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Deciphering the history of hydrologic and climatic changes on carbonate lowstand surfaces: calcrete and organic-matter/evaporite facies association on a palimpsest Middle Jurassic landscape from Portugal

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ABSTRACT

The unusual occurrence of calcretes and prominent organic matter in the Middle Jurassic (Lower Bathonian, Serra de Aire Formation) of the Lusitanian Basin of western Portugal (Western Iberian Margin) revealed a complex palimpsest exposure record, here interpreted as reflecting hydrological changes caused by phases of emergence and immersion. It serves as a potential model for understanding stratigraphic development at lowstand surfaces in carbonate successions. The exposure-dominated facies association grades upwards into peritidal and lagoonal limestones, and the interval is assigned to the regressive peak of a Transgressive-Regressive Facies Cycle (2nd order) of the thick Middle Jurassic carbonate ramp succession.

The Galinha Quarry, Fátima region, NE of Lisbon, a type section for this lowstand assemblage, exhibits varied calcretes, with black-clasts, interbedded with, and grading into: organic-rich marly/clayey seams and lenses, locally with carbonate nodules; carbonates with evaporite traces; microbial laminites; black-clast and fenestral limestones; some lithofacies are dolomitized. The palynofacies contains phytoclasts associated with less refractory, more prone to degradation components, which suggests natural combustion/pyrolysis (wild fires). The lowstand surface represents a low relief landscape with small depressions/ponds bordering a more distal marginal-littoral setting; the partly subaerial and partly subaqueous settings were subjected to lengthy exposure and to fluctuating, very shallow water bodies and water table. Coeval climatic regime was a seasonally dry/wet one, with dry/semi-arid phases dominating over the sub-humid, as shown by the combined record of intense calcrete development, rhizogenic structures, microbial mats, brecciation, desiccation, evaporites and wild fire evidence. However, sea level rise caused changes to shallow, sea-water influenced restricted lagoonal-peritidal settings.

Comparisons and differences with modern and ancient coast marginal carbonates are made to provide a guide to the variability in such lowstand deposystems in the stratigraphic record.

1. Introduction

Shallow water platform interior carbonates are very widespread in the stratigraphic record and typically display abundant evidence of changes in depth-related facies and subaerial exposure. The literature is heavily biased towards discussions on the origins of the facies changes that characterise these carbonates, commonly cyclic, and whether these changes reflect auto- and/or allocyclic processes (e.g. Koerschner and Read, 1989; Wilkinson et al., 1997; Lehrmann and Goldhammer, 1999; Burgess and Wright, 2003). Characteristically these settings undergo phases of emergence and immersion causing changes in drainage and hydrology yet few studies have looked in detail at how hydrological changes are manifested in the sediment record, favouring instead to focus on patterns in sedimentation and cyclicity, real or assumed. During these lowstands, exposed carbonate platforms typically produce extensive, low relief carbonate plains which have the potential to preserve, typically subtle, records of complex hydrological, climatic and environmental changes (Kabanov et al., 2010; Miller et al., 2012). These changes, in addition to climatic changes, also reflect shifts in local hydrology as marine pore waters are replaced by meteoric ones, as vadose zones potentially deepen as base level falls, and later as sea levels rise before flooding, the meteoric lens is affected by marine inundation to produce brackish and finally marine pore waters (Rasmussen

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and Neumann, 1988). This study focuses not on evidence of sequential environmental changes over 10s of metres of stratigraphy (e.g. Schnyder et al., 2009), but on how terrestrial deposits in carbonate successions can preserve the histories of rarely documented, hydrological changes.

In such platform interior successions, pedogenic horizons (paleosols) have been typically documented capping tidal-flat cyclothems (e.g. James, 1984; Strasser, 1988; Martin-Chivelet and Gimenez, 1992; Wright, 1994; Strasser and Hillgärtner, 1998; Pomoni-Papaioannou and Kostopoulou, 2008). In this study from the Middle Jurassic (Lower Bathonian) of the Lusitanian Basin of Portugal, we report pedogenic carbonates partly interbedded with and overlain by peritidal deposits. These pedogenic carbonates are rare within the same interval over the basin and are unusual in that they are associated with the prominent occurrence of organic-rich deposits (either as interbedded organic-rich layers or as coaly seams and lenses), coupled with calcitized gypsum crystals and nodular evaporites. Organic-matter enrichment of littoral sediments in evaporitic or semi-enclosed settings is common in some modern and ancient environments (e.g. Warren, 1990; Schnyder et al., 2009), but there are differences in the present case, as will be described.

Although a direct comparative approach using modern soil analogues has proved a great benefit to elucidating paleosols, the presence of different ecosystems in the past means that non-actualistic soil types remain to be discovered in the stratigraphic record (e.g. Kabanov et al., 2010), warranting careful assessment of any well exposed ancient example, such as those we document here. Besides their use in deciphering ancient climates, landscapes and ecosystems, they increasingly have a role in improving our understanding of eustasy and cyclostratigraphic problems (e.g. Strasser and Hillgärtner, 1998; Pomoni-Papaioannou and Kostopoulou, 2008; Christ et al., 2012), as low lying carbonate depositional areas can have low surface-erosion rates and may precisely record relative sea level positions (e.g. Miller et al., 2012).

A wide range of literature on carbonate paleosols and calcretes over the geological record exists (e.g. Freytet and Plaziat, 1982; Esteban and Klappa, 1983; Wright and Tucker, 1991; Martin-Chivelet and Gimenez, 1992; Wright, 1994, 2007; Strasser and Hillgärtner, 1998; Alonso-Zarza, 2003; Schnyder et al., 2009; Alonso-Zarza and Wright, 2010; Matthewman et al., 2012; and many references therein), but there are remarkably few published works on these matters concerning the Middle Jurassic, namely in similar palaeolatitudes.

In contrast to other studies, in the present case the unravelling of crucial changes was not guided by the existence of an obvious disconformity palaeosurface, neither by previously known indicators of climate change, as for instance extensive karstification (e.g. Miller et al., 2012). It was the detailed analysis of the paragenetic features in a specific interval of an almost entirely marine carbonate succession that led to recognition of an exceptional prolonged exposure (not common peritidal intermittent emersion caps), and consequently to decipher shifts in local hydrology and in climatic regime. Therefore, this study offers additional awareness on the need of careful search for evidence of terrestrial-dominated "breaks" in apparently continuously shallow-marine ramp successions, with obvious implications in the understanding of relationship between sea-level/base-level changes and the stratigraphic record. The facies assemblage and related settings addressed here bear significant singularities distinguishing them from more common models deduced from modern analogues and geological record, and offer additional clues which may be useful for better interpretation of the geological record elsewhere.

The aims of this paper are:

- To document palaeo-calcretes and associated deposits exhibiting highly variable pedogenic and diagenetic products, commonly grading from one to another laterally and vertically within a common sedimentary context and substrate (limestones), thus ruling out contrasting bedrock lithologies or very different depositional settings as major controls of calcrete facies variability.
- To relate these features to the development of changing hydrological conditions on a Middle Jurassic carbonate lowstand landscape with a complex range of depositional and taphonomic settings, with both input from wild fires and local areas of organic matter preservation.
- To contrast this setting with those of other pre-Quaternary carbonate platforms and modern examples.
- To reinforce awareness on the relevance of identifying palimpsest exposure records to improve understanding of palaeoclimate, former sea-level and cyclostratigraphic architecture.

2. Geological setting

The Lusitanian Basin (LB) of West-Central Portugal, in the Western Iberian Margin (Fig. 1) is associated with the opening of the North-Atlantic Ocean. The main rifting phase leading to ocean opening between Iberia and Newfoundland occurred in the Late Jurassic and Early Cretaceous (e.g. Wilson et al., 1989; Pinheiro et al., 1996; Pena dos Reis et al., 2000; Alves et al., 2002).

The basin is bounded to the east by uplifted Hercynian basement and to the west (offshore) by basement horsts, and it is infilled by c. 5000 m of sediments ranging in age from the Upper Triassic to the Upper Cretaceous, mostly from the Jurassic. The Triassic corresponds to terrigenous deposits of the earliest stages of basin formation, but from the Sinemurian the sea gradually flooded the basin. The Upper Triassic-Callovian succession corresponds to the first megasequence or major cycle of the basin development (Wilson et al., 1989; Soares et al., 1993; Azerêdo et al., 2014), here assigned to a Major Transgressive-Regressive Cycle (1st order) *sensu* Hardenbol et al. (1998) and Jacquin and de Graciansky (1998a); (Fig. 2). During the Early and Middle Jurassic about 1000 metres of carbonate sediments formed on a W/NW dipping ramp system with variable morphologies, controlled by sea-level changes and tectonics. This thick carbonate infill of the LB begins with marginal-marine and restricted marine facies, but these grade rapidly upwards into hemipelagic fossiliferous marl-limestone series (including organic-rich facies with black-shales, considered as potential hydrocarbon source-rocks) which characterize most of the Lower Jurassic (e.g. Soares et al., 1993; Duarte et al., 2010, 2012; and many references therein). In the Middle Jurassic, low- and high energy facies are clearly distinguished, having developed over the E/SE to W/NW low-gradient deepening trend of the ramp system, and a wide range of inner- and mid-ramp limestones and dolostones (including good reservoir analogues) crop out in the eastern part of the basin (e.g. Soares et al., 1993; Azerêdo, 1998; Azerêdo et al., 2003; and many references therein).

The Middle Jurassic is separated from the Upper Jurassic by a basinwide disconformity, spanning at least from the Late Callovian to the Early Oxfordian, which among a range of facies also includes an organic-rich unit with hydrocarbon source-rock potential (e.g.Wilson et al., 1989; Azerêdo et al., 2002a, 2002b; Silva et al., 2014; and many references therein). In contrast, the Middle Jurassic series over the basin have not significant organic-rich units. Therefore, there are almost no previous organic-matter studies published for these series in the LB; exceptions are recent palynofacies and TOC analyses of the sediments across the Middle–Upper Jurassic boundary, thus including a small interval of marine latest Middle Jurassic (Silva et al., 2014), and TOC and palynofacies data for Middle Jurassic marine deposits obtained from a few samples of ancient oil exploration well cores at very specific locations in the basin (Gonçalves et al., 2013, 2014).

The Middle Jurassic inner- and mid-ramp facies crop out chiefly at two broad limestone provinces, forming two ranges of hills north of Lisbon, named the Maciço Calcário Estremenho (MCE) and the Maciço de Sicó (MS) (Fig. 1). The first stage of the inner ramp evolution, characterized by thin progradational tidal flats, subtidal sand sheets and detached shoals, developed during the Bathonian into stacked barrier sandbodies with back-barrier lagoonal and peritidal facies often, but not