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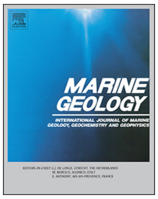

Origin and implications of orbital-induced sedimentary cyclicity in Pliocene well-logs of the Western Mediterranean

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ABSTRACT

The climatic origin of astronomically induced sedimentary cycles in the Mediterranean and adjacent areas during the late Neogene and Quaternary remains puzzling; as cycles have been linked to concomitant but seasonally opposite changes in African summer monsoon precipitation (Eastern Mediterranean sapropels) and Atlantic regulated winter-precipitation (carbonate cycles on the Atlantic side of the Mediterranean). Particularly, little is known about the cyclic sedimentation on orbital time scales in the Western Mediterranean, with the prime exception of the Messinian sapropels from the Sorbas basin (southern Spain).

Here we show that regular alternations in Pliocene downhole logs from the industrial drill-site Muchamiel-1, located along the Balearic Promontory in the Western Mediterranean, are related to eccentricity (bundles) and to obliquity and precession cycles (basic meter-scale alternations). We establish an astronomically based age model for the interval between 5.33 and 2.8 Ma, by first correlating cycle bundles to eccentricity and then the basic dominantly precession-related cycles to the 65°N summer insolation of La2004. The striking bed-to-bed similarities between the Muchamiel-1 well-logs and other records from both the Atlantic margin and the Central Mediterranean suggest that the same climatic forcing was responsible for the formation of carbonate cycles across the Western Mediterranean and adjacent Atlantic. We conclude that formation of alternating carbonate-rich/carbonate-poor beds was controlled by Western Mediterranean cyclogenetic mechanisms as well as by peri-Mediterranean precipitation associated with changes in the North Atlantic System (NAS). These findings highlight the importance of peri-Mediterranean precipitation on the sedimentary cyclicity by dictating terrigenous (clay) supply and potentially on the hydrology of the basin by providing additional freshwater required for sapropel formation. Consequently, cyclic sedimentation in the Mediterranean results from the combined effect of precipitation changes driven by (i) the North African monsoon, (ii) the Atlantic system, and (iii) intrabasinal Mediterranean atmospheric dynamics.

1. Introduction

The Mediterranean basin is sensitive to orbital-forced climate oscillations due to its geographic position and land-locked configuration. In areas with high sedimentation rates, climate signals are therefore recorded in sedimentary archives at sufficiently high resolution to reveal orbital-scale oscillations (e.g., Lourens et al., 1992). Astronomically induced variations in the incoming solar radiation translate into warmer-wet and cooler-dry climate phases, which modify the composition of the sediment deposited on the seafloor, resulting in cyclic sedimentation patterns (Strasser et al., 2006). Intensified precipitation and fluvial discharge during warmer-wet phases at times of precession minima (Northern Hemisphere Summer Insolation [NHSI] maxima) promote the formation of carbonate-poor layers or sapropels, whereas arid phases at times of precession maxima (NHSI minima) promote the formation of carbonate-rich marls (Rossignol-Strick, 1983; Hilgen, 1991b; Langereis and Hilgen, 1991; Lourens et al., 1996). Couplets of carbonate-rich/carbonate-poor beds are deposited in the entire Mediterranean, while sapropel/marl alternations are predominantly formed in the Eastern basin (e.g., Rohling et al., 2015). In

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fact, the carbonate cycles may show a more complex build-up, having additional carbonate-poor marly beds associated with precession maxima (quadruplets of Hilgen, 1991b; De Visser et al., 1989; Hilgen et al., 2003), likely reflecting carbonate dilution by enhanced eolian dust input (De Visser et al., 1989; Foucault and Mélières, 2000).

The origin of sapropels, identified as dark coloured, sometimes laminated beds enriched in organic carbon (Rohling and Hilgen, 1991), has been linked to enhanced Nile outflow into the Mediterranean (Rossignol-Strick, 1983). This outflow results from intensified North African monsoonal precipitation in the Nile's drainage area, triggering surface water stratification and sapropel formation in the eastern Mediterranean (Rossignol-Strick, 1983). Enhanced winter precipitation in the northern Mediterranean borderlands and peri-Mediterranean regions is regarded as an alternative freshwater source that may potentially lead to enhanced bottom water stagnation and sapropel formation (Rohling and Hilgen, 1991; Toucanne et al., 2015). Understandably, sapropel formation may result from a combination of both enhanced summer (i.e. monsoonal discharge) and winter precipitation. In such scenarios, not only the provenance of the freshwater can be different, but also the seasonal timing is critical (Rohling et al., 2015). Changes in productivity may also contribute (Van Os et al., 1994), but it is assumed that changes in (net) precipitation and fluvial run-off play a more important role in sapropel formation (Rossignol-Strick, 1983; Rohling and Hilgen, 1991).

By contrast, carbonate cycles in the Mediterranean are produced by changes in the type and/or amount of fine-grained terrigenous clastics (clay, silt) supplied to the basin by fluvial and/or eolian processes in the form of couplets or quadruplet cycles (De Visser et al., 1989; Hilgen, 1991b; Foucault and Mélières, 2000; Mayser et al., 2017). In addition, changes in carbonate dissolution and productivity may also play a role in the development of cyclic carbonate sedimentation (Van Os et al., 1994). Enhanced North African monsoonal rainfall and associated run-off can only account for carbonate-poor cycles formed within the areas of sediment unload, which are typically restricted to the Nile Cone and the southern margin of the Eastern Mediterranean (Emery et al., 1966). In the Western Mediterranean or along the Atlantic margin, the monsoonal fluvial discharge does not exert significant direct control over the hydrology and/or the sedimentary processes. Consequently, a different mechanism may have to explain the origin of carbonate dilution cycles, especially when found in successions deposited along the adjacent Atlantic margin (e.g., Gulf of Cadiz, Ain el Beida in the Gharb Basin; Sierro et al., 2000; van der Laan et al., 2012) (Fig. 1).

Mediterranean depressions and cyclogenetic activity effectively transfer moisture from west to east, increasing winter precipitation in and around the eastern basin (Rohling and Hilgen, 1991; Toucanne et al., 2015). This precipitation however mostly exerts influence over relatively small areas (Trigo et al., 2002); therefore, by itself it cannot explain the origin of both the cyclic Western Mediterranean and North Atlantic records. Conversely, peri-Mediterranean precipitation sourced by water vapour from the NAS regularly carries moisture into the Mediterranean (Tsimplis and Josey, 2001; Trigo et al., 2002; Struglia et al., 2004), and has been shown to be an active component of the climate system even at orbital time scales according to recent climate models (Brayshaw et al., 2011; Kutzbach et al., 2014), although Bosmans et al. (2015) argue that most of the enhanced precipitation is of local convective origin. Hence, the combined action of these climate mechanisms (i.e., Mediterranean cyclogenesis and NAS) can potentially explain the carbonate cycles in the Western Mediterranean and adjacent Atlantic margin; however, this hypothesis still needs confirmation from long and continuous cyclic sedimentary records that can help identifying an Atlantic origin of the wet/dry phases producing the cycles.

In this paper, we analyse micropaleontological samples (cuttings) and downhole logs from the Muchamiel-1 well (Mu-1; ~855–680 m below sea level [mbsl]), located along the Balearic Promontory (BP) in the Western Mediterranean (Fig. 1). Well-logs provide a continuous and uniform high-resolution sedimentary archive with standard measurement spacings (0.15 m), which are independent of core recovery (Worthington et al., 1988). The Mu-1 logs display characteristic cyclic patterns that can potentially be correlated to coeval cyclic Mediterranean and/or Atlantic successions. Following statistical analysis, we generate a high-resolution astrobiochronological age model for the Mu-1 well. Given its critical location and extended Pliocene record, we use the Mu-1 site to better understand the origin of the sedimentary cyclicity observed in the Western Mediterranean and Atlantic regions, and its potential link with orbital-induced climate variations. We specifically discuss the importance of peri-Mediterranean precipitation in the formation of carbonate and sapropel/marl cycles, starting from the striking similarities between the Mu-1 logs and Atlantic and Sicilian records. Finally, we examine how obliquity-driven glacial cycles and associated Mediterranean aridification during the Pliocene influence the cyclic patterns shown by the well-log data.

2. Material and methods

The Mu-1 well was drilled at a water depth of ~115 m along the Balearic Promontory (38.4°N-0.3°E; Fig. 1). The base of the Neogene succession was reached at ~1250 mbsl, where it unconformably overlays Cretaceous limestones. Four well-differentiated lithological units comprise this Neogene succession (Appendix A). The base is formed by a thick unit of light grey calcareous claystones deposited during late Tortonian-early Messinian times (pre-evaporitic unit in Appendix A). The overlying unit corresponds to a series of whitish gypsum/anhydrite beds intercalated with grey limestone beds (evaporitic unit in Appendix A), accumulated during the first phase of the Messinian Salinity Crisis (MSC; Ochoa et al., 2015). The next lithological unit, known as the Micritic Unit (Appendix A), consists of ~15 m of non-evaporitic, well-cemented claystones and limestones interpreted to have been deposited during the Messinian-earliest Pliocene (Ochoa et al., 2015). Finally, ~230 m of calcareous silty claystones comprise the uppermost recovered sediments (post-evaporitic unit in Appendix A). In this study, we specifically focus on the post-evaporitic succession (~862–680 mbsl), and discuss our results in relation to the age of the underlying Micritic unit (~875–862 mbsl: Appendix A).

2.1. Downhole logging data

We study these sediments by integrating different well-log records (Gamma ray-GR, sonic DT-slowness, and resistivity-SFLU). The GR measures the amount of natural radiation emitted by rocks and primarily tracks clay content; the sonic evaluates the travel time of P-wave velocity of the geological formation, and the resistivity estimates the ability of rocks (and interstitial fluids) to impede the flow of electrical currents (Ellis and Singer, 2007). Thus, theoretically, well-cemented silts or carbonate-rich rocks display low GR emissions and slowness (high sonic velocities), and high resistivity values; by contrast clay/organic-rich rocks reveal high GR and slowness (low sonic velocities) and low resistivity values.

2.2. Micropaleontological material

Micropaleontological data has been collected from 26 cutting samples, with an average sampling resolution of ~9 m, increasing to ~3 m at the base of the succession. Cutting samples were dried, weighted, disaggregated in tap water and rinsed through sieves of 63-, 150-, and 500-μm. Splits were made of the 150- to 500-μm fraction using a microsplitter. In each sample split, relative abundances of planktic foraminifers were determined by counting a minimum of 200 individuals. Taxonomic identification of planktic foraminifers is based on Kennett and Srinivasan (1983) and Iaccarino et al. (2007), while foraminiferal biostratigraphy follows the existing astrobiochronological framework proposed for the Mediterranean (Hilgen, 1991b; Langereis and Hilgen,