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Controls on High-Frequency Oolite-Microbialite-Coral Reef Sequences, Upper Miocene, SE Spain

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In the 1970's, Esteban and collaborators defined the Terminal Carbonate Complex (TCC) as a distinctive upper Miocene unit distributed around the Mediterranean (Franseen et. al., 1996). The unit consists of oolite, bioclastic units, thrombolite, stromatolites, and some coral reefs, deposited in association with high-amplitude cyclic glacioeustacy and evaporitic drawdown of the Mediterranean (Franseen et. al., 1996). We studied the TCC at two locations in SE Spain, La Molata and Ricardillo (Figure 1). The study areas, approximately 5 km apart, preserve extensive (about 10 km^2) 3-D outcrop of the TCC associated with different substrate elevations. La Molata was deposited at an intermediate elevation relative to the Miocene sea-level signal, whereas Ricardillo was deposited at a high elevation relative to that signal. At Ricardillo and La Molata, the TCC is composed of oolitic, bioclastic, thrombolitic, stromatolitic and reef facies (Figure 1). Oolite units are important reservoirs for oil and gas throughout the world (e.g. Honda et. al., 1989; Marcal et. al., 1998; Llinas, 2003). Recently discovered reservoirs containing microbial facies of offshore Brazil basins are currently enigmatic but important reservoir systems. The TCC in Spain contains many similar facies to those of the recent discoveries, and exceptional outcrops allow for analysis of controls on 3-D variability.

Each area preserves four cyclic sequences that are laterally extensive, largely drape paleotopography, and some maintain uniform thicknesses. Both study areas preserve paleotopography (Franseen et al., 1998). The TCC at La Molata covers 33m of paleotopographic relief over 0.86 km and at La Rellana/Ricardillo it covers 76 m of paleotopographic relief over 1.63 km. Although there are aspects that are unique to each of the two areas and unique to each of the sequences (Figure 2), each of the four TCC sequences commonly has (1) local basal stromatolites; overlain by (2) local thrombolite boundstone; that is overlain by (3) trough cross-bedded ooid grainstone; which grades upward to (4) volcaniclastic-rich planar bedded ooid grainstone; capped by (5) fenestral ooid grainstone. At low elevations, the thrombolite boundstones are thicker and laterally more continuous than at higher elevations. Thrombolites that are stratigraphically high in sequences may be interbedded with trough cross-bedded ooid grainstone.

The pinning point method (Goldstein and Franseen, 1995), which uses facies and diagenetic evidence of ancient positions of sea level (pinning points), was used to quantify relative sea-level history in the two areas (Figure 2). The pinning point relative sea-level curves show that each of four TCC cyclic sequences record relative rises and falls in sea level with amplitudes of 54-84 m.

At intermediate substrate elevations (relative to sea-level turn-around points), sequences have a build-and-fill architecture (e.g., McKirahan et al., 2003; Franseen et al., 2007), characterized by a relief-building phase followed by a relief-filling phase, with the relatively thin sequences draping paleotopography. Microbialites dominate deposition during the relative sea-level rises, draping paleotopography and building topographic relief. Oolites dominate deposition during the relative sea-level falls and fill topographic relief. Minor thrombolite boundstones deposited during the sea-level fall were deposited as tabular bodies rather than high-relief mounds, due to limited accommodation. The sequences are depositionally asymmetrical, with the majority of the deposition occurring during the relative fall in sea level.

At higher substrate elevations, close to the highstand position, sequences thicken and yield internal stratigraphic character that is inconsistent with a build-and-fill model. Apparently, the build-and-fill model requires an intermediate substrate elevation and non-optimal carbonate productivity during rapid sea-level change.

Both areas show increasing biotic diversity from sequence 1 (most restricted conditions) through 3 (most normal marine conditions). This change likely results from a regional decrease in aridity. Decreasing aridity during TCC deposition is supported by other regional observations: (1) the TCC was deposited immediately after major evaporite deposition; (2) the latest Messinian phase in the Mediterranean is dominated by the Lago Mare fresh-to-brackish water deposits; and (3) a major meteoric diagenesis event occurred after deposition of sequence 4 (Li et al., 2010). Some facies are specific to a particular sequence at both locations (Figure 2), suggesting distinctive environments at particular times.

On the basis of the similarities between the two closely spaced areas and the biostratigraphic and magnetostratigraphic controls (Franseen et al., 1998), the four sequences in the two areas are interpreted to represent the same four events of sea-level change. Time-equivalent shallow-water strata at the same elevations across the region indicate that paleotopography is largely preserved. Thus, surfaces at equal elevations in the two areas would have experienced the same sea level history. This allows for construction of a composite relative sea-level curve incorporating data from the two areas (Figure 2), which is useful in developing quantitative constraints on sedimentary process and response in carbonate systems of similar character.

Our current age dating (based on paleomagnetic data; Franseen et al., 1998), indicates that the entire TCC was deposited between 100-400 ky (25-100 ky for each sequence), sea level fluctuations had minimum amplitudes of 53.6-83.5 m (estimated rates of 53-334 cm/ky), and the widespread occurrence of TCC strata in the Mediterranean are suggestive of glacioeustacy.

Local paleogeographic and paleoceanographic controls appear to have been important for differing sequence character between the two areas. Preserved and reconstructed paleogeography indicates the La Molata area was within an embayment, protected from waves and with more restriction than the La Rellana/Ricardillo area. Facies differences within sequences support this paleogeographic interpretation. In sequences 1 and 2, stromatolites and thrombolites at La Molata may indicate more restriction, whereas grainy beach deposits at La Rellana/Ricardillo indicate an open connection. In sequences 2 and 3, greater abundance of skeletal grains at La Rellana/Ricardillo further supports the idea of more open marine conditions there. More abundant, thicker, laterally continuous *Porites* boundstone at La Rellana/Ricardillo, compared to dominance of thrombolites at La Molata, adds further support to more normal marine conditions with better wave energy at La Rellana/Ricardillo and relatively more restricted waters at La Molata.

Results from this study can aid in predicting lithofacies distribution and geometries in outcrop and the subsurface for cyclic oolite-microbialite-coralgal reef systems. Comprehension of the depositional controls of paleotopography, relative sea level, and paleogeography are essential to understanding and predicting lithofacies distributions and geometries for subsurface analogs containing oolites and microbialites.

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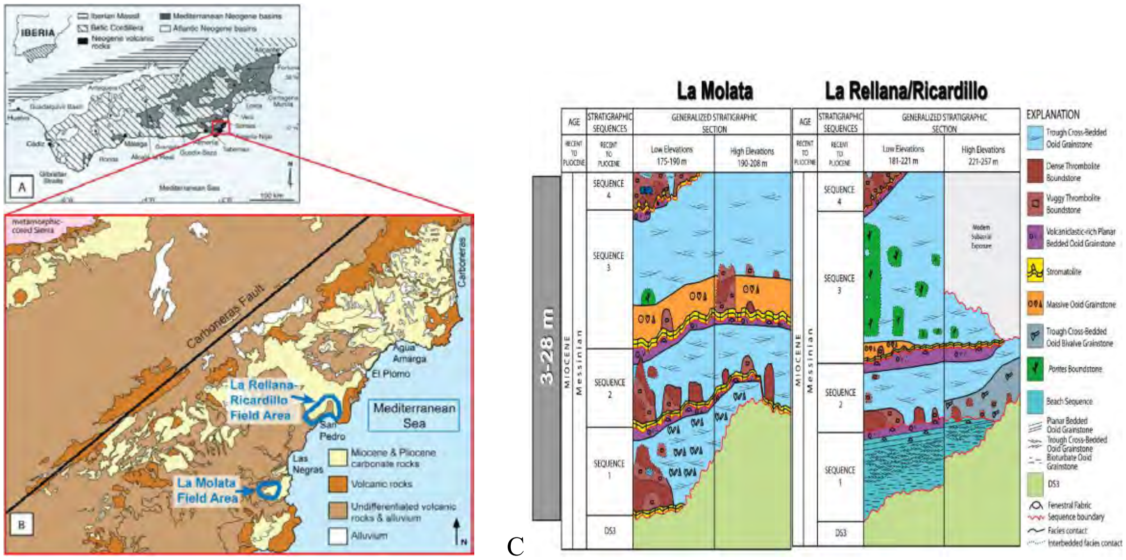

Figure 1. A) Location map of Neogene basins within the Betic Cordillera of southern Spain. Red Box outlines the Cabo de Gata volcanic province. B) Generalized geologic map of the Cabo de Gata region and location of the La Molata and La Rellana/Ricardillo field areas with the Carboneras fault to the west. C) La Molata and La Rellana/Ricardillo TCC general stratigraphy and lithofacies distributions in relation to elevation.

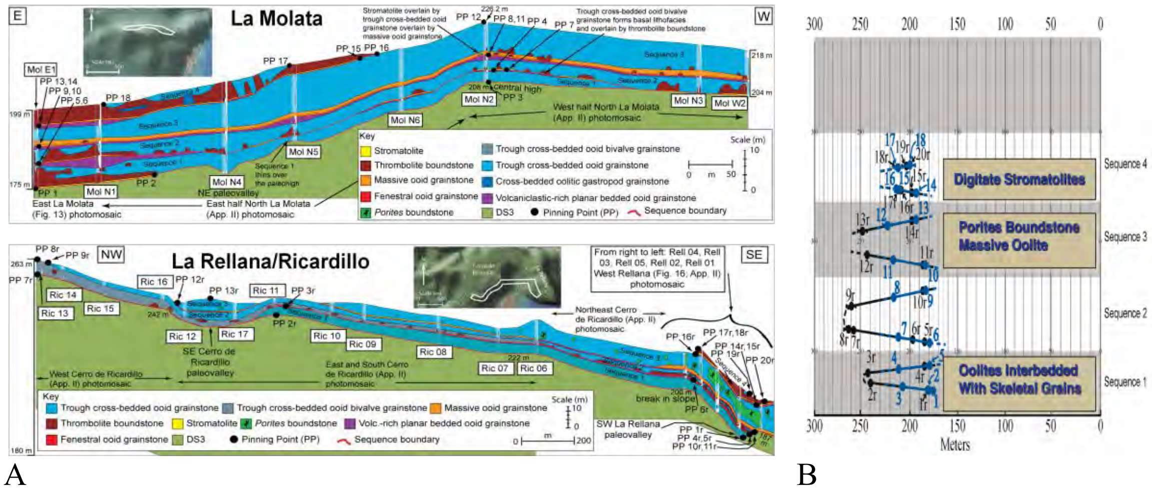

Figure 2. A) Cross-section of the La Molata field area (upper) and the La Rellana-Ricardillo field area (lower). Pinning points (PP) are indicated and used to construct the quantitative relative sea-level curve in B. Thrombolite boundstones are more abundant on La Molata and build topographic relief stratigraphically lower in the section during relative sea-level rises. Where present on La Rellana-Ricardillo, thrombolite boundstone is thicker and more laterally extensive at the lower elevations and becomes isolated at higher elevations Oolites fill in topographic relief during the relative falls in sea level at both locations. B) Combined quantitative relative sea-level curve with pinning points (numbered dots) for the La Molata (blue) and La Rellana/Ricardillo (black) field areas. Facies occurrences specific to sequences at both locations are indicated.