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Review

Offshore remobilization processes and deposits in low-energy temperate-water carbonate-ramp systems: Examples from the Neogene basins of the Betic Cordillera (SE Spain)

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ABSTRACT

General facies models developed for modern and ancient Mediterranean temperate-water carbonates in the last two decades have shown that the style of deposition on outer-ramp, slope, and basin environments in low-energy areas such as the Mediterranean Sea differs overall from that of high-energy open-ocean areas, given the wider variety of smaller-scale topographic and hydrodynamic conditions in the former setting. However, these depositional models generally lack relevant information about sedimentary processes, transport mechanisms and controlling factors on offshore sediment redeposition, which are potential sources of information for sequence stratigraphic, palaeoclimate and exploration studies. Several examples from the Neogene Betic basins of the western Mediterranean region have been selected to integrate the processes and controlling factors on the offshore sediment transport and the resulting deposits. Additional published data from other Mediterranean localities have also been considered.

An idealized model of temperate-water carbonate deposition in the study examples comprises a shallow-water coastal belt and a shoal area developed landwards of a carbonate-factory zone, and deeper-water outer-ramp, slope, and basin settings below the storm wave base. The environments off the factory bear a variety of remobilized deposits characterized by distinctive features. These deposits include storm shell beds, sediment gravity flows (debrites and turbidites), bed packages with hummocky and swaley cross-stratification (HCS and SCS), slope sandwaves, and channel as well as lobe deposits.

The different types of redeposited facies resulted from various offshore sediment-transport processes interacting with the local conditions. Storm shell beds developed in low-energy protected basins, regardless of the ramp profile. Debrites and turbidites formed in the distal parts of moderately-steep ramps within moderately energetic hydrodynamic contexts. Similar gradients but with higher hydrodynamic energy and appropriate sediment grain size favoured the formation of deposits with HCS and SCS in relatively deep-water settings. The circulation pattern of currents within the basin was the main factor controlling the formation of downslope migrating sandwaves. In the case of channel and lobe deposits, hydrodynamic-flow behaviour through the channels and at the transition point conditioned the features of the resulting deposits.

Offshore resedimentation is consistent with a highstand shedding model in the case of storm-driven event deposits (storm beds, sediment gravity flows and deposits with HCS–SCS) while offshore directed and persistent unidirectional currents generated prograding margin clinoforms during falling and low sea levels.

This review provides a concise depositional framework to understand the different redeposition processes operating in low-energy, temperate-water carbonate ramps and to interpret remobilized deposits in low-energy regions such as the Mediterranean Sea.

1. Introduction

In the last three decades, research on the temperate/cool-water carbonate-depositional realm has significantly expanded knowledge on these previously poorly-understood types of deposits, achieving a degree of comprehension comparable to that of tropical carbonates (Nelson, 1988; James and Clarke, 1997; Pedley and Carannante, 2006a). All these studies have provided new data on aspects such as sequence stratigraphy applied to temperate/cool-water carbonates (Pedley and Grasso, 2002; Betzler et al., 2005; Massari and Chiocci, 2006), diagenetic changes (Knoerich and Mutti, 2003; Smith and Nelson, 2003; Rivers et al., 2008), diversity of the carbonate factory areas across the different ramp settings (Martín et al., 2004; Nalin and Massari, 2009; Moissette et al., 2010; James et al., 2013) and geometry of the carbonate units (Hansen, 1999; Benisek et al., 2010; Tomas et al., 2010). One relevant aspect has been the better characterization of the outer-ramp, slope, and basin-transition settings (Braga et al.,

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2006a; Fornós and Ahr, 2006; Betzler et al., 2011; James and Bone, 2011), as well as the better understanding of the processes and controlling factors of offshore sediment transport and the resulting deposits (Butler et al., 1997; James et al., 2009; Puga-Bernabéu et al., 2009; Anderskouv et al., 2010). This issue is especially important in low-energy areas such as the Mediterranean Sea. The Present-day Mediterranean is a microtidal, wave-dominated sea (*ca*. 0.3 m tidal range; Albérola et al., 1995), with the fair-weather wave base at ~3–5-m depth (Shipp, 1984) and the storm-weather wave base at ~20–25-m depth, down to 40 m under severe storm conditions (Backstrom et al., 2008; Vacchi et al., 2012). As a consequence, in the Mediterranean Sea the style of carbonate deposition in offshore settings differs from that of high-energy, open-ocean temperate/cool-water carbonate platforms (Pedley and Carannante, 2006b). The best-represented examples of the latter are the modern and ancient shelves from southern Australia (James and Bone, 1991, 2011; Boreen and James, 1995). The South Australian Continental Margin constitutes a wide shelf (up to hundreds of kilometres) with well-developed Pleistocene–Holocene prograding slope clinoforms. In this setting, carbonate deposition is powerfully influenced by a high-energy, swell dominated hydrodynamic regime (James and von der Borch, 1991; James et al., 2001), which results in three discrete zones of sedimentation: a shallow neritic zone with carbonate production and landward sediment transport; a middle neritic zone characterized by sediment reworking; and a deep neritic and upper slope zone of high sediment accumulation (James and Bone, 2011). In contrast to the open-ocean carbonate platforms, the sediment transport and deposition mechanisms, as well as the resulting deposits, can be highly diverse in the Mediterranean ramps, as a result of a wider variety of topographic and hydrodynamic conditions (Martín et al., 1996, 2004, 2009; Fornós and Ahr, 1997, 2006; Betzler et al., 2000, 2011; Tropeano and Sabato, 2000; Pedley and Grasso, 2002; Braga et al., 2003; Titschack et al., 2005; Vigorito et al., 2005; Longhitano et al., 2010).

General facies models for modern and ancient Mediterranean temperate-water carbonates illustrate the facies distribution and depth-controlled biogenic components on the carbonate ramps (Carannante et al., 1988; Fornós and Ahr, 1997; Pedley and Grasso, 2002; Braga et al., 2006a; Betzler et al., 2011), but they overall overlook depositional features related to offshore sediment redeposition. Within the Mediterranean region, most examples of offshore redeposited sediments come from outcrops in southern Spain, Italy and Greece. However, these outcrops are disconnected, the information is scattered throughout the scientific literature and it often includes only general interpretations of the remobilized deposits, disregarding the factors controlling the offshore transport (Gläser and Betzler, 2002; Pedley and Grasso, 2002; Dermitzakis et al., 2009; Reynaud and James, 2012).

The aim of this review is to synthesize the information on the offshore redeposition mechanisms and controlling factors on Mediterranean low-energy temperate-water carbonate ramp systems, as well as the main sedimentary characteristics of the resulting deposits. The main plausible scenarios are referred to using specific examples from the Neogene Betic basins, which are also compared with other similar Mediterranean cases. An integrated model for offshore redeposition is presented, highlighting the wide variability of redeposited facies found within these basins, and finally, a synthesis of the sea level, tectonics and climate controls. The excellent quality of the outcrop exposures and broad facies variability within precise sedimentary contexts in the Neogene Betic basins provide a solid foundation and a useful depositional framework for interpreting similar deposits not only in Mediterranean regions and in the Neogene, but in other areas and epochs, especially where outcrops are dispersed and/or poorly-preserved.

2. Overview of the temperate-water carbonate ramps in the Neogene Betic basins

The Neogene Betic basins formed and evolved as a result of the uplift of the Betic Cordillera, the westernmost segment of the Alpine orogenic belt, during the Miocene (Weijermars, 1991). Two major types of basins can be recognized, the Atlantic-linked and the Mediterranean-linked basins, with some narrow marine passages (straits) connecting them in the early uplifting stages (Martín et al., 2001, 2009; Betzler et al., 2006). These basins were partially infilled with temperate-water carbonate deposits ranging in age from the Middle Miocene (Serravallian) to the Early Pliocene (Zanclean) (Fig. 1).

Temperate-water carbonates formed in a wide spectrum of ramps, from gentle homoclinal to distally steepened, with diverse physiographic and hydrodynamic situations. These carbonates accumulated on a variety of sub-environments extending from the coast to the basin. Some of these deposits have been described in detail and extensively studied in recent years (see Braga et al., 2006a for a comprehensive review). Compositionally, they mainly consist of bioclasts of bryozoans, coralline algae, bivalves (mostly pectinids and oysters), and, to a lesser extent (but locally abundant), barnacles, brachiopods, benthic foraminifera, echinoids, and solitary corals. Therefore, these accumulations are composed of the typical foramol (*sensu* Lees and Buller, 1972) or heterozoan (*sensu* James, 1997) associations, characteristic of the temperate- and cool-water carbonate-platform realm. In the Mediterranean-linked Betic basins, temperate-water carbonate deposits alternate in time with tropical (warmer-water) coral-reef deposits. In the Late Miocene examples, these alternations have been interpreted as climatically controlled, related to cyclic global cooling and warming events (Martín and Braga, 1994; Brachert et al., 1996; Sánchez-Almazo et al., 2001; Martín et al., 2010). Since the Early Pliocene only temperate-water carbonates formed in the Mediterranean. Coral reefs disappeared from the region at the end of the Messinian (Martín et al., 2010; Perrin and Bosellini, 2012). These Pliocene temperate-water carbonates are thought to be the result of temperature variations related to the opening of a more northern gateway (the Strait of Gibraltar) that admitted cooler surface water into the Mediterranean (Martín et al., 2010). Oxygen isotope values of foraminifers collected from laterally-equivalent basinal marl deposits confirm that sea-surface water-temperature variations controlled the type of carbonate that formed at any specific time in these basins (Sánchez-Almazo et al., 2001, 2007; Martín et al., 2010).

In the sedimentary model proposed for Neogene temperate-water carbonates from the Betic basins (Fig. 2), the most significant feature is the existence of a carbonate-factory zone (*sensu* Martín et al., 1996), where maximum carbonate (skeletal) production took place. On open ramps, this factory zone was a relatively calm area affected only by storms, situated seawards of shoals, below the fair-weather wave base, and was affected only by storms (Martín et al., 1996, 2004; Braga et al., 2006a). Other factories are related to sheltered settings in shallow waters such as embayments (Martín et al., 2004), or small coastal depressions bounded by submarine cliffs (Betzler et al., 2000; Aguirre et al., 2008). These latter carbonate factories are relevant for palaeonvironmental reconstructions although they were not volumetrically important. Sediment in the factories consists of poorly bedded, coarse-grained floatstones to rudstones, with well-preserved bioclasts that exhibit low fragmentation and abrasion. Most of the bioclasts are from organisms that grew *in situ* with relatively slow growth-rates compared to tropical counterparts. Although mixed in different proportions, fossil groups within factory zones tend to be spatially partitioned, commonly with bivalves (and bryozoans) in shallow-water settings, and coralline algae in deeper-water locations (Martín et al., 2004; Puga-Bernabéu et al., 2007a, 2007b). Seagrass meadows were presumably common in factory areas in some carbonate ramps (Betzler et al., 2000; Braga et al., 2003).

Outer-ramp and slope settings are located seawards of the factory zone in homoclinal and in distally steepened carbonate ramps respectively. Minor production, linked to the growth of small, delicate-branching forms of bryozoans and coralline algae, took place in outer-ramp and slope settings, resulting in the formation of fine-grained background packstone deposits (Martín et al., 2004). These packstones pass laterally into silty marls, and marls deposited in basinal settings