Evolution of depositional environments after the end of Messinian Salinity Crisis in Nijar basin (SE Betic Cordillera)

Maria Angela Bassetti [a,*], Pietro Miculan [b,1], Francisco Javier Sierro [c,2]

[a] *IUEM-UMR 6538, Technopole Brest-Iroise, Place N. Copernic, 29280 Plouzané, France*
[b] *Dipartimento di Scienze della Terra e Geo-ambientali, via Zamboni 67-40126 Bologna, Italy*
[c] *Departamento de Geologia y Paleontología, Facultad de Ciencias, Plaza Merced s/n 37008 Salamanca, Spain*

Abstract

The Messinian succession is exceptionally well preserved in the intramontane sedimentary basin of Nijar in the Internal Betic Cordillera (SE Spain).

Gypsum-olistostromes and large slabs of the Azagador Member are unconformably overlain by the latest Messinian sediments of the Feos Formation. These deposits, which are studied in detail in the Rambla Los Feos outcrop (basinal area), are characterized by a sedimentary cyclicity and two lithostratigraphic units can be distinguished: (1) a lower one that mainly consists of calcarenitic intervals with laminated pelites and limestone beds (2) an upper unit showing a cyclic alternation of fluvial fan deposits and lacustrine marls, that corresponds to the 'Lago-mare episode'. The sedimentary succession records very precisely the strongly fluctuating environmental conditions during the upper Messinian, as well as the paleomorphological and paleogeographical changes that are likely related to late Miocene and Pliocene tectonic uplift of the Sierra Cabrera (Betic basement).

The dominant fossil content, present throughout the upper unit in the lacustrine white marls of the Feos Formation, is represented by ostracods of the *Loxocorniculina djafarovi* FA, an assemblage of non-marine, aquatic communities which lived in brackish-water bodies (Lago-mare fauna).

Extant ostracod faunas, similar to those documented in the Messinian fossil record and characterised by *Cyprideis*, *Tyrrhenocythere*, loxoconchids and leptocytherids, occur in hypohaline water bodies, in a salinity range of approximately 5–15‰ (mesohaline water).

However, the number of species of Parathetian affinity is low, as observed in other perimediterranean areas (i.e. Apennines).

The marine fauna association (foraminifera) present at levels is thought to be partly reworked, even though a marine influence at the end of the Lago-mare stage is not excluded.

1. Introduction

* Corresponding author. Tel.: +33 298 498891; fax: +33 298 498760.
 E-mail addresses: bassetti@univ-brest.fr (M.A. Bassetti), miculan@virgilio.it (P. Miculan), sierro@usal.es (F.J. Sierro).
[1] Tel.: +39 209 4572; fax: +39 209 4522.
[2] Tel.: +34 923 294 497; fax: +34 923 294 514.

The reconstruction of the depositional events related to the MSC in the Mediterranean areas, represents a topic of major discussion within the scientific community since the discovery of large amount of evaporitic deposits (Hsü et al., 1973a,b; Cita et al., 1978). A large number of papers have contributed over the years to a better understanding

of the latest Messinian complex depositional history. In particular, these contributions were mainly addressed to:

1) establish the onset of the evaporitic conditions;
2) define whether and when the complete isolation of the Mediterranean occurred (the Lago-mare event);
3) discern the processes that led to the return to the normal marine conditions in the lower Pliocene.

However, the comprehension of the different aspects related to MSC is still a controversial issue. The paleogeography and paleoclimatology of the Mediterranean area, the physical and chemical structure of the water column throughout the Messinian, and the possible active role of the biota during the crisis are still poorly understood. During the last decade, high-resolution biostratigraphic, magnetostratigraphic and cyclostratigraphic studies of marine sections in the central and eastern Mediterranean have provided an excellent chronostratigraphic framework for the late Neogene (Hilgen et al., 1995; Krijgsman et al., 1999; Sierro et al., 2001). Thus, knowledge on Messinian time-constraints is greatly improved, especially the issues concerning the Tortonian–Messinian and Messinian–Zanclean boundary ages (Hilgen et al., 2000; Van Couvering et al., 2000). Within the Messinian sedimentary record, a well developed cyclical arrangement of deposits made the astronomical calibration of Messinian events possible, as proposed by Krijgsman et al. (1999, 2001). A general agreement on this chronological sequence is reached in recent years and, according to the proposed model, the Messinian Stage can be subdivided into three different sub-parts:

1) a pre-evaporitic phase (7.25–5.96 Ma), characterized by the occurrence of organic-rich, laminated deposits in deep-water setting related to low-oxygen content and restricted water circulation within the Mediterranean caused by the restriction of Mediterranean–Atlantic gateways;
2) an evaporitic phase (5.96–5.61 Ma) that represents the main episode of evaporite precipitation in the marginal basins (the presence of primary evaporitic deposits in the deep water settings is not yet known, indeed questioned by Roveri et al., 2003);
3) a post-evaporitic phase (or Lago-mare, 5.61–5.33 Ma) that marks a dramatic decrease in water salinity, as primarily indicated by the occurrence of mollusc and euryhaline ostracods of supposed Paratethyan affinity (Lago-mare biofacies of Iaccarino and Bossio, 1999).

Within the perimediterranean areas, the Neogene basins of the Betic Cordillera (Sorbas, Vera, Nijar-SE Spain) offer spectacular views and exceptional preservation of the late Neogene successions and a large number of authors have been working on the sedimentary records of these basins (Riding et al., 1991; Van de Poel, 1991; Martín et al., 1999; Krijgsman et al., 1999; Sierro et al., 1999; Krijgsman et al., 2001; Sierro et al., 2001; Sánchez-Almazo et al., 2001; Fortuin and Krijgsman, 2003; Aguirre and Sánchez-Almazo, 2004) in order to collect data aimed to the paleoenvironmental reconstruction of the evaporitic and post-evaporitic sedimentary history. However, the calibration of Messinian events and the correlation of the stratigraphic units between adjacent basins are not always obvious and the interpretation of the evolution of the basins after the onset of MSC still remains a subject of controversy.

Another unresolved problem is the transition to the brackish water phase (Lago-mare) and the subsequent return to the normal marine conditions in the Zanclean. The Mio/Pliocene boundary marks the synchronous return to the full marine conditions at Mediterranean scale (Iaccarino et al., 1999), but some faunal indications are found that suggest the possibility of marine incursions during the final phase of the hypothesized isolation of the Mediterranean from the Atlantic (Aguirre and Sánchez-Almazo, 2004 in Nijar basin).

The post-evaporitic sedimentary record in Nijar basin is characterized by continuous sedimentation at places (Fortuin and Krijgsman, 2003): in the Gafares area (near to Los Feos locality) the succession reaches up to 100 m in thickness and it was preserved from intense erosion, whereas local scouring and sliding tell about syn- and post-depositional collapse events locally affecting the post-evaporitic sedimentation (Arroyo Gafares); the lateral passages are not always clear because of lack of exposition.

The stratigraphy of the post-evaporitic deposits in the Nijar basin as well as their lateral and vertical changes and paleogeographic aspects is described in detail by Fortuin and Krijgsman (2003) whereas the Lago-mare phase and its significance in the late Messinian events are also discussed by Aguirre and Sánchez-Almazo (2004). In particular, the results presented in the latter paper argue about the hypothesis of a re-establishment of normal marine conditions during the latest Messinian.

In this work we focus the attention on the significance of the evaporitic/post-evaporitic transition on the basis of sedimentological and micropaleontological evidence, the importance of the Lago-mare phase in the Nijar basin and the passage to the Pliocene.

Remarkable works providing sedimentological data and paleogeographical interpretations have been provided by previous authors (Fortuin and Krijgsman, 2003). However, Nijar basin is considered of particular

interest for stratigraphic reconstruction of the post-evaporitic succession as well as it is thought to be an area of great potentiality for correlations at regional scale. In fact, the marked sedimentary cyclicity, the bipartite character of the post-evaporitic deposits (made on clear lithological evidence) and the paleoenvironmental conditions (based on the ostracod fauna), show similarities with perimediterranean marginal basins (i.e. Apennine, Sicily, Cyprus) that can be used to establish a high-resolution stratigraphy at regional scale.

Using the bio-sedimentological approach, sedimentary facies and vertical trend are described in details, as well as possible precessional control on cyclic sedimentation is discussed taking into account the role of biota, in relation with the evolution of sedimentary systems after the end of the salinity crisis and at the Mio/Pliocene transition.

2. Geological setting and stratigraphy

The intramontane sedimentary basins of the Internal Betic Cordilleras formed since the Middle Miocene, by the motion along the NE–SW Trans-Alboran shear zone due to a continental collision between the African and European plates (de Larouzière et al., 1988).

The Nijar basin (Fig. 1) is the southernmost basin bordering the Alboran Sea and it is separated from the Sierra de Gata volcanic highs (Alboran volcanic province) by the still active sinistral Carboneras strike-slip fault (Montenat and Ott d'Estevou, 1999).

The early Messinian sedimentation in Nijar started with a transgressive sequence of coastal and shallow marine fossil-rich calcarenites (Azagador Member) that

Fig. 2. Lithostratigraphy of Messinian–Pliocene units in the Gafares area (modified after Fortuin and Krijgsman, 2003).

unconformably overlies Paleozoic Basement or late Miocene marine sediments. These deposits pass upwards and basinwards into open marine hemipelagic marls (Abad Member), indicating rapid deepening of the environments. The sedimentary sequence continues with a large amount of gypsum deposits (Yesares Formation), corresponding to the Messinian Salinity Crisis (MSC) of the Mediterranean (Van de Poel, 1991; Huibregtse et al., 1998). Hypersaline conditions were reached during isolation of the Mediterranean in the Messinian times as the results of closure of Gibraltar Arc by tectonic uplift (Weijermars, 1988). The evaporitic phase is recorded by the gypsiferous strata of the Yesares Formation, which is subdivided into three members (Van de Poel, 1991): Oolite Member, Gypsum Member and Manco Member (Fig. 2). The Oolitic Member is the marginal facies and
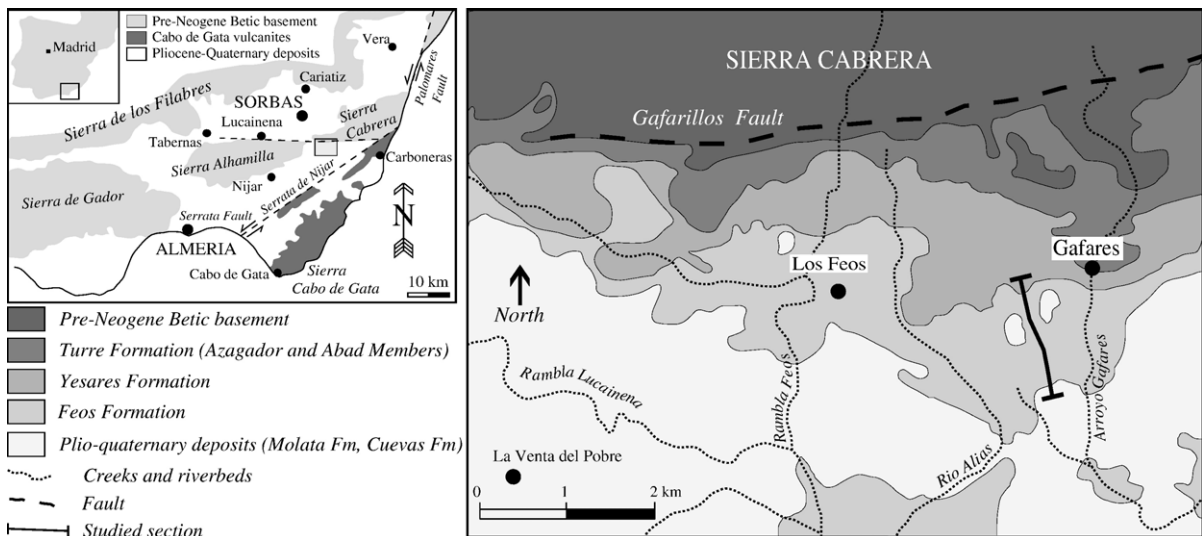

Fig. 1. Location and schematic geological map of Nijar area (modified after Fortuin and Krijgsman, 2003).

consists of mixed clastic-evaporitic strata, rich in oolites that are considered as the local equivalent of the Late Messinian Terminal Carbonate Complex (Dabrio et al., 1981; Riding et al., 1991; Fortuin and Krijgsman, 2003).

The Gypsum Member is characterized by massive gypsum beds with interbedded sandy-pelitic intervals. The gypsum is composed both of coarse, primary selenite and possibly reworked, laminated fine-crystalline gypsum.

The Manco Member consists of diagenetically altered vuggy limestones associated with marly and sandy strata (Van de Poel, 1991).

A dark Mn-enriched layer is found at the top of the Yesares Formation and it represents a useful stratigraphic marker that can be followed laterally across the entire basin (Fortuin and Krijgsman, 2003) tracing the base of the Feos Formation (Van de Poel et al., 1984; Van de Poel, 1991).

The Feos Formation corresponds to the post-evaporitic unit recording the "Lago-mare episode" of the Mediterranean (Cita et al., 1978; Rouchy et al., 2001). This units shows a variety of lithofacies and strong lateral thickness variations. It is well represented in the Nijar basin and provides one of most spectacular record of the Lago-mare episode in the western perimediterranean basins. The maximum thickness is reached in the Gafares area where the Feos Formation is overlain by the Cuevas Formation (Pliocene fossiliferous sandstones). Towards the basin margins (East and West), this unit becomes incomplete, because of lateral thinning and erosional gaps affecting the late Messinian deposits.

The sedimentation of the Nijar basins is tightly linked to the tectonic activity of the Nijar-Vera major faults (Serrata, Gafarillos and Palomares strike-slip faults). According to Huibregtse et al. (1998), this fault zone controls the Neogene deformation of the SE Internal Betic Cordillera. The structural analysis reveals that a clockwise rotation of stress field (from a NW–SE to N–S orientation) occurred in the early Messinian that coinciding with an increasing activity of Palomares and Gafarillos fault zones. In particular, a late Messinian active phase has been recognised and may be associated with the uplift of the Sierra Cabrera basement.

3. Studied section

Several sections have been visited in the Nijar area. However, the most complete record of the post-evaporitic succession is found in the Los Feos section, outcropping near the Arroyo Gafares (Fig. 1). Minor faults and vegetation cover affect the outcropping but the section is mainly exposed and the overall succession has been reconstructed through correlation. It exceeds

140 m thickness and covers the Yesares/Feos (Messinian)–Cuevas Formations (Pliocene) stratigraphic interval. The lower limit of the Yesares Formation on the older Miocene sediments (Upper Abad Member) locally appears chaotic and, therefore, may have been affected by gravity sliding (and/or tectonics) during sea level oscillations related to the evaporitic phase. The limit between the Yesares Member and the Feos Formation is put in correspondence of the Mn-enriched level (Van de Poel, 1991). The vertical passage to the poorly stratified, fossiliferous calcarenites of Cuevas Formation is lithologically marked by one meter approximately of coarse-grained, well sorted, intensively bioturbated sandstones.

Lithological and sedimentological observations based on detailed visual inspection are provided here, together with petrographic analyses performed on rock slabs polished and thin sectioned, under the conventional transmitted light microscopy.

A total number of 73 samples were selected for micropaleontological analyses: they have been collected mostly from the Feos Formation stratigraphic interval, since the sediments from the lowermost member (Yesares) show a very poor faunal content.

For each sample, 10 to 100 g of dried rock was soaked in tap water and washed through a 150 μm sieve. All dried residues were separated from the <63 μm fraction and briefly checked under a stereo-microscope for the micropaleontological analysis sample selection, depending on fossil abundance and presence of significant faunal assemblages. Among the 73 samples, 39 samples have been represented on the graphic (Figs. 7 and 8), the others result in sterile or bearing a poor and undistinguishable fauna.

4. Lithostratigraphy and sedimentology of the Messinian units

The studied section is characterized by marked sedimentary cyclicity and a number of eight cycles have been distinguished (after Fortuin and Krijgsman, 2003). The cycles are here grouped into three lithostratigraphic units, as shown in Fig. 3 and summarized in the following paragraphs.

4.1. The Gypsum Member (cycles I, II, III)

Each cycle consists of intervals dominated by distinct gypsarenite–gypsorudite bodies, alternating with calciclastic sequences. The cycles are based by beds up to 80 cm thick of coupled banded-massive selenite (Fig. 4A), locally mixed with carbonate that passes
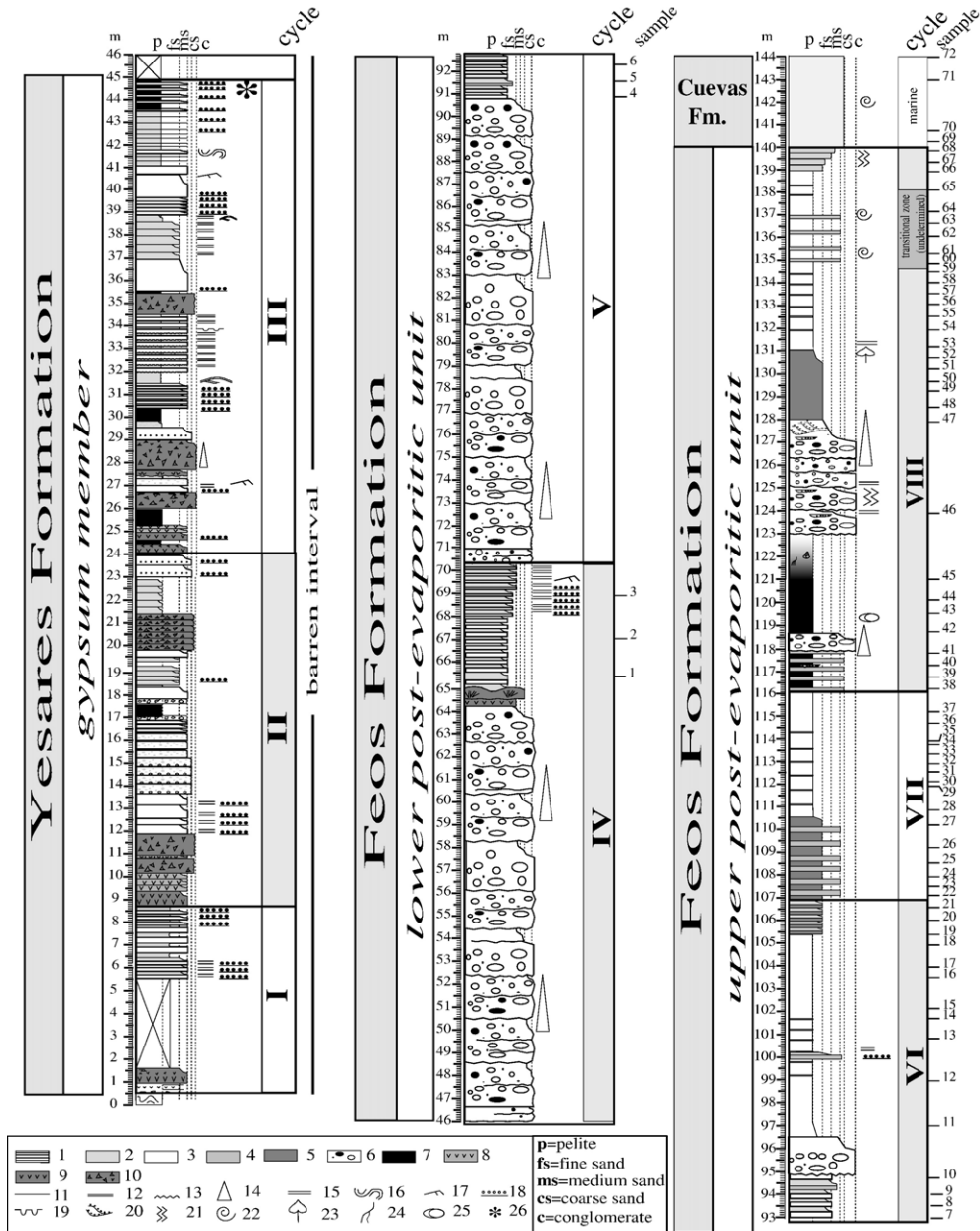
Fig. 3. Detailed lithological log of Los Feos section. Key: (1) carbonate/marls alternations (F1); (2) whitish silty marl (F2); (3) calcisiltite/calcarenite (F3); (4) sandstone (F4); (5) dark grey sand (F5); (6) conglomerates (F6); (7) pelite (F7); (8) banded selenite (F8); (9) massive selenite (F9); (10) gypsum rudite (F10); (11) sharp contact; (12) gradational contact; (13) scoured, sharp contact; (14) normally graded interval; (15) horizontal laminae; (16) slumped bed; (17) cross laminae; (18) graded bed (normal); (19) load cast; (20) thorough cross stratification; (21) bioturbation (intense); (22) shell (complete); (23) plant material; (24) root; (25) nodules and concretions; (26) Mg-rich horizon.

upward to gypsarenites and gypsorudites vertically organized in distinct, amalgamated beds. The gypsorudites are crudely graded and include large slabs of rocks (up to 20 cm).

Laminated pelites are locally found interbedded with the primary evaporitic deposits, represented by twinned gypsum crystals with their long axes oriented normal to the bedding. These gypsum-bearing deposits underlie a relatively thick interval (up to 16 m) of normally graded, medium to coarse grained whitish sandstones. Vuggy coarse grained sandstones (4 m), with abundant rounded pebbles at their base and clay chips are found in cycles
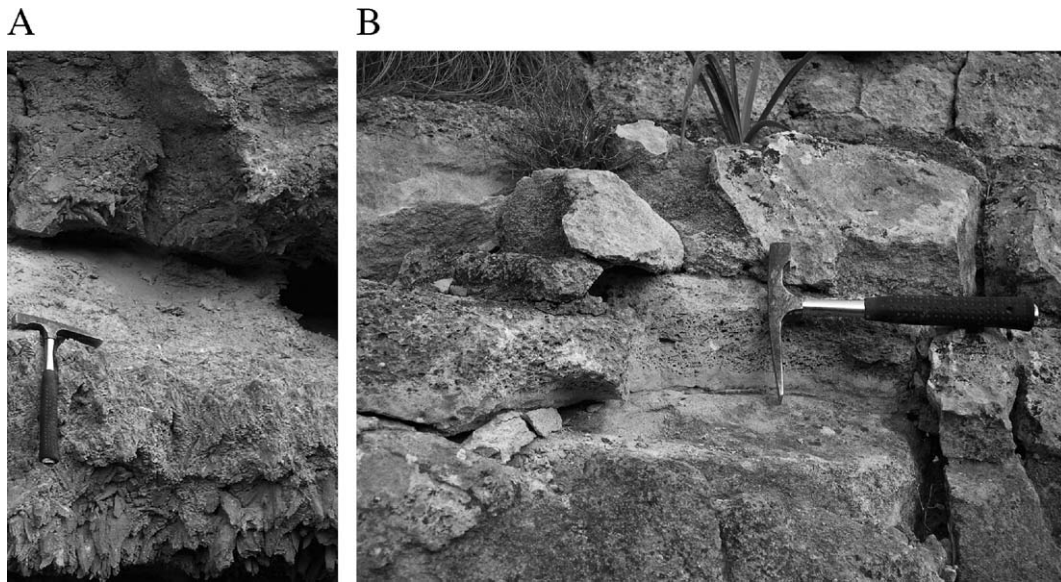
Fig. 4. Los Feos sedimentary facies (A) vertical gypsum selenite bed, at the base crystals up to 20 cm long are observed. They vertically reduce their size (upwards in the same interval); (B) massive vuggy limestone.

II, but not in cycles I and III. The vugs were clearly occupied by dissolved gypsum crystals, as they preserve the selenite shape (Fig. 4B).

The uppermost part of the cycle is made of very fine grained calcarenitic beds draped by cm thick pelite intervals.

This unit corresponds to the Yesares Formation, as defined by Fortuin and Krijgsman (2003), also on the basis of the dark Mn-enriched horizon that is found at the top of cycle III.

4.1.1. Interpretation

The alternation of selenite beds, gypsarenites, calcareous rudites and facies altered by gypsum dissolutions suggests a cyclical alternation of evaporative and detrital depositional events (Fortuin and Krijgsman, 2003). The vertical selenite is interpreted as growing as bottom crust in the deep part of the basin, during the evaporative event. In contrast to the well preserved fabrics of the selenite, the gypsum-altered facies (gypsum rudite and highly porous sandstones) are related to gravitationally displaced
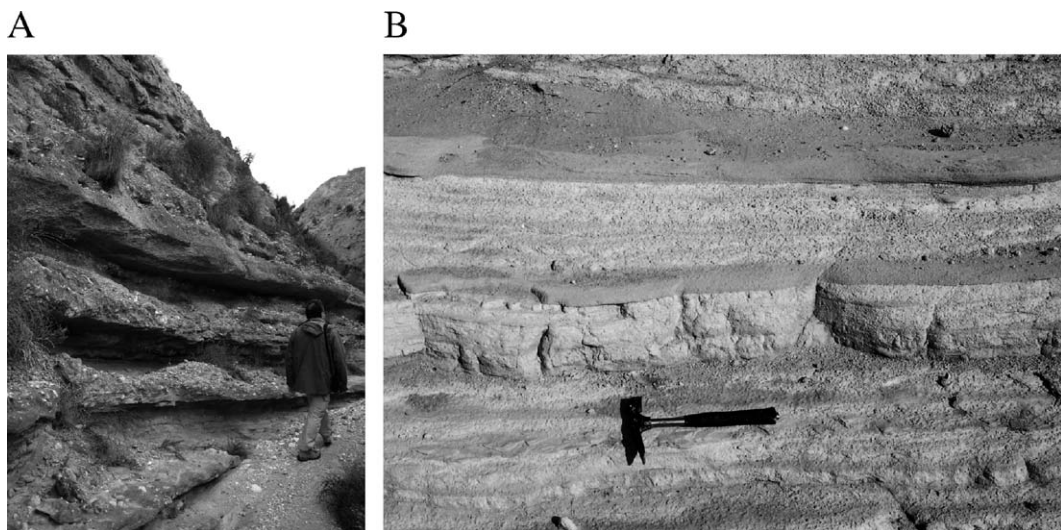

Fig. 5. Los Feos sedimentary facies: (A) thick conglomeratic beds made of structureless sandy matrix-rich breccias containing heterogeneous clast material, (B) laminated mudstone capped by fine-grained turbidites.

deposits. These depositional events occurred in response to even slight changes of base level in the marginal areas possibly triggered by the Sierra Cabrera uplift (Fortuin and Krijgsman, 2003).

4.2. The lower post-evaporitic unit (cycles IV, V)

This unit that mainly consists of fining upward cycles (facies sequences) made of thick conglomeratic beds at the base vertically passing to calcarenitic intervals, laminated pelites and limestone beds. The conglomeratic intervals consist of thick succession (up to 20 m, Fig. 5A) of structureless sandy matrix-rich breccias that contain calcareous clasts of various sizes, metamorphic basement debris of the nearby Sierra Cabrera and large blocks from the coral reefs (*Porites*). The pebbles are sub-rounded and they are mixed with pebbly-coarse sandstone. The beds range from 0.5 to 1.5 m approximately; they are crudely graded and frequently amalgamated with irregular erosional surfaces at their base.

The uppermost parts of these cycles are made of alternating laminated mudstone and calcarenitic turbidites alternations (Fig. 5B).

4.2.1. Interpretation

These coarse grained deposits correspond to the lower part of the Feos Formation and this facies is interpreted as depositional product of gravelly gravity flows, possibly high-concentration turbidity currents (Lowe, 1982). After rapid settling or freezing of the matrix-supported gravels, residual sediments were probably deposited gradually to form the poor, normal gradation of some breccia beds in the submarine slope depositional environment. On the other hand, the massive mudstone and calcarenitic turbidites reflect a deposition directly from the suspension load, whereas the mudstone laminae may be distal turbidites.

4.3. The upper post-evaporitic unit (cycles VI, VII, VIII)

This unit is made of cyclic alternations of fluvial deposits and lacustrine marls. The fluvial facies association comprises channel fill conglomerates, sheetflood sandstones and mudstone facies.

The channel fill facies consists of erosive-based channels filled with massive, poorly sorted and well-rounded conglomerates which fine upwards in the top few decimetres to pebbly sandstone (Fig. 6A). The conglomeratic bodies are up 2 m thick and the clasts are sparse within a poorly sorted coarse sand matrix.

The sandstone beds are laterally continuous and their basal surfaces are planar non-erosive to gently erosive. Beds are massive, planar stratified and, occasionally, thoroughly cross stratified. Sandstones are poorly to moderately sorted, coarse grained, laterally passing to conglomeratic lenses and interbedded with dark grey silty sand.

The mudstone facies consist of brown to red coloured pelitic intervals up to 4 m thick and are massive or rarely showing a faint horizontal lamination. They show
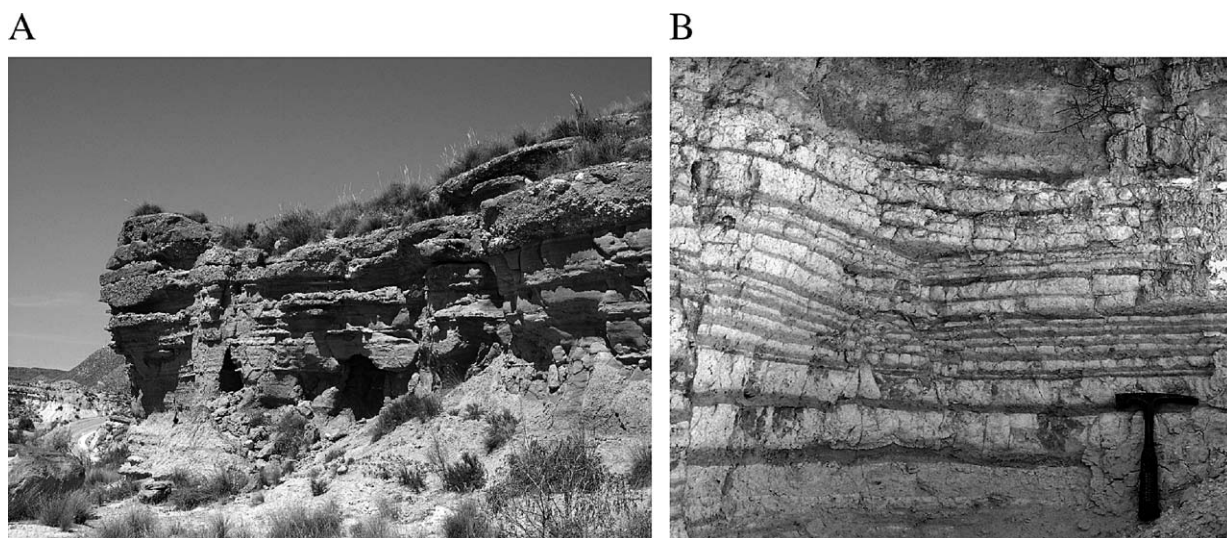
A

B

Fig. 6. Los Feos sedimentary facies: (A) sheetstone sandstone passing upwards to fluvial channel fill conglomerates; (B) alternation of massive, well cemented limestone and grey marls tabular sheets (lacustrine facies).

pedogenetic features, as described further, and contain remains of terrestrial gastropods.

The lacustrine deposits consist of up to 5 m thick alternations of massive, well cemented limestone and grey marl tabular sheets (Fig. 6B). The carbonates are white and they show an extensive peloidal texture, only visible in thin sections. These deposits contain a rich ostracod fauna.

4.3.1. Interpretation

The last three cycles described above form the uppermost part of the Feos Formation (Fortuin and Krijgsman, 2003).

The lenticular geometry, erosional base, fining upwards nature of the coarse grained bodies, as well as the rounded clasts and coarse grained sandy matrix suggest deposition in fluvial channels during flooding stages. The fining upwards trend of the sequence at the top of the channels suggests decreasing energy during deposition in waning flow condition.

The sheet-like sandstone beds indicate deposition from poorly confined floods with current features (plane-parallel lamination) of likely upper flow regime of small depth.

The alternation of lacustrine and fluvial facies suggests a deposition in a (shallow water) lake where the cyclical deposition records expansion and contraction of a non-saline lake across a fluvial dominated floodplain, according to base level oscillations. The micritic limestone is interpreted as deposited from suspension in still lacustrine water bodies.

5. Petrography and microfossils

5.1. Petrography

The studied material consists of a number of samples from the representative facies from the post-evaporitic units.

5.1.1. Pelites (F4, Fig. 3)

Pelites show very heterogeneous microfacies, from the facies with iso-oriented phyllosilicates to facies with siliciclastic dominant component or peloids, according to the depositional environment to which they belong. Remarkable pedogenetic features are observed in samples 42–46. The main type of pedologic features encountered at micro-scale consists of significant porosity caused by cracking due to desiccation during subaerial exposure. Pore walls are often coated with vadose cement or detrital sediments. The sediments are mottled by patches of various colour, possibly related to Fe hydromorphic soil.

5.1.2. Sandstones (F6, F7, Fig. 3)

Coarse-grained, heterogeneous clasts are the main components of arenitic deposits. They are mixed with occasional fossil remains and peloids of micritic material (intraformational clasts, reworked from the underlying beds). The clasts are often associated to crystal cementing coats (sparite). The presence of sparite is, nonetheless, unpredictable and possibly related to vadose fluids.

5.1.3. Calcisiltite/calcarenites (F8, F9, Fig. 3)

They show an irregular distribution of clastic material (quartz crystals and fibrous grains from the meta-morphic basement) within a micritic cement. Occasion-ally, a peloidal fabric is observed and the intrapeloid space is filled with sparite cement. Rare ostracod and foraminifera tests are found. The calcisiltitic microfacies differ from the calcarenites in the content of fine-grained siliciclastic material that appears to be higher than in the calcarenitic deposits, where we find it coarser but more scattered.

5.1.4. Lacustrine limestones and marls (F10, Fig. 3)

Carbonate content in these deposits is dominant in these deposits, although it is mixed with a very minor fraction of fine siliciclastic particles and/or organic matter. They are characterized by an overall homogeneous and mainly micritic fabric. At micro-scale, no corrosion, vuggy porosity or encrustation growing in cavities is observed. The carbonate and marls do not show any lamination, probably due to intense bioturbation (they contain rich ostracod fauna, see following paragraph).

5.2. Ostracods

Fossil ostracod shells occur at different levels in the Feos Formation. In many cases they are abundant and relatively well-preserved.

27 ostracod species, belonging to 11 genera were identified (Table 1, Fig. 7). Significant variations in composition and species diversity of the ostracod assemblages occur through the section. Two main assemblages can be recognised.

The first one has low species diversity and it is do-minated by *Cyprideis agrigentina* along with rare speci-mens of *Tyrrhenocythere* spp. Hereinafter it is referred to as the *Cyprideis* Ostracod Fossil Assemblage or OFA1. It occurs in samples 10, 14, 21, 30 and 40. Sample 30 is almost completely made up by *C. agrigentina*.

The second assemblage has rather high species diversity and is characterised by the abundant occurrence of *Candona* cf. *venusta* and *Loxocorniculina djafarovi* associated with *Amnicythere* spp., *Euxinocythere* aff.

Table 1
Abundances of ostracods in the Los Feos section

Species	Samples																					
	10	14	16	19	20	21	30	31	32	33	34	35	36	38	39	40	53	54	55	57	58	66
Candona cf. *pontica*																	R		c	c	r	
Candona cf. *venusta*			a	a	a	r		r	c	c	a	a	A	a	c		c	c	a	c	c	
Candona sp.						r															R	
Cypria robusta					c			R			R		R		R		r		R	r	R	
Amnicythere palimpsesta																				r	r	
Amnicythere cf. *pontica*								c	r	R		R		R	r				R			R
Amnicythere aff. *polymorpha*								R	R		R			R								
Amnicythere aff. *subcaspia*																			R	R	R	
Amnicythere aff. *cymbula*											R			R					R	r	R	
Amnicythere cf. *rosalinae*			R	R	R				R		R	R		r	R		r	r	R	R	R	R
Amnicythere sp. A								R														
Amnicythere sp. C				R	c			R		R	R		R	R					R			
Amnicythere sp. D																					r	
Amnicythere sp. E													R	R							R	
Amnicythere sp. G			R	R	r								R	r	R						R	
Euxinocythere aff. *praebaquana*			c	r	r			r	R	R	R	R	R	c	R		R	R	r	R		R
Mediocythereis sp.																						R
Cyprideis agrigentina	a	a			r	a	A		R						c	a			R	R	R	R
Cyprideis anlavauxensis		a			R											c					R	
Tyrrhenocythere pontica	R			r				c	c		R	R	R	R	R	R	R	R	R	R	R	R
Tyrrhenocythere ruggierii								c							c	R					R	
Loxoconcha sp. A			R	r	r	R		R	r	R	R	R	R	c	R		R	R	r	r	R	
Loxoconcha sp. B	R		R						R					R			R	R			R	R
Loxoconcha aff. *mulleri*	R		R	r		R		R						R	R						R	R
Loxocorniculina djafarovi	R		c	c	c			r	c	a	a	a	a	a	R	R	a	a	a	a	c	R
Loxocauda cf. *limata*			R	r	R	R				R	R	R	R	R			R	R	R	R	R	
Cytherura aff. *pyrama*			R			R		R	R				R						R		R	

Species frequencies. R (very rare): 1–5 specimens; r (rare): 6–15 sp.; c (common): 16–40; a (abundant): 41–100; A (very abundant): more than 100 specimens.

praebaquana and loxoconchids. This *Candona*, leptocytherids, loxoconchids Ostracod Fossil Assemblage (OFA2) typically occurs in samples 16, 19, 20, 33–36, 38, 53–55, 57, 58. Transitional assemblages can be recognised in samples 31, 32 and 39.

The ostracods gradually disappear between samples 59 and 66. The samples 59, 60, 61 and 64 still contain a very poor ostracod assemblage. The sample 66 yielded very rare euryhaline ostracods mixed with planktic and benthic foraminifera. Ostracod shells, which often appear in pristine conditions, are better preserved than foraminiferal tests.

5.3. Foraminifera

The occurrence of foraminifers depends on the stratigraphic position: the lowermost cycles do not show any significant foraminifera (up to cycle VII), also because of the presence of intensively reworked sedimentary material. In contrast, the last cycle (VIII) contains a rich fauna. Foraminifera are found from the

87 m upwards of the studied section and the first sample with a rich assemblage is the number 50 (Fig. 7). Samples 8, 24, 28 contain very few foraminifer tests. Among the samples selected for foraminifera analysis, only few of them contain ostracods as well (see Figs. 7 and 8). However, these samples do not show a significant ostracod association (usually very poorly preserved and undeterminable).

Benthic and planktonic fauna are mixed in the samples 41, 47, 48, 49, 50 (*Orbulina universa, Globigerina bulloides, Turborotalia quinqueloba, Globigerinoides obliquus Globorotalia scitula* sinistral, *Globorotalia miotumida* group, *Globorotalia menardii* 4 group, *Cibicidoides, Lenticulina, Rosalina, Uvigerina* spp., *Bolivina* spp. etc). Deep water species (*Sphaerodinellopsis, Melonis barleanus*) are mixed with very shallow water elements (*Elphidium* spp., *Nonion bouneanum*). The co-occurrence of foraminifera living at so different environmental settings seems to indicate that they are totally reworked. This is confirmed by the appearance of these foraminifera in fluvio-lacustrine deposits.
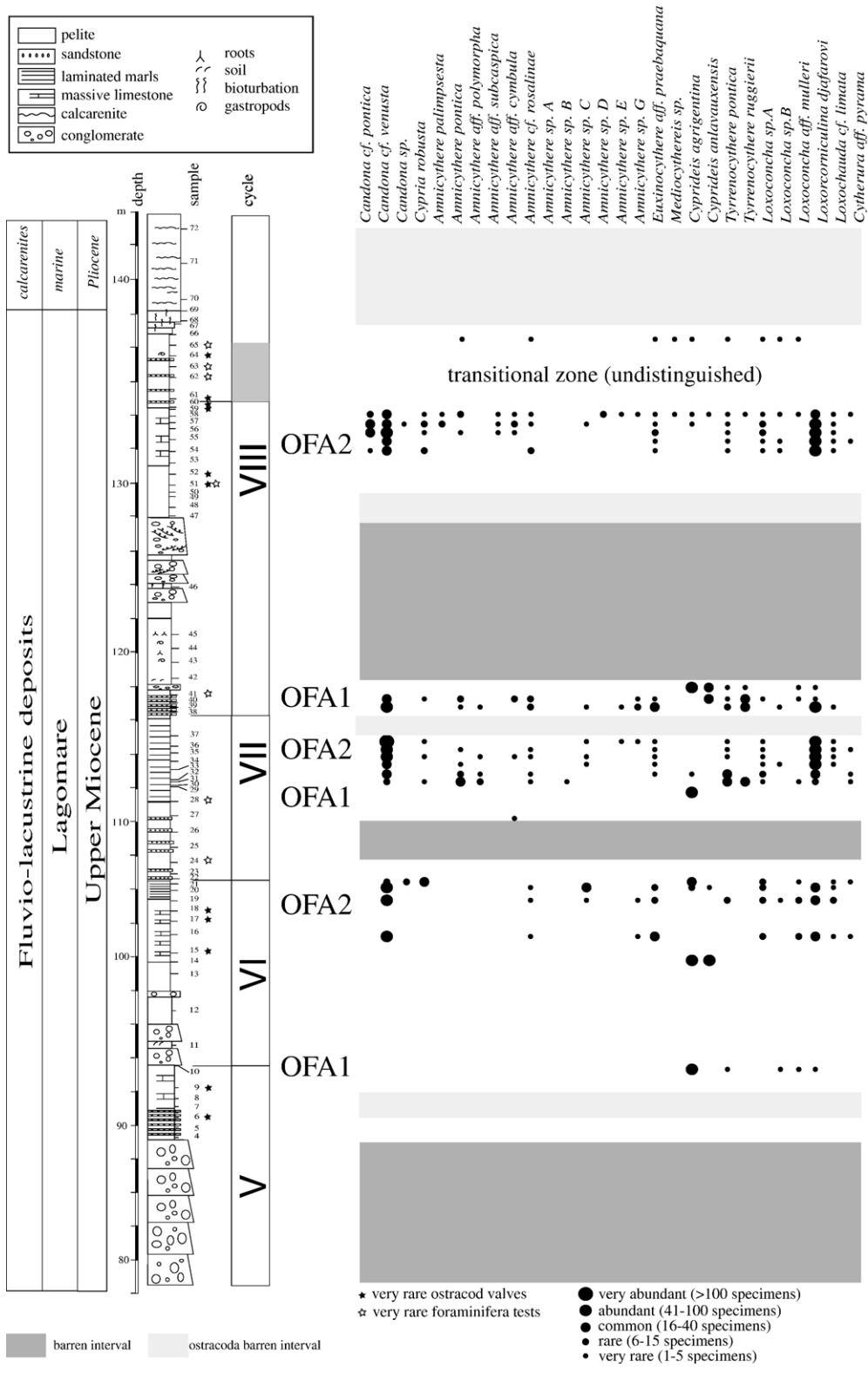
Fig. 7. Vertical distribution of ostracods in the upper post-evaporitic unit at Los Feos. OFA1: *Cyprideis* Ostracod Assemblage; OFA2: *Candona*, Leptocytherids, Loxoconchids Ostracod Fossil Assemblage.
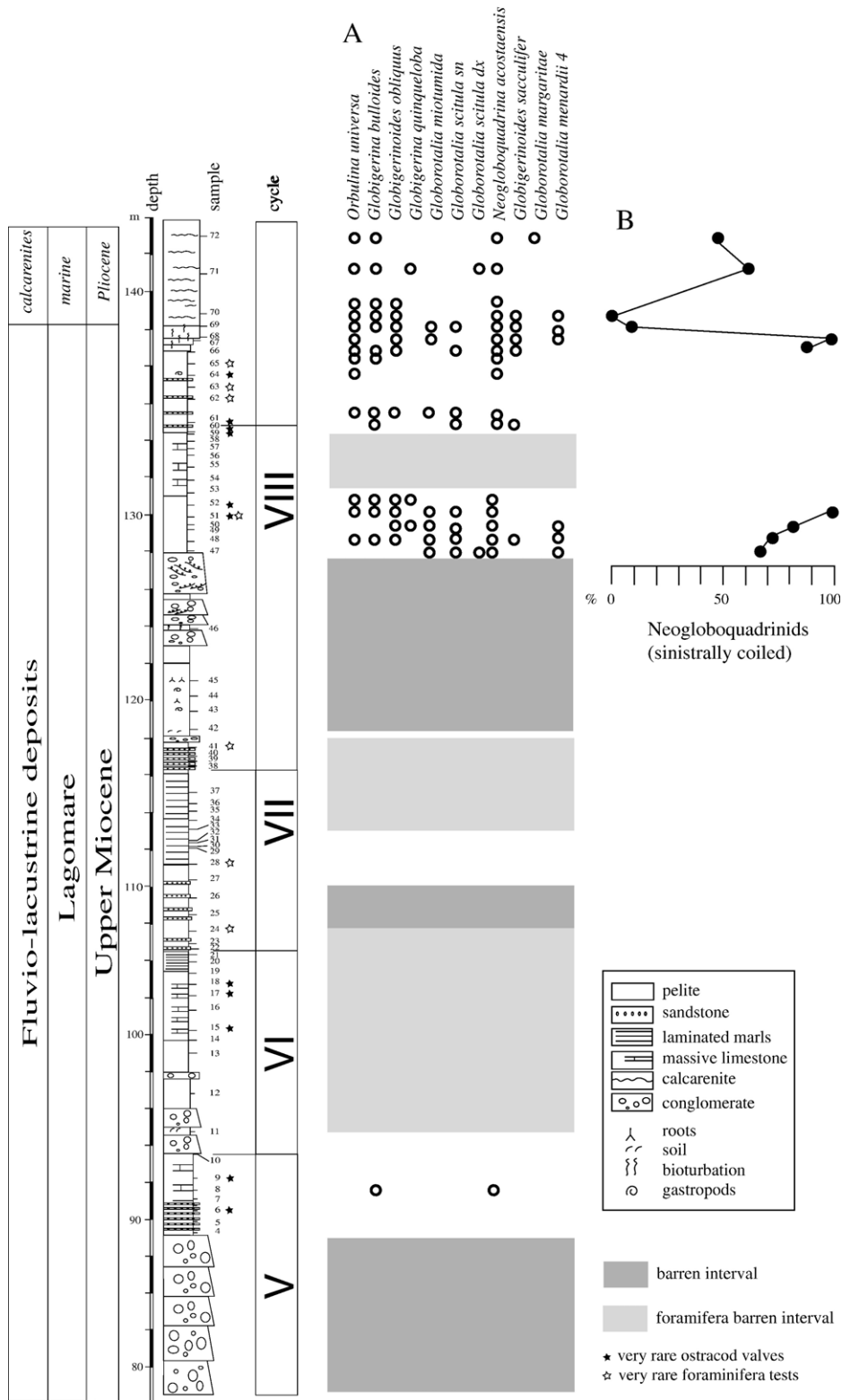
Fig. 8. (A) Distribution of planktonic foraminifera in the Messinian upper post-evaporitic unit (Lago-mare) and Pliocene at Los Feos. (B) Schematic graph showing the percentage variations of sinistrally coiled Neogloboquadrinids (percentage versus depth).

The number of planktonic foraminifera notably increased in cycle VIII (samples 60, 61, 67, 68, Fig. 8A) and the assemblage is dominated by the same species including specimens of the *G. miotumida* and *G. menardii* 4 groups. However, from sample 69 upwards a drastic change in faunal association is observed that may correspond to the Mio/Pliocene transition; sinistral specimens of the *G. scitula* group, as well as the *G. miotumida* and *G. menardii* 4 groups disappear and the benthic foraminifera, typical of middle to outer shelf environment, become dominant. This is consistent with the presence of Bivalves such as *Amussium* sp., that also indicates a shallow water, marine environment, within the continental shelf.

The first common occurrence of *Globorotalia margaritae* that has been dated at 5.08 Ma in the Mediterranean (Lourens et al., 1996) is found in sample 72.

6. Discussion

Because the Messinian record in the Nijar basin is one of the most complete, rhythmically bedded successions outcropping in the marginal basins our findings confirm that the cyclical character of the latest Messinian deposits, vastly described and discussed in former studies (Fortuin and Krijgsman, 2003), is an important feature that allows a supra-regional correlation (otherwise impossible in non-marine deposits spanning a short time interval), considering that the faunal content suggests common Lago-mare characteristics in Messinian units studied in the Mediterranean area (eastern Mediterranean, Apenninic foredeep).

In addition to the cyclicity, in Nijar basin, the late Messinian basinal succession shows an easily recognizable bipartite character. On the basis of lithofacies and sedimentological features, the post-evaporitic sedimentary record is subdivided into two units, the lower post-evaporitic unit and the upper post-evaporitic unit. The former one is mainly characterized by hyperconcentred gravity flow and turbiditic deposits. It is, therefore, made of thick, coarse-grained strata, interbedded with turbiditic calcarenites. The faunal content is very poor and likely reworked by mass transport.

On the other hand, the upper post-evaporitic units consist of an alternation of fluvial marls/conglomerates and lacustrine laminites are found, where a rich ostracod fauna is well preserved. The passage from the lower to the upper post-evaporitic units is marked by a quite abrupt change in sedimentary facies.

The ostracod assemblages, dominated by species of the euryhaline genera *Cyprideis*, *Tyrrhenocythere*, *Candona*, *Amnicythere*, *Euxinocythere*, *Loxocorniculina*,

Loxoconcha, etc., can be confidently interpreted as residual assemblages of brackish water communities which lived in hypohaline water bodies (inferred salinity range 5–15‰, Bassetti et al., 2003). They are all referable to the *L. djafarovi* Fossil Assemblage of Bassetti et al. (2003), which characterises the uppermost part of the Messinian Stage (Lago-mare facies sensu Cita et al., 1978) in the Mediterranean.

The peculiar ostracods of the Messinian Lago-mare were first recognised by Ruggieri (1958) in Northern Italy and then identified throughout the western Mediterranean area from Italy to France and Spain (Carbonnel, 1978; Roep and Van Harten, 1979; Gliozzi, 1999; Bonaduce and Sgarrella, 1999; Bassetti et al., 2003 among others).

A comparison of the ostracod assemblages collected in Los Feos section with those recently studied by two of the Authors (Bassetti et al., 2003) in the Romagna-Marche area of the North-Eastern Italy (Adriatic basin) demonstrates that 26 out of 27 species identified at Los Feos are present in both areas.

The common occurrence of *Cyprideis* and *Tyrrhenocythere* species probably documents an overall shallow water environment. Consequently, the alternation of the different fossil assemblages (OFA1 and OFA2, see above) in the upper part of the Feos Formation is likely related to variations in the depth of the submerged surface where ostracods lived. The OFA2 assemblage, dominated by *Candona*, *Loxocorniculina*, *Loxoconcha* and leptocytherids such as *Amnicythere* and *Euxinocythere*, seems to indicate deeper water depth than the *Cyprideis* Ostracod Fossil Assemblage (OFA1). This hypothesis is confirmed by the sedimentological data, as the OFA2 occurs within the basinal lacustrine laminites, at the top of the cycles VI, VII and VIII corresponding to the episodes of maximum water base-level.

The peculiar brackish-water ostracod fauna which inhabited the western Mediterranean area during the late Messinian (Lago-mare phase) that is now documented by the widespread occurrence of the *L. djafarovi* Fossil Assemblage (Bassetti et al., 2003) has unambiguous affinities with the Pontian and Dacian ostracod faunas of the central and eastern Parathetys.

These affinities, which are in primis facies affinities, have been taken as a proof of a faunal migration from the brackish-water lakes of the Eastern Parathetys into the Western Mediterranean Lago-mare (Krstic, 1971a; Carbonnel, 1978; Gliozzi, 1999; Gliozzi and Grossi, 2004).

As a matter of fact, modern researches on Pontian and Dacian ostracod faunas of the Parathethyan basins (Krstic,

1971b, 1972; Sokac, 1972; Krstic, 1975, 1977; Olteanu, 1989a,b,c; Krstic and Stancheva, 1989; Sokac, 1989; Olteanu, 1995) document fossil assemblages similar to but certainly different from those of the western Mediterranean area (Bassetti et al., 2003). The typical *L. djafarovi* Fossil Assemblage, recorded throughout the western Mediterranean, has never been described yet in the eastern Mediterranean (Aegean Basin).

In our opinion, the present knowledge of the late Miocene ostracod faunas cannot support the hypothesis of a rapid faunal spread from the Parathethyan basins to the Mediterranean Lago-mare as a consequence of a sudden inundation of the Mediterranean desiccated basins by the waters from Parathethys. It seems more probable that the brackish-water lakes of the western Mediterranean hosted an endemic fauna during the late Messinian.

Corroborating studies on ostracod taxonomy are expected in order to verify this hypothesis.

Unfortunately, little can be said about the timing of the Zanclean marine inundation, although the presence of *G. margaritae* and the absence of *G. puncticulata* indicate a lower Pliocene age for the Cuevas Formation. Further east, in the deeper part of the basin, silty marls from the base of Pliocene contain a fauna that can be attributed to the *Sphaerodinellopsis* acme of lowermost Pliocene (Fortuin and Zachariasse, personal communication).

The sharp lithologic transition from the whitish marls/sandstones alternation to the Cuevas Formation through an intensively bioturbated surface, designated as the Mio/Pliocene boundary is described by several authors (Fortuin and Krijgsman, 2003; Aguirre and Sánchez-Almazo, 2004).

The occurrence of foraminifera throughout the post-evaporitic unit was interpreted as an indication of the return of normal marine condition during the latest Messinian (Aguirre and Sánchez-Almazo, 2004) at an age clearly predating the onset of Pliocene reflooding. The possibility of persistence of marine influxes during the general dilution of the Mediterranean waters at the end of the Messinian (Blanc-Valleron et al., 1998 in Cyprus basin, Spezzaferri et al., 1998 in Cretan basin) or a re-establishment of normal marine conditions in the Mediterranean during the Lago-mare phase (Aguirre and Sánchez-Almazo, 2004 in Nijar basin), has been put forward by several authors during the last years, but there is no general agreement on this topic. In particular, the main argument in favour of the latter hypothesis is the occurrence of marine benthic and planktic foraminifera, however we consider that they are almost certainly reworked in the Nijar basin. The

foraminiferal assemblages observed in the Lago-mare deposits from Nijar, if they were autochthonous, would indicate deposition in an open-marine deep water environment as suggested by the high percentage of planktonic foraminifera and the diverse assemblage of benthic foraminifera. This is incompatible with the ostracods observed in the same levels that indicate a brackish water environment, suggesting that either the foraminifers or the ostracods have been reworked. Here we present some evidence that indicate that planktonic foraminifera were reworked during deposition of the Lago-mare sediments. Although there are some short-term influxes of sinistral Neogloboquadrinids in the Atlantic margin of Morocco (Krijgsman et al., 2004), this group is mainly dextral in the latest Messinian. However, the vast majority of the specimens observed in the Lago-mare are sinistrally coiled (Fig. 8B). By contrast, Neogloboquadrinids from the Cuevas formation are mainly dextral. A second argument in favour of foraminifer reworking is the continuous presence of sinistral specimens of the *G. menardii* 4, and *G. miotumida* groups, which are typical of the Late Tortonian and early Messinian in the Mediterranean (Sierro et al., 1993, 1999, 2001), respectively. Forms of *G. menardii* 4 disappeared from the Mediterranean at 7.5 Ma (Krijgsman et al., 1995) and the group of *G. miotumida* at 6.5 Ma (Sierro et al., 2001). Although *G. miotumida* is still present in the latest Messinian from the Atlantic margin of Morocco (Krijgsman et al., 2004), and therefore this species could have invaded the Mediterranean at that time, the co-occurrence of these forms with specimens of *G. menardii* 4 (sinistral), and the absence of *G. margaritae* which is already abundant in the Atlantic domain at that time are difficult to explain.

If we assume that the Pliocene starts in correspondence of the lithological passage marked at the base of the Cuevas Formation, the vertical change of the faunal assemblage below the passage to the Pliocene suggests that the hydrology of the Lago-mare very likely changed towards conditions inhospitable for the brackish fauna, characterized by higher salinity.

The marked cyclicity of the late Messinian deposits in Nijar basin has been discussed by Fortuin and Krijgsman (2003) as related to Mediterranean climate changes in the Earth's precession. In fact, the units containing Lago-mare facies are composed of a number of cycles that are consistent with a precessional-driven climatic origin of small scale sedimentary cycles.

Lithological and paleontological evidence found in Nijar basin, can be used to strengthen the correlation with the Lago-mare units at a supra-regional scale.

In particular, a cyclical feature has been described in the Adriatic foredeep for the upper Messinian deposits (Roveri et al., 2001) and its relation with a precessional origin has been discussed by Roveri et al. (2004). In the Apennines, up to five cycles have been recognised in the lowermost unit (p-ev1) and 3 to 4 cycles have been traced for the uppermost unit (p-ev2) that is the one showing the most peculiar Lago-mare features in terms of faunal content (Bassetti et al., 2003). This agrees with the number of 8–9 cycles present in the post-evaporitic Mediterranean units such as in the Upper Evaporites in Sicily (Keogh and Butler, 1999), Sorbas Basin (Krijgsman et al., 2001) and, obviously, in the Nijar basin (Fortuin and Krijgsman, 2003; this paper).

As stated before, the microfossil association (ostracods) found in Nijar basin is very similar to the one studied in the Apennine foredeep. It allows to establish an outstanding correspondence with the Nijar basin succession both from a paleoenvironmental and stratigraphic point of views. In particular, the upper post-evaporitic unit of Los Feos has been here defined as the real Lago-mare unit, on the basis of fossil abundance and characteristics, and it forms the uppermost three cycles of the latest Messinian succession, which are consistent with the 3–4 cycles defined elsewhere in the Mediterranean (Cyprus, Rouchy et al., 2001; Abu-Madi Formation in Nile Delta, Dalla et al., 1997, Tertiary Piedmont Basin, Ghibaudo et al., 1985).

Independent age constraint does not exist in the Nijar basin for establishing the beginning of Lago-mare phase. However, paleogeographic reconstructions in this area (Krijgsman et al., 2001; Fortuin and Krijgsman, 2003) give an estimation of 5.60–5.64 Ma for the end of marine sedimentation in Betic marginal basins.

7. Conclusions

Lithological observations integrated with faunal data evolution found in the post-evaporitic succession exposed in Nijar basin suggest that:

1) The Messinian post-evaporitic deposits can be subdivided in two major sub-units (lower post-evaporitic unit and upper post-evaporitic unit), recording several oscillations of base level in the Nijar basin likely influenced by tectonic activity and regional climate variations. Paleodepth variations are also documented by the alternation of ostracod faunas in the upper post-evaporitic unit;

2) The ostracod fossil assemblages collected in the Feos Formation are very similar to coeval assemblages from Spain, France and Italy and can be easily referred to the

L. djafarovi Fossil Assemblages of the uppermost Messinian, which document the wide spreading of the same ostracod communities throughout the western Mediterranean area. The low number of ostracod species common both to western Mediterranean and Parathetys suggests that the Lago-mare fauna is likely endemic at Mediterranean scale;

3) The lithological cyclicity and the microfossil content in the Los Feos Formation permit the establishment of a regional correlation at Mediterranean scale: the upper Messinian deposits in the Nijar basin can be correlated with the ones defined in the circum-Mediterranean marginal basins, on the basis of their strong similarities. In particular, the Lago-mare facies, defined on the ostracod biofacies, seems to be an event that marks the end of the Messinian at a regional scale;

4) The presence of planktonic and benthic foraminifera does not represent the ultimate proof of the persistence of a marine environment during the Lago-mare phase in Nijar basin. On the contrary, in our opinion the majority of the foraminifera tests found within the post-evaporitic succession are reworked. However, during the final part of the Lago-mare stage, significant changes in the ostracod faunal association may suggest the possibility of important hydrologic changes towards conditions characterized by higher salinity, possibly marine. This would represent the first evidence of marine influence in a transitional interval predating the main inundation in the early Pliocene.

Acknowledgements

Appendix A. Ostracod species reference list

Ostracod species recognised in the study are listed below. Some basic references are quoted to elucidate the species concepts adopted in the present work.

Candona (*Caspiocypris*?) cf. *pontica* Sokac, 1972: cf. *Candona* (*Caspiocypris*) *pontica* n.sp., Sokac, 1972, p. 40, pl. 15, figs. 4–8; cf. *Candona* (*Caspiocypris*) *pontica* Sokac, Sokac, 1989, pp. 677–678, pl. 2, figs. 1–3 (non-*Candona* (*Pontoniella*) *pontica* Agalarova, 1961).

Candona (*Zalanyiella*) cf. *venusta* (Zalanyi, 1929): *Caspiolla venusta* (Zalany), Carbonnel, 1978, p. 111, pl. 1, figs. 13–14; cf. *Candona* (*Zalanyiella*) *venusta* (Zalanyi), Sokac, 1989, p. 683, pl. VI, figs. 3–4.

Cypria robusta (Devoto, 1968): *Bullocypris* n.g. *robusta* n.sp., Devoto, 1968, pp. 399–403, text-figs. 1–7.

Amnicythere palimpsesta (Livental, 1929): *Amnicythere palimpsesta* (Livental), Krstic and Stancheva, 1989, p. 777, pl. XIII figs. 6–7; *Amnicythere palimpsesta* (Livental), Stancheva, 1990, pp. 58–59, pl. XX, figs. 3–4.

Amnicythere cf. *pontica* Sheidaeva: *Amnicythere idonea* (Mandelstam, Markova, Rozyeva and Stepanajtys), Carbonnel, 1978, p. 112, pl. 1 fig. 18, pl. 2 figs. 4–5 (non-*Amnicythere idonea* Mandelstam, Markova, Rozyeva and Stepanajtys, 1962 fide Krstic and Stancheva, 1989).

Amnicythere aff. *polymorpha* (Olteanu, 1989): aff. *Leptocythere* (*L.*) *polymorpha* n.sp., Olteanu, 1989a, pp. 138–139, pl. 2 fig. 11, pl. 17 figs. 1–8.

Amnicythere aff. *subcaspia* (Livental, 1929): *Amnicythere subcaspia* Livental, Bonaduce and Sgarrella, 1999, pl. 1, fig. 7 (non-*Leptocythere subcaspia* Livental, 1929).

Amnicythere aff. *cymbula* (Livental, 1929): aff. *Leptocythere cymbula* Livental, Boomer et al., 1996, p. 81, fig. 4 A–H.

Amnicythere cf. *rosalinae* (Schneider in Agalarova, Djafarov and Halivov, 1940): *Leptocythere propinqua* (Livental), Gliozzi, 1999, p. 199, pl. Ic; cf. *Amnicythere rosalinae* Schneider in Agalarova, Djafarov and Halivov, Krstic and Stancheva, 1989, pl. XI, fig. 2.

Amnicythere sp. C: *Amnicythere accicularia* Olteanu, Bonaduce and Sgarrella, 1999, pl. 2, fig. 7 (non-*Leptocythere* (*Amnicythere*) *accicularia* Olteanu, 1989).

Amnicythere sp. D: cf. *Leptocythere* sp., Carbonnel, 1978, pl. 2, fig. 6 (not fig. 7).

Amnicythere sp. E: *Amnicythere litica* (Livental), Carbonnel, 1978, pl. 2 fig. 9 (non-*Leptocythere litica* Livental fide Krstic and Stancheva (1989).

Euxinocythere (*Maeotocythere*) aff. *praebaquana* (Livental): *Maeotocythere* aff. *praebaquana* (Livental in Agalarova et al.), Carbonnel, 1978, pp. 113–114, pl. 2, figs. 2–3.

C. agrigentina Decima, 1964: *Cyprideis pannonica agrigentina* n.subsp., Decima, 1964, pp. 108–111, pl. VI, figs. 4a–8b, pl. VII, figs. 1–10, pl. VIII, figs. 1–2, pl. XIV, figs. 16–21; *Cyprideis pannonica pseudoagrigentina* n.subsp., Decima, 1964, pp. 111–113,

pl. VIII figs. 3a–7b, pl. IX, figs. 1a–2b, pl. XV, figs. 1–2.

Cyprideis anlavauxensis Carbonnel, 1978: *Cyprideis anlavauxensis* n.sp., Carbonnel, 1978, p. 112, pl. I fig. 8, pl. 2 figs. 10–11; cf. *Cyprideis tuberculata calabra* n. subsp., Decima, 1964, pp. 127–129, pl. IV figs. 7a–9b, pl. V, figs. 1a–8c., pl. XIV figs. 10–11.

Tyrhenocythere pontica (Livental in Agalarova et al., 1961): *Tyrrhenocythere pontica* (Livental in Agalarova et al.), Krstic, 1977, pl. II, figs. 1–2; *Tyrrhenocythere pontica* (Livental in Agalarova et al.), Carbonnel, 1978, p. 116, pl. 2, fig. 17.

Tyrrhenocythere ruggierii Devoto in Colacicchi, Devoto, and Praturlon, 1967: *Tyrrhenocythere ruggierii* sp.n. Devoto in Colacicchi, Devoto and Praturlon, 1967, pp. 31–35, text-figs. 5–8; *Tyrrhenocythere ruggierii* Devoto, Gliozzi, 1999, pp. 201–202, pl. 3a–c.

Loxoconcha sp. A: *Loxoconcha eichwaldi* Livental–Carbonnel, 1978, p. 114, pl. 1, fig. 4 (non-*Loxoconcha eichwaldi* Livental, 1929 fide Krstic and Stancheva, 1989).

Loxoconcha aff. *mülleri* (Mehes, 1908): *Loxoconcha mülleri* Carbonnel, 1978, p. 116. pl. 1, figs. 6, 7, 12 (non-*Cythereis mülleri* Mehes, 1908).

Loxoconcha sp. B: *Loxoconcha kochi* Mehes, Carbonnel, 1978, 114, pl. 1 figs. 5, 9, 10 (non-*Loxoconcha kochi* Mehes, 1908).

L. djafarovi (Schneider in Suzin, 1956): *Loxoconcha* (*Loxocorniculina*) *djafarovi* Schneider in Suzin, Krstic, 1972, 253–254, pl. 6, figs. 1–3; *Loxoconcha* (*Loxocorniculina*) *djafarovi* Schneider in Suzin–Krstic and Stancheva, 1989, 781–782, pl. 15 fig. 5.

Loxocauda cf. *limata* (Schneider in Agalarova, Djafarov and Halilov, 1940): *Loxocauda limata* Schweyer–Carbonnel, 1978, p. 114, pl. 2, fig. 15.

Cytherura aff. *pyrama* (Schneider): *Semicytherura* aff. *rara* (G.W. Müller), Cita, Vismara Schilling, and Bossio, 1980, pl. 19, figs. 11–12.

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