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Cyclic coastal sedimentation in Sorbas (Messinian, SE Spain)

Sedimentación costera cíclica en Sorbas (Messiniense, SE de España)

Cristino José Dabrio and María Dolores Polo

Departamento de Estratigrafía, Universidad Complutense de Madrid, José Antonio Nováis 2, 28040-Madrid, España.
dabrio@geo.ucm.es, dpolo@geo.ucm.es

ABSTRACT

Shifts of the shoreline in the Late Messinian Sorbas Member can be correlated with oscillations of the precession index and eccentricity curves. Close inspection reveals three orders of sea level oscillations with variable amplitudes. The first order, with amplitudes of tens of meters, correlates well with oscillations in the Precession Index curve. The second order of fluctuations, with metric amplitudes, fits well in a millennial/submillennial periodicity. The smaller-scaled third order fluctuations, with amplitudes around 0.5 m, are assigned to decadal periodicity. Comparison with examples in SE Spain indicates that the two pervasive smaller scale periodicities persisted since the Late Miocene in Western Mediterranean, independent of the dominant orbital forcing (precession vs. orbital eccentricity).

Key-words: *Cyclic sedimentation, cyclostratigraphy, beach facies, Messinian.*

RESUMEN

Los cambios costeros registrados en el Miembro Sorbas (Messiniense Terminal) pueden correlacionarse con oscilaciones de las curvas del Índice de Precesión y la excentricidad. Se reconocen tres órdenes de cambios del nivel del mar con magnitudes distintas. Las de primer orden (amplitud: decenas de metros) corresponden a oscilaciones de la curva del índice de precesión. Las de segundo orden (amplitud métrica), encajan en un patrón milenario. Las de tercer orden, con amplitud 0.5 m, se asimilan a periodicidad decenal. Diversos ejemplos muestran que las dos periodicidades menores persisten en el Mediterráneo occidental desde el Messiniense, independientemente del parámetro orbital dominante (precesión o excentricidad).

Palabras clave: *Sedimentación cíclica, cicloestratigrafía, facies de playa, Messiniense.*

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Introduction

Studies of the Late Messinian Sorbas Member (SMb) of the Caños Formation and its, at least in part, lateral equivalent, the Terminal Carbonate Complex (TCC) received a strong impulse following the erection of a cyclostratigraphic framework of the sedimentary filling of basins in SE Spain (Fig. 1) tuned with astrochronology (Krijgsman *et al*., 2001). It is interesting because the semi-isolated nature of the basin over-amplified the astronomically-induced climate changes producing successions with cyclic patterns (Roveri *et al*., 2009) related to base level and (or) related sediment flux changes.

This paper focuses on the analysis of small-scale fluctuations of base level recorded in the coastal deposits of the SMb that we have measured using detailed facies analysis with particular attention to primary sedimentary structures.

This procedure allows estimating 'absolute' sea levels at the time of deposition and quantification of amplitudes. It sheds light on the pervasive small scale cyclicity. Besides, it opens the way for discussing the age and duration of beach processes.

Cyclostratigraphy

The up to 70 m thick SMb is a clastic unit made up of coastal calcarenite and carbonate-rich sandstone that merges towards the north-east into basinal fine micaceous sands and mudstones illustrating the interplay of coastal environments (Roep *et al.*, 1998). Cyclostratigraphy allowed correlating a refined version of the stratigraphic succession to the astronomical precession (PI) and eccentricity (EC) curves (Fig. 2). The problem of applying astrochronology in Sorbas is the absence of reliable dating. Thus, it depends on counting cycles and there is controversy about assigning cycles to Yesares and Upper Manco Mb., Feos Fm., and TCC.

We propose that major changes in the progradation or retrogradation trends correlate with ten precession cycles. Former interpretations by Krijgsman *et al.* (2001) assumed only 3 cycles, which we correlate with maxima of eccentricity (Fig. 2). However, detailed analysis of the stratigraphy of SMb reveals more internal erosion surfaces and episodes of progradation that record oscillations of sea level less pronounced than those described in Roep *et al.* (1998), more in agreement with Roveri *et al.* (2009).

The amplitude of PI cycles, related to the EC curve indicates that lagoon facies in barrier island systems occurred only during episodes of maximum amplitude of both curves viz. oscillations 4 and 9, when the largest transgressions are recorded. The remaining episodes correspond to progradation of beaches without barrier island development (Fig. 3).

Similarly, maximum falls of sea level between oscillations 5 and 6 promoted temporal cessation of the clastic beach progradation and flourishing stromatolite growth.

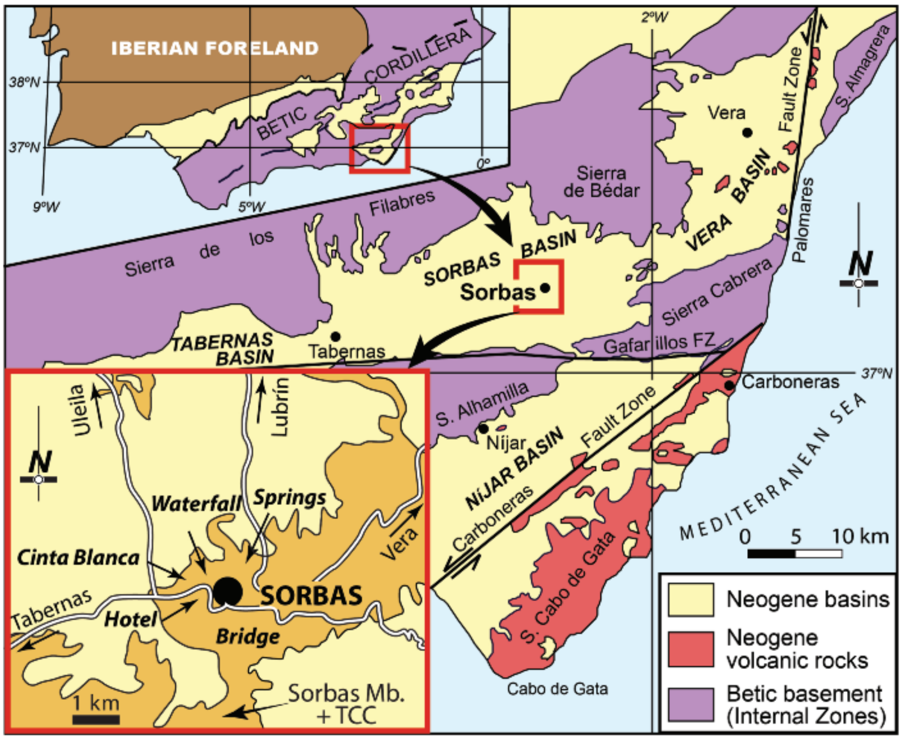

Fig. 1.- Location maps of study sites.

Fig. 1.- Mapas de localización de los puntos estudiados.

Syn-sedimentary tilting increased the accommodation space towards the east/northeast during oscillation 5 triggering the sliding of a semi consolidated calcarenite slab and extensive deformation of the underlying fine-grained sediments near Rio de Aguas Bridge (Fig. 1).

Subtle tectonic deformation after oscillation 8 controlled the location and geometry of lagoon depocenters during oscillation 9 (Roep *et al.*, 1998).

Second order fluctuations

Detailed investigation within the ten episodes of progradation reveals the occurrence of erosional surfaces and repetitions of the vertical sequence of progradation (Fig. 3), formerly assigned to normal (autocyclic) changes of beach profile and progradation trends. We offer an alternative interpretation for the changes using the outcrop of Cinta Blanca gorge, located a few metres north of the road to Tabernas (Fig. 1). This small gorge exposes a prograding barrier island (oscillation 8), separated from the underlying prograding sequence (oscillation 7) by an erosion surface.

Vertical repetitions of facies include various members depending on the location along the beach profile (Fig. 4). In distal parts (Waterfall), with only wave ripple cross laminated and parallel laminated calcarenite, gentle unconformities (dashed lines) reveal the vertical piling (Fig. 4A).

In the upper shoreface facies, repetitions include planar erosion surfaces, wave-ripple cross-lamination and wave trough cross-bedding. Sequences become more complex closer to the shoreface-foreshore transition: flat erosion surface, wave-ripple cross-lamination (wx-lam) and an intricate arrangement of wave trough cross-bedding (WXB) and planar cross-bedding of plunge step facies (PS) pointing to seaward (Fig. 4B). Higher up on the foreshore facies, sequences incorporate seaward inclined parallel lamination (//-lam) of foreshore facies and local landward directed planar cross bedding (SB) interpreted as swash-bar facies (Figs. 3 and 4).

Repetitions on the uppermost foreshore include: erosion surface, local planar cross bedding pointing to seaward (plunge-step facies, PS) and seaward-inclined parallel lamination (foreshore facies), with *Thalassinoides* burrows at the top, and cementation forming beach rocks (BR).

All these features can be integrated in a model of a prograding beach with repeated oscillations of sea level (Fig. 4). Relatively smooth erosion surfaces can be traced laterally from the shoreface to the uppermost burrowed foreshore and berm. Erosion of beach rocks topping sequences in the western part of the outcrop produced irregular, angular clasts of parallel laminated calcarenite draping irregular erosion surfaces (Fig. 4C).

Downslope the erosion surfaces, the size of beach rock clasts decreases, and roundness increases, owing to longer transport and abrasion.

We assume that fluctuations of sea level included an initial fall of sea level that allowed wave erosion of the topographically lower parts of the beach profiles. Lower sea levels also favoured early cementation of the upper foreshore to form beach rock. During the ensuing rise of sea level waves fractured and eroded the beach rocks. Several layers of fragmented beach rock record successive tops of sequences generated during second-order fluctuations (Fig. 4C). Renewed progradation at topographically more-elevated sea stands (highstand) piled up a new beach sequence (Fig. 4).

The described changes might result from piling of water by wind setup during storms or prolonged periods of storminess. Storms produce erosion surfaces that interrupt the general sequence or progradation and are followed upwards and laterally by the same type of sedimentary structures. No piling up of sequentially arranged sedimentary facies occurs, and the outcrop includes single sequences of sedimentary structures (Fig. 3), instead of vertical repetitions (Fig. 4). Thus, we prefer invoking repeated decimeter to meter sized oscillations of sea level instead of storms as the forcing control behind vertical repetitions of facies.

Bourillot *et al.* (2010) interpreted as tidal bars similar sequences (erosion surface, asymmetrical wave ripple cross lamination, and seaward inclined parallel lamination) exposed close to Rio de Aguas Bridge. They also suggested tidal currents to explain the vertical repetitions of sequences with beach rock fragments at Cinta Blanca (Fig. 4C). We do not share these ideas.

Fluctuations of sea level at metric scale had not been adequately recognized and interpreted before in the SMb, although they were reported in the TCC of Góchar, and interpreted as high-frequency eustatic oscillations (Dabrio and Polo, 1995), with no precise indication of duration.

It is possible to quantify the relative magnitude of sea level rise in sequences where plunge step (PS) facies have been

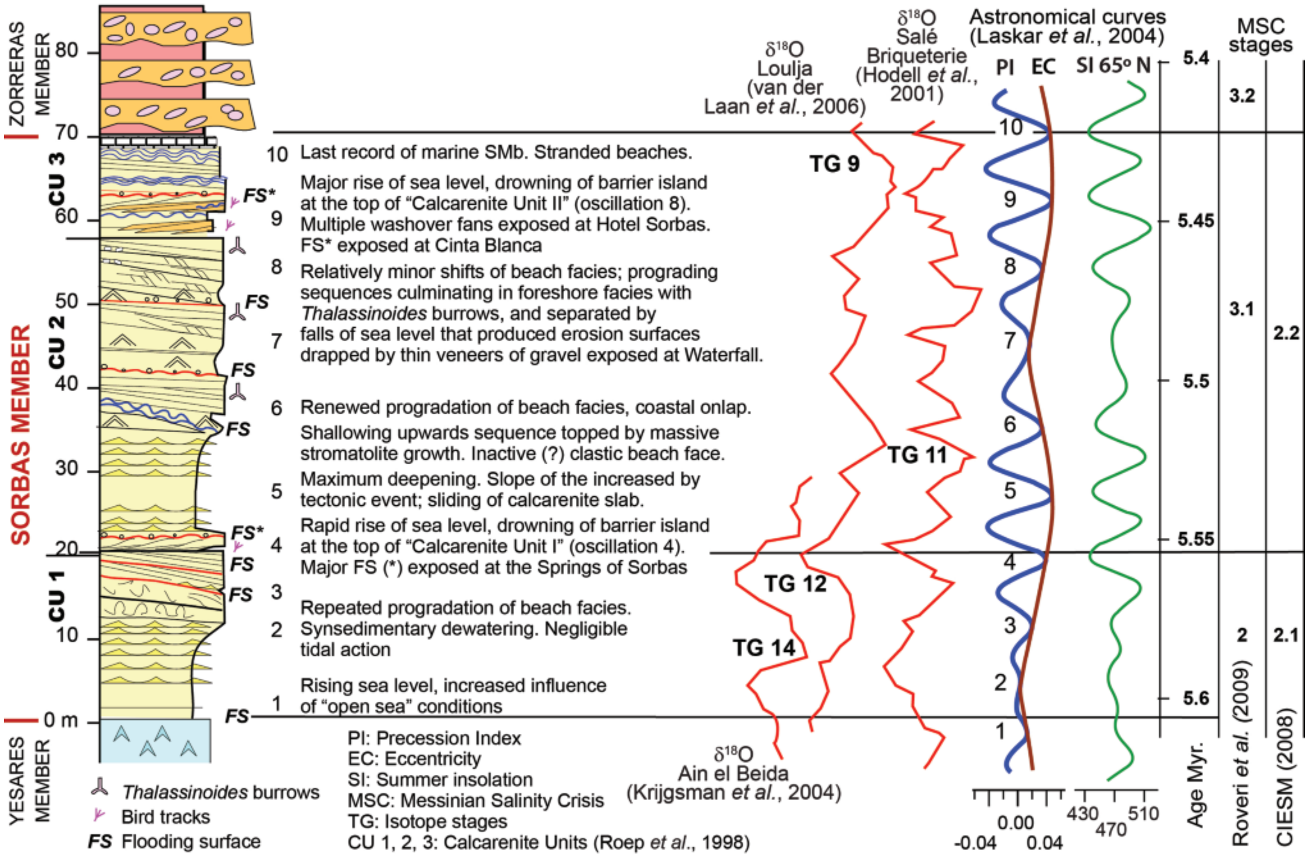

Fig. 2.- Synthetic stratigraphic section of the Sorbas Mb, in the type locality, and correlation with the δ^{18}O and astronomical curves compiled by Roveri *et al.* (2009). See text for explanation.

Fig. 2.- Sucesión sintética del Miembro Sorbas en la localidad tipo y correlación con las curvas astronómicas y de δ^{18o} recopiladas por Roveri et al. *(2009). Más explicación en el texto.*

preserved, because it marks the position of sea level at the time of deposition (Roep *et al*., 1998). The vertical distance between the uppermost PS below the erosion surface and the oldest one above it is the minimum value of the rise of sea level (no correction for compaction has been made). Measured values range from 0.5 to 1.0 m (Fig. 4D).

Third order fluctuations

Fluctuations of sea level of still smaller scale and higher frequency were previously recognized inside any of the second order fluctuations as vertical and lateral shifts of the PS facies. As many as 6 positions of the PS facies have been recognized in some places (Fig. 4E). These changes illustrate relatively rapid deposition at higher and lower sea levels, with amplitudes of 0.2-0.5 m, which caused the shoreline to recede or advance several meters (Roep *et al*., 1998). They haven't been reported from the TCC of Góchar.

Discussion: timing and duration of fluctuations

A key point for our reasoning is calculating the temporal duration of the described orders of cyclicity. This is problematic because: (1) the conformable or unconformable nature of the lower and upper limits of the SMb is controversial and (2) the number of precession cycles lost across the MSC erosion surface. We accept the essentially conformable nature of both limits of the SMb (as Krijgsman *et al*., 2001, and Roveri *et al*., 2009), and adopt the limits and durations of Roveri *et al.* (2009).

Referring to the time span available for deposition of the SMb, there are various suggestions: 5.67 Ma (base) to 5.50-5.54 Ma (top) (Krijgsman *et al*., 2001), 5.6 to 5.42 Ma (Roveri *et al*., 2009), and 5.67-5.5 Ma (Aufgebauer and McCann, 2010). Calculations indicate durations around 180-200 Ka for the whole SMb, with average duration of 18-20 Ka for individual oscillation of the PI curve. Magnitudes of sea level change caused by these first order oscillations reached tens of meters (Roep *et al*., 1998). The precession index (PI) curve correlates well with the observed field data, but it is not clear how precession exerted such a tight control on sea level. We assume that the warmer, moister part of the precession cycles coincided with a rise of sea level and transgression, whereas the cooler, more arid phase was related to basinward progradation of calcarenite beaches, with reduced clastic input. Therefore, progradation took place mostly during late highstands and early sea-level falls.

Concerning the second order of fluctuations, we were unable to count the total number of oscillations recorded in each larger-scale prograding units described above. Nevertheless, considering that the time available for progradation was about half of the PI oscillation (the arid phase), and that the minimum number of second-order fluctuations observed in a single first-order prograding unit is, at least, five to seven, we deduce values of periodicity close to the

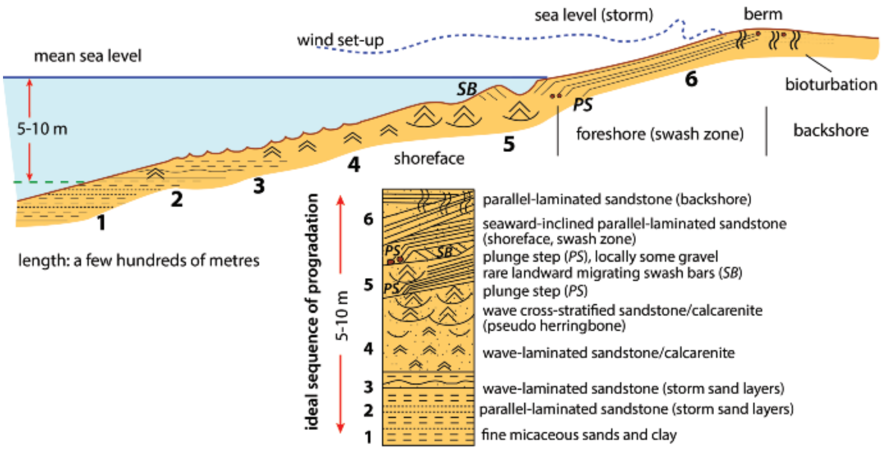

Fig. 3.- Updated ideal sequence of a prograding beach in the Sorbas Member.

Fig. 3.- Secuencia ideal actualizada de progradación de una playa del Miembro Sorbas.

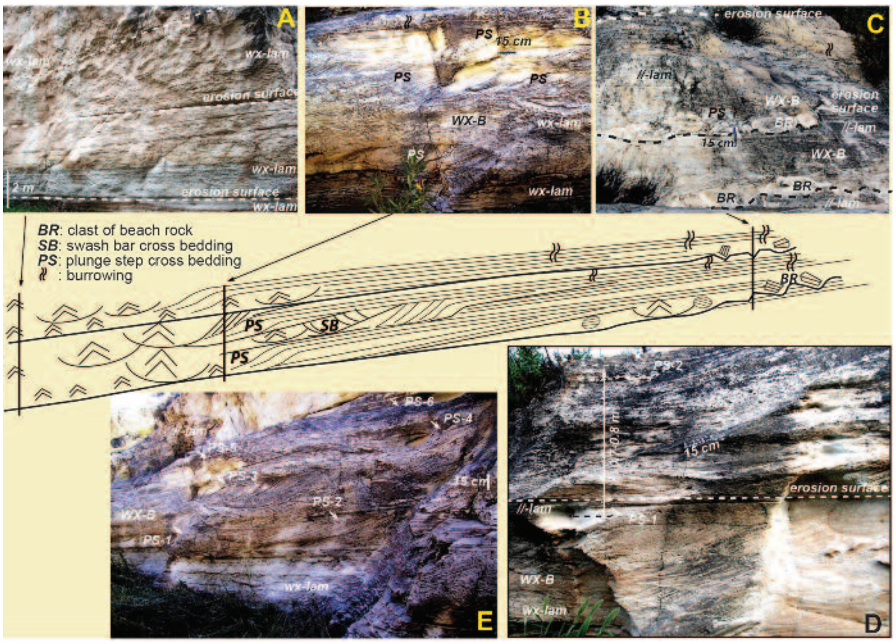

Fig. 4.- Piling up of sequences generated by a rise of sea level in the SMb, and photographs of key features. See text for explanation.

Fig. 4.- Apilamiento de secuencias generadas por una subida del nivel del mar en el SMb y fotografías de rasgos característicos. Explicación en el texto.

millennial/submillennial scale, with measured amplitudes of sea level oscillation very similar to the reported in the OIS 5e prograding beaches of La Marina-El Pinet (Dabrio *et al.*, 2011) and the prograding Holocene beaches of Roquetas (Goy *et al.*, 2003).

The third, smaller-scale, order of fluctuations involved changes of sea level very similar to those reported from La Marina-El Pinet (Dabrio *et al.*, 2011) and Roquetas (Goy *et al.*, 2003). These were assigned to decadal (and/or centennial?) minor fluctuations of sea level, likely controlled by the North Atlantic Oscillation (NAO) index and variations of solar activity (Hale and Double Hale cycles).

If the former deductions are right, we can conclude that millennial to submillennial scale and decadal fluctuations of sea level have occurred at least since the Late Miocene in the Western Mediterranean. This means that these are independent of the major forcing orbital controls: a marked influence of the Precession Index oscillations in Miocene and an eccentricity forcing during Late Pleistocene and Holocene.

Conclusions

Two pervasive orders of small scale fluctuations of sea level occur superimposed to the already known precession-controlled cyclicity during the Late Messinian (5.6 to 5.42 Ma).

The examples studied record oscillations of sea level with millennial and centennial-to-decadal periodicities. Comparison with more recent case studies suggests that fluctuations are independent of the main orbital forcing active at the time of deposition, at least since Messinian times.

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