C. R. Geoscience 346 (2014) 90–98

Contents lists available at ScienceDirect

Comptes Rendus Geoscience

www.sciencedirect.com

Stratigraphy, sedimentology

The Early Pliocene reflooding in the Western Mediterranean: New insights from the rias of the Internal Rif, Morocco

L'ennoiement Pliocène inférieur en Méditerranée occidentale : nouvelles données des rias du Rif interne, Maroc

Jean-Jacques Cornée [a,*], Philippe Münch [a], Mihaela Melinte-Dobrinescu [b], Abdelkhalak Ben Moussa [c], Frédéric Quillévéré [d], Hara Drinia [e], Ali Azdimousa [f], Abdelouahed Ouazani Touhami [c], Gilles Merzeraud [a], Séverine Fauquette [g], Michel Corsini [h], Pierre Moissette [d], Najat Feddi [i]

[a] *Géosciences Montpellier, UMR CNRS 5243, université Montpellier, 2, place Eugène-Bataillon, CC 060, 34095 Montpellier cedex 05, France*
[b] *National Institute of Marine Geology and Geo-ecology (GEOECOMAR), Bucharest, Romania*
[c] *Département de géologie, université Abdelmalek-Esaadi, 93003 Tetuán, Morocco*
[d] *Laboratoire de géologie de Lyon : Terre, planètes, environnement, UMR CNRS 5276, Université Lyon-1, 27–43, boulevard du 11-Novembre-1918, 69622 Villeurbanne cedex, France*
[e] *National and Kapodistrian University of Athens, Faculty of Geology and Geoenviromment, Athens, Greece*
[f] *Laboratoire de géosciences appliquées, faculté des sciences, université Mohammed-I^{er}, Oujda, Morocco*
[g] *Institut des sciences de l'Évolution (UM2-CNRS 5554), CC 061, Université Montpellier, 2, place Eugène-Bataillon, 34095 Montpellier cedex 5, France*
[h] *Laboratoire Géoazur, université Nice – Sophia Antipolis, 06560 Nice, France*
[i] *Laboratoire Biodiversité et dynamique des écosystèmes, université Cadi Ayyad, Faculté des Sciences Semlalia, boulevard Prince-Moulay-Abdelah, Marrakech, Morocco*

ARTICLE INFO

Article history:
Received 12 December 2013
Accepted after revision 10 March 2014
Available online 24 April 2014

Keywords:
Zanclean
Alboran Sea
Morocco
Rias
Depositional geometries
Biostratigraphy
Reflooding
Mediterranean

ABSTRACT

New field and micropalaeontological investigations have been conducted in four of the Pliocene rias of the internal zone of the Rif in Morocco, on the southern margin of the Alboran Sea. We found that marine sediments outcropping in these rias were deposited mainly during the Early Zanclean, between 5.04 and 3.8 Ma. After a transgressive episode that led to the deposition of terrestrial to marine conglomerates, dark clays deposited first at shallow palaeo-depths and then at bathyal palaeo-depths. The rias were then infilled with a shallowing upward succession comprising marine clays and sandstone and, locally, terrestrial sediments that indicate their final emersion. No Gilbert-deltas were observed in these rias. The presence of transgressive deposits at the bottom of the rias, also identified in other basins of the external zone of the Rif, and the absence of Gilbert deltas question a catastrophic reflooding after the Messinian Salinity Crisis in this area.

* Corresponding author.
E-mail address: jean-jacques.cornee@gm.univ-montp2.fr (J.-J. Cornée).

http://dx.doi.org/10.1016/j.crte.2014.03.002
1631-0713/

1. Introduction

During the Latest Miocene, the Mediterranean experienced the ''Messinian Salinity Crisis'' (MSC), characterized by both thick evaporitic deposits and strong erosion of the margins (e.g., Chumakov, 1973; CIESM, 2008; Clauzon, 1973; Hsü et al., 1973; Lofi et al., 2005, 2011; Ryan and Cita, 1978). This event is related to a temporary cessation of seawater exchanges between the Mediterranean and the Atlantic Ocean through the last marine gateway: the South Rifian corridor. During the Latest Messinian and/or the Earliest Zanclean, the Mediterranean was reflooded by Atlantic waters through the Gibraltar straight and Pliocene deposits sealed the erosional surfaces built up by the MSC (e.g., Blanc, 2002; Estrada et al., 2011; Garcia-Castellanos et al., 2009; Lofi et al., 2003). Onshore, Zanclean sediments were often deposited in rias related to Gilbert delta accumulations (Breda et al., 2007; Clauzon, 1978, 1982; Clauzon et al., 1990). Nevertheless, the sedimentary infilling within the Pliocene rias of the internal Rif of Morocco remains poorly studied, except the works of Wildi and Wernli (1977) and Wernli (1988). Here, we provide new biostratigraphic and sedimentological constraints on these sediments in order to better understand the dynamics and chronology of the Pliocene reflooding in the vicinity of the Gibraltar sill. For this, we conducted new detailed field investigations in the Tetouan–Martil, Oued Laou–Tirinesse, Tihissasse and M'Ter rias (Fig. 1), and collected 32 samples in which calcareous nannoplankton, benthic and planktonic foraminifers have been analysed (Supplementary material, plus Fig. 2 for an index of calcareous nannofossils species).

2. Geological setting

The Pliocene rias of the internal zone of the Rif were deposited after the main paroxysmal tectonic events of the chain (Chalouan et al., 2008). Sediments accumulated in several palaeovalleys, which widen toward the Mediterranean: Tetouan–Martil, Tirinesse–Oued Laou, Tihissasse and M'Ter (Fig. 1). The Pliocene infilling of these palaeovalleys is known since a long time (Fallot, 1937; Gentil and Boistel, 1905; Morel, 1987; Wernli, 1988; Wildi and Wernli, 1977). The Messinian drainage network of the Rifian coastal ranges was considered to be similar to the present one (Loget and Van Den Driessche, 2006) or even smaller (Wildi and Wernli, 1977). In the Tetouan–Martil ria, Ben Moussa (1994) showed that Pliocene deposits comprised, from bottom to top: conglomerates, black clays, and yellowish sandstones. In borehole samples collected from the black clays, Feinberg and Lorenz (1970) found the planktonic foraminiferal index species *Globorotalia margaritae*, then pointing to a Zanclean age (Feinberg and Lorenz, 1970). The Oued Laou ria is composed of two connected basins, the Tirinesse and Oued Laou basins, located south and north of the ria, respectively (Wildi and Wernli, 1977). These authors first mentioned that the Tirinesse Basin comprises fluvial conglomerates at the base overlaid by blackish sandy clays. Despite the lack of precise biostratigraphic data in the Tirinesse Basin, it is considered to be a remnant of an Early Pliocene basin emplaced on a Messinian (Pontian) erosional surface (Wernli, 1988; Wildi and Wernli, 1977), or a tectonically controlled basin (Benmakhlouf and Chalouan, 1995; Morel, 1987; Saji and Chalouan, 1995). In the Oued Laou Basin, the succession comprises black clays mainly found in cores, then yellowish sandstones and conglomerates. Feinberg and Lorenz (1970) and Wildi and Wernli (1977) mentioned *Globorotalia margaritae* in some of the clayey beds, known as the Tassefete Marls Formation, from the base of the basin infilling, then pointing again to the Zanclean.

In the Tihissasse and M'Ter rias, yellowish sandstones are mentioned on geological maps. Although no plankton index species were found, the discovery of a jaw fragment of *Hippopotamus amphibius* in some associated breccias suggests that it could have been deposited during the Early Pliocene (Morel, 1987). As a whole, precise dating of deposits still lack in these rias and the general sedimentary geometry remains poorly constrained.

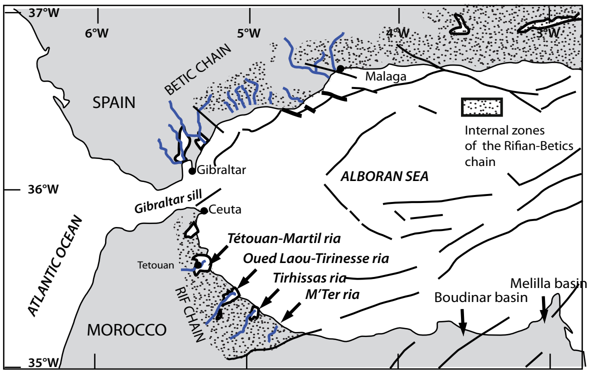

Fig. 1. Location of the Pliocene rias of the internal zone of the Rif in the Alboran Sea. Blue: present-day rivers.
For interpretation of the references to colour in this figure, the reader is referred to the online version of this article.

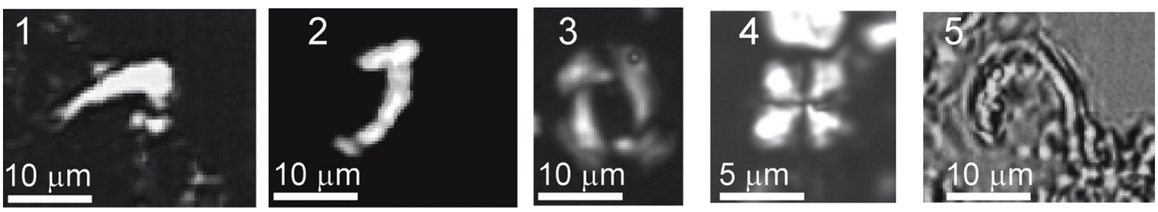

Fig. 2. All microphotographs at LM (light microscope); Figs. 1–4 in crossed nicols; Fig. 5 – polarized light. 1 – *Ceratolithus acutus* Gartner & Bukry; Sample RIF 8. 2 – *Ceratolithus acutus* Gartner & Bukry; Sample RIF1. 3–*Reticulofenestra pseudoumbilicus* (Gartner) Gartner; Sample RIF 30. 4 – *Sphenolithus abies* Deflandre in Deflandre & Fert; Sample RIF 13. 5 – *Amaurolithus primus* (Bukry & Percival) Gartner & Bukry; Sample RIF 8.

3. Results

3.1. Tetouan–Martil palaeoria

The Pliocene deposits from the Tetouan–Martil ria comprise, from the bottom to the top, three main lithological units:

- basal conglomerates, which crop out only two kilometres north-northeast from the city of Tetouan (location in Fig. 3);
- dark clays, at the least 100 m-thick according to borehole data (Feinberg and Lorenz, 1970), which crop out in the vicinity of the city of Tetouan. The clays change upward into silty marls with interbedded sandstones. Sample RIF 1 (Fig. 3A; Supplementary material) yielded the planktonic foraminifers *Globoturborotalia nepenthes* (Last Appearance Datum [LAD] = 4.37 Ma, thus pointing to Zone PL1 (Berggren et al., 1995), and the nannofossil *Ceratolithus acutus* (First Appearance Datum [FAD] = 5.32 Ma and LAD = 5.04 Ma, Di Stefano and Sturiale, 2010; Raffi et al., 2006;), which points to Zones NN12 and CN10b of Martini (1971) and Okada and Bukry (1980), respectively. Benthic foraminifers are dominated by *Bolivina* gr. (*e.g.*: *B. spathulata, B. dilatata*);
- to the southwest, the sandy marls are overlain by coarse-grained limestones and conglomerates with planar oblique bedding and littoral fauna (bivalves, barnacles, red algae, Ben Moussa, 1994). To the east, along the shoreline at Azlah, the transition between clays and overlying sandy deposits is well exposed (Fig. 3B). At the base, some silty marls are capped by a firm-ground. They are overlaid by ~20 m of detrital sediments. These include fine to coarse-grained sandstones with parallel and low-angle planar bedding, rudstones with erosive bases and transported bivalves, and, at the top, beach-rocks, palaeosoils and oyster-rich muds. The uppermost deposits of the palaeo-ria in the Azlah area (samples RIF 5 and 6; Fig. 3B) yielded Late Miocene to Early Pliocene nannofossils. As they overlay the Early Zanclean dark marls, these deposits are attributed to the Zanclean, not younger than late Early Pliocene (3.8 Ma, based on the occurrence of *R. pseudoumbilicus*, Raffi et al., 2006).

3.2. Oued Laou–Tirinesse palaeoria

3.2.1. Tirinesse Basin

3.2.1.1. Sedimentary succession and ages. The Tirinesse Basin is a rectangular, NNE–SSW-trending narrow depres-

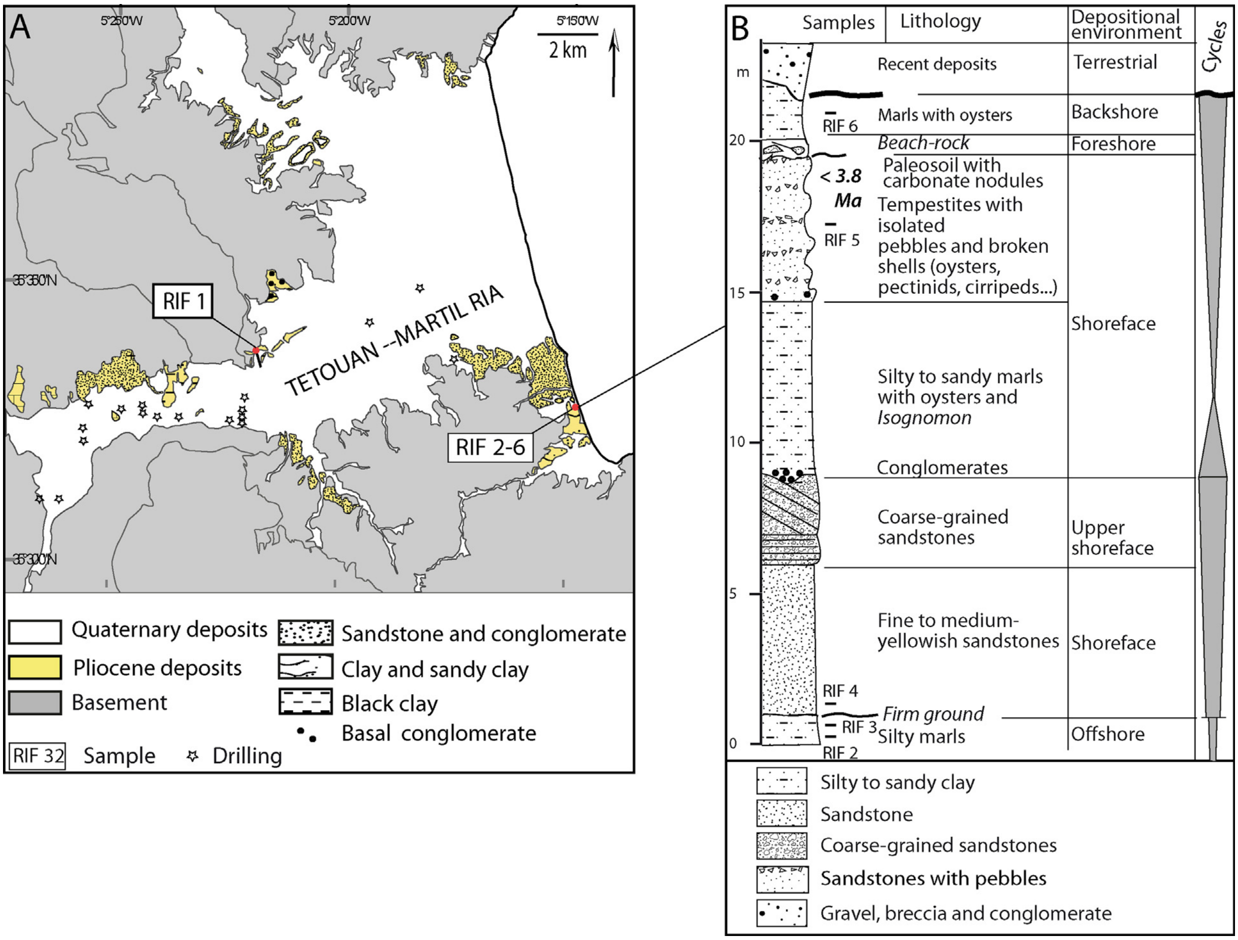

Fig. 3. (Colour online). The Tetouan–Martil ria. A. Map of outcrops and location of samples. B. Azlah section.

sion, 1.5 km wide, infilled with Pliocene sediments (Fig. 4A). To the north, it is reduced to a north–south-trending, 0.5-km-wide, palaeovalley with patchy outcrops. The basin is filled, from the bottom to the top, by three main sedimentary units.

The Ibouharane conglomerates (Fig. 4B), 30 m thick, outcrop to the southwest.

From the base up to 20 m, this unit consists of two coarsening upward, prograding sequences. They are comprised of gravels with centimetre-sized pebbles, upward changing into conglomerates with imbricated pebbles then into chaotic, poligenic conglomerates with rounded blocks reaching 1.5 m in diameter. Conglomerates are badly sorted and mostly barren of fossils. They

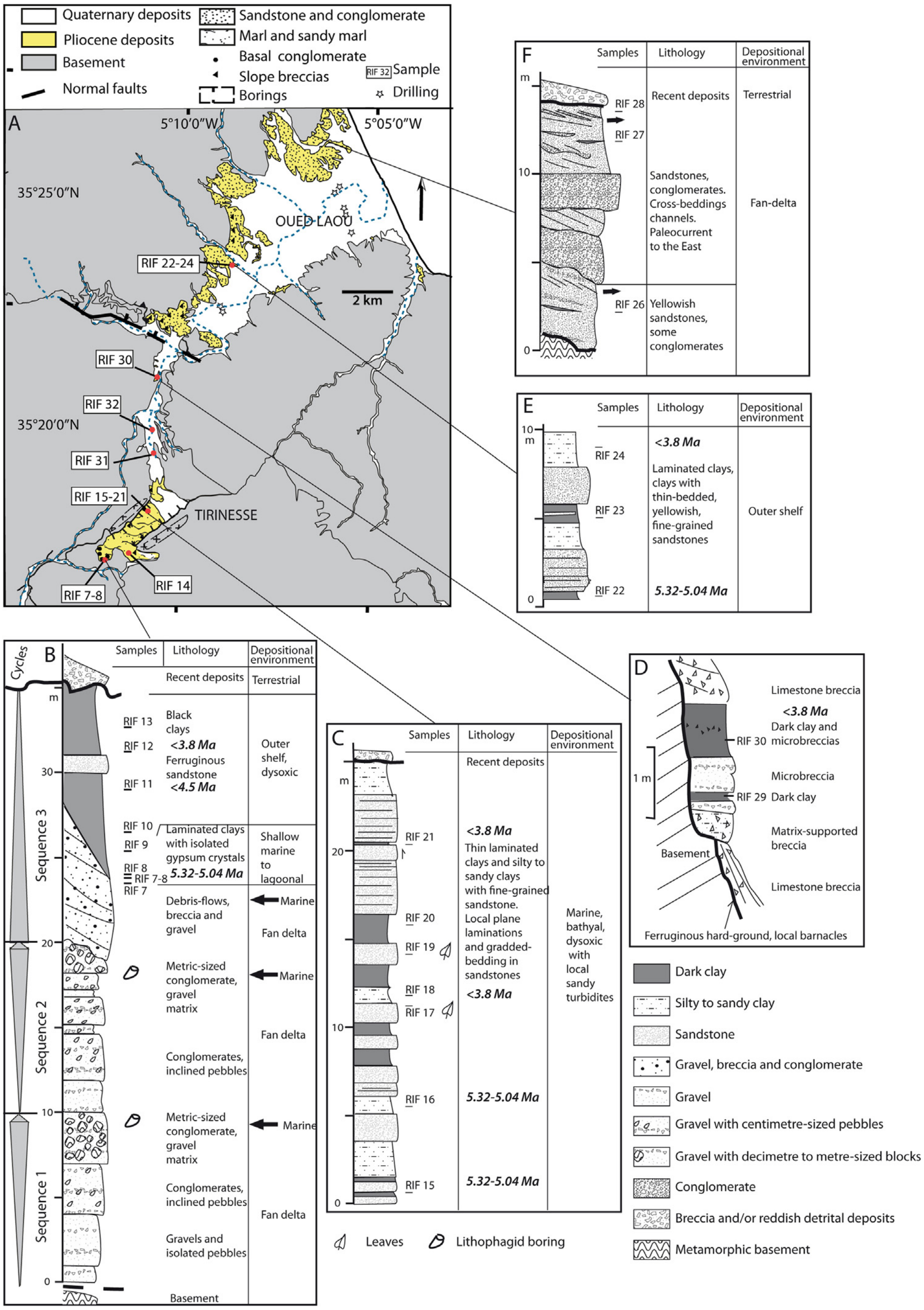

Fig. 4. (Colour online). The Tirinesse–Oued Laou ria. A. Map and location of samples. B. Ibourouhene section. C. RIF 15-21 section. D. Tirinesse North section. E. Klih section. F. National road section.

comprise basement-derived pebbles and display a gravel-dominated matrix, suggesting fan delta deposits. In the uppermost part of the two sequences, we found some borings and rare oysters, indicative of discrete marine influence and of retrogradational deposits.

Between 20 m and 28 m, the Ibouharane conglomerates are overlain by breccias with a gravel-dominated matrix. They are barren of fauna, except rare marine bivalves at their top.

Between 28 m and 35 m, there are ~10 m of dark clays. In their lower part, the clays are barren in benthic fauna and display isolated gypsum crystals, probably partly diagenetic in origin, which could indicate localized evaporitic conditions. Above in the clays, samples RIF 10 and 13 yielded an oligospecific assemblage of the benthic foraminifers *Eponides repandus* and *Nonion scaphum*. Although planktonic foraminifers are rare and poorly preserved within these clays, nannofossils are abundant. We identified *Ceratolithus acutus* (FAD = 5.32 Ma and LAD = 5.04 Ma; Di Stefano and Sturiale, 2010; Raffi et al., 2006), indicating an Early Zanclean age (samples RIF7-8 and RIF 8; Fig. 4B; Supplementary material). Thus a third retrograding sequence developed above the Ibouharane conglomerates, from fan delta deposits to marine clays.

In the central part of the basin, dark clays with interbedded sandstones poorly crop out (grey sands of Tirinesse Formation of Wildi and Wernli, 1977). Depending on the irregular initial topography of the underlying basement, these deposits are several tens of metres thick. For Maurer (1968), their thickness might exceed 100 m. In section RIF 15-21 (Fig. 4C), the sandstones consist of coarse to fine-grained normally graded beds containing terrestrial leaves. In clayey intervals, samples RIF 15 and RIF 18 are barren of microfauna, RIF 16 is characterized by almost 90% of *Bolivina spathulata* and RIF 21 is dominated by different genera of bolivinids (see Supplementary material). Marly interbeds RIF 15 and 16 provided *Ceratolithus acutus*. Samples RIF 16 and RIF 21 provided *Globoturborotalia nepenthes* (LAD = 4.37 Ma; Wade et al., 2011), pointing to Zone PL1 of Berggren et al. (1995).

Between the Tirinesse and the Oued Laou basins, patchy outcrops of silty marls occur close to the basement (RIF 30 to 32, Fig. 4A). These outcrops yielded Late Miocene to Early Pliocene calcareous nannofossils (Supplementary material).

In the Tamrabete valley, at the southeasternmost tip of the Tirinesse Basin, decametres-thick subaerial breccias rest uncomformably upon the Zanclean silty clays (Fig. 4A). The age of these breccias remains unknown, related to the Villafranchian (Maurer, 1968) or to the Pleistocene (Morel, 1987).

3.2.1.2. Margins of the basin. The linear, abrupt margins of the basin have been identified as NE–SW-striking normal faults whose origin is still debated. Moreover, a flat surface, dipping northward with a 0.5° angle, occurs on the top of the margins. This surface is known as the "Pontian surface" (Maurer, 1968) and should correspond to a Messinian terrestrial surface. According to Wildi and Wernli (1977), these margins correspond to normal faults that transected both the Pontian surface and the Pliocene deposits. The Tirinesse Basin should be a post-Pliocene graben that should have lowered the "Pontian surface" in the centre of the basin. According to Saji and Chalouan (1995), normal faults were active prior to and during the Pliocene. Several new observations allow us to shed new light on these margins.

The northwestern margin of the Tirinesse Basin is abrupt. The basement here consists of carbonates and its top surface displays microkarst features and fissures, as well as thin iron coatings overlain by breccias cemented by silty clays, and then by Pliocene clays (*e.g.*, N35° 18.1616′, W05° 11.627′, +388 m). At RIF 30 location, interbedded clays and slope breccias onlap the basement (Fig. 4D). Barnacles are locally preserved *in situ* on the wall of the basement. Slope breccias often drape the initial surface; they are a few metres-thick and are observed only at the basin margin.

The southern margin of the Tirinesse Basin is a major cliff. Our investigations indicate that the basement is coated by iron hydroxides and that slope breccias are present. In RIF 14, the micritic matrix of the breccia yielded Late Miocene – Early Pliocene nannofossils (see Supplementary material). At the top of the cliff, a marine planation surface occurs between +570 m and +580 m. The marine origin of this surface is demonstrated by the intense bioerosion of lithophagid molluscs on this surface, together on the upper part of the cliff (Fig. 4A; Fig. 5). Borings are coated by iron oxides and infilled by micritic deposits.

3.2.2. The Oued Laou Basin

The Oued Laou Basin is NE–SW trending. It is 2 km wide to the southwest, at the mouth of the Tirinesse Basin, and reaches a width of 6 km along the Mediterranean coastline. Most of the Oued Laou Basin is covered by terrestrial, Quaternary deposits. Some Pliocene outcrops occur on the northern side of the basin (Fig. 4A; Wildi and Wernli, 1977), as well as boreholes in its central recovered Pliocene sediments (Feinberg and Lorenz, 1970).

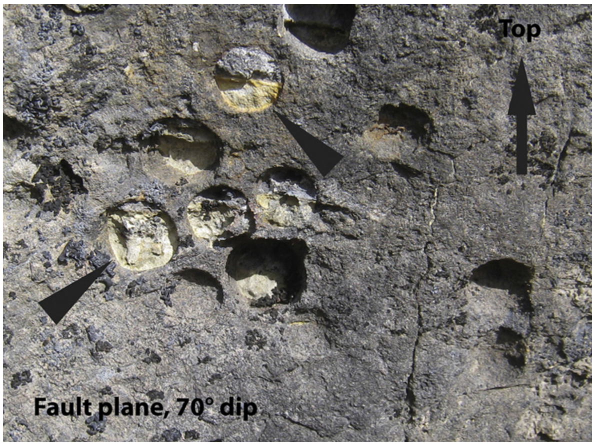

Fig. 5. (Colour online). Borings of lithophagid molluscs on the fault plane bounding the southeastern edge of the Tirinesse Basin. Note the geopetal structure resulting from incomplete infilling of the borings.

From bottom to top, the main lithological units are:

- dark clayey marls (Tassefete marls Formation) with planktonic foraminifers. In the boreholes, the clayey marls reach a maximum thickness of 70 m, and the position of the underlying basement remains unknown. *Globorotalia margaritae* was detected within this unit (Feinberg and Lorenz, 1970; Wildi and Wernli, 1977), then pointing to a Zanclean age. These authors mentioned slope breccias interbedded in the clayey marls against the basement;
- the clayey marls change upward into 10-m-thick dominant marine, yellowish fine-grained sandstones (Fig. 4E; Yellow Sands Formation). The succession comprises decimetre to metre-thick fine-grained sandstones with rare planktonic foraminifers, broken bryozoans and terrestrial leaves. Sandstones beds with horizontal laminations are separated by marly interbeds and by some conglomerates with erosive base. Sample RIF 22 yielded benthic foraminifers dominated by *Bolivina* and *Cibicidoides* and samples RIF 23 and 24 yielded an abundant and well-diversified assemblage of benthic foraminifers (Fig. 4E; Supplementary material). In sample RIF 22, we found Late Tortonian to Gelasian planktonic foraminifers (Supplementary material) and the Zanclean nannofossil *C. acutus*. In samples RIF 23 and RIF 24, we found Late Miocene to Early Pliocene planktonic foraminifers and nannofossils (Supplementary material), including *Reticulofenestra pseudoumbilicus*, associated with reworked Cretaceous, Oligocene and Early-Middle Miocene taxa. Since samples RIF 23 and RIF 24 overly RIF 22, they are assigned an age not younger than 3.8 Ma based on the occurrence of *R. pseudoumbilicus* (Raffi et al., 2006);
- in the northern part of the palaeo-ria, on the northern side of the valley, we found a 15-m-thick conglomeratic succession, with diversified basement-derived material. This succession comprises flat, decametre-long lenses-shaped conglomerate bodies with centimetre-sized pebbles and erosive bases, yellowish sandstones and gravel beds, with cross-bedding and some clayey lenses (Fig. 4F). Deposits lack fossils here and structures (oblique bedding, imbricated pebbles, clinoform bodies) indicate a general eastward transport of sediments in fluvial setting.

3.3. Tihissasse and M'Ter palaeorias

In the Oued Tihissasse and M'Ter palaeorias, some metres of yellowish sandstones interbedded with breccias onlap the metamorphic basement or silty clays (Tihissasse). The sandstones and rare argillaceous lenses are devoid of fossils, but the facies are very similar to the Late Zanclean deposits of the Oued Laou and Tetouan–Martil rias. Only some poorly preserved benthic foraminifers (*Bulimina* and *Globobulimina*) were found in the clayey lenses.

4. Discussion

4.1. Ages

In the Tetouan–Martil and Oued Laou–Tirinesse palaeorias, all the black clays outcrops yielded *G. nepenthes* and *C. acutus*, pointing to the Early Zanclean in the time interval between 5.32 Ma and 5.04 Ma. Despite previous authors mentioned *G. margaritae* in these rias (Feinberg and Lorenz, 1970; Wildi and Wernli, 1977), typical representatives of this taxon were not found in any of the studied samples. This is in accordance with the presence of *C. acutus*, as the first common occurrence of *G. margaritae* occurs between 5.09 and 5.06 Ma in the Mediterranean (Gennari et al., 2008; Iaccarino et al., 1999). As suspected by Wildi and Wernli (1977), the Tassefete marls Formation of the Oued Laou Basin is now proven to be coeval with the Tirinesse grey sands Formation. In the Tetouan–Martil and Oued Laou basins, the black clays are progressively replaced upward by marine yellowish sandstones and conglomerates, in turn passing upward into terrestrial deposits (cf. § 4.5). The marine deposits yielded *R. pseudoumbilicus*, indicating a Zanclean age, not younger than 3.8 Ma. As a consequence, the Pliocene marine sedimentation within the rias of the internal zone of the Rif developed during the Zanclean only, within a 5.32–3.8 Ma interval. It consequently lasted ~1.6 Ma. No other marine deposits are recorded later, except Eemian marine terraces on the Present-day coastline, indicating that the rias emerged at least since ~3.8 Ma.

In the Oued Tihissasse palaeoria, the Early Pliocene age proposed from the occurrence of *H. amphibius* (Morel, 1988) appears to be a maximum age. Boisserie et al. (2011) proposed that the expansion of *Hippopotamus* towards southern Europe occurred in Latest Pliocene times. Thus, we suggest that the Oued Tihissasse Pliocene deposits correlate with the Latest Zanclean deposits of Oued Laou–Tirinesse and Tetouan–Martil palaeorias.

4.2. Paleoenvironment evolution

The Tetouan–Martil ria is characterized by terrestrial then littoral conglomerates at the base (Ben Moussa, 1994), above an erosional surface cutting metamorphic rocks. Above, dark clays infilled the palaeoria. The clays yielded a diverse assemblage of benthic foraminifers from offshore setting, with some indication of stressed conditions (*Bolivina* Bolivina spathulata and *B. dilatata* reach 26%). Upward, both in the innermost and outermost parts of the palaeoria, the clays are replaced by carbonate or sandy/conglomeratic deposits. The associated fauna reveal littoral setting (molluscs, Ben Moussa, 1994). Beach-rocks, palaeosoils and oyster banks also indicate emersions and backshore setting (Fig. 3B). Thus, the Zanclean Tetouan–Martil ria recorded a major transgressive-regressive sedimentary cycle leading to an almost complete infilling of the palaeovalley (Za1 to Za2 eustatic cycles, Lugowsky et al., 2011).

In the Oued-Laou–Tirinesse palaeoria, the oldest deposits are the Ibouharane conglomerates (Fig. 4B), which correspond to gravity flow deposits. Conglomerates are organized into three superimposed sequences. The two lowest ones, coarsening upward, are essentially constituted by an alternation of more or less concentrated debris-flow deposits, with some marine fossils at the top (oysters, lithophagid borings). This suggests fan delta deposits episodically influenced by marine conditions on top of each sequence. The uppermost one comprises matrix-supported conglomerates (fan delta) topped by marine clays. In their lowermost part, the clays are barren in benthic fauna but provided calcareous nannofossils; they also yielded isolated crystal gypsum, possibly indicating evaporitic conditions in a bayhead. In their uppermost part, the clays provided an oligospecific *Eponides repandus* assemblage (together with *N. scaphum*), indicative of an outer shelf setting. Thus, the Ibouharane conglomerates recorded two minor transgressive pulses, then a major one leading to the drowning of the ria and the deposition of the dark clays. Above, the Tirinesse grey sands and the Tassefete marls Formation always display abundant and diversified assemblages of planktonic foraminifers. The associated benthic foraminifers indicate outer shelf to bathyal environments (150 to 350 m depth *bsl*), sometimes dysoxic as indicated by the occurrence of abundant *B. spathulata* and/or *B. dilatata* (Supplementary material). This estimation for the maximum palaeodepth of the Zanclean ria (150 to 350 m) is in accordance with the geometry of the Tirinesse Basin. Indeed, the bored, marine planation surface recorded on the southern margin of the basin (Fig. 4A) is currently at around +580 m elevation, and the silty clays occur up to +380 m elevation, corresponding to ~200 m palaeodepth. The margins of the basin are bored (Fig. 5), incrustated by iron films and sealed by the silty clays. Because of steep margins, slope breccias composed of basement-derived material are interbedded in the sediments at the foot of the submarine cliffs. As a whole, the Tirinesse Basin corresponds to the passive infilling of a depression that was formed prior to the deposition of Early Zanclean sediments. Its origin is doubtless tectonic regarding the geometry of the margins, but it was formed before the Early Zanclean.

In the Oued Laou Basin, the bathyal marls (Tassefete marls Formation) are topped by the Yellow sands Formation, which is still indicative of marine environments. Indeed, the Yellow Sands Formation yielded planktonic foraminifers together with well diversified benthic foraminifers with abundant *Cibicidoides* (RIF 23, 24; Supplementary material) pointing to an outer shelf depositional setting. Upward, yellow sandstones and conglomerates exhibit a vertical transition from marine to fluvial deposits with palaeocurrents to the east. These fluvial deposits are restricted to the northern margin of the basin and correspond to localized fan-delta from tributaries. In the whole ria, lateral changes from continental to marine deposits were not observed, only a general aggradational geometry. Thus, the Oued Laou Basin was a palaeovalley infilled by deep marine clayey sediments during the Earliest Zanclean transgression (Za 1 cycle, Lugowsky et al., 2011). A general shallowing upward trend is then recorded by the deposition of the Yellow Sands Formation during the Zanclean and before 3.8 Ma, up to fluvial deposits. These fluvial deposits developed over some square kilometres and are connected to small delta fans in upstream areas.

4.3. Implications for the Pliocene reflooding in the Alboran Sea

The investigated rias of the internal zone of the Rif reflect a passive infilling of palaeovalleys, which occurred mainly during the Early Zanclean, and which is firstly characterized by the deposition of clays and silts, and then by sandstones and conglomerates originating from the margins. This situation is similar eastward in the Boudinar and Melilla basins, in the external zone of the Rif (Fig. 1). In the Boudinar Basin, Azdimousa et al. (2006), Cornée et al. (2006a), El Kharim (1991), and Guillemin and Houzay (1982) mentioned the infilling of Zanclean deposits, clays, sandstones, and localized conglomerates, onlapping a very low-angle Messinian erosional surface. In the Melilla–Nador Basin, Cornée et al. (2006b) and Guillemin and Houzay (1982) described a Messinian erosional surface characterized by small palaeovalleys and kilometre-wide landslide scars. There, two transgressive-regressive cycles were identified and the earliest dates from the Latest Messinian? to the Earliest Pliocene (Cornée et al., 2006b).

This situation is different from that of the northern side of the western Mediterranean, where prograding, early to Middle Pliocene Gilbert delta have been described (*e.g.*, Breda et al., 2007, 2009; Clauzon, 1978, 1982, 1990; Clauzon et al., 1990). These Gilbert deltas result in "overfill" conditions of incised valleys which should have been rapidly drowned during the Pliocene reflooding. They are characterized by stacked, often high-angle dipping (15° to 25°), progradational conglomeratic bodies, each 50 to 250 m thick, and separated by marly intervals or erosional surfaces. These Gilbert-type deltas display component facies organized in topset, foreset, and toeset. Topset were emplaced into terrestrial to shallow marine depositional environments, foresets into submarine slope and toesets mostly display sandstones to laminated mudstones from the epibathyal zone. According to Bache et al. (2012), these Gilbert-deltas were deposited in response to a step-2 ultra-rapid reflooding of the Mediterranean.

In Morocco, such Gilbert-deltas are not identified in Pliocene deposits. The palaeovalley fill displays aggradational to very low-angle progradational geometry. Neither giant Pliocene conglomeratic foresets nor pronounced lateral changes of facies can be seen in Pliocene successions. In the Oued Laou–Tirinesse palaeoria, conglomerates occur upstream at the bottom of the valley fill. These are local terrestrial deposits interpreted as gravity flow facies developed into fan deltas environment. Other continental conglomerates cap the Pliocene marine deposits and are also small fan deposits. All the conglomerates are organized in small sequences (about a ten of metres thick) and have limited extent (some square kilometres at the most). This suggests a low sediment-supply rate into the palaeorias along the Moroccan margin of the Alboran Sea during the Latest Messinian?–Early Pliocene. This can be explained by small catchment areas and by warm and very dry climate in North Africa (Fauquette et al., 2006). This situation is rather similar to the present-day one, as proposed by Loget and Van Den Driessche (2006), and by Wildi and Wernli (1977).

In the Tirinesse Basin, three transgressive pulses are recorded in the post-MSC deposits (sequences 1 to 3 of the Ibouharane conglomerates) during the Latest Messinian(?)–Earliest Zanclean. The third pulse led to the drowning of the palaeoria and the deposition of deep marine deposits. This result indicates first a progressive infilling of the rias in relation with limited transgressive pulses and then a general flooding during the Early Zanclean. Such a pattern has also been evidenced in Melilla (Cornée et al., 2006a, 2006b; Rouchy et al., 2003) or in Bajo Segura along the Spanish coast (Caracuel et al., 2011). This is not fully compatible with the amplitudes of the two successive important sea-level rises proposed by Bache et al. (2012). Pérez-Asensio et al. (2013) proposed a two-step reflooding scenario with first limited transgressive–regressive glacioeustatic cycles, then a "catastrophic" reflooding of the Mediterranean. Our results are more in accordance with such a scenario and with reconstructions from other marginal basins (*e.g.*, Sicily, northern Apennines, and Spain) suggesting a gradual refill of the Mediterranean beginning in the Latest Messinian and culminating with the Zanclean flooding (Gennari et al., 2008; Manzi et al., 2009; Omodeo-Salè et al., 2012; Roveri et al., 2008a, 2008b). The observed transgressive systems tracts, together with the absence of Gilbert deltas in the investigated rias, question the catastrophic aspect (*e.g.*, Bache et al., 2012; Blanc, 2002; Loget and Van Den Driessche, 2006; Pérez-Asensio et al.,2013) of the Zanclean reflooding of the Mediterranean. Indeed, along the South Alboran margin the major Zanclean flooding appears rather progressive as exemplified by the continental to restricted marine transition observed in Earliest Zanclean deposits in the Tirinesse Basin.

5. Conclusion

The Pliocene sedimentary cycles in the rias of the internal zone of the Rif represent the infilling of palaeovalleys during the Latest Messinian?–Early Zanclean. The base of these palaeorias comprises two limited transgressive sequences and a third one culminating with the overflow of the palaeoria. Therefore, the change from continental to deep marine depositional environments is rather progressive and occurred between 5.32 Ma and 5.04 Ma. The rias were then progressively infilled by detrital materials from the margins of the palaeovalleys, and finally emerged. The transition from marine to continental deposits, which occurred before 3.8 Ma, does not match the hallmarks of typical Gilbert-deltas type geometries, but rather corresponds to a continuous shallowing upward general trend. Even if the last major marine transgression recorded in the Moroccan palaeorias is significant, it does not fully match the proposed "catastrophic" scenario.

Acknowledgements

This work was partly funded by the French National Program Actions Margesand by the French-Moroccan PHC Volubilis MA 27070ZD. This paper is ISEM contribution No. 2014-020. M. Roveri, G. Jimenez-Moreno, and S. Bourquin are thanked for constructive reviews.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.crte.2014.03.002.

References

Azdimousa, A., Poupeau, G., Rezqi, H., Asebriy, L., Bourgois, J., Ait Brahim, L., 2006. Géodynamique des bordures méridionales de la mer d'Alboran ; application de la stratigraphie séquentielle dans le bassin néogene de Boudinar (Rif oriental, Maroc). Bull. Inst. Sci. Rabat 28, 9–18.

Bache, F., Popescu, S.-M., Rabineau, M., Gorini, C., Suc, J.-P., Clauzon, G., Olivet, J.-L., Rubino, J.-L., Melinte-Dobrinescu, M.C., Estrada, F., Londeix, L., Armijo, R., Meyer, B., Jolivet, L., Jouannic, G., Leroux, E., Aslanian, D., Dos Reis, A.T., Mocochain, L., Dumurdžanov, N., Zagorchev, I., Lesić, V., Tomić, D., Çağatay, M.N., Brun, J.-P., Sokoutis, D., Csato, I., Ucarkus, G., Çakir, Z., 2012. A two-step process for the reflooding of the Mediterranean after the Messinian Salinity Crisis. Basin Res. 23, 1–29.

Ben Moussa, A., 1994. Les Bivalves néogènes des secteurs occidental et oriental du Maroc septentrional (Façade atlantique et méditerranéenne) Biostratigraphie, paléobiogéographie et paléoécologie. Doc. Labo. Géol. Lyon 132, 1–281.

Benmakhlouf, M., Chalouan, A., 1995. Évolution néogène du bassin de Tétouan-Martil, Rif septentrional. Maroc. Geogaceta 17, 98–100.

Berggren, W.A., Kent, D.V., Swisher, C.C., Aubry, M.P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W.A., Kent, D.V., Aubry, M.P., Hardenbol, J. (Eds.), Geochronology time scale and global stratigraphic correlation, 54pp. 129–212 [SEPM Spec. Publ.]

Blanc, P.-L., 2002. The opening of the Plio-Quaternary Gibraltar Strait: assessing the size of a cataclysm. Geodin. Acta 15, 303–317.

Boisserie, J.-R., Fisher, R.E., Lihoreau, F., Weston, E.M., 2011. Evolving between land and water: key questions on the emergence and history of the Hippopotamidae (Hippopotamoidea, Cetancodonta Cetartiodactyla). Biol. Rev. 86, 601–625.

Breda, A., Mellere, D., Massari, F., 2007. Facies and processes in a Gilbert-delta-filled incised valley (Pliocene of Ventimiglia NW Italy). Sediment. Geol. 200, 31–55.

Breda, A., Mellere, D., Massari, F., Asioli, A., 2009. Vertically stacked Gilbert-type fan deltas of Ventimiglia (NW Italy): the Pliocene record of an overfilled Messinian incised valley. Sediment. Geol. 219, 58–76.

Caracuel, J.E., Corbi, H., Gianetti, A., Monaco, P., Soria, J.M., Tent-Manclus, J.E., Yébenes, A., 2011. Paleoenvironmental changes during the Late Miocene (Messinian)-Pliocene transition (Bajo Segura Basin, southeastern Spain): sedimentological and ichnological evidence. Palaios 26, 754–766.

Chalouan, A., Michard, A., El Kadiri, K., Negro, F., Frizon de Lamotte, D., Soto, J.I., Saddiqi, O., 2008. The Rif Belt. In: Michard, A. (Ed.), Continental evolution: the geology of Morocco. pp. 203–302.

Chumakov, I., 1973. Geological history of the Mediterranean at the end of the Miocene-the beginning of the Pliocene according to new data. In: Ryan, W.B.F., Hsü, K.J. (Eds.), Initial reports of the deep sea drilling project, XIII. US Govt. Printing Office, Washington, DC, pp. 1241–1242.

CIESM, 2008. The Messinian salinity crisis mega-deposits to microbiology–A consensus report. In: Briand, F. (Ed.), CIESM Workshop Monographs, 33, pp. 1–168.

Clauzon, G., 1973. The eustatic hypothesis and the pre-Pliocene cutting of the Rhone Valley. In: Ryan, W.B.F., Hsü, K.J. (Eds.), Initial reports of the deep sea drilling project, XIII. US Govt. Printing Office, Washington, DC, pp. 1251–1256.

Clauzon, G., 1978. The Messinian Var canyon (Provence Southern France) -paleogeographic implications. Mar. Geol. 27, 231–246.

Clauzon, G., 1982. Le canyon messinien du Rhône : une preuve decisive du *desiccated deep-basin model* (Hsü Cita et Ryan, 1973). Bull. Soc. geol. France 24, 597–610.

Clauzon, G., 1990. Restitution de l'évolution géodynamique néogène du bassin du Roussillon et de l'unité adjacente des Corbières d'apres les données écostratigraphiques et paléógéographiques. Paleobiol. Cont. 17, 125–155.

Clauzon, G., Suc, J.-P., Aguilar, J.-P., Ambert, P., Cappetta, H., Cravatte, J., Drivaliari, A., Domenech, R., Dubar, M., Leroy, S., Martinell, J., Michaux, J., Roiron, P., Rubino, J.-L., Savoye, B., Vernet, J.-L., 1990. Pliocene geodynamic and climatic evolutions in the French Mediterranean region. Paleontol. Evol. Mem. Espec. 2, 132–186.

Cornée, J.-J., Münch, P., Mauffret, A., Quillévéré, F., Conesa, G., Gorini, C., Ammar, A., 2006a. Onshore and offshore view of the Melilla and Boudinar basins (Morocco). EGU 06, Vienne. Geophys. Res. [Abstracts 8, 09094, abstract and poster].

Cornée, J.-J., Ferrandini, M., Saint Martin, J.-P., Munch, P., Moullade, M., Ribaud-Laurenti, A., Roger, S., Saint Martin, S., Ferrandini, J., 2006b. The Late Messinian erosional surface and the subsequent reflooding

in the Mediterranean: New insights from the Melilla–Nador Basin (Morocco). Palaeogeogr. Palaeoclimatol. Palaeoecol. 230, 129–154.
Di Stefano, A., Sturiale, G., 2010. Refinements of calcareous nannofossil biostratigraphy at the Miocene/Pliocene Boundary in the Mediterranean region. Geobios. 43, 5–20.
El Kharim, Y., 1991. Sédimentologie et palynologie du Néogène du bassin de Boudinar: implications paleogeographiques et paleoclimatiques (Rif nord-oriental, Maroc). Unpubl. Doctoral dissertation, Documents des Laboratoires de Géologie, Lyon117, 153 p.
Estrada, F., Ercilla, G., Gorini, C., Alonso, B., Vazquez, J.T., Garcia-Castellanos, D., Juan, C., Maldonado, A., Ammar, A., Elabbassi, M., 2011. Impact of Atlantic waters in the Alboran Basin during the Zanclean flooding. Geo-Mar. Lett. 31, 361–376.
Fallot, P., 1937. Essai sur la géologie du Rif septentrional. Notes Mem. Serv. Geol. Maroc 40, 555 p.
Fauquette, S., Suc, J.-P., Bertini, A., Popescu, S.-M., Warny, S., Bachiri Taoufik, N., Perez Villa, M.-J., Chikhi, H., Feddi, N., Subally, D., Clauzon, G., Ferrier, J., 2006. How much did climate force the Messinian salinity crisis? Quantified climatic conditions from pollen records in the Mediterranean region. Palaeogeogr. Palaeoclimatol. Palaeoecol. 238, 281–301.
Feinberg, H., Lorenz, H.G., 1970. Nouvelles données stratigraphiques sur le Miocène supérieur et le Pliocène du Maroc nord-occidental. Notes Serv. Geol. Maroc 30 225, 21–26.
Garcia-Castellanos, D., Estrada, F., Jimenez-Munt, I., Gorini, C., Fernandez, M., Verges, J., De Vicente, R., 2009. Catastrophic flood of the Mediterranean after the Messinian salinity crisis. Nature 462, 778–781.
Gennari, R., Iaccarino, S.M., Di Stefano, A., Sturiale, G., Cipollari, P., Manzi, V., Roveri, M., Cosentino, D., 2008. The Messinian–Zanclean boundary in the northern Apennines. Stratigraphy 5, 307–322.
Gentil, L., Boistel, A., 1905. Sur l'existence d'un remarquable gisement Pliocène à Tétouan (Maroc). C. R. Acad. Sci. Paris 140, 1725–1727.
Guillemin, M., Houzay, J.-P., 1982. Le Neogene post-nappes et le Quaternaire du Rif nord-oriental. Stratigraphie et tectonique des bassins de Melilla, de Kert, de Boudinar et du piémont des Kebdana. Notes Mem. Serv. Geol. Maroc 314, 7–239.
Hsü, K.J., Cita, M.B., Ryan, W.B.F., 1973. The origin of the Mediterranean evaporites. In: Ryan, W.B.F., Hsü, K.J. (Eds.), Initial reports of the deep sea drilling project, XIII. US Govt. Printing Office, Washington, DC, pp. 1203–1231.
Iaccarino, S.M., Castradori, D., Cita, M.B., Di Stefano, E., Gaboardi, S., McKenzie, J.A., Spezzaferri, S., Sprovieri, R., 1999. The Miocene/Pliocene boundary and the significance of the Earliest Pliocene flooding in the Mediterranean. Mem. Soc. Geol. Italiana 54, 109–131.
Lofi, J., Rabineau, M., Gorini, C., Berné, S., Clauzon, G., De Clarens, P., DosnReis, A.T., Mountain, G.S., Ryan, W.B.F., Steckler, M.S., Fouchet, C., 2003. Plio-Quaternary prograding clinoform wedges of the western Gulf of Lion continental margin (NW Mediterranean) after the Messinian Salinity Crisis. Mar. Geol. 198, 289–317.
Lofi, J., Gorini, C., Berné, S., Clauzon, G., Dos Reis, A.T., Ryan, W.B.F., Steckler, M.S., 2005. Erosional processes and paleo-environmental changes in the western gulf of Lions (SW France) during the Messinian salinity crisis. Mar. Geol. 217, 1–30.
Lofi, J., Sage, F., Loncke, L., Gaullier, V., Deverchère, J., Maillard, A., Thinon, I., 2011. Refining our knowledge of the Messinian Salinity Crisis in the offshore domain through seismic profile interpretation and multi-site approach. Bull. Soc. geol. France 182, 163–180.
Loget, N., Van Den Driessche, J., 2006. On the origin of the Strait of Gibraltar. Sediment. Geol. 341–356 188–189.
Lugowsky, A., Ogg, J., Gradstein, F.M., Ault, A., 2011. Time Scale Creator 4. 2. 5 software. , [Last accessed: 13 oct.]http://www.tscreator.org
Manzi, V., Lugli, S., Roveri, M., Schreiber, B.C., 2009. A new facies model for the upper gypsum of Sicily (Italy): Chronological and paleoenvironmental constraints for the Messinian salinity crisis in the Mediterranean. Sedimentology 56, 1937–1960.
Martini, E., 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci, A. (Ed.), Proceedings of the Second International Conference on Planktonic Microfossils, 2, Ed. Tecnosci, Roma, pp. 739–785.
Maurer, G., 1968. Les montagnes du Rif central. Étude géomorphologique. Trav. Inst. Sci. Cherifien, Geol. Geogr. Phys. 4 [499 p.]
Morel, J.L., 1987. Évolution récente de l'orogène rifain et de son avant-pays depuis la fin de la mise en place des nappes (Rif, Maroc). Unpubl. doctoral dissertation, Université Paris-Sud. Geodif. Mem. 1988, 4 [583 p.]
Okada, H., Bukry, D., 1980. Supplementary modification and introduction of code nubers to the Low Latitude Coccolith Biostratigraphy Zonation (Bukry, 1973, 1975). Mar. Micropal. 51, 321–325.
Omodeo-Salè, S., Gennari, R., Lugli, S., Manzi, V., Roveri, M., 2012. Tectonic and climatic control on the Late Messinian sedimentary evolution of the Nijar Basin (Betic Cordillera Southern Spain). Basin Res. 24, 314–337.
Pérez-Asensio, J.N., Aguirre, J., Jiménez-Moreno, G., Smiedl, G., Civis, J., 2013. Glacioeustatic control on the origin and cessation of the Messinian salinity crisis. Glob. Planet. Change. 111, 1–8.
Raffi, I., Backman, J., Fornaciari, E., Palike, H., Rio, D., Lourens, L., Hilgen, F.J., 2006. A review of calcareous nannofossil astrobiochronology encompassing the past 25 million years. Quat. Sci. Rev. 25, 3113–3137.
Roveri, M., Bertini, A., Cosentino, D., Di Stefano, A., Gennari, R., Gliozzi, E., Grossi, F., Iaccarino, S.M., Lugli, S., Manzi, V., Taviani, M., 2008a. A high-resolution stratigraphic framework for the Latest Messinian events in the Mediterranean area. Stratigraphy 5, 323–342.
Roveri, M., Lugli, S., Manzi, V., Schreiber, B.C., 2008b. The Messinian salinity crisis: a sequence-stratigraphic approach. GEOACTA Spec. Publ. 1, 117–138.
Rouchy, J.M., Pierre, C., Et-Touhami, M., Kerzazi, K., Caruso, A., Blanc-Valleron, M.-M., 2003. Late Messinian to Early Pliocene paleoenvironmental changes in the Melilla Basin (NE Morocco) and their relation to Mediterranean evolution. Sediment. Geol. 163, 1–27.
Ryan, W.B.F., Cita, M.B., 1978. The nature and distribution of Messinian erosional surfaces–indicators of a several-kilometer-deep Mediterranean in the Miocene. Mar. Geol. 27, 193–230.
Saji, R., Chalouan, A., 1995. Le bassin pliocène intramontagneux de Tirinesse et son mode d'ouverture (Rif interne Maroc). Geogaceta 17, 110–112.
Wade, B.S., Pearson, P.N., Berggren, W.A., Pälike, H., 2011. Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. Earth Sci. Rev. 104, 111–142.
Wernli, R., 1988. Micropaléontologie du Néogène post nappes du Maroc septentrional et description systématique des foraminifères planctoniques. Notes Mem. Serv. Geol. Maroc 331.
Wildi, W., Wernli, R., 1977. Stratigraphie et micropaléontologie des sédiments pliocènes de l'Oued Laou (côte méditerranéenne marocaine). Arch. Sci. Genève 30, 213–228.