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Testing models for the Messinian salinity crisis: The Messinian record in Almería, SE Spain

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Abstract

Neogene intermontane basins in Almería Province, SE Spain, display excellent exposures of Messinian (Late Miocene) sequences. The Sorbas, Almería-Níjar and Vera basins maintained connection with the Mediterranean throughout the Messinian, except during the major desiccation phase leading to the formation of salt in the deep centre of the Western Mediterranean. These basins were part of the Western Mediterranean with no separate link to the Atlantic Ocean. The presence of normal marine sediments in these basins reflects the Western Mediterranean watermass. Messinian pre-evaporitic sediments in the basins of southeastern Almería do not show gradual change towards evaporite deposits. Instead they contain stenohaline invertebrates right up to a major erosion surface that separates them from overlying gypsum deposits. This contradicts suggestion of progressive salinity increase in this part of the Western Mediterranean prior to the Messinian Salinity Crisis (MSC); it also indicates that initiation of evaporite precipitation was not synchronous throughout the Mediterranean Basin. There is no major erosion surface within or at the top of the evaporites in these Almería basins, and the gypsum beds exhibit upward transition to siliciclastic and carbonate deposits. This is inconsistent with a model of Messinian Mediterranean evaporite formation whereby deposition of marginal evaporites was followed by their erosion during drawdown that resulted in formation of evaporites in the centre of the Western Mediterranean. The presence of stenohaline biotas in siliciclastic deposits interbedded with the gypsum and in the Messinian post-evaporitic sediments, challenges the view that a long-standing large body of brackish water (the Lago Mare) filled the Western Mediterranean following the MSC and prior to Early Pliocene flooding. It also contradicts the concept of many relatively small brackish basins spread across an otherwise desiccated Western Mediterranean basin. The basins of southeastern Almería record normal marine Early Messinian sedimentation that was abruptly interrupted by sealevel fall. This drawdown most likely resulted in precipitation of evaporites in the central deep Western Mediterranean basin. Following this episode, final marine reflooding of the Western Mediterranean took place during the Late Messinian, and the Mediterranean Sea rose to a level similar to, or higher than, that preceding the Salinity Crisis.

Keywords: Almería; Evaporites; Messinian Salinity Crisis; Palaeoenvironments; Western Mediterranean; Spain

1. Introduction

Essentially, the Messinian Salinity Crisis (MSC) concept is that temporary isolation from the world ocean resulted in Mediterranean desiccation during the Late

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Miocene Messinian Stage (Hsü et al., 1973). This interpretation astutely accounted for thick Messinian salt and gypsum deposits beneath the deep floor of the present-day Mediterranean Sea, but at the same time it raised many questions of detail (Cita, 1991). Now, more than thirty years later, numerous uncertainties remain despite considerable efforts during the past decade to reconstruct these remarkable events (e.g., Rouchy and Saint-Martin, 1992; Cornée et al., 1994; Gautier et al., 1994; Butler et al., 1995; Clauzon et al., 1996; Cunningham et al., 1997; Riding et al., 1998; Krijgsman et al., 1999a).

The deep Mediterranean evaporites have been recognized on seismic profiles, but have not been drilled to their base and their nature and age are incompletely known. Information obtained from Messinian onland exposures around the present-day Mediterranean Sea has been used to elucidate the timing of the MSC (Gautier et al., 1994; Krijgsman et al., 1999a) as well as the palaeoenvironmental changes leading to evaporite deposition in the Mediterranean centre (e.g., Schreiber et al., 1976; Decima et al., 1988; Pierre et al., 1997; Blanc-Valleron et al., 2002). The Messinian successions in these emergent marginal basins have also been the main source of data for interpretation of the post-evaporitic events and the timing of final reconnection of the Mediterranean Sea with the open ocean (e.g., Riding et al., 1998; Orszag-Sperber et al., 2000; Rouchy et al., 2001, 2003; Aguirre and Sánchez-Almazo, 2004).

Using combined information provided by submarine seismic profiles together with that from drill cores and from onland outcrops in marginal basins, several models accounting for the evolution of the Mediterranean during the MSC have been proposed (Hsü et al., 1973; Cita et al., 1978; Sonnenfeld, 1985; Butler et al., 1995; Clauzon et al., 1996; Riding et al., 1998; Orszag-Sperber et al., 2000; Rouchy et al., 2001, 2003; among others). These models substantially differ in crucial aspects such as overall stratigraphic relationships, basic sedimentological models of evaporite formation, and large-scale palaeoenvironmental interpretation of the Mediterranean during post-evaporitic Messinian times.

The Neogene intermontane basins in Almería Province (SE Spain) (Fig. 1) constitute a group of relatively small but highly significant onland outcrops of Messinian marine sediments. These well-preserved and readily accessible Messinian successions have made possible detailed palaeontological, sedimentological and chronostratigraphical investigations that provide key information for interpretation of the MSC (Cita et al., 1980; Riding et al., 1991a; Gautier et al., 1994; Martín and Braga, 1994; Riding et al., 1998, 1999; Krijgsman et al., 1999a; Saint Martin et al., 2000; Goubert et al., 2001; Krijgsman et al., 2001; Lu et al., 2001; Aguirre and Sánchez-Almazo, 2004). These marginal basins adjacent to the present-day Mediterranean in SE Almería (Almería-Níjar, Sorbas and Vera basins), clearly reflect events during the Crisis, since they maintained connection with the Mediterranean throughout the Messinian, except during the MSC itself. At the same time, some important variations exist between the sequences that these basins contain, and these differences are also instructive.

Here we briefly review the sedimentary record of the Almería-Níjar, Sorbas and Vera basins to test concepts regarding the Messinian evolution of the Western Mediterranean area. We suggest that although the deposits in these three basins cannot reflect all the events that occurred in the Mediterranean basin during the Messinian, any proposed interpretation of the Western Mediterranean has to be consistent with their marine sedimentary record.

2. Geological setting

Miocene uplift of the Betic Cordillera led to emergence of a series of islands in this region where the Mediterranean Sea connected with the Atlantic Ocean. These emerging islands were surrounded by subsiding marine basins that were filled by sediments resulting from the erosion of adjacent basement uplands (Montenat, 1990; Weijermars, 1991). Continued uplift of the Betic chain increased the separation of the Mediterranean Sea and Atlantic Ocean. Whereas the Guadalquivir Basin, the foreland basin of the Betic Cordillera, remained open to the Atlantic Ocean, most of what are now Betic intermontane basins were linked to the Mediterranean Sea (Esteban et al., 1996; Braga et al., 2002, 2003). Closure of the last Betic seaway connecting the Mediterranean Sea with the Atlantic Ocean took place in the Early Messinian (Martín et al., 2001) (Fig. 2A, B). Inner basins, more remote from the present-day coast, such as the Granada and Guadix basins, became isolated from the Mediterranean even before the Messinian (Rouchy, 1982). The closure of the connection in the eastern part of the Betic Cordillera took place during the Late Tortonian (Krijgsman et al., 2000). In contrast, outer basins such as Almería-Níjar, Sorbas and Vera (the SE Almería basins) (Fig. 1) remained connected to the Mediterranean (Fig. 2B) up to the onset of desiccative drawdown that marked inception of the MSC proper. Subsequently, these basins were reflooded by the Mediterranean in the latest Messinian, until their emergence during the Pliocene. This history was complicated by mutual separation of the SE Almería basins due to differential uplift of intervening areas. The Sorbas Basin became separated from the Almería-Níjar Basin due to final emergence of Sierra

Alhamilla at the end of the Tortonian (Weijermars et al., 1985; Martín and Braga, 1994). Separation of the Vera and Almería-Níjar basins took place in the Late Messinian when the submarine high, precursor of the Sierra Cabrera, eventually emerged (Riding et al., 1998; Braga et al., 2003). The Taza-Guercif Basin (Rifian Corridor) was emergent at 6.0 Ma (Krijgsman et al., 1999b), roughly coincident with deposition of the youngest Abad marls.

3. Key questions

What are the outstanding questions concerning the Salinity Crisis that may be addressed by study of successions in SE Almería? The Salinity Crisis is bracketed by two key events: (i) the inception of desiccative drawdown of the Western Mediterranean basin, and (ii) final refilling that reestablished normal marine salinities. It has been suggested that substantial salinity fluctuations may have occurred both during the inception of drawdown and during final refilling. In the first case, it has been proposed that fringing reefs pre-dating substantial drawdown were ecologically influenced by elevated salinities and geometrically defined by falling sealevel (Esteban et al., 1978). Gradual long-term salinity increase in the main Mediterranean Sea has also been suggested to account for aspects of the basinal sequences (e.g., Schreiber et al., 1976; Troelstra et al., 1980; McKenzie et al., 1980; Orszag-Sperber et al., 1980; Decima et al., 1988; Pierre et al., 1997; Kouwenhoven et al., 1999; Krijgsman et al., 1999a; Seidenkrantz et al., 2000; Bellanca et al., 2001; Blanc-Valleron et al., 2002; Krijgsman et al., 2002). In the second case, it has been proposed that following deep desiccation the Western Mediterranean, including the SE Almería basins, was initially refilled by brackish water, the Lago Mare, prior to recovery of marine salinities (Cita et al., 1978, 1980; Rouchy et al., 2001, 2003).

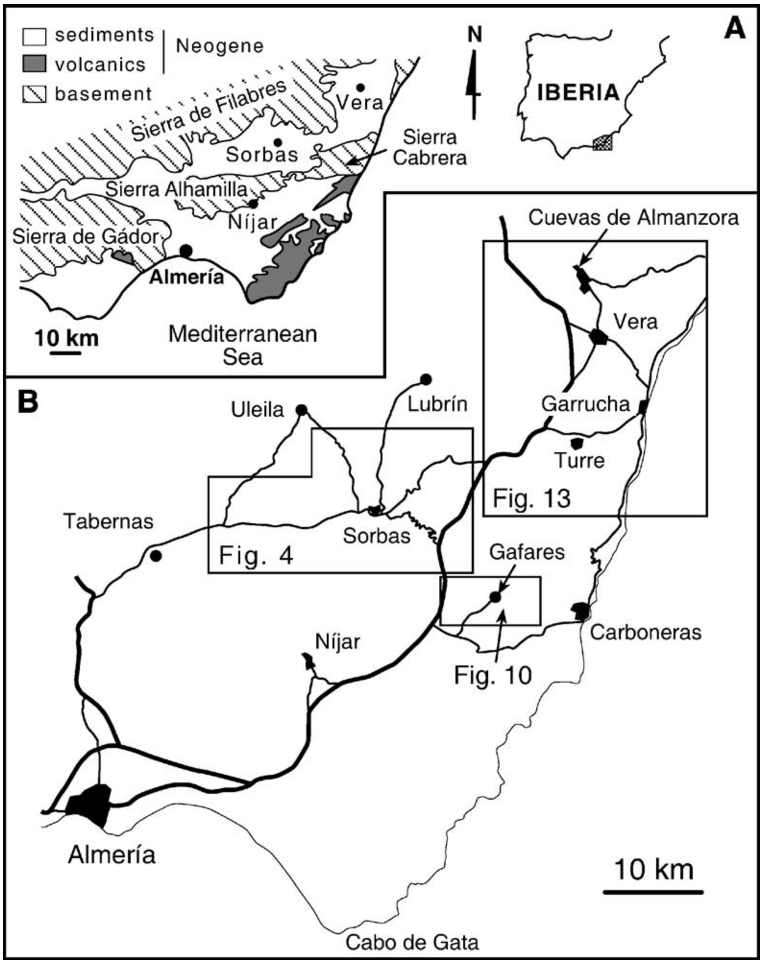

Fig. 1. (A) Neogene basins in southeastern Almería. The basins are named after their principal towns. (B) Geographical location and main roads. Insets show areas of geological maps in Figs. 4,10 and 13.

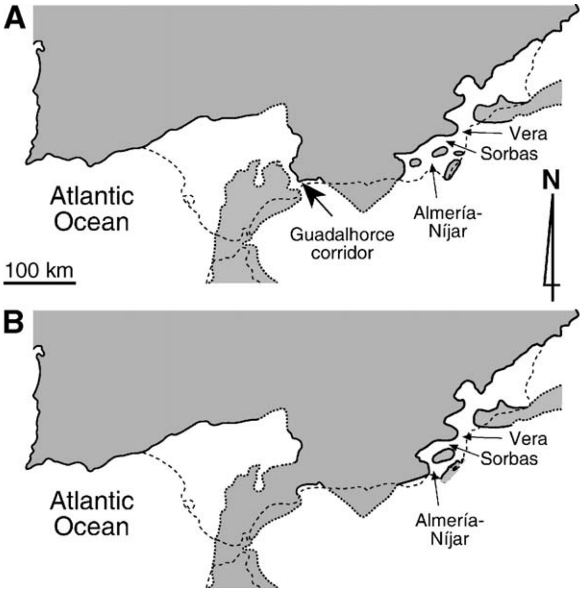

Fig. 2. Palaeogeography of the Betic Cordillera, (A) in the earliest Messinian and (B) during pre-evaporitic reef growth (~6 Ma). The Guadalhorce Corridor was the last seaway connecting the Mediterranean Sea with the Atlantic Ocean through what would become the Betic Cordillera. The Almería-Níjar, Sorbas and Vera basins remained connected to the Mediterranean up to the moment of desiccative drawdown (after Martín et al., 2001 and Braga et al., 2003).

Additional questions concern events connected with the deposition of thick evaporites on the floors of the deep Mediterranean basins. Formation of these deposits must have involved repeated brine replenishment, but it is unclear to what extent Mediterranean sealevels may have recovered during these episodes of replenishment and evaporation. At first sight, it would seem that high marginal basins such as those in SE Almería are not likely to offer direct information concerning details of deep basin evaporite sedimentation. However, two of these marginal basins, Sorbas and Almería-Níjar, do contain evaporite deposits up to 130 m thick. So what is the relationship between these relatively thin marginal evaporites and the much thicker ones of the adjacent deep Mediterranean? Furthermore, it is to be expected that evaporative drawdown on the scale envisaged in the Western Mediterranean must have result in erosion of marginal basin successions such as those in Almería. Can this erosion be recognized within the Messinian sequence?

Thus, at least three fundamental questions arise: (i) Is progressive salinity increase recorded in the Almería marginal basins during MSC inception, as proposed? (ii) What is the relationship between the evaporites of these marginal basins and those of the deep Mediterranean; might they be coeval as proposed (Krijgsman et al., 1999a)? (iii) Was marine refilling preceded by Lago Mare conditions in Almería, as proposed?

4. Messinian record in SE Almería basins

4.1. Sorbas Basin

The Sorbas Basin contains up to 700 m of Mid-Miocene to Pleistocene sediments (Ott d'Estevou and

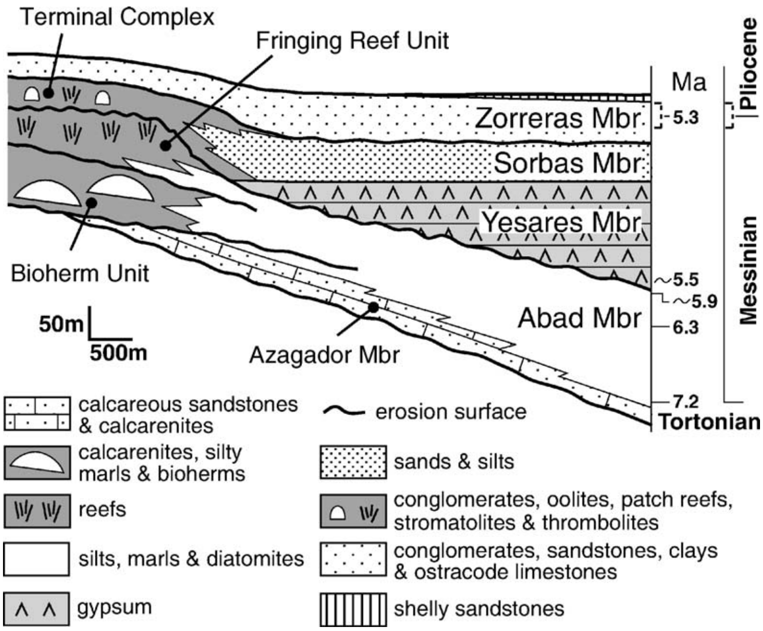

Fig. 3. Messinian to Early Pliocene stratigraphy of the Sorbas Basin (modified from Martín and Braga, 1994).

Montenat, 1990; Mather, 1993; Martín and Braga, 1994). The Messinian part of this sequence can be separated into pre-evaporitic, evaporitic and post-evaporitic deposits, according to their stratigraphic position relative to thick gypsum deposits (Yesares Gypsum, Ruegg, 1964) at the basin centre (Figs. 3 and 4).

4.1.1. Pre-evaporitic sequence

Basin margin carbonates pass basinward to marls, silty marls and diatomitic marls (Ott d'Estevou, 1980; Ott d'Estevou and Montenat, 1990; Martín and Braga, 1994). Marginal carbonate units consist of: (i) Azagador Member, temperate bioclastic carbonates; (ii) Bioherm Unit, platform carbonates with *Halimeda* and coral patch reefs (Braga et al., 1996; Martín et al., 1997, 1999); and (iii) Fringing Reef Unit, coral-stromatolite reefs and talus (Riding et al., 1991a; Braga and Martín, 1996). Minor erosion surfaces separating these units at the basin margins die out basinward as all the units pass laterally into the marls of the Abad Member. The fringing reef deposits contain regular echinoids, together with scleractinians, coralline algae, *Halimeda* and marine bivalves (Riding et al., 1991a). At the basin centre, the Abad marls contain foraminifers and calcareous nannoplankton that indicate normal marine salinities (Baggley, 2000). The top of these marls, immediately below the Yesares Gypsum, has been dated at 5.9 Ma (Gautier et al., 1994) and 5.96 Ma (Krijgsman et al., 1999a) at the basin centre.

4.1.2. Evaporites

A basinwide, highly irregular erosion surface (the sub-Yesares surface), is incised into the pre-evaporitic deposits with relief of up to 240 m (Riding et al., 1998). This minimum value of relief can be measured (with correction for slight deformation) from the top of the Fringing Reef Unit to the base of the flat-lying beds of Yesares Gypsum at the northern margin of the gypsum outcrop. The karstic character of this surface can be observed on top of the basin margin reef carbonates at Cariatiz (Riding et al., 1991a; Martín et al., 1993) and Rambla de Góchar where the Sorbas Member fills an irregular surface incised into the Fringing Reef Unit (Dabrio et al., 1985; Martín et al., 1993; Roep et al., 1998). In the Hueli area, 4 km SSE of Sorbas town, the Yesares Gypsum directly overlies the Bioherm Unit (Fig. 4), suggesting that carving of this erosion surface removed the Fringing Reef Unit prior to Yesares deposition. In the Hueli-Cuesta Encantada area, the erosion surface can be traced below the gypsum beds from the top of reef bioherms to the top of basinal marls (Fig. 4). From this area the surface can be physically traced without interruption to the basin centre at the Molino del Río Aguas section (Fig. 4). Here and elsewhere in the basin centre its erosive nature is shown by bed geometries and the stratigraphic patterns of the overlying gypsum beds. The Yesares Gypsum fills narrow palaeovalleys up to 30 m deep and 500 m wide with north–south (Molino del Río Aguas, Riding et al., 1999) (Fig. 5) and east–west orientations that truncate, and locally gully into, the Abad marls (Fig. 6, 1 km north–east

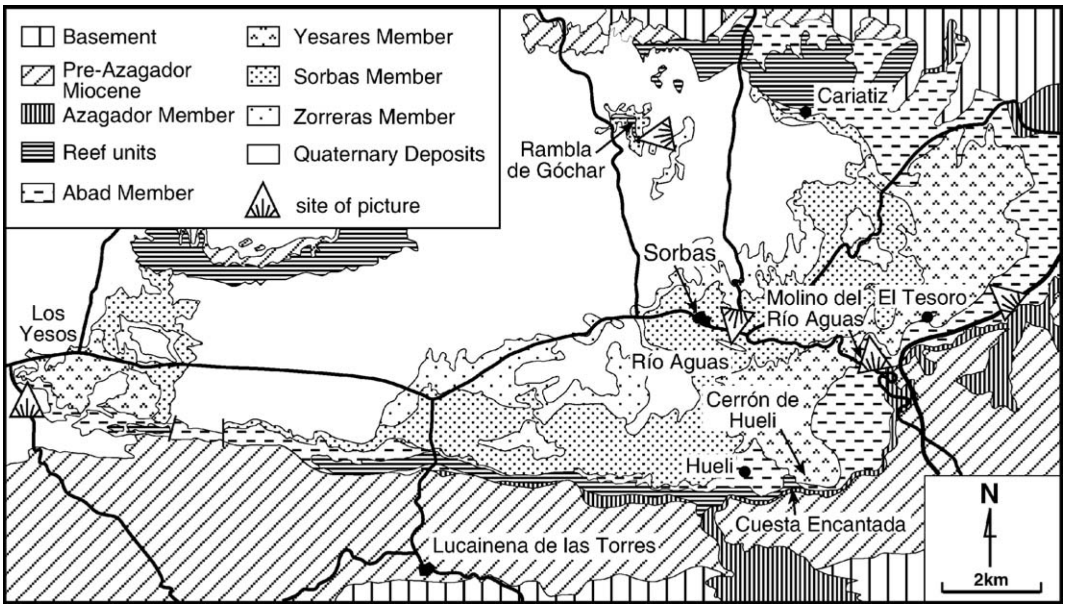

Fig. 4. Geological map of the Sorbas Basin. Modified from Montenat (1990).

of El Tesoro, Riding et al., 1999). The lowermost gypsum beds filling these depressions are onlapped by higher gypsum units (Riding et al., 1998, 1999, 2000) (Figs. 5 and 6). The sub-Yesares erosion surface can also be observed at Los Yesos, the westernmost outcrop of the gypsum in the Sorbas Basin (Fig. 7).

Despite this field evidence, existence of the sub-Yesares erosion surface was disputed by Fortuin et al. (2000) because observation of the contact is complicated by dissolution effects, local faulting and block falls. They argued for a conformable transition from Abad Member marls to Yesares Gypsum based on a constant number of pre-evaporitic precession cycles in the basin centre sections, even though these could also be expected to be affected by the same complications as those suggested to affect recognition of the erosion surface.

At the basin centre, the Yesares Gypsum is 130 m thick and consists of gypsum-pelite cycles (12–13 cycles, according to Dronkert, 1977 and Rosell et al., 1998, 14 cycles according to Krijgsman et al., 2001). The top two marl–silt interbeds within the Yesares Gypsum in the Río Aguas section, 4.5 km east of Sorbas town, contain well-preserved planktic marine foraminifers (Table 1). The Yesares Gypsum thins laterally as it onlaps the eroded surface. The onlap geometries in the basal part are clearly seen on the north-western side of Cerrón de Hueli. At its westernmost outcrop the Yesares Gypsum consists of only 4 cycles, 75 m thick in total, (Saint Martin et al., 2000; Goubert et al., 2001). At this locality the pelitic interbeds contain rich marine fossil assemblages, including echinoids, scaphopods, pectinid bivalves and bryozoans (Saint Martin et al., 2000; Néraudeau et al., 2001).

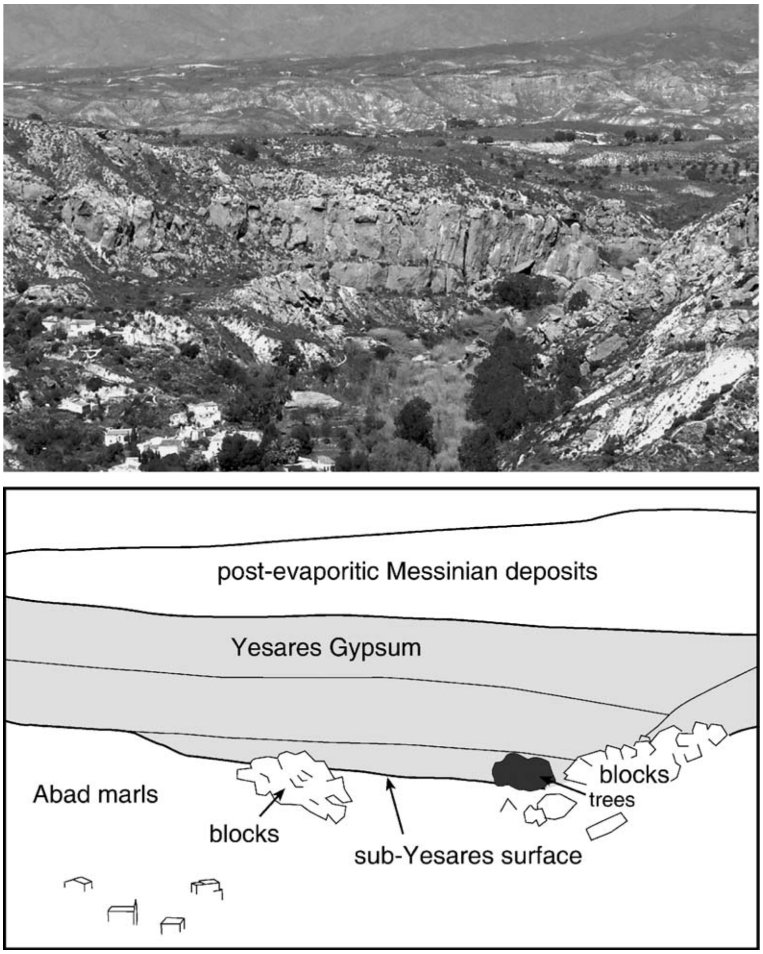

Fig. 5. The base of the Yesares Gypsum at Molino del Río Aguas. The lowermost gypsum horizon is wedge shaped with a convex base and flat top. It pinches out laterally, demonstrating that the Yesares Gypsum onlapped depressions excavated in the underlying pre-evaporitic deposits (Abad marls). Molino del Río Aguas, 4 km ESE of Sorbas town, viewed from the south-east. Blocks fallen from overlying gypsum beds only locally obscure the contact. This locality is described in Riding et al. (1999).

4.1.3. Post-evaporitic deposits

The Yesares Gypsum grades upwards into the 70 m thick Sorbas Member (Roep et al., 1979). This consists of basin centre marls, silts and sands (Fig. 8) that pass marginally into the so-called Terminal Complex, a heterogeneous deposit that includes coarse siliciclastic sediments, oolite, giant microbial domes, and coral patch reefs (Dabrio et al., 1985; Ott d'Estevou and Montenat, 1990; Martín et al., 1993; Braga et al., 1995; Roep et al., 1998) (Fig. 9). Basin centre sediments of the Sorbas Member contain abundant and generally well preserved foraminifers and calcareous nannoplankton at certain horizons (Table 1) (Riding et al., 1998; Sánchez-Almazo et al., 1999). The foraminiferal assemblages do not show features typical of reworking, such as size sorting and mixture of species of different stages.

The Sorbas Member and Terminal Complex are overlain by 75 m of fluviatile clays, sandstones, and conglomerates. Within this overlying sequence there are up to four beds (each <2 m thick) of lacustrine ostracode limestone (Mather and Stokes, 2001) and on top of the sequence there is 5–10 m of marine shelly sandstone (Montenat and Ott d'Estevou, 1977). Ruegg (1964) included both the fluviatile–lacustrine and the marine sediments in the Zorreras Member, and according to Ott d'Estevou and Montenat (1990) the contact between these continental and marine deposits is conformable. The spatial relationships of both units, however, instead suggest that they are separated by an unconformity, above which the shelly sandstone has a more limited areal extent than the underlying deposits. The lower part of the continental sediments of the Zorreras Member is Messinian in age (Martín-Suárez et al., 2000), whilst the marine sandstone is probably Early Pliocene (Civis et al., 1977; Ott d'Estevou and Montenat, 1990).

4.2. Almería-Níjar Basin

The sedimentary fill of the Almería-Nijar Basin consists of Mid-Miocene to Quaternary deposits (Dabrio

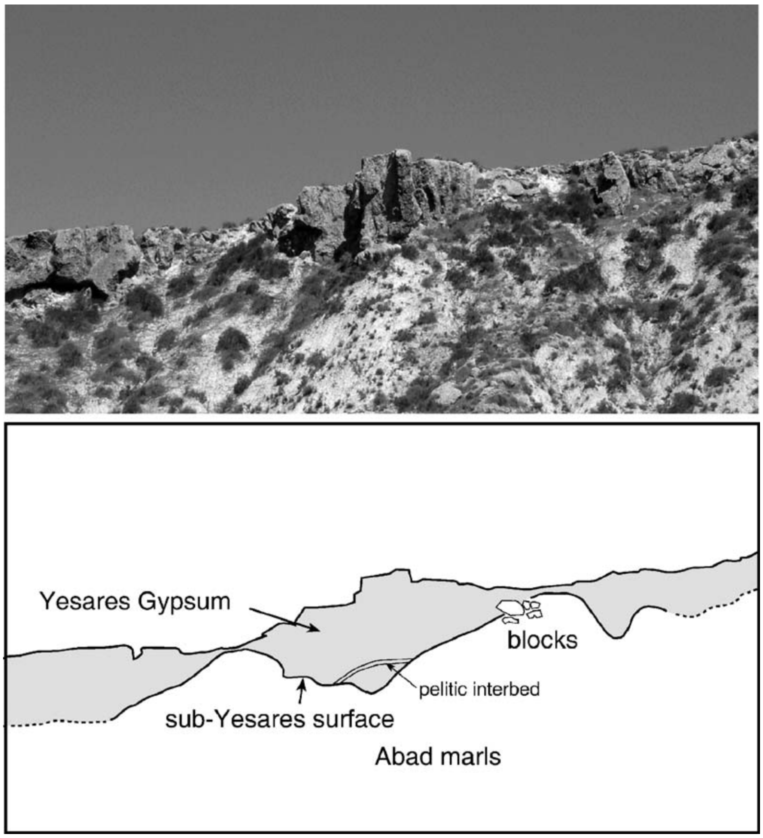

Fig. 6. Base of the Yesares Gypsum, 1 km northeast of El Tesoro. The gypsum beds fill palaeo-gullies with relief of up to 10 m carved into the underlying Abad marls. In the palaeo-gully in the centre of the photograph, the lowermost gypsum bed (arrowed) is 2 m thick and only occurs in the very bottom of the gully. It is separated from the overlying gypsum by a pelitic interbed. The overlying gypsum onlaps the marls at the gully sides. These relationships show that this contact is essentially undisturbed and is not an artifact of deformation.

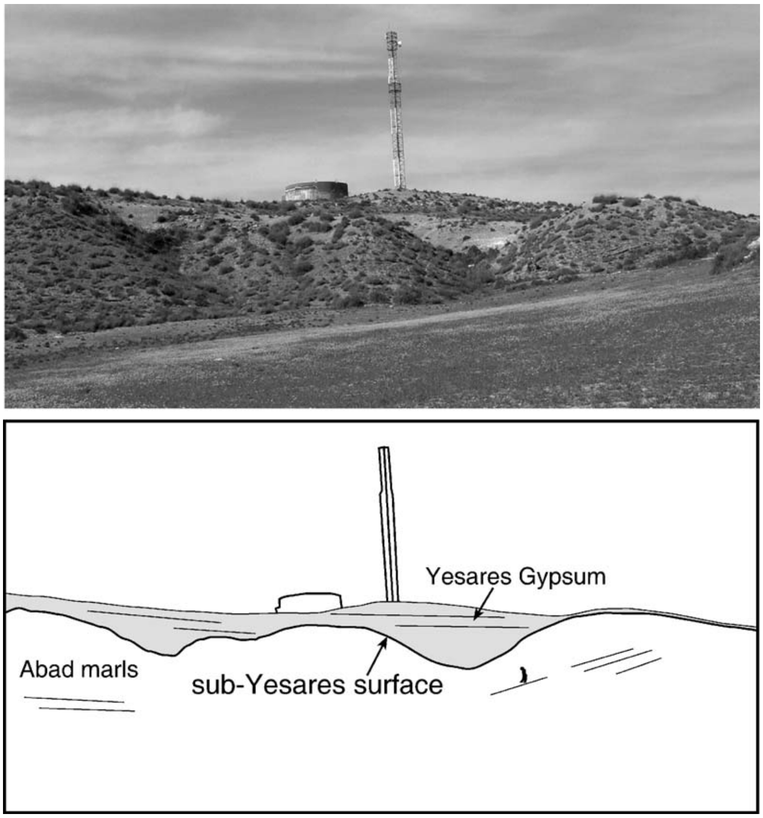

Fig. 7. Base of the Yesares Gypsum at Los Yesos. View looking north. The gypsum fills irregular gullied relief excavated into the underlying Abad marls. Towards the right, angular unconformity is observed between the Abad marls, which are slightly folded and dip northwestwards (to the left), and the gypsum which dips northeastwards.

et al., 1981; Serrano, 1990; Montenat et al., 1990; Aguirre, 1998). Messinian pre-evaporitic deposits at the basin margin comprise mixed siliciclastic and bioclastic sediments overlain by coral reefs (Dabrio et al., 1981). Coeval basinal sediments include marls, silty marls and diatomitic marls of the Abad Member, the top of which is dated at ~5.9 Ma (Sierro et al., 2001) (Figs. 10 and 11). The Yesares Gypsum overlies the Abad Member and consists of cycles of selenitic gypsum and siliciclastic beds (van de Poel, 1991; Lu et al., 2001). The transition between the underlying Abad Marls and the overlying gypsum units is described as conformable by van de Poel (1991) and Fortuin and Krijgsman (2003), but there is field evidence of angular unconformity between them (Aguirre and Sánchez-Almazo, 2004) (Fig. 12). The Yesares Gypsum unit gradually changes upwards as the gypsum beds thin and the siliciclastic interbeds concomitantly thicken (Lu et al., 2002; Aguirre and Sánchez-Almazo, 2004) (Fig. 11A). The base of a sub-unit of deformed strata, several metres above the top gypsum bed, interpreted as an erosional and collapse surface due to gypsum dissolution (Fortuin and Krijgsman, 2003), may actually be a result of synsedimentary slumping (Aguirre and Sánchez-Almazo, 2004).

At the northern margin of the basin, the post-evaporitic deposits consist of fluviodeltaic conglomerates, sands, and silts, which laterally interdigitate with marine silty marls. In distal sections (Fig. 11B), towards the basin centre, the Yesares Gypsum beds show gradual upward transition to silty marls containing foraminifers (Table 1) and intercalated thin turbidite sandstones (Aguirre and Sánchez-Almazo, 2004). Brackish environments in the deltaic transition zone to the marine domain are indicated by brackish ostracodes with charophytes, scarce oligohaline benthic foraminifers, and cerithiid gastropods (van de Poel, 1991, 1994; Aguirre and Sánchez-Almazo, 2004).

Foraminifer abundance, species richness and planktic/benthic ratio all progressively increase from middle to top of the post-evaporitic unit (Table 1). As in the post-evaporitic deposits in the Sorbas Basin, representatives of the *Globorotalia miotumida* group (sensu Sierro, 1985) are common in the foraminiferal assemblages. The 'last regular occurrence' of this group has been thought to occur

Table 1
Foraminifers and calcareous nannoplankton from the evaporitic and post-evaporitic deposits in the Sorbas and Almería-Níjar basins

	Sorbas Basin		Almería-Níjar Basin	
	Evaporitic unit (pelitic interbeds)	Post-evaporitic unit	Evaporitic unit (pelitic interbeds)	Post-evaporitic unit
Planktic foraminifers	*Globigerina bulloides*	Globigerina cf. bulloides	Globigerina spp.	*Globigerina cf. decoraperta*
	Globigerina cf. decoraperta	Globigerina cf. decoraperta	Globigerinoides spp.	Globigerina falconensis
	Globigerina multiloba	Globigerina falconensis	Globorotalia group *miotumida*	Globigerina sp.
	Globigerina sp.	*Globigerina multiloba*	Globorotalia group *scitula*	Globigerinoides bolli
	Globigerinoides obliquus	Globigerina sp.	Neogloboquadrina acostaensis	Globigerinoides quadrilobatus
	Globigerinoides extremus	Globigerinoides extremus	Neogloboquadrina humerosa	Globigerinoides trilobus
	Globigerinoides sacculifer	Globigerinoides obliquus	Turborotalita *quinqueloba*	Globorotalia group *miotumida*
	Globigerinoides trilobus	Globigerinoides sacculifer		*Neogloboquadrina acostaensis*
	Globorotalia group *miotumida*	Globigerinoides trilobus		*Neogloboquadrina humerosa*
	Neogloboquadrina acostaensis	Globorotalia group *miotumida*		*Orbulina universa*
	Orbulina universa	Globorotalia group *scitula*		*Turborotalita multiloba*
	Turborotalia obesa	Neogloboquadrina acostaensis		*Turborotalita quinqueloba*
	Turborotalita *quinqueloba*	Neogloboquadrina humerosa		
		Orbulina universa		
		Turborotalia obesa		
		Turborotalita multiloba		
		Turborotalita quinqueloba		
Benthic foraminifers	*Ammonia becarii*	Ammonia becarii	Ammonia becarii	Ammonia becarii
	Ammonia tepida	Anomalinoides	Brizalina spathulata	Ammonia *cf. perlucida*
	Anomalinoides granosus	Asterodiscorbis	Brizalina sp.	Ammonia tepida
	Asterigerinata planorbis	Brizalina spathulata	Cassidulina spp.	Asterigerinata planorbis
	Bolivina spp.	Bulimina aculeata	Cibicides refulgens	Astrononion boueanum
	Brizalina aff. dilatata	Bulimina costata	Cibicidoides pseudoungerianus	Bolivina arta
	Bulimina *minima*	Bulimina inflata	Cibicidoides spp.	Bolivina marginata
	Cibicides refulgens	Cibicides lobatulus	Elphidium macellum	Brizalina dilatata
	Cibicidoides sp.	Cibicidoides	Elphidium sp.	Brizalina spathulata
	Elphidium crispum	Elphidium fischtelianum	Melonis soldanii	Brizalina sp.
	Elphidium fischtelianum	Elphidium sp.	Nodosarids indet.	Bulimina aculeata
	Elphidium margaritaceum	Eponides	Nonion sp.	Bulimina costata
	Elphidium sp.	Globobulimina cf. auricula		*Bulimina elongata*
	Fissurina sp.	Gyroidina sp.		*Bulimina cf. minima*
	Glandulina laevigatus	Hopkinsina bononiensis		*Bulimina* sp.
	Globulina gibba	Lobatula lobatula		*Cassidulina* spp.
	Gyroidinoides sp.	Melonis pompilloides		*Cibicides refulgens*
	Haynesina germanica	Nonion padanum		*Cibicides* sp.
	Lagena laevis	Rectuvigerina/Hopkinsina spp.		*Cibicidoides dutemplei*
	Lobatula lobatula	Trifarina bradyii		*Cibicidoides ungerianus*
	Neoconorbina terquemi	Uvigerina peregrina		*Cribroelphidium* sp.
	Oolina sp.			*Elphidium macellum*
	Parafissurina sp.			*Elphidium* sp.
	Planulina ariminensis			*Globocassidulina subglobosa*
	Polymorphina sp.			*Gyroidina altiformis*

(continued on next page)

Table 1 (*continued*)

	Sorbas Basin		Almería-Níjar Basin	
	Evaporitic unit (pelitic interbeds)	Post-evaporitic unit	Evaporitic unit (pelitic interbeds)	Post-evaporitic unit
	Porosononion granosum Reussella spinulosa Rosalina globularis			*Hanzawaia boueana* *Hanzawaia* sp. *Haynesina depressula* *Heterolepa bellincioni* *Melonis soldanii* *Neoponides* sp. *Nonion* sp. *Planulina ariminensis* *Pullenia quinqueloba* *Rectuvigerina/Hopkinsina* spp. *Siphonina cf. planoconvexa* *Trifarina bradyi* *Uvigerina peregrina* *Uvigerina striatissima* *Uvigerina* sp.
Nannoplankton calcareous	Not studied	Amaurolithus aff. primus *Amaurolithus cf. amplificas* *Calcidiscus leptoporus* *Ceratolithus cf. acutus* *Coccolithus miopelagicus* *Coccolithus pelagicus* *Discoaster quinqueramus* *Helicosphaera carteri* *Sphenolithus moriformis* *Triquetrorhabdulus rugosus*	Not studied	Not studied

Data from van de Poel (1992), Riding et al. (1998), Sánchez-Almazo et al. (1999), Goubert et al. (2001) and Aguirre and Sánchez-Almazo (2004).

in the Messinian at a calibrated age of 6.5 Ma (Sprovieri et al., 1996; Hilgen and Krijgsman, 1999; Krijgsman et al., 1999a; Sierro et al., 2001; Krijgsman et al., 2002). However, the following observations suggest that the *G. miotumida* species group did persist through the post-evaporitic unit: 1) Prior to the supposed last occurrence in the pre-evaporitic deposits, the group exhibits a discontinuous record and species composing the group are absent

Fig. 8. Gradual transition from the top of the Yesares Gypsum to post-evaporitic sandstones and silts of the Sorbas Member. Gypsum cones progressively thin while the siliciclastic interbeds thicken. Arrows indicate cones in the highest gypsum bed. Río Aguas section, near Sorbas town. The stratigraphy at this site is described in detail by Krijgsman et al. (2001).

Fig. 9. Coral (*Porites*) patch reefs (arrow) in post-evaporitic deposits at Rambla de Góchar (Sorbas Basin). This locality is described in detail in Martín et al. (1993).

for long intervals before reappearing (Sierro et al., 2001; Blanc-Valleron et al., 2002). 2) In the Atlantic domain (Ain el Beida, Morocco), the last occurrence of *G. miotumida* is recorded in Chron C3An.1n at about 6.2 Ma (Benson et al., 1995), much later than its supposed global disappearance. 3) Specimens of species belonging to the group have been recorded in the pelitic interbeds in the Yesares gypsum without having been considered to be reworked (Iaccarino et al., 1975; Hsü et al., 1978a). 4) In the post-evaporitic deposits of the Almería-Nijar Basin the foraminiferal assemblages do not show features indicative of reworking, such as size sorting and mixing of foraminifers from stages older than the Messinian. Furthermore, foraminifers that are common in pre-evaporitic Messinian deposits such as *G. bulloides* are rare in the post-evaporitic deposits. If reworking were a general phenomenon, then species such as *G. bulloides* should be more conspicuous in the post-evaporitic

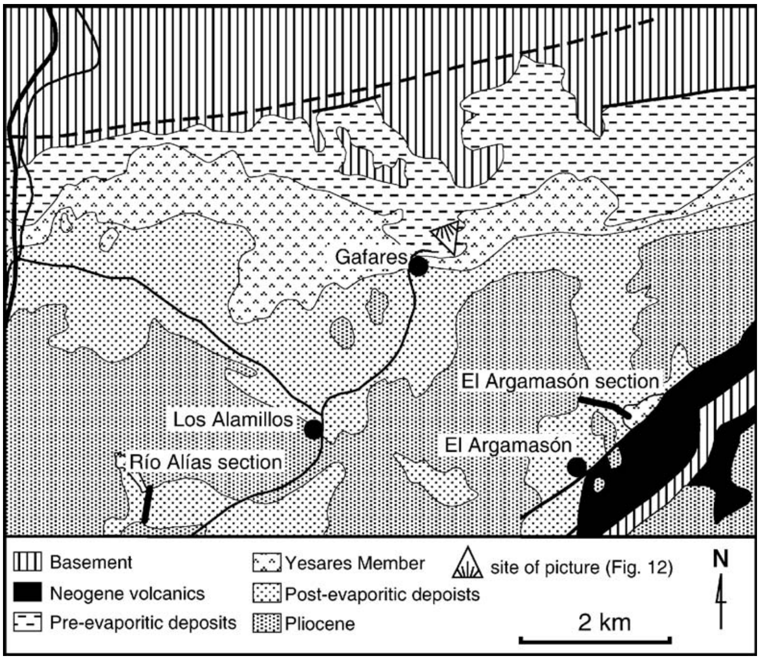

Fig. 10. Geological map of the northern part of the Almería-Níjar Basin. Modified from Aguirre and Sánchez-Almazo (2004).

deposits. 5) Species of the *G. miotumida* group have been reported from post-evaporitic deposits at many Mediterranean localities (Vera basin by Cita et al., 1980; Carboneras-Nijar basin by van de Poel, 1992, 1994; Cyprus basins by Rouchy et al., 2001; different sites of the western Mediterranean by Iaccarino and Bossio, 1999). In these cases, the possibility that the foraminifers reflect marine influxes has at first been considered, but then rejected in favour of the view that the assemblages are more likely to have been reworked. If our interpretation, that the *G. miotumida* group did persist in post-evaporitic deposits, is correct then the previously recognized apparent last occurrence of the *G. miotumida* group (Sprovieri et al., 1996; Hilgen and Krijgsman, 1999; Krijgsman et al., 1999a; Sierro et al., 2001; Krijgsman et al., 2002) in the Mediterranean results from sampling being restricted to pre-evaporitic Messinian marls together with the mistaken assumption that subsequent occurrences must necessarily be reworked. Palaeomagnetic samples from the post-evaporitic unit have reversed polarity (Dinarès-Turell et al., 2004) suggesting Chron C3r, which ranges 6.04–5.24 Ma (Lourens et al., 1996), indicating Late Messinian or earliest Pliocene age. The absence of Pliocene foraminifers makes it likely that this post-evaporitic unit is Messinian in age (Aguirre and Sánchez-Almazo, 2004; Dinarès-Turell et al., 2004).

At the northwestern margin of the basin, in the Níjar area, bioclastic, oolitic and microbial carbonates unconformably overlie the pre-evaporitic reefs (Dabrio et al., 1981; Riding et al., 1991b). Lower Pliocene silts and fine-grained sands unconformably overlie the Messinian deposits (Montenat et al., 1990).

4.3. Vera Basin

The Neogene record of the Vera Basin comprises Early Miocene to Pliocene sediments (Barragán, 1997) (Fig. 13). The Messinian marginal deposits include coral reefs (Ott d'Estevou et al., 1990) and mixed siliciclastic and bioclastic sediments (Braga et al.,

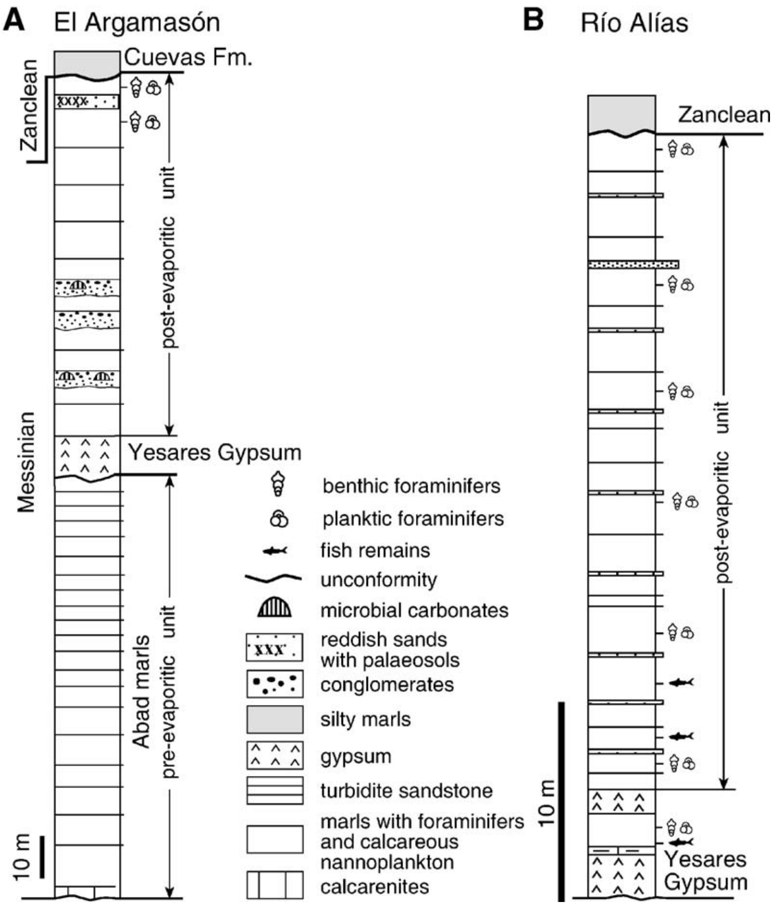

Fig. 11. Messinian to Early Pliocene stratigraphy of the northeastern part of the Almería-Níjar Basin at El Argamasón (A) and Río Alías (B) sections. See Aguirre and Sánchez-Almazo (2004) for additional information.

2001). These shallow-water deposits pass laterally into basinal silty marls and marls with turbiditic siliciclastics and carbonates (Fig. 14). No primary evaporite deposits occur in the Vera Basin (Montenat and Bizon, 1976; Ott d'Estevou et al., 1990). In the Cuevas de Almanzora section a succession of Early Messinian to Early Pliocene fine-grained sediments has been described as continuous (Montenat et al., 1976; Ott d'Estevou et al., 1990; Benson and Rakic-El Bied, 1991). However, an up to 12 m thick succession of thin-bedded marls and clays (laminites), including very thin turbiditic sands, with brackish water ostracodes and characean algae (Cita et al., 1980; Geerlings et al., 1980; Benson and Rakic-El Bied, 1991; Fortuin et al., 1995) represents the latest Messinian deposits and a sharp, inclined surface underlies the Pliocene sandy marls (Fortuin et al., 1995) (Fig. 14). The age of the laminites is bracketed by strontium isotope dates (Fortuin et al., 1995) of 5.8 Ma, at the top of the underlying marine marls, and 5.1 Ma, at the base of the overlying Pliocene marine sediments (Cita et al., 1980). In this Cuevas de Almanzora section, the transition from Messinian marine marls to thin bedded sediments containing brackish fauna (Fortuin et al., 1995) is not exposed (Fig. 14) as this part of the section is covered by recent debris and soil. At other localities in the Vera Basin, Early Pliocene deposits are clearly separated by an erosion surface from underlying marine Messinian sediments (Fortuin et al., 1995). Pliocene to Quaternary deposits also blanket a deeply incised surface offshore of the Vera Basin (Fortuin et al., 1995). West of Garrucha, olistostrome deposits (Fig. 13) include blocks of diverse provenance, e.g., metamorphic basement and Messinian

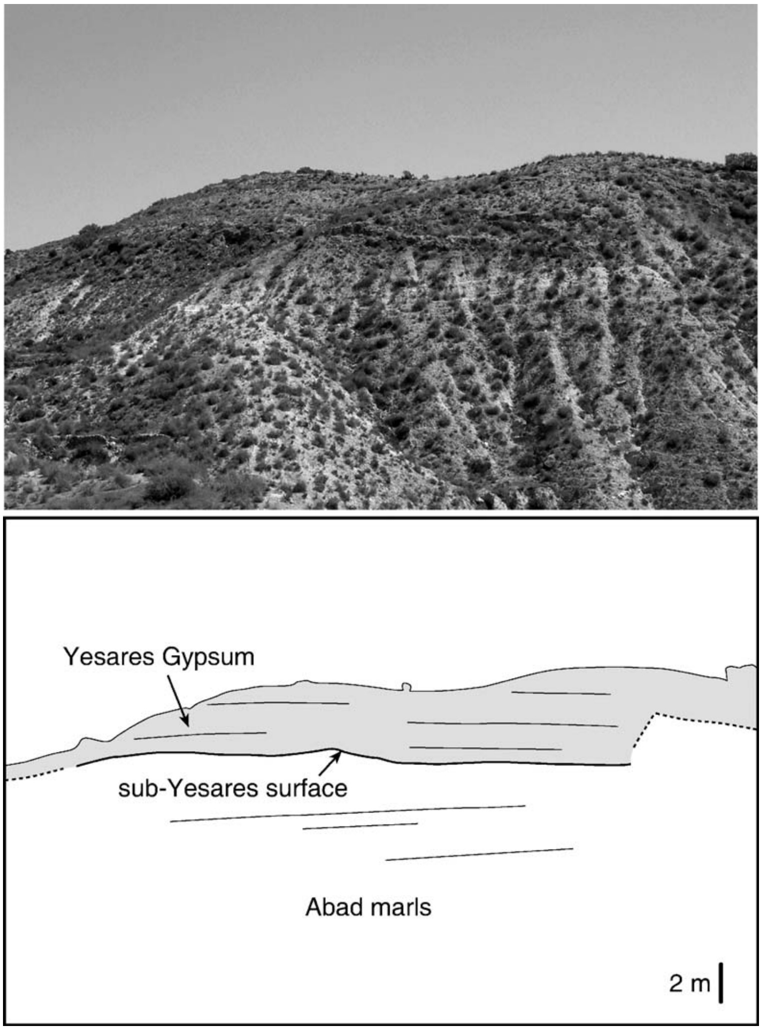

Fig. 12. The Yesares Gypsum unconformably overlying pre-evaporitic marls and diatomitic marls. Lines delineate bedding in the marls and gypsum deposits. Gafares (Almería-Níjar Basin).This locality is described in Aguirre and Sánchez-Almazo (2004).

bioclastic and reef carbonates and gypsum. The age of this chaotic deposit is controversial. It was regarded as Early Pliocene by Ott d'Estevou et al. (1990) based on the presence of Pliocene planktic foraminifers in the overlying sediments, whereas Fortuin et al. (1995) considered it to be Late Messinian. The olistrostromes occupy depressions scoured into Messinian deposits and show evidence of eastward transport (Fortuin et al., 1995), indicating a source at the western margin of the Vera Basin, in particular at its transition to the Sorbas Basin.

5. Testing proposed models

The sedimentary record of the Almería-Níjar, Sorbas and Vera basins indicates that these basins adjacent to the present-day coast remained connected to the Mediterranean Sea during most of their Messinian evolution. This is shown by their marine basin centre successions that are continuous except for an erosional event in the Late Messinian, and local development of fluviatile and lacustrine facies in the latest Messinian. In addition, the geological records of adjacent Neogene Betic basins clearly indicate that no direct connection between the Mediterranean Sea and the Atlantic Ocean through the Betic Cordillera existed, after ~7 Ma (Garcés et al., 1998; Martín et al., 2001; Braga et al., 2003), i.e., for most of the Messinian. A principal implication of this is that the marine waters in the SE Almería basins were not directly linked to the Atlantic Ocean and therefore must have been contiguous with those of the adjacent main Western Mediterranean water body. Thus, the presence of marine sediments in the Almería-Níjar, Sorbas and Vera basins during the Messinian implies that the Western Mediterranean basin was also filled by marine waters whenever the SE Almería basins were marine. We now return to the key questions posed initially. These relate to (i) pre-evaporitic conditions, and particularly whether progressive salinity increase is recorded in the SE Almería marginal basins prior to evaporate deposition, (ii) the

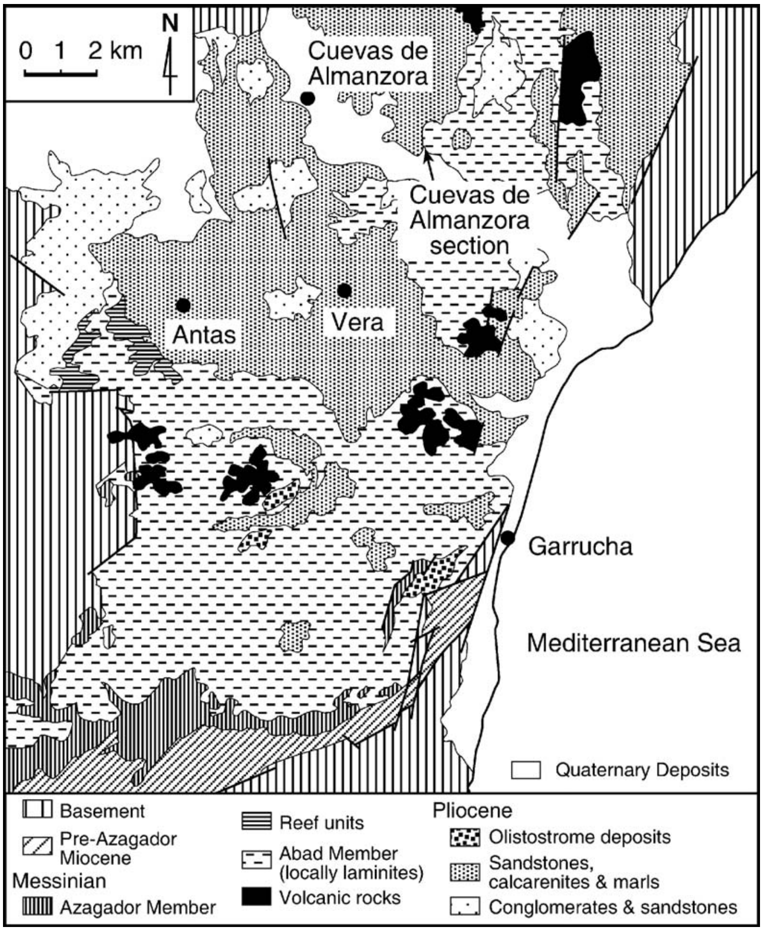

Fig. 13. Geological map of the Vera Basin. Modified from Montenat (1990).

relationship between the evaporites of these marginal basins and those of the deep Mediterranean, and (iii) whether final marine refilling of these basins was preceded by brackish Lago Mare conditions.

5.1. Pre-evaporitic evolution

Available evidence indicates that fossil assemblages are normal marine throughout the pre-evaporitic Messinian sequence (Baggley, 2000; Goubert et al., 2001; Sierro et al., 2001, 2003) up to the erosion surface below the Yesares Gypsum, and that there is no gradual transition from normal marine sediments to evaporite deposits (Krijgsman et al., 1999a; Baggley, 2000; Sierro et al., 2001, 2003). Towards the basin margins, the youngest fringing reef deposits contain stenohaline regular echinoids, together with scleractinians, coralline algae, *Halimeda* and diverse assemblages of marine bivalves (Riding et al., 1991a; Jiménez and Braga, 1993). At the basin centres, fine-grained sediments immediately beneath the sub-Yesares erosion surface contain foraminifers and calcareous nannoplankton that indicate normal marine salinities (Sierro et al., 1993; Baggley, 2000; Sierro et al., 2001, 2003). Baggley (2000), in particular, stressed the lack of any indication of salinity increase in the marls beneath the sub-Yesares surface. According to Baggley (2000), the foraminiferal assemblages reflect shallowing in the Late stages of

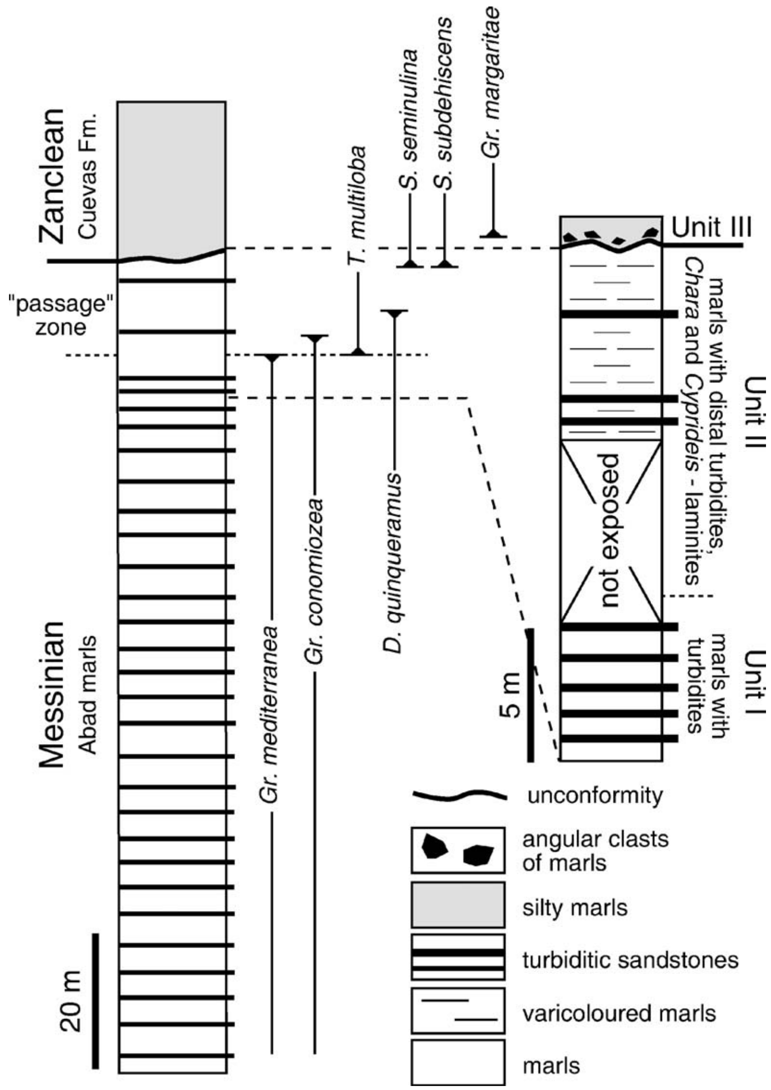

Fig. 14. Messinian to Early Pliocene stratigraphy and main bioevents at Cuevas de Almanzora section according to Benson and Rakic-El Bied (1991). Detailed column of the “passage zone” from Fortuin et al. (1995).

Abad marl deposition and changes in oxygenation of the bottom waters. The general tendency towards lowering of sea-level recorded by the foraminiferal assemblages is in agreement with the relative sea level fall shown by reefs at the basin margins, which is the net result of sea-level oscillations (Braga and Martín, 1996).

Changes in the diatom and foraminiferal assemblages in the Abad Member, previously attributed to salinity increase preceding gypsum formation (Rouchy, 1980; Troelstra et al., 1980), may have resulted from water stratification (Martín and Braga, 1994; Goubert et al., 2001) or changes in nutrient content (Sierro et al., 1997). Some degree of isolation from the open ocean, both for the Mediterranean Sea and the SE Almería basins, is suggested by amplified fluctuations in stable isotopic values of foraminifer tests (Sánchez-Almazo et al., 2001), by benthic foraminiferal assemblages (Sánchez-Almazo et al., 2001; Goubert et al., 2001), and by relatively low-diversity assemblages of planktic foraminifers and calcareous nannoplankton (Sierro et al., 1997; Sánchez-Almazo et al., 2001; Sierro et al., 2003).

In contrast to the record in the SE Almería basins, transition from marine to hypersaline conditions prior to evaporite formation have been reported from many peri-Mediterranean basins, e.g., Sicily (Schreiber et al., 1976; McKenzie et al., 1980; Decima et al., 1988; Bellanca et al., 2001; Blanc-Valleron et al., 2002), Cyprus (Orszag-Sperber et al., 1980; Krijgsman et al., 2002), and Gavdos (Kouwenhoven et al., 1999; Krijgsman et al., 1999a; Seidenkrantz et al., 2000). These transitions are reflected in the sedimentology, mineralogy, stable isotope values, and fossil assemblages. At first sight, it would seem reasonable to postulate that similar signs of transition existed in SE Almería basins but were removed by sub-Yesares erosion. There are difficulties with this, however. The transitional deposits in Falconara/Gibliscemi (Sicily) are suggested, on the basis of biostratigraphic and cyclostratigraphic analyses, to be precisely coeval with the top beds of the pre-evaporitic deposits in the Sorbas Basin (Krijgsman et al., 1999a; Blanc-Valleron et al., 2002, Fig. 11). In particular, Krijgsman et al. (1999a) suggest bed-to-bed correlation of the transitional deposits at Falconara/Glibiscemi, interpreted as reflecting increased salinity (Blanc-Valleron et al., 2002), with the uppermost preserved Abad marls in the Sorbas Basin which do not show any salinity increase (Baggley, 2000). In addition the stenohaline biotas of the Fringing Reefs in SE Almería clearly indicate normal marine conditions at this same level. Consequently, if the correlation between Almería and Sicily suggested by Krijgsman et al. (1999a) and Blanc-Valleron et al. (2002) is correct, then inference of gradual long-term evolution towards evaporite basin conditions must be discarded for the Western Mediterranean. The logic of this is that fully marine conditions in the Sorbas sections at this level must indicate the general environment of the Western Mediterranean, whereas locally restricted conditions, e.g., in Sicily, may only have local significance. The SE Almería record gives no indication, on a geological time scale, of gradual change from marine to hypersaline conditions. Rather, the environmental changes leading to evaporite formation were abrupt from a geological perspective.

Local variations in conditions influencing seawater salinity in the Mediterranean region are likely due to variety of factors. Differential tectonic uplift is one important factor, well exemplified in southern Spain where evaporite precipitation due to isolation from the Mediterranean occurred at different times in a number of marginal basins, in many cases long before inception of the MSC. This is evident in the Granada (Late Tortonian), Lorca and Fortuna (Late Tortonian or Early Messinian depending on the authors) basins (Rouchy, 1982; Riding et al., 1998; Garcés et al., 1998; Krijgsman et al., 2000; Garcés et al., 2001). Similar isolation from the main Mediterranean water mass could account for the gradual increase in salinity reported (references above) in many basins in central and eastern Mediterranean, including Sicily, Cyprus and Gavdos. But other factors are likely to have operated. For example, we speculate that a salinity gradient may have developed between normal marine waters in the Western Mediterranean and waters with higher salinities further east where evaporation may not have been balanced by Atlantic water inflow.

A plausible explanation for the abrupt onset of evaporite conditions in the Western Mediterranean, as reflected in SE Almería, is tectonic uplift of the westernmost Alpine chains (Weijermars, 1988; Martín and Braga, 1996) causing temporary closure/restriction of the Atlantic portal.

5.2. Evaporite formation in the deep and marginal Mediterranean basins

The following stratigraphic, sedimentological and palaeontological features of the evaporites in the SE Almería basins are of direct significance for understanding their genesis and relationships with the evaporites deposited in the deep Mediterranean centre. a) In these three basins, evaporites only occur in the Sorbas and Almería-Níjar basins. No primary evaporite deposition is recorded in the Vera Basin (Montenat and Bizon, 1976; Ott d'Estevou et al., 1990). b) Evaporites in the Sorbas and Almería-Níjar basins are separated from underlying deposits by an erosional surface (Figs. 3,5–7,12), which in the case of the Sorbas Basin had an original relief difference of ~240 m (Riding et al., 1998, 1999). c) The evaporite sediments are mainly gypsum; no halite has been recorded. The brines were of marine origin as evidenced by geochemical signatures (Playà et al., 1997; Lu et al., 2001, 2002) and by fossil assemblages in the siliciclastic interbeds (Riding et al., 1998; Saint Martin et al., 2000; Goubert et al., 2001). d) The gypsum beds onlap the underlying erosion surface, indicating that they formed during relative sea-level rise (Martín and Braga, 1994; Riding et al., 1998, 1999; Aguirre and Sánchez-Almazo, 2004) (Fig. 5). They gradually change upwards into siliciclastic deposits (the Sorbas Member) by progressive thickening of terrigenous beds and concomitant thinning and final disappearance of the gypsum layers (Fig. 8). No erosion surfaces occur within or immediately above the Yesares Gypsum (Dronkert, 1977; Krijgsman et al., 2001).

These observed stratigraphic features contradict two step desiccation model of Clauzon et al. (1996) of the Mediterranean during the MSC. Clauzon et al. (1996) postulated i) an initial relatively small (few hundred of metres) drawdown leading to formation of marginal basin evaporites, followed by ii) final drawdown, resulting in salt precipitation in the Mediterranean centre while the evaporites previously formed in the marginal basins were exposed to erosion. In opposition to this model, in the Sorbas and Almería-Nijar basins, instead of gradual transition from pre-evaporitic (fringing reefs and Abad Member) to evaporitic deposits (Yesares Member) there is a marked erosion surface between them. Additionally, instead of the top of the Yesares Gypsum being eroded, it shows well-exposed gradual transition to the overlying sediments of the Sorbas Member.

The erosion surface beneath the Yesares Gypsum means that dates for the top of the underlying Abad marls (Gautier et al., 1994; Krijgsman et al., 1999a; Sierro et al., 2003) can only reflect the age of the youngest uneroded Abad marl, not the age of the beginning of gypsum formation in the Sorbas and Almería-Níjar basins. Nonetheless, these dates provide the best currently available constraint on the timing of the start of evaporite precipitation in the Mediterranean centre if, as suggested by Riding et al. (1998, 1999), the major erosion surface below the gypsum in the Sorbas Basin was carved during Mediterranean drawdown and deep desiccation.

The distribution of evaporites in the SE Almería basins also challenges the view that onset of evaporite deposition occurred simultaneously in marginal basins and in the centre of the deep Mediterranean basin (Krijgsman et al., 1999a). Precipitation of evaporites over the floor of a Mediterranean Sea that filled both the deep and marginal basins could be expected to have promoted evaporite formation in the Vera Basin, but this is not recorded.

We reason that since the evaporites in the Sorbas and Almería-Níjar basins precipitated from marine brines, they cannot be exactly coeval with shallow-water evaporites deposited in the deep Mediterranean, at a level more than 1 km lower than that of these marginal basins (Riding et al., 1998). We therefore infer that marginal basin evaporites, such as those in SE Almería, must have precipitated prior to drawdown, or during reflooding. Evaporites formed prior to drawdown would have been prone to exposure and erosion as Mediterranean sealevel fell. In contrast, evaporites formed during reflooding would have been deposited on the eroded landscape that developed during deep desiccation of the Mediterranean centre. In the case of the SE Almería evaporites, it is clear that they overlie a major erosion surface, and that their tops are not eroded. From these fundamental stratigraphic relationships we conclude that evaporites in the Sorbas and Almería-Níjar basins did not predate Mediterranean drawdown but instead were formed during final refilling of the Western Mediterranean (Riding et al., 1998, 1999). We also suggest that it is the erosion surface below the Yesares Gypsum, rather than the Yesares Gypsum itself, that is coeval with a Mediterranean base level hundreds of metres below the floor of the SE Almería basins (Fig. 15). The Yesares Gypsum therefore formed during relative sea-level rise (Riding et al., 1998, 1999) from brines fed by normal marine waters of the Mediterranean, as suggested by geochemical data (Playà et al., 1997; Lu et al., 2002) and stenohaline biotic components, such as echinoids, in the fossil assemblages (Saint Martin et al., 2000; Goubert et al., 2001). Thus, the SE Almería evaporites postdate the deep Mediterranean basin evaporites (Riding et al., 1998, 1999). Furthermore, these marginal evaporites preferentially accumulated in barred basins, partially isolated from the main Mediterranean water body, such as the Sorbas and Almería-Níjar basins, rather than in basins more fully connected to the Mediterranean such as the Vera Basin (Fig. 10).

5.3. Post-evaporitic evolution

Sediments overlying the Yesares Gypsum in the SE Almería basins show three features relevant to understanding Late Messinian events in the Western Mediterranean basin. Firstly, they contain marine fossil assemblages, at least in certain horizons. These fossils include echinoids, scleractinians and bivalves of undeniable marine origin in shallow basin-margin sediments (Martín et al., 1993; Riding et al., 1998; Roep et al., 1998). Secondly, they continue to exhibit the onlapping relationships with the sub-Yesares erosion surface that were initiated by the Yesares Gypsum beds. This is observed at localities where shallow-water post-evaporitic deposits rest on eroded pre-evaporitic coral-reef platforms (Riding et al., 1998; Martín et al., 1999). Thirdly, fluviatile, deltaic and lacustrine deposits (the Zorreras Member) with brackish fossil assemblages have a limited extent within the SE Almería basins both in their vertical and lateral distribution (Ott d'Estevou and Montenat, 1990; Mather and Stokes, 2001; Aguirre and Sánchez-Almazo, 2004).

These features suggest that at least for significant periods during the post-evaporitic Late Messinian the Western Mediterranean Sea was a fully marine basin (Fig. 15), and that it had recovered to levels similar to, or higher than, those prior to the MSC when pre-evaporitic fringing coral reefs formed. The occurrence of planktic foraminifers and calcareous nannoplankton in deeper basinal silty marls (Sánchez-Almazo et al., 1999; Aguirre and Sánchez-Almazo, 2004) is in agreement with the presence of marine faunas at the margins of the basins reflooded by marine waters. Although there is little information regarding Late Messinian marine deposits in central parts of the deep Western Mediterranean, it appears that the Upper Evaporites are overlain by Messinian marls with small and dwarf planktic foraminifers at Sites DSDP 372 and ODP 974B and 975B (Hsü et al., 1977, 1978a,b; Cita et al., 1978; Comas et al., 1996; Iaccarino et al., 1999; Iaccarino and Bossio, 1999). Iaccarino et al. (1999, appendices A and C) record up to 30 species of planktic foraminifers, all of which are Messinian in age and therefore do not suggest reworking from earlier stages. Cita et al. (1978) and Iaccarino and Bossio (1999) interpreted these Late Messinian marls as brackish (Lago Mare) deposits, but the latter authors also stated in the conclusion that "in Hole 975B it cannot be entirely ruled out that at the end of the Messinian marine incursions from the Atlantic could have arrived and been mixed with the lacustrine water" (Iaccarino and Bossio, 1999, page 539). We see in these foraminifer assemblages the deep basin record of the marine sea waters that necessarily had to fill the western Mediterranean to account for the occurrence of corals and echinoids in the SE Almería basins.

Late Messinian deposits with sedimentary features and fossil assemblages characteristic of brackish palaeonvironments, and reported as "Lago Mare facies", have been recorded in many Mediterranean localities, e.g., Sicily (Ruggieri and Sprovieri, 1976; Cita and Colombo, 1979), Apennines (Cipollari et al., 1999; Gliozzi, 1999; Roveri et al., 2001; Bassetti et al., 2003, 2004; Matano et al., 2005), Cyprus (Di Stefano et al., 1999; Orszag-Sperber et al., 2000; Rouchy et al., 2001), DSDP and ODP sites (Lawrence, 1973; Schreiber et al., 1976; Blanc-Valleron et al., 1998; Pierre et al., 1998; Spezzaferri et al., 1998; Iaccarino and Bossio, 1999), and Spain (Cita et al., 1980; Geerlings et al., 1980; Fortuin et al., 1995; Fortuin and Krijgsman, 2003). The sedimentary record of the SE Almería basins, however, does not support the hypothesis of a large body of brackish water (the "Lago Mare") (Cita et al., 1978; Fortuin and Krijgsman, 2003) filling the Western Mediterranean throughout the Late Messinian. The Messinian post-evaporitic history of the SE Almería basins also conflicts with the view that many independent brackish basins were present, perched at different

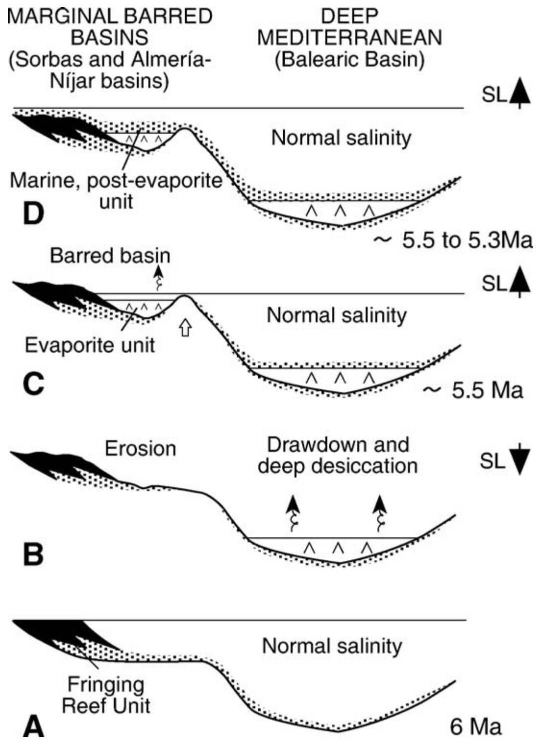

Fig. 15. Model of Messinian events in the SE Almería basins relative to the deep Western Mediterranean. (A), The Sorbas Basin had an open connection with the Mediterranean during deposition of the pre-evaporitic deposits. (B), Shortly after ~5.9 Ma, during drawdown and desiccation of the deep Mediterranean Basin, the pre-evaporitic sediments in the SE Almería basins were deeply eroded. (C), Refilling of the Western Mediterranean culminated in reflooding of the SE Almería basins. Local deposition of evaporites took place in barred basins such as Almería-Níjar and Sorbas, but not in the Vera Basin. (D), As Mediterranean reflooding continued, sealevel rise restored open marine conditions to all the SE Almería basins, depositing post-evaporitic marine sediments with coral reefs, planktic foraminifers and calcareous nannoplankton (modified after Riding et al., 1998).

altitudes in a generally non-marine Mediterranean basin (Orszag-Sperber et al., 2000; Rouchy et al., 2001, 2003). Instead, the occurrence of the post-evaporitic Messinian marine deposits in SE Almería implies the presence of normal marine waters filling the Western Mediterranean, with sea level at least as high as it was during the formation of pre-evaporitic Messinian reefs (Fig. 15). Any variations in salinity that may have occurred due to incomplete connection with the Atlantic Ocean are therefore likely to have been only temporary excursions from normal marine waters. In this respect, the significance of the SE Almería basins, which admittedly are quite small, is that they contain marine Messinian sediments. This gives these basins a regional significance that far exceeds their limited physical extent and is a key to understanding the MSC in the Western Mediterranean, because the only way that marine conditions could have occurred in any of the SE Almería basins was for a coeval body of marine water to have filled the Western Mediterranean Sea up to the elevation of these basins (Fig. 15).

The Zorreras Member in the Sorbas and Almería-Níjar basins has been interpreted as Late Messinian Lago Mare sediments due to the occurrence of lacustrine carbonates with brackish ostracode faunas (van de Poel, 1992, 1994; Fortuin and Krijgsman, 2003). Rather than a representing Mediterranean-wide Lago Mare, however, these thin (<2 m) and laterally restricted (<15 km extent) deposits formed in small, ephemeral lakes (Mather and Stokes, 2001) or deltas (Aguirre and Sánchez-Almazo, 2004). Furthermore, these essentially continental sediments pass laterally and vertically into marine sediments within the basins in which they occur (Ott d'Estevou and Montenat, 1990; Mather and Stokes, 2001; Aguirre and Sánchez-Almazo, 2004), and therefore reflect only local subaerial deposition.

Lower Pliocene marine bioclastic sandstones and silts unconformably overlie the Messinian sequences in SE Almería. In the Almería-Níjar basin, the unconformity below the Lower Pliocene rocks is a major erosion surface (Montenat et al., 1990; Aguirre, 1998; Aguirre and Sánchez-Almazo, 2004), carving a topography that strongly differs from Late Messinian palaeogeography, mainly due to uplift and tectonic re-structuring of the region. As a result of this regional uplift, the Lower Pliocene sediments do not completely onlap the Late Messinian marine rocks and relative sea level during the Lower Pliocene remained at lower levels than in the Late Messinian (Mather and Stokes, 2001; Braga et al., 2003). The effects of this differential uplift can be seen by comparing Late Messinian and Early Pliocene relationships in the Sorbas and Almería-Nijar basins. At the margins of the Sorbas Basin, Lower-Pliocene coastal deposits lie at the toe of slope of Late Messinian carbonate platforms (Terminal Complex-Sorbas Member) that rise to more than 150 m above this level (Braga et al., 2003). In contrast, at the northern margin of the Almería-Níjar Basin the difference in altitude between shallow water (deltaic) Late Messinian rocks and coastal Zanclean (Early Pliocene) deposits is only a few tens of metres.

A similar tectonic origin for an erosion surface associated with Messinian and Pliocene sediments in the vicinity of Site 976B in the Alboran Basin has been invoked by Comas and Soto (1999, p. 338). Comas et al. (1999, p. 570) consider the hiatus related to this erosion surface to be associated with contemporaneous uplifting and structures related to the culmination of a steep reverse fault at Site 977. They report that the entire Lower Pliocene sequence is missing in the eastern flank of the Yusuf Ridge and all older reflectors are uplifted and dragging up on the steep-faulted ridge flank (Comas et al., 1999, p. 570). This erosion surface has also tentatively been related to emersion of basements highs (Comas and Soto, 1999, p. 339), although it extends to the adjacent relative depressions (Comas et al., 1999). Comas et al. (1999, p. 560) suggested a "general" correlation of this surface "with the top of the Messinian evaporite sequence recognized throughout the Mediterranean". However, the ages of the deposits underlying and overlying the surface are very poorly constrained in the Alboran Basin. Comas et al. (1999, p. 568) doubted whether the gravel overlying the surface in Site 978 is latest Messinian or Pliocene. In Hole 977B, Siesser and de Kaenel (1999, p. 230) reported common and abundant calcareous nannofossils in Zone NN12b (middle part of the NN12 zone of Martini, 1971, spanning the Late Messinian–Early Pliocene), although the calcareous matrix surrounding the pebbles of the gravel marking the erosion surface contains calcareous nannofossils of older Miocene zones. According to Siesser and de Kaenel (1999, p 229) calcareous nannofossils suggested that the major hiatuses in Hole 976B are Lower Tortonian and between the Early and Late Pliocene. These authors considered that the Late Tortonian, Messinan and Early Pliocene intervals (calcareous nannoplankton Zones NN11 to NN12 of Martini, 1971) consist of open marine fine-grained sediments. They did not recognise any interruption in the record of "common to abundant Neogene nannofossils" within, below or above NN12 and consequently they were not able to date any erosion surface in the Late Messinian–Pliocene interval. In short, additional research is needed to constrain the timing and regional significance of the erosion surface associated with Late Messinian–Early Pliocene sediments in the Alboran Sea.

6. Conclusions

The Almería-Níjar, Sorbas and Vera basins (SE Almería basins) adjacent to the present-day Mediterranean in SE Spain, contain well-exposed and almost continuous Messinian marine sequences. These small basins maintained connection with the Mediterranean throughout the Messinian, except during the major drawdown phase of the Messinian Salinity Crisis. As a result, they contain an exceptional record of the events preceding and postdating the MSC. Successions in other Neogene basins of the Betic Cordillera to the north and west show that there was no direct connection between the Mediterranean Sea and the Atlantic Ocean through the Betic Cordillera after the earliest Messinian. Consequently, for most of the Messinian the SE Almería basins were isolated from the Atlantic and their marine connection was with the Mediterranean. This setting of the SE Almería basins does not preclude substantially different Messinian histories elsewhere in the Mediterranean region, but it does require that such other histories must be consistent with those recorded in SE Almería. This particularly applies to the Western Mediterranean. The stratigraphy and palaeoenvironmental history of the SE Almería basins therefore provide a unique record against which models of the MSC can be tested.

Fossil assemblages in the marine pre-evaporitic sediments of these basins do not support the hypothesis that gradual salinity increase affected shallow marine biotas in the Western Mediterranean prior to the MSC. Specifically, there is no evidence of gradual change from pre-evaporitic marine sediments to the Yesares Gypsum. Instead, a major erosion surface separates the gypsum from the underlying marine deposits, which contain stenohaline invertebrates to their very top. The only obvious sign of changing conditions is that benthic foraminifers and stable isotopic values indicate some degree of isolation from the open ocean.

The presence of an erosion surface below the gypsum, with no gradual transition from underlying sediments, together with absence of a major erosion surface within the evaporites in the SE Almería basins or immediately overlying them, contradicts two step model of Clauzon et al. (1996) of the Messinian evaporite formation in the Mediterranean. Similarly, the lack of gypsum in the Vera Basin suggests that evaporite precipitation was not synchronous throughout the Mediterranean in both deep and marginal basins.

The occurrence of stenohaline invertebrate assemblages in siliciclastic deposits interbedded with the gypsum beds, and in the Messinian post-evaporitic sediments, is not consistent with the view that a long-standing, large body of brackish water (the Lago Mare) filled the Western Mediterranean following drawdown and prior to an Early Pliocene reflooding, nor does it agree with the concept of many relatively small brackish basins distributed through a generally empty Western Mediterranean basin.

In summary, our reading of the sedimentary record in the SE Almería basins (Fig. 15) (Riding et al., 1991a, 1998, 1999; Aguirre and Sánchez-Almazo, 2004) is that normal marine deposits were substantially eroded (sub-Yesares surface) following abrupt sealevel fall that we suggest represents Mediterranean drawdown. It was during this sealevel fall that evaporites formed on the deep Mediterranean floor. The overlying Yesares Gypsum beds and post-evaporitic Sorbas Member deposits that onlap the sub-Yesares erosion surface, represent final marine reflooding of the Western Mediterranean following deep desiccation. The gypsum in the SE Almería basins therefore formed in the silled marginal Sorbas and Almería-Níjar basins and postdates the evaporites of the central Mediterranean. Subsequently, in the Late Messinian, Mediterranean sea-level recovered to heights similar to, or higher than, those preceding initial drawdown. Latest Messinian Zorreras Member continental deposits containing brackish fossil assemblages rather than representing a widespread Lago Mare are stratigraphically and spatially restricted and pass laterally to marine deposits within the individual basins. They reflect transition to the generally non-marine conditions associated with the uplift and erosion of the Betic Cordillera that continue to the present-day.

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