The Bajo Segura Basin (SE Spain): implications for the Messinian salinity crisis in the Mediterranean margins

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ABSTRACT: The analysis of the Messinian and Pliocene stratigraphy of the Bajo Segura Basin (a marginal basin of the western Mediterranean) has revealed three synthems deposited in a high sea-level context: T-MI (late Tortonian-Messinian), MII (Messinian), and P (early Pliocene), bounded by two lowstand erosional surfaces (intra-Messinian and end-Messinian unconformities). With respect to the salinity crisis, we propose the following series of events: 1) pre-evaporitic or pre-crisis phase (T-MI synthem); 2) first sea-level fall and subaerial exposure (intra-Messinian unconformity), possibly related to the precipitation of the Lower Evaporites; 3) syn-evaporitic phase (MII synthem), recorded both by selenitic gypsum (Upper Evaporites) as well as by lagoon deposits (Lago-Mare); 4) second sea-level fall and subaerial exposure (end-Messinian unconformity), characterized by deeply incised palaeovalleys; and 5) post-evaporitic or post-crisis phase (P synthem), which coincides with the definitive restoration of open marine conditions in the basin. A combined biostratigraphic and magnetostratigraphic study revealed that all the events linked to the salinity crisis (from the end of the pre-evaporitic phase to the beginning of the post-evaporitic phase) occurred within the chron C3r (c. 5.9-5.2 Ma).

INTRODUCTION

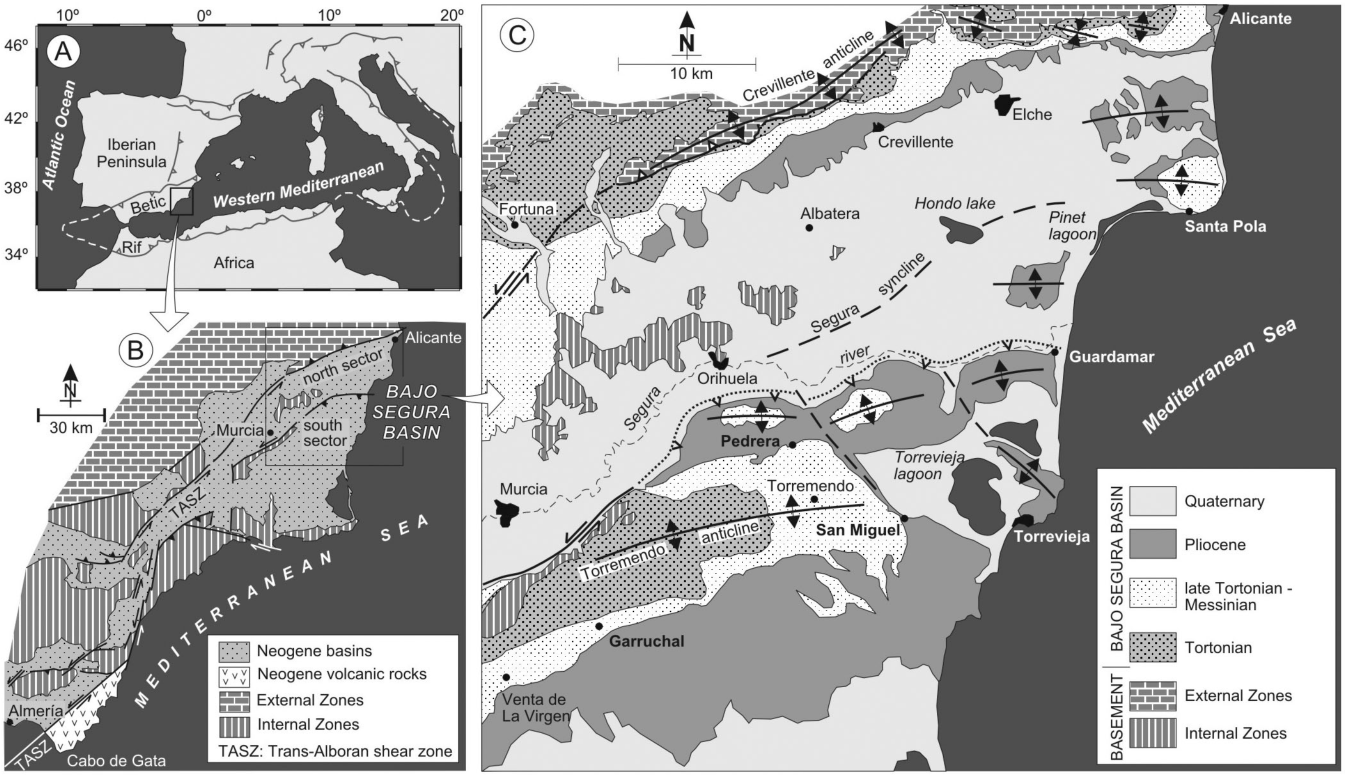
In the marginal sectors of the Mediterranean, the Messinian Salinity Crisis is expressed by two fundamental events; one is the precipitation of evaporites, which accumulated in marine basins periodically isolated from the main body of water of the Mediterranean, and the other is the formation of subaerial erosional surfaces (Messinian unconformities), often with morphologies of incised valleys. Additionally, in these basins, another two sedimentary records linked to the crisis are available. One is the called Lago-Mare episode (latest Messinian), which occurred at the end of the evaporitic phase and which is characterized by the development of hypohaline (or brackish) environments, while the other is the complete reflooding of the Mediterranean at the onset of the Pliocene, which is the event definitively marking the end of the salinity crisis. The Bajo Segura Basin presents an adequate record to illustrate the stratigraphic expression and establish the chronology of the events related to the salinity crisis. Specifically, our study offers data on the above-mentioned events: 1) Messinian erosional phases, 2) evaporitic sedimentation, 3) Lago-Mare episode, and 4) Pliocene reflooding.

GEOLOGIC SETTING

The Bajo Segura Basin is located in the Betic Cordillera (southern Iberian Peninsula), which, together with the Rif (North Africa), constitute the two westernmost Alpine orogens of the Mediterranean (text-fig. 1A). This basin forms part of the Neogene basins of the eastern Betic Cordillera (text-fig. 1B), which seals the contact between the two major geological domains of this orogen: the External Zones (to the north) and the Internal Zones (to the south).

The Bajo Segura Basin formed at the beginning of the Late Miocene, resulting as a subsident trough associated with one of the major tectonic structures of the Betic Cordillera: the northern segment of the Trans-Alboran shear zone (Larouzière et al. 1988) (text-fig. 1B). This structure is a left-lateral fault zone formed as the result of the lithospheric convergence between the Iberian and African plates. The tectonic activity of the Trans-Alboran shear zone continued until the late Pliocene and Quaternary (Alfaro et al. 2002), when a great number of folds formed syngenetically with the movement of this fault zone. The two major folds are the Torremenedo and Crevillent anticlines, located to the south and north of the basin, respectively. Positioned between the two anticlines is the Segura syncline, which constituted a sedimentary trough filled by Quaternary deposits, that separates two geographic sectors (north and south) in which the Tortonian to Pliocene stratigraphic record is well exposed (text-fig. 1C).

The sedimentary fill of the Bajo Segura Basin, which has been described in detail by Montenat (1990a) and Montenat et al. (1990), begins in the Tortonian with a thick succession (more than 2000m) of marine sediments. Basically, the stratigraphic organization of the Tortonian record is characterized by the stacking of several regressive or shallowing-upward sequences, each generated by the progradation of shallow marine depositional systems over slope and deep-basin depositional systems. At the top of the last regressive sequence a transgressive surface is recognized, giving rise to the Messinian sedimentation, though the first deposits over this surface are latest Tortonian in age. The stratigraphic record of the Messinian and Pliocene has been separated into three synthems (T-MI, MII, and P) limited by two basin-wide unconformities (intra-Messinian and end-Messinian). Within each synthem several depositional systems, or associations of facies related to certain sedimentary environments (*sensu* Fisher and McGowen 1967), were differentiated. All of these contained the keys to interpret



TEXT-FIGURE 1
(A) Location of the Betic Cordillera in the western Mediterranean. (B) Geological map of the eastern end of the Betic Cordillera showing the position of the Bajo Segura Basin (simplified from Montenat 1990). (C) Geological map of the Bajo Segura Basin (simplified from Montenat 1990).

the events related to the Messianian salinity crisis in the Bajo Segura Basin, the subject that will be treated in the following sections.

MESSINIAN AND PLIOCENE LITHOSTRATIGRAPHIC AND BIOSTRATIGRAPHIC RECORD

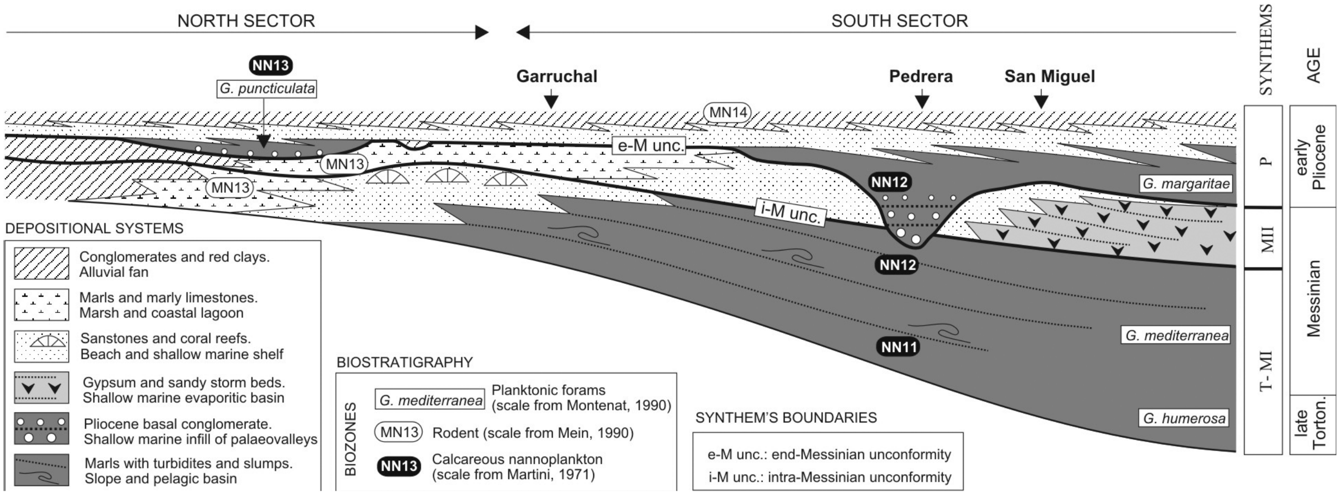
To reveal the manifestations of the Messinian salinity crisis in the Bajo Segura Basin, we have constructed a general stratigraphic framework that include both the three above-mentioned synthems, as well as the bounding unconformities (text-fig. 2). This framework has been established combining and updating the data of Montenat et al. (1990), Calvet et al. (1996), Lancis (1998), Caracuel et al. (2004), Soria et al. (2005), and Soria et al. (2006). The reference biostratigraphic scale comes from Mein (1990), Montenat (1990b), and Martini (1971; in Berggren et al. 1995).

T-MI synthem (late Tortonian-Messinian)

This synthem forms a tract of four laterally interfingering depositional systems. From proximal to distal, they are: 1) alluvial mudstones and conglomerates; 2) saline-water lagoon marls, with abundant ostreids occasionally bored by lithophags bivalves; 3) coastal and shallow marine sandstones (locally with coral reefs) with pectinids, ostreids, serpulids, and, in some stretches, with abundant *Thalassinoides* trace fossils; and 4) slope and basin marls, with frequent sapropels, diatomites, turbidites and slumps. This synthem is interpreted as a sedimentation stage in a high sea-level context. The abundant levels containing rodents in the margin-lagoon marls has enabled a dating of this system as late Turolian or Messinian (Martín Suárez and Freudenthal 1998), corresponding to the MN13 biozone of Mein (1990). From the planktonic forams (Montenat et al. 1990), most of the basin marls belong to the *Globorotalia mediterranea* biozone (Messinian), although at the bottom of these marls, the *Globorotalia humerosa* biozone (late Tortonian) was recognized. Given the data of calcareous nannoplankton (Lancis 1998), the determination of the NN13 biozone in the upper part of the basin marls is compatible with a Messinian age.

MII synthem (late Messinian)

This synthem overlies an erosional surface modelled at the top of the T-MI synthem, called the intra-Messinian unconformity. This surface shows features of wide and shallow palaeovalleys in the north sector (Soria et al. 2005) and subaerial exposure, such as karstic breccias and caliche-like carbonate crusts, in the south sector (Soria et al. 2006). Thus, the intra-Messinian unconformity is identified as a lowstand erosional surface generated by a sea-level fall during the Messinian (see text-fig. 2 that both below and above the unconformity the MN13 rodent biozone -Messinian- has been identified). The MII synthem defines a tract of four depositional systems, composed (from proximal to distal) by: 1) alluvial mudstones and conglomerates; 2) brackish-water lagoon marls, containing *Chara sp, Cyprideis torosa* and *Ammonia tepida;* 3) beach sandstones (locally with stromatolites and oolitic grainstones); and 4) shallow marine evaporites. In this evaporitic system, episodes of precipitation of selenitic gypsum alternate with the deposition of sandy tempestites derived from marginal beaches of the marine basin. This synthem is interpreted as the record of a marine reflooding of the basin after the subaerial erosional phase that characterizes



TEXT-FIGURE 2
Stratigraphic framework for the Bajo Segura Basin during Messinian and Pliocene.

the intra-Messinian unconformity. The Messinian age for the MII synthem is supported by the presence of rodent fossils in the margin-lagoon marls (Alfaro et al. 1995; Martín Suárez and Freudenthal 1998), belonging to the MN13 biozone of Mein (1990)

P synthem (early Pliocene)

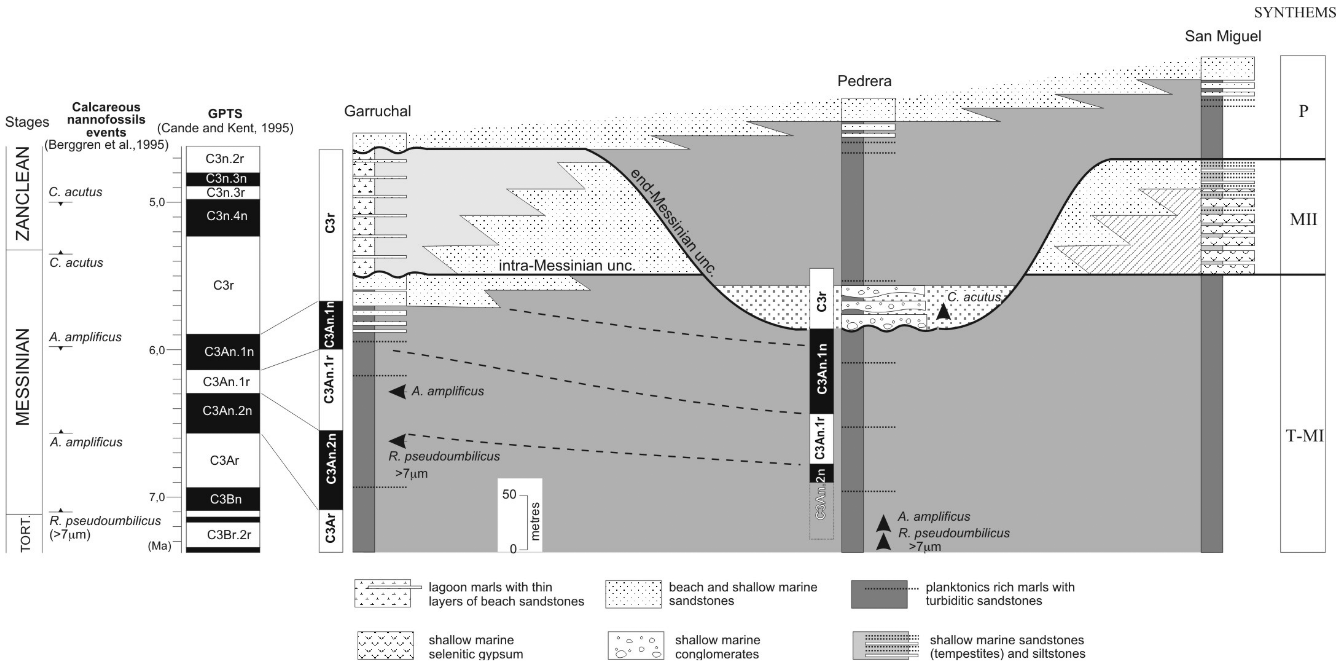
This synthem is separated from the previous one by an erosional surface called the end-Messinian unconformity. This surface shows features of incised palaeovalleys, both in the north sector (Caracuel et al. 2004; Soria et al. 2005) as well as in the south one (Soria et al. 2006). In this latter sector, the palaeovalley of the greatest proportions is exposed (200 m deep), this, over its trajectory, entirely eroding the MII synthem and the upper part of the T-MI synthem (text-fig. 2). Another noticeable feature of the end-Messinian unconformity is the presence of fluvial channels filled with sand and gravel (Soria et al. 2005), a feature that indicates not only its subaerial character but also its interpretation as a lowstand erosional surface. The P synthem is composed of four stacked depositional systems. The lower one forms an assemblage of conglomerates and sands located in the deepest part of the above-mentioned incised palaeovalleys. This assemblage was deposited into a shallow marine or coastal embayment, as a consequence of a marine flooding after the lowstand erosional phase that characterizes the end-Messinian unconformity. These basal conglomerates and sands of the P synthem evolved upwards towards a second depositional system dominated by marine marls rich in planktonic organisms, which indicates both a progressive deepening as well as the complete infilling of the incised palaeovalleys. Over these marine marls, two upper depositional systems (alluvial and coastal-shallow marine) prograded, reflecting the high sea-level context of the early Pliocene.

Previous data indicate an early Pliocene age for the P synthem. The first marine deposits that filled the palaeovalley located in the south sector have been assigned to the NN 12 (Lancis 1988) and *Globorotalia margaritae* (Montenat et al. 1990) biozones, both jointly being indicative of the Zanclean stage. The marine fill of the palaeovalley located in the north sector also occurred during the Zanclean, but somewhat later, as indicated by the NN13 and *Globororalia puncticulata* biozones. The end of the sedimentation of the P synthem, when the alluvial and coastal systems prograded, occurred also in the early Pliocene, as demonstrated by the presence of rodent fossils belonging to the MN14 biozone of Mein (1990) (Soria et al. 1996).

The three synthems differentiated in the Bajo Segura have a special significance in the Messinian and Pliocene stratigraphy of the Mediterranean marginal basins. The T-MI synthem characterizes the pre-evaporitic sedimentation, when in most marine basins marls, diatomites and sapropels accumulated. The MII synthem altogether reflects the Lago-Mare episode (brackish lagoon marls), the Terminal Carbonate Complex of Esteban (1979) (beach sandstones and stromatolites), and the evaporitic deposition (shallow marine gypsum). Finally, the P synthem, dominated by planktonic-rich marls, registers the open-marine sedimentation throughout the Mediterranean basin during the early Pliocene.

CHRONOLOGY OF THE MESSINIAN AND PLIOCENE EVENTS

To detail the chronology both of the synthems as well as of the above-mentioned unconformities, we performed a combined biostratigraphic (calcareous nannoplankton) and palaeomagnetic study in the Garruchal and Pedrera sections (text-fig. 3), using as a reference the calcareous nannofossil events scale of Berggren et al. (1995) together with the geomagnetic polarity timescale – GPTS – of Cande and Kent (1995). The FAD and LAD of two species – *Amaurolithus amplificus* and *Ceratolithus acutus* – served to identify the chrons of the GPTS. The species *A. amplificus* was found to be present in a normal zone within the T-MI synthem (lower part of Pedrera section), which corresponds to chron C3An.2n; also, this species was found in the upper part of the T - MI synthem (Garruchal section) in a reverse zone, for which the only possible assignment is chron C3An. 1r. Finally, *C. acutus,* a species that marks the beginning of the Pliocene (Zanclean stage), was recognized throughout the P synthem (Pedrera section) in coincidence with a reverse zone corresponding to the chron C3r.



TEXT-FIGURE 3
Biostratigraphic (calcareous nannoplankton) and palaeomagnetic combined study in the Garruchal and Pedrera sections (see location in text-figs. 1C and 2), indicating that both the intra-Messinian unconformity as well as the end-Messinian unconformity fit into the chron C3r.

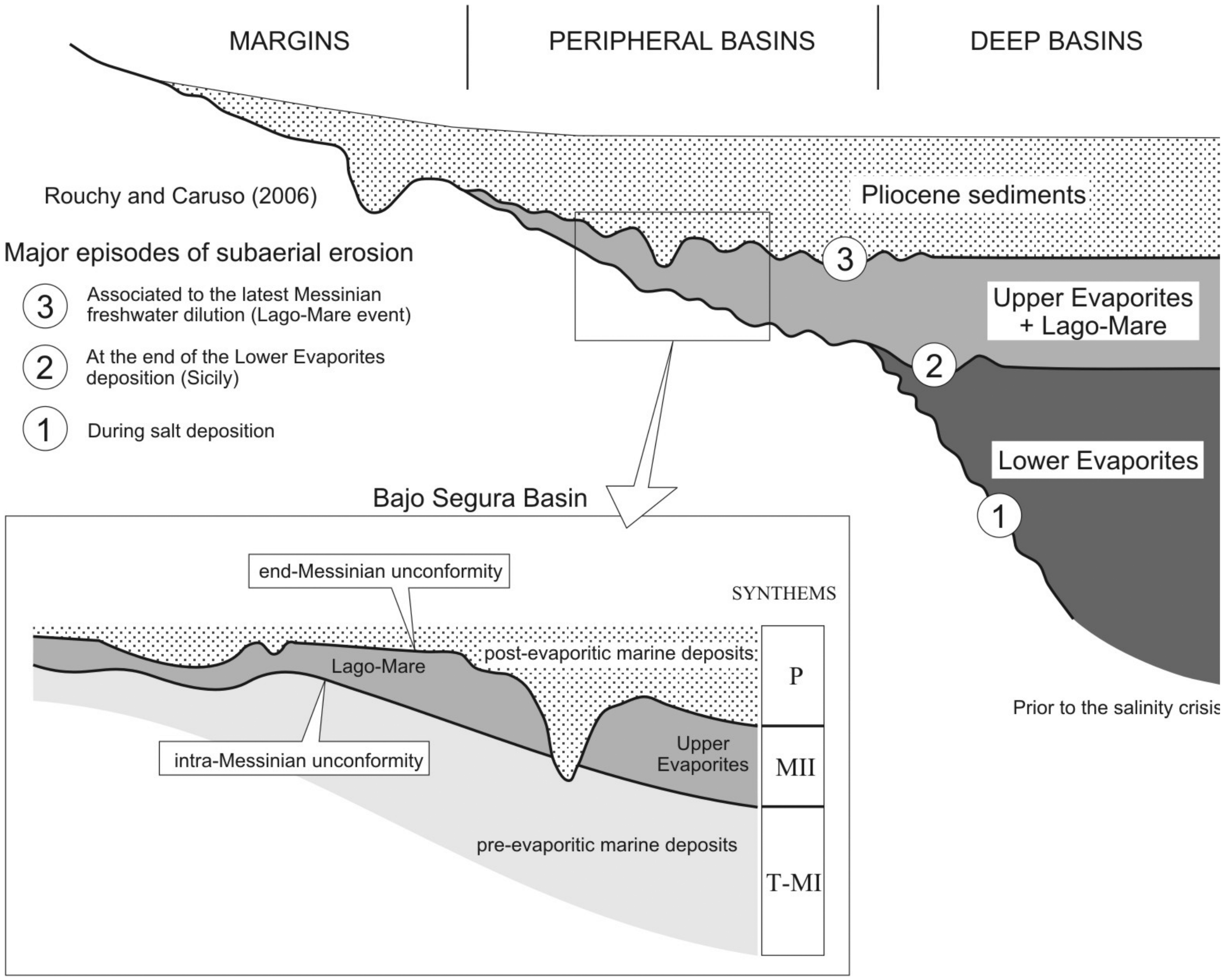
From this combined biostratigraphic and magnetostratigraphic study, it was found that both the end of the sedimentation of the T-MI synthem, as well as the two lowstand erosional surfaces (intra- and end-Messinian unconformities) and also the onset of the P synthem occurred in chron C3r (c. 5.9-5.2 Ma).

IMPLICATIONS FOR THE MEDITERRANEAN SALINITY CRISIS

The Mediterranean salinity crisis during the Messinian is a complex, multi-phased event (Rouchy and Caruso 2006) for which one of the principal manifestations is the accumulation of evaporites both in the central parts (abyssal plains) as well as in the marginal sectors (peripheral basins) of the Mediterranean. The existence of Messinian evaporites (gypsum and halite) in the centre of the Mediterranean (Nesteroff 1973; Hsü et al. 1973b; Friedman 1973) forces us to assume a lowstand sea-level context (desiccated deep basin; Hsü et al. 1973a; Hsü et al. 1973c) and, consequently, a subaerial erosional surface throughout the circum-Mediterranean area (Ryan and Cita 1978; Clauzon 1982).

Our stratigraphic model for the Bajo Segura Basin, a typical marginal basin of the Mediterranean, shows that the evaporites and the correlative deposits of the MII synthem, are bounded at the base and top by subaerial erosional surfaces (intra- and end-Messinian unconformities). The key question consists of ascertaining which of these two erosional surfaces represents the stage of evaporitic precipitation (desiccation) of the centre of the Mediterranean. In this regard, considering data of other authors outside the study area, we examine two alternatives. First, based on the model presented by Clauzon et al. (1996) for the correlation between the marginal basins (i.e. Sicily and Sorbas) and the central basins, is the contention that the major erosion and accumulation of abyssal evaporites occurred after the deposition of the marginal evaporites. This would imply, on the one hand, that our end-Messinian unconformity represents the salinity crisis in the centre of the Mediterranean, and, on the other, that the definitive reflooding and end of the crisis took place in the early Pliocene, coinciding with the Pliocene highstand phase documented in the Bajo Segura Basin. The second alternative, proposed by Riding et al. (1998, 1999) and Braga et al. (2006) in their study of the Sorbas Basin and other basins in the Almería area, posits that the greatest erosion occurred immediately prior to the precipitation of the marginal evaporites, demonstrated by the presence of an erosional surface (intra-Messinian erosion, according to these authors) that separates the pre-evaporitic marine deposits (Abad member) from the evaporites (Yesares Gypsum member). This second model implies that the reflooding of the Mediterranean is recorded by the marginal evaporites during the Messinian, before the Pliocene reflooding considered in the classical works on the Messinian salinity crisis (e.g. Hsü et al. 1977). This model can be applied to the Bajo Segura Basin, where the intra-Messinian unconformity has been documented as an erosional surface separating the pre-evaporitic deposits (T-MI synthem) from the syn-evaporitic and evaporitic deposits (MII synthem). Also, the Bajo Segura Basin could have withstood the Messinian reflooding (according to Riding et al. 1998 and 1999, and Braga et al. 2006), which would be registered by the deposition of the MII synthem in a high sea-level context.

The integrated scenario recently proposed by Rouchy and Caruso (2006) for the Mediterranean basin as a whole can be used to explain the existence of two erosional surfaces (intra- and end-Messinian unconformities) recognized in the Bajo



TEXT-FIGURE 4
Correspondence of the intra- and end-Messinian unconformities with the main erosional surfaces related to the Messinian salinity crisis in the Mediterranean basins (simplified from Rouchy and Caruso 2006).

Segura Basin (text-fig. 4). Under such a scenario, our intra-Messinian unconformity would be correlative with the two major events characterizing the Messinian salinity crisis in the centre (deep or abyssal basins) of the Mediterranean; one is the precipitation of the Lower Evaporites and the other is the erosional surface that separates the Lower Evaporites from the Upper Evaporites. This latter erosional event is classically considered as being the record of the extreme fall in sea level that provoked the drying of the Mediterranean (Hsü et al. 1973a). The end-Messinian unconformity, situated at the top of the evaporites and of the lagoon deposits grouped in the MII synthem, would fit with the erosional phase associated to the latest Messinian freshwater dilution (Lago-Mare event) recently proposed by Rouchy and Caruso (2006). According to these authors, as a result of this erosional event, the Upper Evaporites may have been completely removed and the Lower Evaporites themselves deeply affected. These features are surprisingly similar to those observed for the end-Messinian unconformity, whose main expression is the deeply incised palaeovalley that completely eroded, at certain points, the syn-evaporitic deposits of the MII synthem. It is worth pointing out that, according to our data, the erosional character of the end-Messinian unconformity is due to a major fall in the sea level, as an alternative to the freshwater dilution proposed by the aforementioned authors.

CONCLUSIONS

In the Bajo Segura Basin, we find the most significant events related to the Messinian salinity crisis in the marginal basins of the Mediterranean. Our study proposes the following series of events.

Pre-evaporitic (or pre-crisis) phase, registered by the sedimentation of the T-MI synthem in a high sea-level context.

First subaerial erosional phase corresponding to the intra-Messinian unconformity, indicating a sea-level fall that is recorded both by the carving of shallow palaeovalleys as well as by karstification processes and the precipitation of caliche-like carbonate crusts. Applying the model of Rouchy and Caruso (2006), this sea-level fall could be correlative with the beginning of the deposition of the Lower Evaporites during a high-aridity and glacial period.

Syn-evaporitic phase, represented by the MII synthem sedimentation, and which records a sea-level rise that culminates with the complete reflooding of the basin in a highstand context. This phase is characterized by the precipitation of selenitic gypsum under shallow marine conditions, coeval with coastal and lagoon deposits. According to the model in Rouchy and Caruso (2006), the gypsum and the widely developed lagoon deposits recognized in our MII synthem would correspond to the Upper Evaporites and the Lago-Mare episode, respectively, which characterized an interval of global warming and sea-level rise.

Second subaerial erosional phase, expressed by the end-Messinian unconformity and generated by the sea-level fall that gave rise to deeply incised palaeovalleys, which locally eroded the entire MII synthem. We do not know the significance that this phase has in relation to the evaporites deposited in the centre (abyssal plains) of the Mediterranean. This doubt will remain until the evaporitic suite of the central Mediterranean is completely recognized.

Post-evaporitic (or post-crisis) phase, recorded by the sedimentation of the P synthem. In an initial stage of sea-level rise, the deeply incised palaeovalleys were filled by coastal or shallow-marine deposits; in the next stage, which culminated in a high sea-level context, most of the basin registered open marine conditions.

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