of these cycles changes across the ramp, and based on their bounding surfaces they can be correlated in a down-dip section (Fig. 6). The overall stratal architecture of the stacked cycles shows a retrogradational pattern and the backstepping ramp unit is interpreted to represent a transgressive systems tract of a third- or fourth-order cycle (Figs. 2 and 6; Thrana et al., 2006). Three cycle types can be recognised:

Siliciclastic-dominated cycles

Proximal cycles of the ramp unit are relatively thin (0.7–2 m) and dominated by siliciclastic facies (Fig. 7A). They comprise alternations of alluvial conglomerates and inner to middle ramp sandy calcarenites (Fig. 4A). The siliciclastic part of each cycle consists of 0.3 to 1.5 m thick beds of prograding alluvial streamflow and debris-flow conglomerates (facies association 1) locally overlying a distinctive bed or surface (2–10 cm in vertical thickness) with varying degrees of calcrete development indicating subaerial exposure. The alluvial siliciclastics are typically succeeded by a truncating flooding surface (Fig. 4A) and inner to middle ramp sandy calcarenites and grainstones (0.3 to 1.1 m in vertical thickness; facies association 3).



FIGURE 5 | **A**) Surface characterised by in situ colonies of *Crassostrea gryphoides* (Schlotheim). **B**) Firmground development with maximum flooding surface (MFS) at top. Sediments above are more carbonate-rich than those below the MFS. **C**) Mixed carbonate-siliciclastic cycle. Highstand carbonates comprising *Porites* and bioclastic grainstones are cut by a pot-holed regressive surface of marine erosion (RSME) and succeeded by beach conglomerates (cgl). A combined transgressive surface and sequence boundary (TS/SB) marks a distinct transition from marginal-marine coarse siliciclastics into outer ramp packstones (pcs).

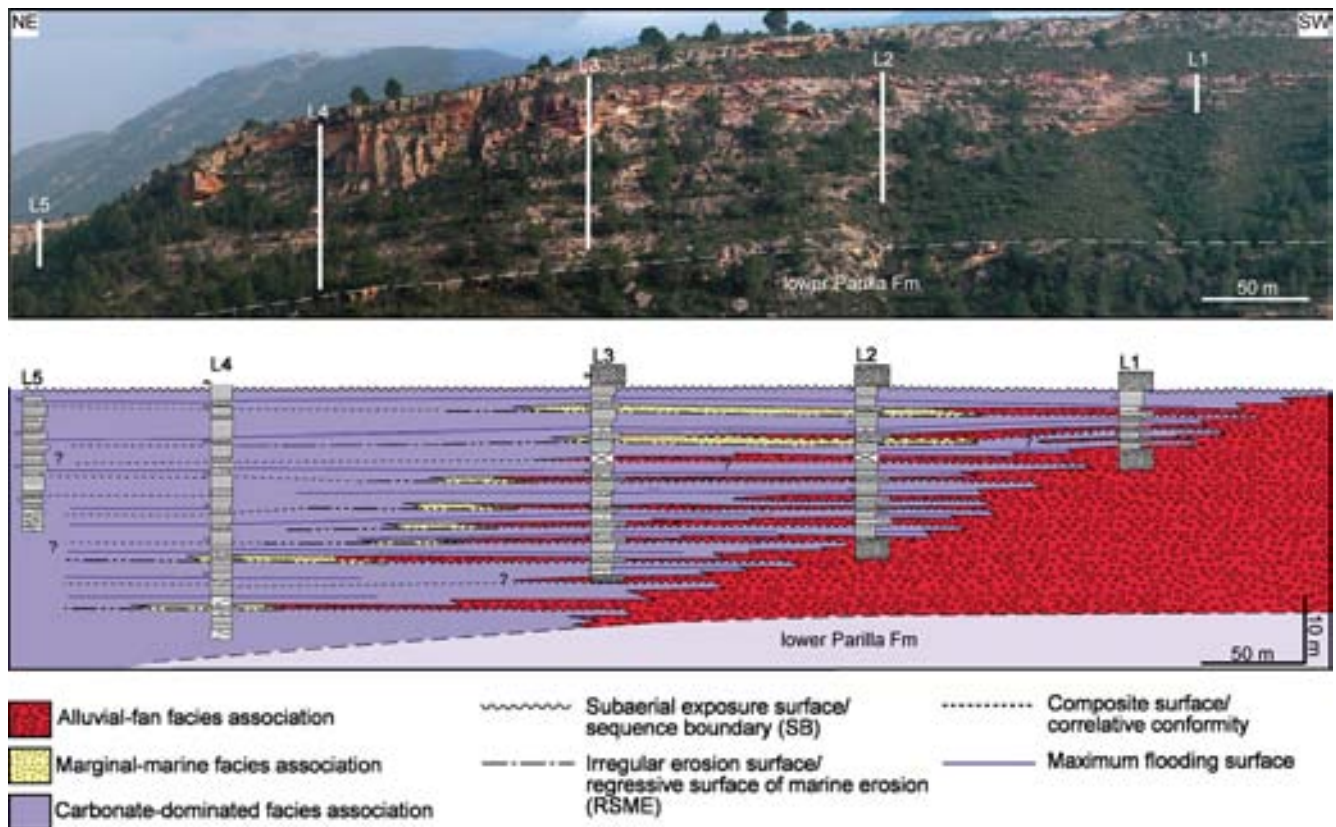


FIGURE 6 | Outcrop photo and correlation panel of facies associations and depositional architecture within the studied succession. The five lithological logs (L1–L5) correspond to an updip–downdip transition. Note the lateral shift from siliciclastic-dominated to mixed and finally carbonate-dominated facies belts, and the distribution of key surfaces. (See Fig. 3 for details of the sedimentological logs).

Pure carbonate facies are scarce, but the marine part of the cycles is characterised by a general increase in carbonate relative to siliciclastic content towards the top of the beds. The upper boundary of the carbonate-dominated beds is in some cycles succeeded by a surface with calcrete development. Locally a thin stromatolitic crust caps the landward portion of the calcarenite units (Fig. 4D).

Surfaces carrying *in situ* oyster colonies and disarticulated shell concentrations occur within the cycles, typically in the upper part of the sandy calcarenites, and were probably associated with sediment starvation (Martinius, 1995; Parras and Casadío, 2005). Some oyster colonies were subsequently eroded and reworked, with the incorporation of disarticulated shells into the overlying alluvial deposits.

Mixed carbonate – siliciclastic cycles

Mid-ramp deposits show well-developed cycles (1–8 m) of interbedded marine carbonates and marginal-marine to alluvial siliciclastics (Fig. 7B). The basal beds of siliciclastic units are characterised by parallel-stratified pebbly conglomerates and sandstones representing beach and mouth-bar gravels (0.2–1.5 m) (facies association 2). These beds rest on a highly irregular and pot-holed ero-

sive surface that cuts into the underlying carbonates (Fig. 5C), and marks a major basinward shift in the shoreline. The beach deposits are locally succeeded by subaerial exposure surfaces with associated calcrete, and texturally immature red-bed conglomerates (facies association 1) indicating a transition from a marine to alluvial depositional environment. This progradational alluvial part of the cycles is not always preserved, being locally replaced by thin zones of coarser clast material on top of the beach deposits.

The coarse siliciclastic part of the cycles is capped by a relatively sharp surface overlain by 0.1–1 m of fine-grained bioclastic sandstones or packstones containing foraminifers and rhodalgal material (facies association 3; Fig. 5C). Surfaces with oyster colonies are associated with these deposits, as well as pervasive bioturbation and firmground development, particularly at the top of the units (Fig. 5B). The bioclastic sandstones and packstones are interpreted to represent an outer ramp depositional environment and thus an abrupt shift to a deeper water environment. The upper parts of the mid-ramp cycles, succeeding the firmground surfaces, are characterised by inner to middle ramp boundstones and grainstones (1–4 m) containing a diverse fauna. Coral biostromes and

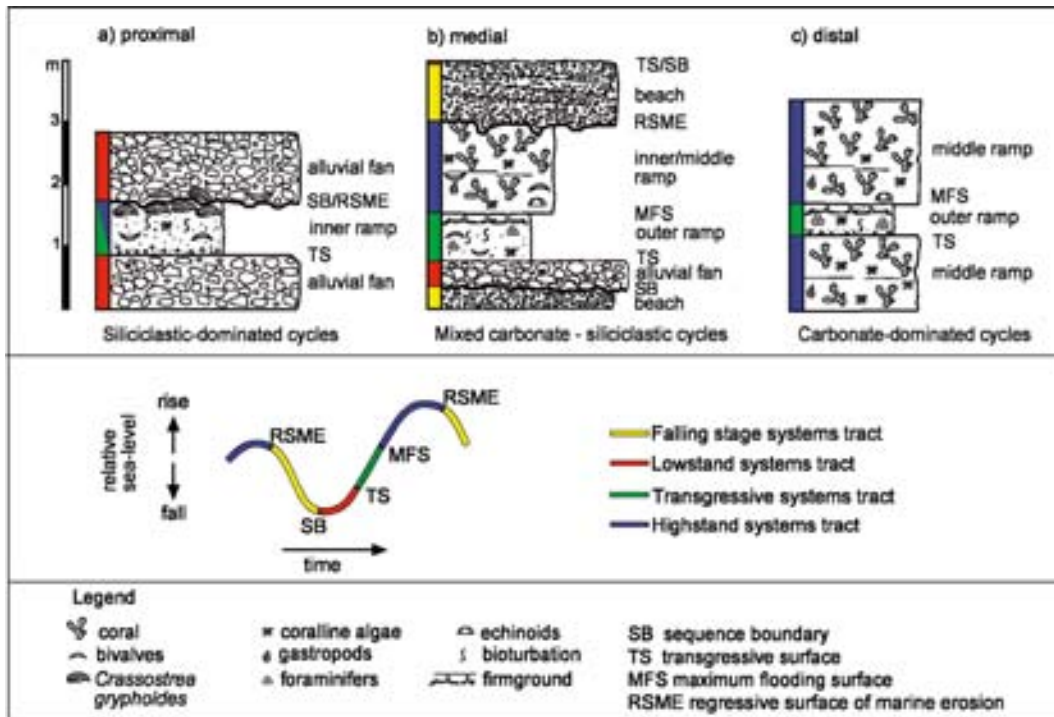


FIGURE 7 | Idealised models of the development of three cycle types and their typical position on the ramp in relation to a relative sea-level curve. (a) Proximal siliciclastic-dominated cycles (corresponding to the position of L1, Figs. 3 and 6). (b) Medial mixed carbonate-siliciclastic cycles (corresponding to the position of L2). (c) Distal carbonate-dominated cycles (corresponding to the position of L4). Vertical scale in metres.

patch reefs are common within these beds, and a shallowing-upward coral-zonation has been observed, suggesting an aggrading to prograding trend. The top of each carbonate unit is cut by the irregular, erosive surface that corresponds to the basal boundary of the marginal-marine siliciclastics.

Carbonate-dominated cycles

The small-scale cyclicality can be traced into the more distal part of the ramp where carbonate successions are dominant (Fig. 6). The cycles are typically 1–4 m thick and consist of coral boundstones, grainstones rich in coral fragments alternating with sandy packstones dominated by foraminifers and coralline algae, and locally beds of silty wackestone (Fig. 7C). The carbonate-dominated cycles show a major difference from the mixed cycles in their lack of coarse siliciclastic lowstand deposits (see below). However, a thin lag of reworked pebbles and sand (0.03–0.15 m) on top of inner to middle ramp boundstone and grainstone units, some of which are truncated, may be a distal equivalent to the conglomerates overlying the pot-holed erosion surface and/or the subaerial exposure surface. The horizon below the lag thus represents a combined surface (or a correlative conformity) formed during periods of the most seaward extent of the shoreline. This lag assemblage is succeeded by outer ramp packstones

and wackestones (0.2–1 m thick) which contain subordinate amounts of fine-grained siliciclastics. Like the corresponding mixed carbonate – siliciclastic cycles, the top of this part of the sequence is characterised by a surface with firmground development, above which grainstones with biostromes and patch reefs of *Porites* and *Tarbellastrea* again accumulated (1–2.5 m thick). At this time, carbonate production was high and grainstones were shed basinwards to form laterally extensive blankets from the mid to the distal ramp.

DISCUSSION

Model cycles for proximal, mid and distal parts of the Parilla Formation ramp are shown in Fig. 7. Sediment accumulation was evidently subject to frequent and dramatic changes in the relative supply of siliciclastic and carbonate sediments. The former were sourced by one or more fluvial systems draining the adjacent landmass, while the carbonates are of biogenic origin and mainly formed *in situ*. Constraining the average duration of the cycles is difficult, due to poor chronostratigraphic control for the succession; however, the sedimentary succession of the Parilla Fm. is ascribed to Tortonian (Wrobel, 2000), a period of ca 4.43 m.y. according to Gradstein et al. (2004). The sedimentary unit described in this paper re-

presents only a part of the Tortonian Parilla Fm., and there are a number of major depositional breaks (Thrana et al., 2006), so that each of the 10-12 cycles recognised here probably represents considerably less than 0.5 m.y.

Variations of this frequency may have a number of origins, but in this depositional setting the most likely are autocyclicality, tectonism, climatic variations or sea-level change. Autocycles may develop as a consequence of the unforced internal dynamics of carbonate and siliciclastic sedimentation in association with background subsidence, and are often used to explain the development of such alternating facies (Martinius, 1995; Moleenaar and Martinius, 1995; Monstad, 2000). The subsidence rate must have been fairly uniform during deposition of the Parilla Fm. as the different facies associations show a repetitive vertical pattern throughout the succession. However, the evidence of periodic subaerial exposure of deposits does suggest periodic relatively drastic seaward shifts of the shoreline. Furthermore, the apparent absence of channel features or lenticular siliciclastic sediment bodies, precludes a dominant influence by fan-delta lobe switching on the depositional architecture of the Parilla Fm. Variation in sediment dispersal patterns most likely contributed to the variability within cycles, but appears to have been subordinate to a dominant external control on cycle formation. Tectonism could have periodically influenced siliciclastic supply through intermittent rejuvenation of the source area. However, although the Lorca Basin has a strike-slip origin and underwent periodic subsidence throughout the Miocene (Montenat et al., 1990), there is little evidence of episodes of significant tectonic movement along the southern basin margin during accumulation of these ramp deposits. Sedimentary structures suggesting seismic activity have not been observed and the sediment package as a whole was clearly not subject to progressive tilting as accumulation proceeded (Fig. 2), effects which might be expected had the adjacent basin-bounding fault been frequently active during sedimentation. Moreover, tectonic activity would most likely be too erratic to create the rhythmic nature of the cycles. Similarly there is no obvious evidence of high-frequency climate change controlling, for example, carbonate production or siliciclastic sediment supply. Landward of the ramp, red beds constitute most of the Parilla Fm. but the cycles lose their identity at the transition into the continental deposits. Although the latter contain calcrete horizons, suggesting periods of locally reduced rates of siliciclastic accumulation, there is no apparent systematic pattern to their vertical distribution. Neither is there any other regular alternation of facies to suggest that the mechanism responsible for cycle development in the marine deposits also controlled fluvial sedimentation at the basin margin.

With respect to the fourth alternative, we see clear evidence of relative sea-level change. This is most apparent in mid-ramp cycles, where beachface gravels rest on a pot-holed erosion surface cut into mid-ramp carbonate deposits (Fig. 5C). Such surfaces are typical of wave scour that occurred as a result of a basinward shift in the shoreline due to a marked fall in sea level (Hunt and Tucker, 1992; Plint and Nummedal, 2000). The lower surface of the beach conglomerates is thus interpreted to be the expression of a regressive surface of marine erosion (RSME), with the overlying gravels and coarse sands representing falling stage deposits (falling stage systems tract; Plint and Nummedal, 2000). As a consequence of this fall in base level, the marginal marine depositional environment was eventually succeeded by a prograding fluvial system. These alluvial conglomerates probably correspond to the lowstand part of the cycles (lowstand systems tract) bounded at the base by a subaerial exposure surface interpreted to represent a high-frequency sequence boundary (Figs. 6 and 7). Landward, in the proximal siliciclastic-dominated cycles, the falling-stage beach conglomerates merge with the lowstand continental red beds, and the regressive surface of marine erosion coincides with the sequence boundary (Fig. 6). Erosion of oyster colonies and the reworking of their shells into the overlying fluvial conglomerates was probably a result of the same regressive events.

In the carbonate-dominated distal ramp cycles, pebble lags and erosional truncation of *Porites* boundstones (composite surfaces) likely reflect the same falling trend in sea level (Fig. 6), but this part of the more steeply dipping ramp probably remained deep enough to avoid subaerial exposure and significant siliciclastic influx during periods of relative sea-level fall. Siliciclastic material may have bypassed the carbonate ramp during lowstands, however no clastic wedges have been observed within the basin. The facies architecture indicates that the siliciclastic system was to a large degree fed by weakly channelised fluvial systems from the alluvial fan, and this may explain the scarce evidence of significant fluvial incision and down-cutting into the ramp during sea-level falls. However, the relatively uniform amount of siliciclastics deposited during repeated progradation of the siliciclastic system suggest that the sediment supply was fairly constant.

In proximal and mid-ramp cycles there is an abrupt transition from the coarse siliciclastic facies upwards into bioclastic sandstones, sandy calcarenites and packstones (Figs. 4A and 5C) which are here interpreted to be a consequence of rising sea level and initial transgression. The boundary is attributed to a transgressive surface overlying the lowstand alluvial deposits in proximal and medial cycles, which in places coincides with the sequence boundary on top of the falling stage beach conglomerates

(Fig. 5C). In the proximal and mid-ramp cycles the carbonate ramp facies succeeding the transgressive surface are characterised by intense bioturbation and surfaces with extensive oyster colonisation suggesting low accumulation rates, presumably during the period of marine flooding. The upper boundary of these transgressive beds is usually represented by a laterally extensive firmground related to the period of maximum flooding (Fig. 5B). The most distal parts of the ramp probably lay beyond the window of optimal carbonate production during the period of rapid sea-level rise. This is reflected in the slight increase in fine-grained “background” siliciclastics within the calcarenites and packstones of the transgressive systems tracts. In this position on the ramp, as well as in mid-ramp areas, the maximum flooding represented a turning point from mixed deposits to pure carbonate facies. In the proximal cycles, however, distinct units of pure carbonate deposits are poorly developed, but an increase in carbonate content relative to siliciclastics occurs within the late transgressive beds. This may reflect improved growth conditions for carbonate producing organisms due to the relative rise in sea level and resulting retreat of the siliciclastic depocentre.

Once sea level had risen enough to allow efficient circulation, and the influx of suspended siliciclastics was diminished, the carbonate factory went into full production and the rate of sediment supply eventually caught up with the increase in accommodation space. The ramp was widened during deposition of the highstand systems tracts, as indicated by maximum distribution of pure carbonate facies such as coral boundstones and grainstones. Aggradational to progradational coral colonies up to 4 m thick provide a minimum measure of the magnitude of sea-level change involved in the development of the cycles.

The simple sequences in the Parilla Fm. were dependent on high-frequency changes in relative sea level and the variation in sediment supply. This is reflected in the reciprocal sedimentation pattern; high carbonate production during rising and highstands in relative sea level, and prograding siliciclastic systems into the basin during lowstands. Although the siliciclastic input into the basin occupied accommodation space that would otherwise have been available for carbonate accumulation, and periodically completely replaced the carbonates, the coarse grain size of the clastics probably prevented a significant reduction in the carbonate production, and a dynamic interplay of the two end members could be sustained.

Although Tortonian high-frequency cyclicality has not been recorded in the other Betic basins in southern Spain, cycles of similar age have been observed within the pelagic carbonates of the Monte dei Corvi in Italy (Cleaveland et al., 2002; Hilgen et al., 2003). The cyclicality

of these sediments has been correlated with orbitally controlled climate changes corresponding to, among others, ~400 k.y. Milankovitch eccentricity cycles, and thus of approximately the same frequency as the Lorca cycles.

The coexistence and interaction of well-defined carbonate and siliciclastic facies are also known from the study of recent depositional systems, although a good modern analogue to the type of hybrid depositional system described in this paper may not yet exist in the literature. However, fan deltas prograding directly onto and interacting with carbonate platforms are described from the Gulfs of the Red Sea (Hayward, 1985; Roberts and Murray, 1988), and may represent a similar depositional setting to the carbonate–siliciclastic transitions described from the Tortonian succession of the Lorca Basin. It can be speculated that some may also display a similar style of cyclicality in response to glacial – interglacial sea-level variations.

CONCLUSIONS

Cycle development across the marine ramp that formed the southern margin of the Lorca Basin during the Tortonian was controlled by high-frequency sea-level change through its influence on the relative importance of carbonate versus siliciclastic sediment supply. Falling-stage and lowstand to early transgressive deposits are largely siliciclastic whereas late transgressive and highstand deposits are predominantly carbonate. In many cycles the switch seems to occur across the maximum flooding surface, probably because of the combined effects of a retreat of the point sources of terrigenous sediment, and the creation of an extensive shallow shelf regime where carbonate-producing organisms could flourish. Falling sea level, on the other hand, reduced the size of the carbonate factory and at the same time forced the siliciclastic-dominated shoreline to migrate basinward, followed by the distal margin of adjacent alluvial-fan systems.

These hybrid cycles suggest that a continuum ought to exist between pure carbonate and siliciclastic end-members. Their apparent scarcity suggests, however, that they may be dependent upon a delicate balance between the relative rates of supply of the two sediment types. Too much siliciclastic input and the shelf is swamped by sand and mud, too little and classic peritidal carbonate cycles form. Siliciclastic supply during accumulation of the Parilla Fm. cycles was evidently not high, but was relatively constant and sufficient to compensate for a decline in carbonate production during falling stage and lowstand intervals. Rising sea level and highstands provided optimal conditions and space for the production and accumulation

of biogenic carbonates. Together the two components preserve a relatively complete record of sea-level oscillations in the Lorca Basin, particularly in the mid-ramp deposits.

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