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ORIGINAL PAPER

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Closure of a seaway: stratigraphic record and facies (Guadix basin, Southern Spain)

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Abstract During the late Tortonian (upper Miocene), the Guadix Basin in S Spain formed one of the Betic corridors that connected the Mediterranean Sea with the Atlantic Ocean. The closure of this connection occurred in a series of steps, documented by three sedimentary units. A lower unit, consisting of basinal marls, shallow-water calcarenites and sands records the formation of a wide seaway. During deposition of the following unit this narrowed to a strait no more than 2 km in wide, triggering an intensification of currents that caused migration of submarine dunes preserved as giant cross-beds in bioclastic sands and conglomerates. Current flowed from the Mediterranean to the Atlantic. The third unit constitutes the youngest marine episode of the filling of the Guadix Basin. At this stage, the connection between the Mediterranean Sea and the Atlantic Ocean was broken, and a system of coastal coral reefs was established in the northern part of the Basin.

Keywords Seaway · Betic corridors · Giant cross-beds · Miocene · Tortonian

Introduction

Seaways are narrow corridors connecting marine basins. During the Miocene, the link between the Mediterranean Sea and the world ocean was reduced to a few seaways in the eastern and western Mediterranean. After the closure of the Indopacific connections, probably during the late early Miocene (Rögl 1998; Harzhauser et al. 2002), increasing restriction culminated in the isolation of the Mediterranean basin and its final desiccation in the Messinian (Hsü et al. 1977; Riding et al. 1998), around 5.96–5.7 Ma ago (Gautier et al. 1994; Clauzon et al. 1996; Krijgsman et al. 1999a). The recent connection of the Mediterranean Sea with the Atlantic Ocean through the Straits of Gibraltar formed after the Messinian Salinity Crisis (Comas et al. 1999). Prior to the evaporite formation, the Mediterranean Sea and the Atlantic Ocean were connected through a series of corridors in southern Iberia (Betic corridors) and north Africa (Rifian corridors) (Esteban et al. 1996). During the late Tortonian, the connection of the oceans in southern Iberia was mainly through the Granada and the Guadix basins (Esteban et al. 1996; Soria et al. 1999) (Fig. 1). Only one corridor, the Guadalhorce Strait, persisted during the early Messinian (Martín et al. 2001).

Using outcrop data from the Guadix Basin we demonstrate that large-scale cross-beds, previously interpreted as the result of platform margin progradation (Soria 1994; Soria et al. 1999), were in fact generated by strong, Atlantic-directed bottom currents. New stratigraphic and micropalaeontological data suggest that the Mediterranean to Atlantic connection through the Guadix Seaway closed at 7.8 Ma at the latest. The fill of the northern margin of the Guadix Basin provides an example of hitherto poorly known stratigraphic sequences of seaways.

Geological setting and stratigraphy

The Guadix Basin lies at the contact between the Internal and External Zones of the Betic Cordillera in Southern Spain. Coarse- and fine-grained late Tortonian marine siliciclastic and carbonate rocks occur as a series of laterally discontinuous exposures in a W–E trending, 20-km long strip along the northern margin of the basin (Fig. 2). The upper Tortonian rocks lie unconformably on a Mesozoic to middle Miocene substrate (Soria 1994; Fernández and Guerra Merchán 1996) and are overlain by continental deposits (Soria 1994; García-Aguilar and

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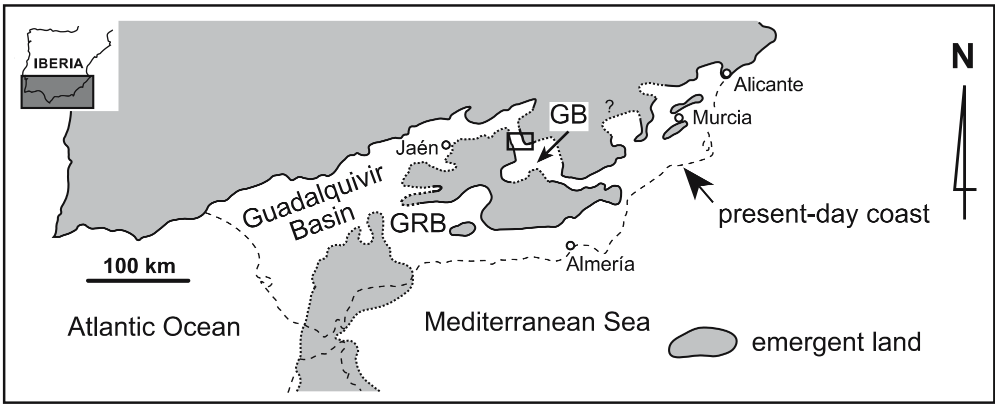
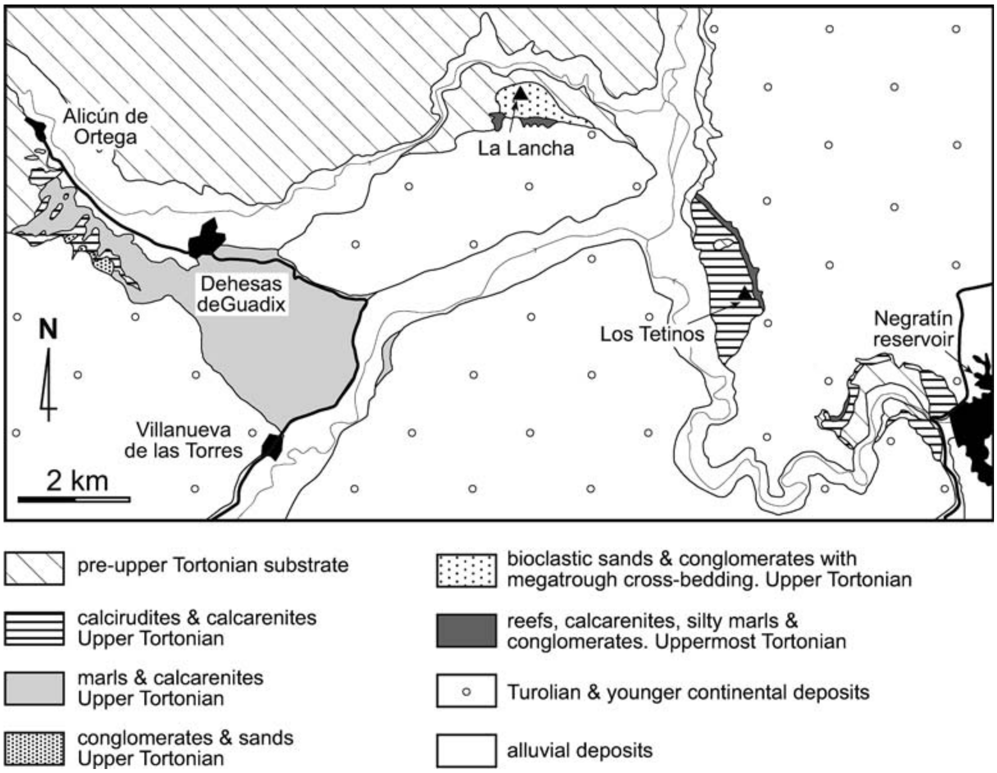


Fig. 1 Palaeogeography of southern Iberia during the Late Tortonian. In the Iberian Peninsula, the connection between the Mediterranean and the Atlantic was through the Guadix and Granada basins. *GB* Guadix Basin; *GRB* Granada Basin

Fig. 2 Geological map of the Guadix seaway area indicating the position of the localities discussed in the text



Martín 2000). Soria (1994) and Soria et al. (1999) proposed that the late Miocene marine sediments were deposited in a seaway connecting the Mediterranean Sea with the Atlantic Guadalquivir Basin. The seaway deposits were subdivided into a series of depositional systems ranging from littoral sands and gravels and deltaic conglomerates to platform carbonates with coral reefs that interfinger basinwards with marls and silty marls (Soria et al. 1999).

However, the occurrence of unconformities and distinct planktonic foraminiferal assemblages indicates that deposits that were previously interpreted as time-equivalent (Soria et al. 1999) in fact formed at distinct stages of basin evolution. The upper Tortonian of the northern margin of the Guadix Basin comprises three unconformity-bounded depositional units (Fig. 3).

Sediments and sequence

Unit 1: bioclastic carbonates and siliciclastics

The lower part of Unit 1 consists of bioclastic sands and conglomerates (calcarenites and calcirudites) unconformably overlying a Mesozoic to middle Miocene substrate. Deposits are a maximum of 60 m thick and wedge-out laterally. The variations in thickness result from the filling of a palaeo-relief, indicated by onlaps in

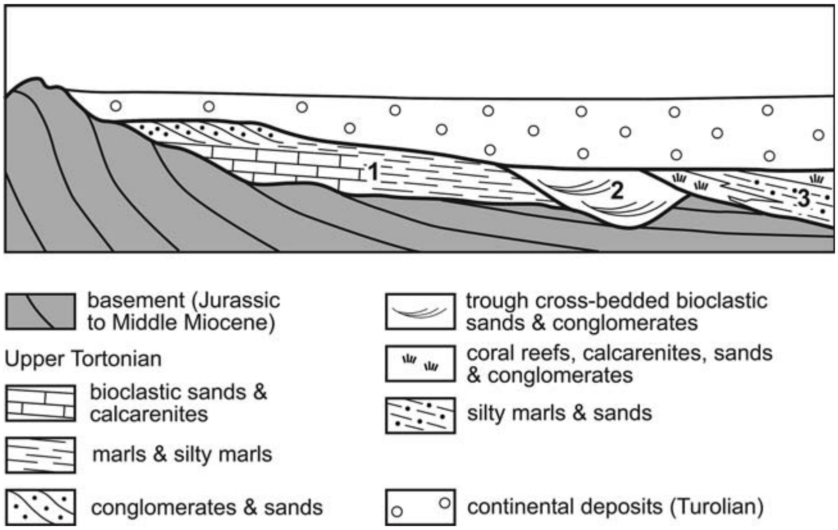


Fig. 3 Stratigraphy of the Upper Tortonian in the Guadix Basin. 1–3 refer to units discussed in the text

the areas west of the Negratin reservoir and of Dehesas de Guadix. Bioclasts consist mainly of bryozoan, mollusc, and brachiopod fragments. The bedding is tabular, with local small to medium-sized cross-beds. These rocks interpreted as platform deposits grade laterally to marls and silty marls with planktonic foraminifers that date Unit 1 between 8.5 Ma (FAD *Neogloboquadrina humerosa*) and 7.8 Ma old (FAD *Globorotalia suterae*).

The upper part of Unit 1, cropping out between Alicún de Ortega and Dehesas de Guadix (Fig. 2), consists of conglomerates and sandstones up to 50 m thick, formed on a Gilbert-type delta (Soria et al. 2003).

Unit 2: giant cross-bedded unit

Unit 2 deposits with giant trough cross-beds (Fig. 4) are a mixture of calcarenites, calcirudites, sandstones, microconglomerates and conglomerates. These unconformably overlie middle Miocene and older marls and marlstones. The unconformity surface is irregular, with erosive incisions cutting more than 2 m into the underlying marls and marlstones (Fig. 5a). Clasts of reworked marlstone, up to 50 cm in diameter, heavily bored by *Lithophaga*, float in a sandstone to microconglomeratic matrix in the lower part of the deposits (Fig. 5b). Smaller (less than 4 cm) polymict clasts occurring throughout the unit consist of fragments of Mesozoic and Cenozoic rocks from the underlying substrate and metamorphic rocks from the Betic basement cropping out at the southern margin of the Guadix Basin. Some of these also contain *Lithophaga* borings. Marine fossils, such as bivalves, brachiopods, and bryozoans, comprise up to 30% of the rocks.

Unit 2 rocks crop out only in the area around the hillock of the La Lancha, extending up to 2 km laterally. Giant cross-beds are well exposed on the western and eastern flanks of the hillock (Fig. 4). Tangential, concave-up cross-beds dip at up to 15° and form compound sets (sensu Anastas et al. 1997) up to 15 m high and

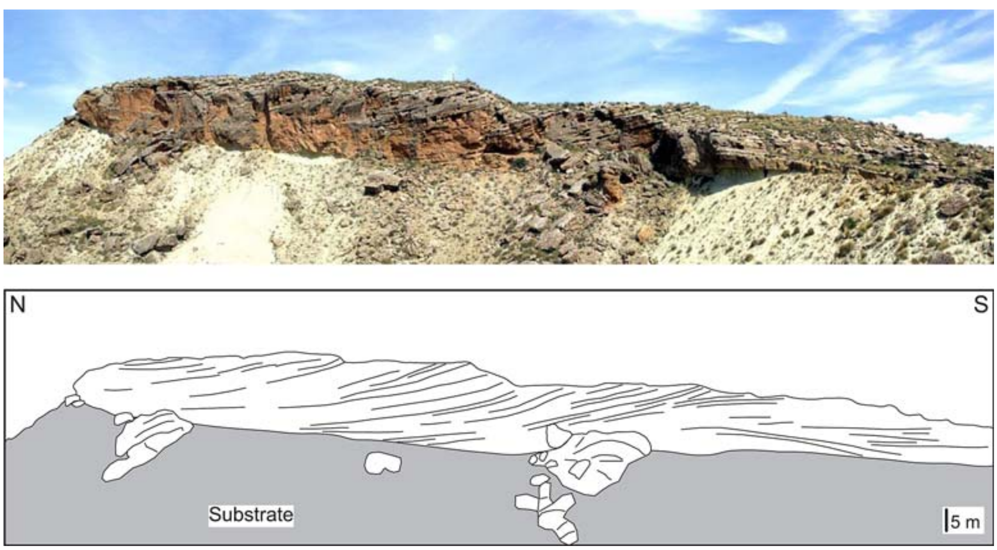


Fig. 4 View of the giant cross-beds at the La Lancha outcrop. Bioclastic sandstones and microconglomerates unconformably overlie middle Miocene marls

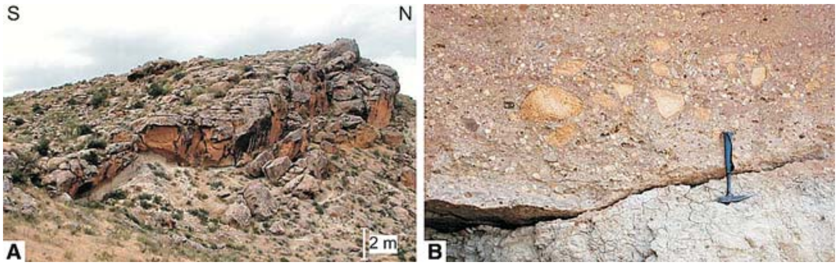


Fig. 5 **a** View of the erosive base of the giant cross-bedded unit (eastern side of the La Lancha outcrop). **b** View of the lithology in the lower part of the giant cross-bedded unit, just above the basal unconformity. *Light-colored* boulders consist of reworked marlstones. Outcrop is located on the eastern side of the La Lancha hillock

more than 70 m long. A view perpendicular to the main direction of progradation of the bodies (Fig. 6) reveals that they are trough cross-bedded with palaeocurrent directions towards the north.

Unit 3: reef and related deposits

The youngest marine Tortonian unit is restricted to the eastern part of the study area. The deposits unconformably rest on the giant trough cross-bedded rocks of Unit 2 (the La Lancha hillock) and on the calcarenites of Unit 1 (the Los Tetinos hillock) (Fig. 2).

At the La Lancha locality, the unit consists of a coral reef wedge with clinoforms prograding to the SE (Fig. 7). The most abundant corals are *Porites* and *Tarbellastrea*. The surface of the unconformity at the base of the wedge is locally iron-stained. In some places up to 1.5 m large boulders of sandstones and conglomerates from Unit 2, together with clasts of marlstone occur above the unconformity mixed with pebbles of phyllite, quartzite, marble and dolostone, also reworked from Unit 2 conglomerates beneath. Sandstone and conglomerate boulders are locally encrusted and overgrown by corals (Fig. 8). Basinwards, these coarse-grained carbonate clinoforms grade into calcarenites and sands and then into fine-grained calcarenites/sands and silty marls. Planktonic foraminiferal assemblages in the silty marls indicate that these reefal deposits are between 7.8 Ma (FAD *Globorotalia suterae*) and 7.4 Ma old (PF event 1 according to Sierro et al. 1993; occurrence of *Globorotalia menardii* Group 2).

At Los Tetinos outcrop, Unit 3 deposits consist of a conglomerate a few decimeters thick with small, dispersed coral fragments. West of the Negratin reservoir, Unit 3 deposits comprise a thin calcarenite interval with marine bivalves (*Pecten* and the oyster *Crassostrea gryphoides*).

The reef unit is overlain by Turolian continental deposits with a conglomerate up to 1.5 m thick containing scattered coral debris together with abundant continental gastropods (*Sphincterochila* spp.).

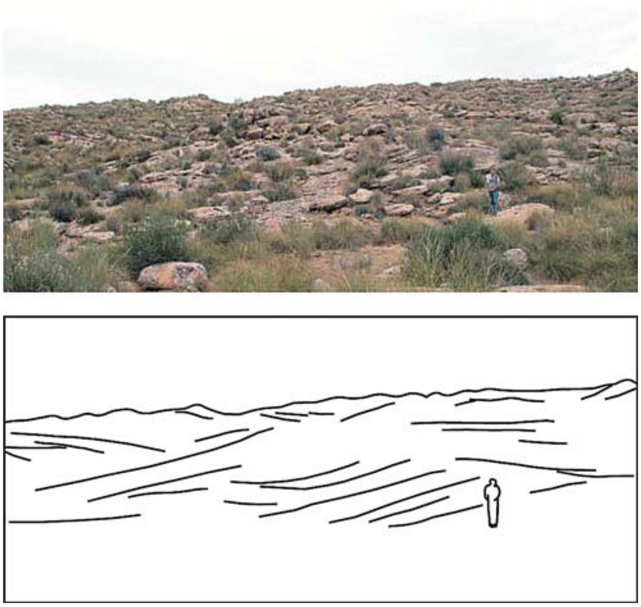


Fig. 6 View perpendicular to the main direction of progradation of the large-scale giant trough cross-bedded bodies. Person for scale

Interpretation

During the Tortonian an important connecting route between the Mediterranean Sea and the Atlantic Ocean was through the northern part of the Guadix Basin, via the Guadalquivir Basin (see Fig. 1). The subdivision of the deposits of the northern margin of the Guadix Basin fill into three unconformity-bounded packages. The distinctive facies arrays of the different units, the differences in the palaeogeographic extension of the deposits, as well as the shifting depocenters, indicate, as shown below, that the connection between the Guadix Basin and the Guadalquivir Basin underwent a gradual closure culminating in a complete separation of Atlantic and Mediterranean waters.

Unit 1 deposits formed in an open-marine corridor with a delta system prograding from the southwestern basin flank (Soria et al. 2003). Deposits along the basin margins are coarser-grained carbonates and mixed siliciclastic carbonate sediments, whereas distal and deeper-water deposits are finer grained. The Guadix Basin was connected to the Atlantic through the

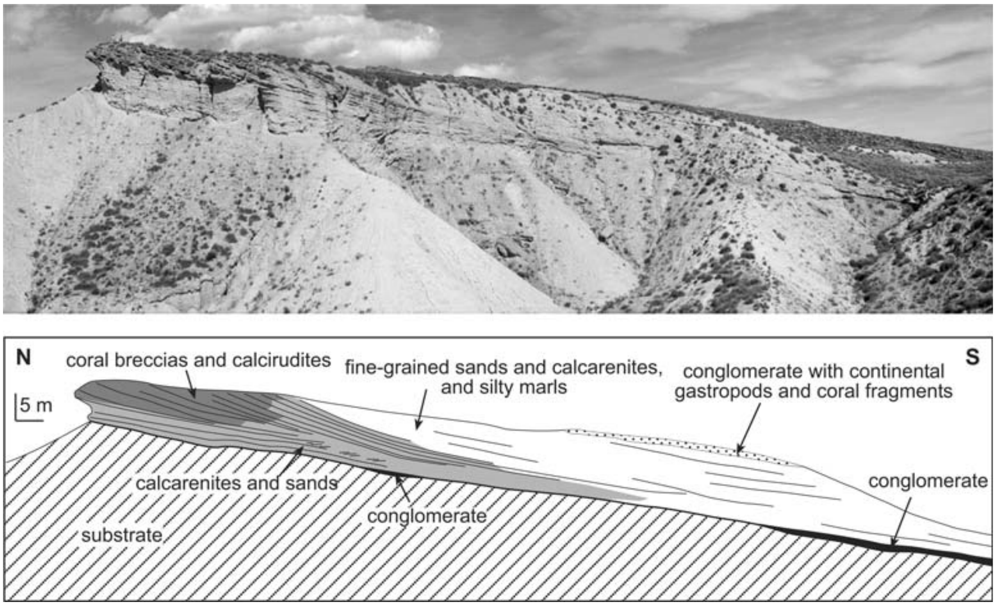


Fig. 7 Reef clinoforms prograding to the south on the southeastern margin of the La Lancha outcrop. The conglomerate on top records the initial stages of continental sedimentation in the area

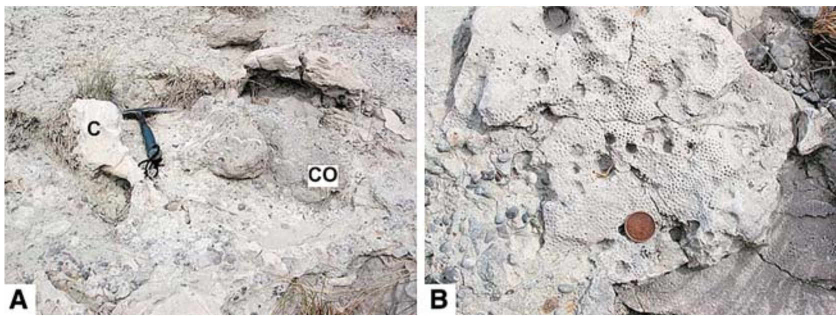


Fig. 8 **a** Conglomerate of Unit 2 (*CO*) with boulders encrusted and overgrown by corals (*C*) (western side of the La Lancha outcrop). **b** Detail of coral crusts

Guadalquivir Basin to the north. Lack of major sedimentary structures indicates that there were no significant bottom currents in this strait at that time.

A palaeocoastline for this stage of the basin evolution can be traced using the distribution of coarser- and finer-grained sediments, and the location of onlap relationships (Fig. 9a). The western limit of the strait was a roughly NNW–SSE coastline, whereas the eastern flank ran NNW–SSE in the northern section swinging to W–E in the area of the Negratín reservoir.

The giant trough cross-bedded deposits of Unit 2, with pebble size clasts, are the result of the migration of submarine dunes under a strong, persistent northward-directed current. This indicates that bottom-water masses in the strait flowed from the Mediterranean Sea into the Atlantic Ocean. According to Anastas et al. (1997), a water depth range for the formation of such dunes can be estimated using the maximum set thickness of compound bodies because, in Recent marine environments, dune height (H) is approximately related to water depth (D) by $H = 0.17$ D. Applying this formula to the thickness of the giant cross-beds allows an estimation of the palaeo water-depth of around 90 m.

Recent large-scale submarine dunes, comparable in size and form to the La Lancha giant cross-bedded bodies and with similar grain sizes, are known to form under current velocities of 0.7–3.0 m/s (Belderson et al. 1982; Nelson et al. 1993; Ramsay et al. 1996; Berné et al. 1998). The lack of reactivation surfaces, sigmoidal bedding, herringbone cross-bedding and mud drapes most likely counters a control of the dunes by tidal currents. All of the sedimentary structures in the giant cross-bedded unit are unidirectional and indicate a northward flow of bottom currents. Similar current velocities of the Mediterranean Outflow Water (MOW) nowadays cause the formation of submarine dunes in the Gulf of Cadiz. Having passed through the Straits of Gibraltar, the MOW flows westwards at a speed of >2 m/s (Ambar and Howe 1979) and progressively decelerates, turning north into the Gulf of Cadiz. In the gulf, compound sand dunes 10 m high with 75 m wavelength develop within a valley on the submarine slope affected by the outflowing Mediterranean undercurrent at velocities of 0.8 m/s (Nelson et al. 1993). It is uncertain whether there was any water mass stratification in the Tortonian seaway during the deposition of Unit 2 sediments, with contrasting flow patterns in the shallower part of the water column.

A palaeogeographic reconstruction of the Guadix seaway at the time of deposition of the giant cross-beds

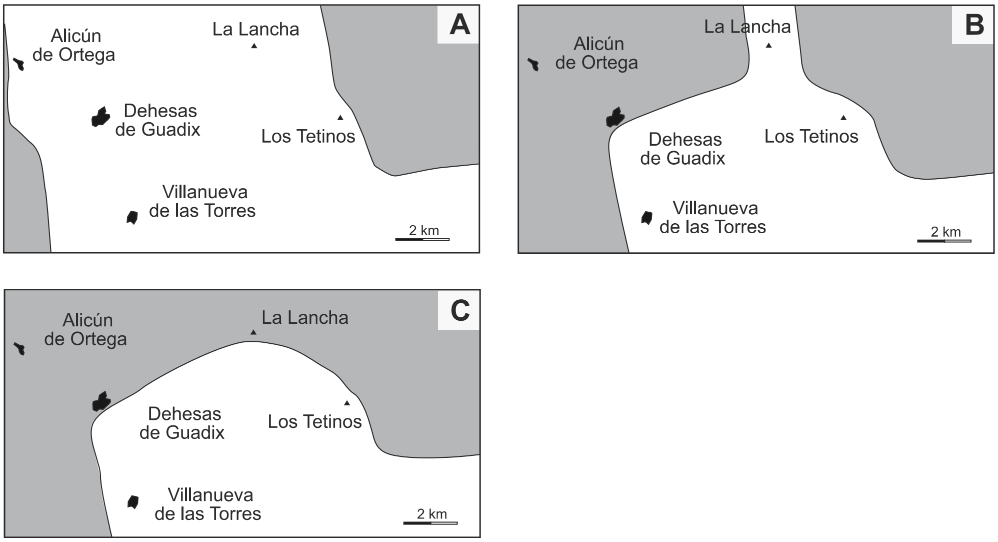


Fig. 9 Palaeogeographic reconstructions of the Guadix Seaway with positions of the localities referred to in the text. **a** Unit 1; **b** Unit 2; **c** Unit 3

is shown in Fig. 9b. Whereas, the eastern coastline of the seaway remained largely unchanged from its original position, uplift along the western flank led to an eastward displacement of the coastline. This shift resulted in a narrowing of the strait to approximately 2 km in the area around La Lancha.

The unconformity separating Units 2 and 3 reflects a profound re-organization of the Guadix Basin. Sediment thickness and lithofacies trends in Unit 3 reveal a roughly E–W trending coast, rimmed by coral reefs, during deposition of these youngest marine deposits. Reef clinoform dips attest to an S–SE deepening.

The palaeogeographic reconstruction of the Guadix Basin during this youngest episode of marine sedimentation is shown in Fig. 9c. At this stage, the connection between the Atlantic and the Mediterranean was shut down due to uplift of the area previously occupied by the seaway and the Guadix Basin was under sole Mediterranean influence.

Discussion

A stepwise reduction of the Atlantic–Mediterranean connection has been deduced from changes in Mediterranean pelagic benthic foraminiferal assemblages during the late Tortonian. Changes in bottom-water oxygenation related to decreased and unstable circulation began at 8.5 Ma (Seidenkrantz et al. 2000), and between 7.9 and 7.6 Ma the oxygen level dropped even further (Seidenkrantz et al. 2000; Kouwenhoven et al. 2003). After 7.6 Ma, improved oxygenation of Mediterranean bottom waters indicates a return to normal marine conditions (Seidenkrantz et al. 2000). At 7.2 Ma, during the earliest Messinian, a severe phase of disturbance affected the Mediterranean deep sea prior to the development of the Messinian Salinity Crisis (Kouwenhoven et al. 2003).

We propose that the evolution of the Guadix Seaway played a major role in this palaeo-oceanographic evolution. Straits and seaways connecting the Mediterranean Sea and the Atlantic Ocean in pre-Messinian times were tectonically controlled, relatively short-lived features. The opening or closure of these gates regulated circulation in the marginal Mediterranean Sea. For the Messinian, Benson (1991) proposed a "siphon" model with Atlantic inflow through the Rifian corridors (northern Morocco) and outflow through the Betic Strait (southern Iberian Peninsula). This view has been in part revised by Martín et al. (2001), who showed that during the early Messinian the Mediterranean outflow was through a narrow gateway located north of Malaga, the Guadalhorce Gateway. Closure of this gateway coincided with the onset of stratification of western Mediterranean water contemporaneous with the initiation of reef platform development in the Betic realm (Martín et al. 2001).

The upper Tortonian circulation pattern between the Atlantic and the Mediterranean Sea is less well known. The Guadalhorce Gateway existed between 7.2 and 6.3 Ma (Martín et al. 2001), and is thus younger than the Guadix Seaway. During the late Tortonian, Atlantic–Mediterranean connections in the Betic region were in the Guadix Seaway and, probably, the northwestern side of the Granada Basin (Braga et al. 1990; Esteban et al. 1996) (Fig. 1). The flooding of the Rifian corridors is dated at around 8 Ma, and maximum water depths in these passages occurred at 7.6 Ma (Krijgsman et al. 1999b; Barbieri and Ori 2000).

The major late Tortonian palaeo-oceanographic event was the decreasing bottom-water oxygenation between 8.5 and 7.6 Ma. It coincides with the narrowing and closure of the Guadix Seaway. No data are available for the date of the closure of the Mediterranean–Atlantic connection through the Granada Basin. However, a latest Tortonian earliest Messinian closure of this passage is indicated by a change from open-marine sedimentation to gypsum formation (Martín et al. 1984; Braga et al. 1990). This change was probably roughly coincident with, or slightly younger than the closure of the Guadix Seaway.

The water volume flowing through the Guadix Seaway for the time of the giant cross-bedded unit formation is roughly 0.145 km^3/s. This figure is based on the assumption of an approximately 2 km wide seaway (Fig. 9b), a water depth of 90 m, and current speeds of around 0.8 m/s. However, a greater water depth, and therefore a higher outflow rate cannot be discounted with our data. Throughflow during deposition of the sediments of Unit 1 was probably higher, as the strait was broader, and likely deeper. As a comparison, recent Strait of Gibraltar throughflow is 1.75 km^3/s (Pickard and Emery 1990).

The 7.6 Ma return to better oxygenation in the Mediterranean deep sea seems to correlate with the maximum flooding of the marine passages in Morocco (Krijgsman et al. 1999b; Barbieri and Ori 2000). Had there been any seaway in the Betic region at this time, it would have been at the northwestern end of the Granada Basin.

These results and previous data on the Atlantic–Mediterranean connections through the Betic corridors (Esteban et al. 1996; Martín et al. 2001) imply that circulation models for the Tortonian palaeo-oceanography of the Mediterranean must be re-evaluated or even corrected. For example, Meijer et al. (2004) propose a model of late Miocene circulation of the Mediterranean, an influx of Atlantic water in an 8 Ma old broad "Betic Strait" at a depth of 30 m, and outflow of Mediterranean water in the same strait, at a depth of 280 m. This, however, is a much larger outflow volume than suggested by outcrop data.

Ancient seaways may be mistaken for portions of open-marine shelf environments as both may show an array of platform to basin facies, such as occurs in Unit 1 deposits in the Guadix Basin. Similar facies also characterize most of the Rifian corridors (Barbieri and Ori 2000). Only when a strait narrows and water flow concentrates in a small section, do the lithofacies and sedimentary structures become characteristic (Unit 2). Only a narrow strait is therefore able to leave an unequivocal record of an ancient seaway.

Conclusions

During the Late Miocene, between 8.5 and 7.8 Ma, the Guadix Basin was one of the Iberian seaways connecting the Mediterranean and the Atlantic. The sedimentary sequence in the northern part of the basin allows the reconstruction of the current regime in the strait and documents the stepwise closure of this connection. During the initial stage, marls and calcarenites were deposited in a seaway more than 11 km wide. As this narrowed to around 2 km, with a depth of approximately 90 m, the flow of the Atlantic Ocean-directed bottom currents accelerated. High flow rates are indicated by northward migrating bioclastic sand and microconglomerate dunes (cross-beds) up to 15 m high and with a wavelength of 70 m. Ages derived from planktonic foraminifers indicate that the Guadix seaway desiccated at around 7.8 Ma. Coral reefs dated at 7.8–7.4 Ma fringed a swell in the former position of the seaway. The initiation of coral reef growth is interpreted as reflecting the formation of a warm-water pool in the Guadix Basin. The sequence of progressive flow restriction and later disruption can be linked to palaeo-oceanographic events in the pelagic and hemipelagic record in the Mediterranean.

This new interpretation of the sedimentary succession of the Guadix Seaway is relevant not only relevant for reconstructing the late Miocene Mediterranean–Atlantic connections in the Iberian peninsula, but also provides a superbly exposed example of the poorly known sediment associations of seaways. From a sedimentological examination alone such deposits may be mistaken for open-shelf sediments, and the giant cross-beds may be misinterpreted as prograding bank or platform edge deposits if there is only limited outcrop information at hand, or if the interpretation has to rely on subsurface data such as seismics.

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