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The Messinian erosional surface and early Pliocene reflooding in the Alboran Sea: New insights from the Boudinar basin, Morocco

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ABSTRACT

New investigations in the Neogene Boudinar basin (Morocco) provide new information about the Messinian Salinity Crisis (MSC) and Zanclean reflooding in the southern part of the Alboran realm (westernmost Mediterranean). Based on a new field, sedimentological and palaeontological analyses, the age and the geometry of both the Messinian erosional surface (MES) and the overlying deposits have been determined. The MES is of late Messinian age and was emplaced in subaerial settings. In the Boudinar basin, a maximum of 200 m of Miocene sediments was eroded, including late Messinian gypsum blocks. The original geometry of the MES is preserved only when it is overlain by late Messinian continental deposits, conglomeratic alluvial fans or lacustrine marly sediments. These sediments are interpreted as indicators of the sea-level fall during the MSC. Elsewhere in the basin, the contact between late Messinian and early Pliocene deposits is a low-angle dipping, smooth surface that corresponds to the early Pliocene transgression surface that subsequently re-shaped the regressive MES. The early Pliocene deposits are characterized by: (i) their onlap onto either the basement of the Rif chain or the late Miocene deposits; (ii) lagoonal deposits at the base to offshore marls and sands at the top (earliest Pliocene; 5.33–5.04 Ma interval; foraminifer zone PL1); (iii) marine recovery occurring in the 5.32–5.26 Ma interval; and (iv) the change from lagoonal to offshore environments occurring within deposits tens of metres thick. This information indicates that at least the end of the reflooding period was progressive, not catastrophic as previously thought.

1. Introduction

One of the most fascinating events in the recent history of the Mediterranean is the Messinian Salinity Crisis (MSC) (Hsü et al., 1973) which occurred between 5.97 Ma and 5.33 Ma (Gautier et al., 1994; Krijgsman et al., 1999a; Manzi et al., 2013; Roveri et al., 2014a). The MSC led to the formation of very thick evaporitic deposits in the central parts of the Mediterranean and to severe erosion of the hinterland margins with the incision of deep erosional canyons (e.g., Chumakov, 1973; Clauzon, 1973; Hsü et al., 1973; Ryan and Cita, 1978; Gautier et al., 1994; Krijgsman et al., 1999a; Lofi et al., 2005, 2011a, 2010b; CIESM et al., 2008). The MSC was caused by the progressive closure of the Betic and South Rifian Corridors between the Mediterranean and the Atlantic Ocean, and the subsequent fall of Mediterranean base level (for an overview see Flecker et al., 2015). During the latest Messinian and/or earliest Zanclean, the Mediterranean was reflooded by Atlantic waters through the Gibraltar Strait (e.g., Hsü et al., 1973; Blanc, 2002; Lofi et al., 2003; García-Castellanos et al., 2009; Estrada et al., 2011; Bache et al., 2012).

Three of the hallmarks of the MSC are still the matter of debate:

(1) For some authors the Mediterranean Sea fully or almost fully desiccated (Chumakov, 1973; Hsü et al., 1973; Ryan and Cita, 1978; Barber, 1981; Clauzon, 1982; Clauzon et al., 1996; Ryan, 2009; Lofi et al., 2011b; Bache et al. 2012) while for others sea-level fall was of moderate amplitude (e.g., Nesteroff, 1973; Néraudeau et al., 2001; Roveri et al., 2001, 2014b; Manzi et al., 2005, 2009).
(2) Some studies claim that the reflooding was rapid to catastrophic (several thousand years of duration: Hsü et al., 1973; Clauzon

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et al., 1996; Pierre et al., 2006; (36 years) Blanc, 2002; Lofi et al., 2003; Loget et al., 2005; (2 years) García-Castellanos et al., 2009; Estrada et al., 2011; Bache et al. 2012). Other studies argue for progressive reflooding (Roveri et al., 2008a,b, 2014b; Cornée et al. 2006, 2014; Caracuel et al., 2011; Omodeo-Salè et al., 2012).

(3) For some authors the age of the reflooding is 5.33 Ma (base of the Pliocene; e.g., Hsü et al., 1973; Pierre et al., 1998; Blanc, 2002). For others it occurred in two steps (e.g., Estrada et al., 2011). Bache et al. (2012) proposed a first step between 5.56 and 5.46 Ma with a moderate and slow sea-level rise (<500 m) then an instantaneous flooding at 5.46 Ma with a sudden 600 to 900 m sea-level rise related to a deepening of the Gibraltar Strait. For Perez-Asensio et al. (2013) the first step occurred at 5.52 Ma (glacioeustatic stage TG11) and the second in the earliest Pliocene, at *ca.* 5.33 Ma (erosion at Gibraltar and then sea-level rise).

In this paper, we shed new light on these debates in the Alboran Sea realm (westernmost part of the Mediterranean) based on the study of key outcrops from the Boudinar basin, northeastern Rif of Morocco, in which we document and describe the Messinian Erosional Surface and lowermost Pliocene deposits.

2. Geological setting

The Alboran Sea is located at the western end of the Mediterranean (Fig. 1A). It is delimited by the Betic and Rif chains that started to build during the Oligocene as a result of the convergence between Africa and Europe (e.g., Jolivet et al., 2006; Chalouan et al., 2008). Since the upper Miocene, thick sedimentary basins were emplaced in the Alboran Sea (e.g., Comas et al., 1999) and along its margins. One of the typical features of the sedimentation in the Alboran Sea is the absence of Messinian evaporites in the offshore domain. This differs from the central part of the western Mediterranean where evaporites (including halite) reach thicknesses up to two kilometres (e.g., Lofi et al., 2011a,b).

The Boudinar basin is located on the southern margin of the Alboran Sea, in the eastern part of the Rif Mountains of northern Morocco (Fig. 1A). It was formed on top of the metamorphic nappes of the Ketama and Temsamane Mountains or on the middle Miocene volcanics of the Ras Tarf Mountain (Fig. 1B). Westward, the Boudinar basin is crosscut by the recent Ras Tarf fault (Guillemin and Houzay, 1982) (Fig. 1C). After an early Miocene deformation of the Rif and subaerial erosion, marine infilling of paleovalleys began from the late Miocene (Tortonian) and lasted up to the early Pliocene (Guillemin and Houzay, 1982; Choubert et al., 1984; Wernli, 1988; Barhoun and Wernli, 1999; Azdimousa et al., 2006) (Fig. 1D).

Late Neogene deposits comprise, from bottom to top, Tortonian continental conglomerates (up to 25 m thick) and marine marls (*ca.* 150 m thick), early Messinian marls and diatomites (up to 40 m thick) and lenses of Messinian *Porites* coral boundstones (*ca.* 10 m thick). In this basin, MSC evaporites have not been identified and the base of the Pliocene deposits has been described as almost conformable on Messinian marls (Guillemin and Houzay, 1982; Azdimousa et al., 2006). No major erosion surface had been observed in this basin in relation with the MSC, only a gap during the sedimentation (Azdimousa et al., 2006). However, the Messinian marl–diatomite alternation is overlain by conglomerates (up to 100 m thick). These latter sediments were considered as submarine fans related to a late Messinian sea-level lowering during the 5.8–5.3 Ma interval (Guillemin and Houzay, 1982; Azdimousa et al., 2006). Above the conglomerates are early Pliocene marine sandy and marly deposits (*ca.* 150 m thick) that exhibit a progradational geometry (Azdimousa et al., 2006). Pliocene sediments were deposited in a deltaic setting which opened seaward to the northeast (El Kharrim, 1991; Azdimousa et al., 2006). New observations allow us to improve our knowledge of the transition between Messinian and Pliocene sediments in this area of the Alboran domain.

3. Methods

Eight key stratigraphic sections have been studied at the transition between Messinian and early Pliocene deposits (Fig. 1B, D). These sections are described along three proximal to distal transects: Aït Abdallah–Saïdia–Main Road, Irachamene–Imessaoûdene–Oued Amekrane, and Iyedderene–Oued Salah (Fig. 1B). Some of the sections (i.e., Aït Abdallah, Iyedderene, Oued Salah) were sampled for calcareous plankton investigations in order to complement biostratigraphic data from previous published studies. A total of 30 samples were studied and 21 provided usable information. For planktonic foraminiferal analyses, loose sediment samples were wet-sieved (mesh sizes between 2 mm and 63 μm). Calcareous nannofossils were studied in the fraction 2–30 μm and separated by decantation method using a 7% solution of H_2O_2. Smear-slides were mounted with Canada balsam and analysed with an Olympus transmitting light microscope at 1200× magnification. Zonal subdivisions are from Wade et al. (2011) for planktonic foraminifers and Martini (1971) for calcareous nannofossils. Calibration of the bioevents follows Wade et al. (2011) for planktonic foraminifers and Raffi et al. (2006) for calcareous nannoplankton.

4. Results

4.1. Northern part of the basin

4.1.1. Ait Abdallah area (N 35°14′25.8″, W 3°40′51″)

At Aït Abdallah (Fig. 1B) Messinian diatomites are missing because of an irregular erosional surface overlain by a *ca.* 70 m thick siliciclastic succession (Fig. 2). Along this surface, chaotic deposits, 4–10 m thick, infill metre-scale depressions in the early Messinian marls (Fig. 3A, 4). Chaotic deposits are composed of clays that contain reworked fragments of selenite gypsum (Fig. 3B). Gypsum fragments are centimetre- to metre-sized. Above are a few metres of conglomerates with metamorphic and volcanic pebbles derived from the basement and Messinian *Porites* reef blocks (Fig. 3C). Well rounded clasts without matrix and cross-stratifications are indicative of fluvial depositional settings. The base of these conglomerates is slightly erosive. To the southwest of Aït Abdallah, towards the Ras Tarf fault, these conglomerates are matrix-supported and reach a thickness of tens of metres (Fig. 3D).

Above the conglomerates are, from bottom to top (Fig. 4): (i) 10 m thick fluvial conglomerates intercalated with laminated, oxidized fine-grained sandstones and clays which yielded wave-ripple, small burrows, desiccation cracks and marine microfauna and nannoflora. These are interpreted as deposited at the transition between continental and marine environments; (ii) these oxidized deposits progressively pass upwards into 40 m thick marine marls with sandstones and shells of the bivalve *Amusium* and bioturbated fine-grained sandstones displaying low-angle laminations and hummocky cross-stratification (HCS). These sediments were repeatedly deposited into shoreface to offshore environments; and (iii) 20 m thick siltstones, conglomerates and sandstones, repeatedly deposited into shoreface to backshore environments.

Two metres below the erosion surface, we found the planktonic foraminiferal species *Globorotalia mediterranea* and *Globorotalia conomiozea*, indicating a latest Tortonian/early Messinian age (Iaccarino, 1985). Between 18 and 70 m above the surface, samples AAB9 to AAB16 yielded *Globoturborotalia nepenthes* (LAD — Last Appearance Datum = 4.37 Ma) and *Globorotalia margaritae* (FCO — First Common Occurrence = 5.08 Ma), pointing to Zone PL1. Samples AAB5 to 10AA9, between 2 and 18 m above the surface, also yielded the nannofossil *Ceratolithus acutus* (FAD — First Appearance Datum = 5.32 Ma; LAD = 5.04 Ma; Raffi et al., 2006), pointing to nannofossil zone NN12. Just above the fluviatile conglomerates, sample AAB5 yielded nannofossil assemblages with *Triquetrorhabdulus rugosus* (LAD = 5.27 Ma, lower part of NN12). As a consequence, the underlying