The Messinian Guadalhorce corridor: the last northern, Atlantic–Mediterranean gateway

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ABSTRACT

Messinian marine deposits of the Guadalhorce River valley in southern Spain record evidence of the last northern gateway that existed between the Mediterranean and the Atlantic. They comprise sandstones and conglomerates with unidirectional cross-bed sets up to nearly 1 km long in their down-sedimentary-dip direction. These cross-bed sets relate to extremely fast (1.0–1.5 m s^{-1}) bottom currents flowing from the Mediterranean into the Atlantic. The Guadalhorce gateway (which had a maximum width of 5 km and a maximum water depth of 120 m) was an important element controlling the Messinian pre-evaporitic oceanic circulation in the Mediterranean Sea, as it acted as a major outflow channel. Its closure limited the exchange of water between the Atlantic and the Mediterranean to the Rifian corridors of Morocco, inducing water-mass restriction and stratification in the western Mediterranean immediately prior to the 'Messinian Salinity Crisis'.

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Introduction

Gateways are narrow passages that connect oceans and serve as pathways for water-mass exchanges (e.g. Hay, 1996). Plate Tectonics controls the position of gateways, although minor tectonic events may open or close them.

The present-day Atlantic–Mediterranean connection is through the Straits of Gibraltar. This passage is the only natural link of the Mediterranean Sea with the world's oceans. The Straits of Gibraltar is a Pliocene structure (Comas *et al.*, 1999), which formed after the 'Messinian Salinity Crisis'. This episode of evaporitic drawdown of the Mediterranean Sea (Hsü *et al.*, 1977), which started at around 6 Ma (Riding *et al.*, 1998), is believed to have been triggered by the isolation of this sea from the world's oceans, by a combination of global sea-level lowering and tectonic uplift closing the Mediterranean-Atlantic connection. Prior to the Messinian (7.2–5.3 Ma), the Mediterranean was connected to the Atlantic Ocean via several Iberian and north African gateways (Esteban *et al.*, 1996). The Iberian seaways, which existed in the area of the Betic Cordillera (southern Spain), became progressively reduced in number and extent by middle-to-late Miocene tectonics, with the last surviving gateway occurring during the early Messinian north-west of Málaga in the region of the Guadalhorce River valley. The Guadalhorce gateway provided a significant control on Messinian pre-evaporitic oceanic circulation in the Mediterranean Sea: it acted as a major outflow channel of Mediterranean water into the Atlantic and its closure induced water-mass restriction and stratification in the western Mediterranean, immediately prior to the 'Messinian Salinity Crisis'.

Geological setting

Horizontal to gently dipping layers of Upper Miocene sediments in the Guadalhorce River valley occur as discontinuous but closely spaced exposures within a N–S belt some 30 km in length (Figs 1 and 2). This succession rests unconformably on a deeply eroded Palaeozoic-to-Lower Miocene basement palaeorelief (Martín-Algarra, 1987; López-Garrido and Sanz de Galdeano, 1999). Orueta (1917) first proposed that these sediments represent the remnants of a Miocene strait connecting the Mediterranean Málaga Basin to the south with the Atlantic Guadalquivir Basin to the north. Subsequent researchers have agreed with Orueta's interpretation and attributed an upper Tortonian age to these deposits on the basis of regional lithostratigraphic correla-

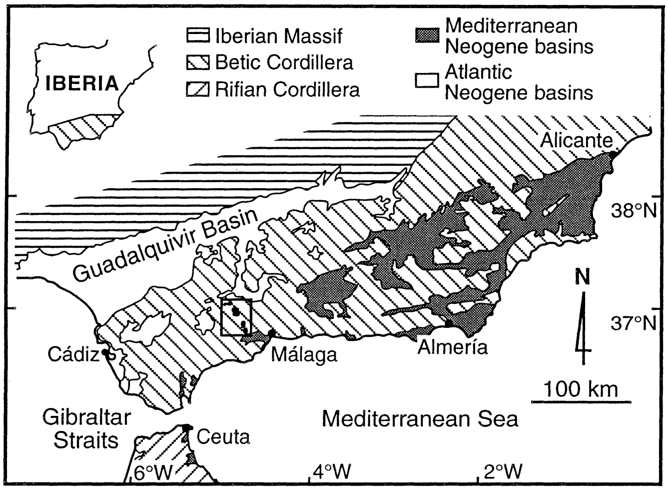

Fig. 1 Geographical and geological setting of the Guadalhorce corridor. Box marks its precise location.

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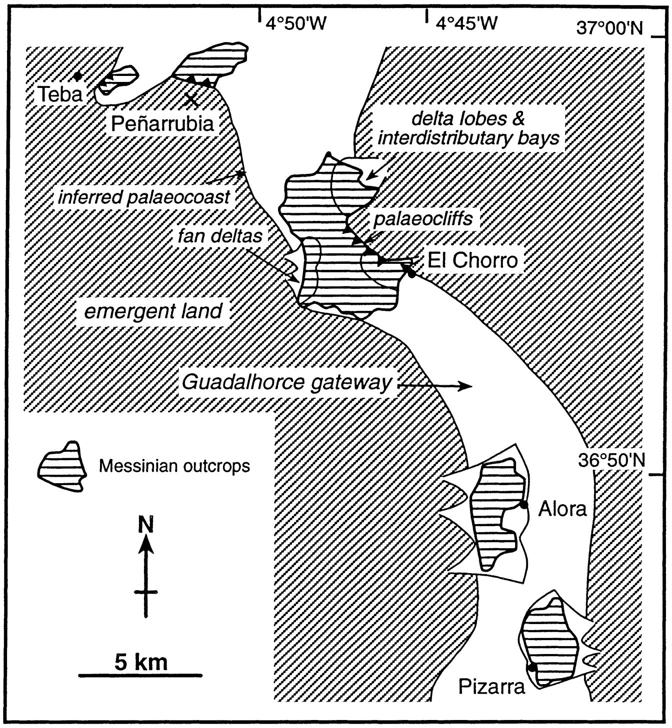

Fig. 2 Geological map and palaeogeographical reconstruction of the Guadalhorce gateway, showing the location of the Teba, Peñarrubia, El Chorro, Alora, and Pizarra exposures.

tions (Rodríguez-Fernández, 1982; López-Garrido and Sanz de Galdeano, 1991, 1999). However, the occurrence of the planktonic foraminifera *Globoratalia* gr. *miotumida*, including *Globorotalia conomiozea*, together with sinistral *Neogloboquadrina acostaensis*, within marls intercalated with carbonates in the northernmost outcrop (Peñarrubia exposures; see Fig. 2), indicates an early Messinian age (i.e. 7.2–6.3 Myr old) for the sediments of the Guadalhorce gateway.

The Guadalhorce gateway was the result of NW- and NE-trending cross-cutting faults that produced structurally depressed, linear depocentres. Significant normal dip-slip movements (with vertical displacements of up to 1 km) developed along these faults that reflect E–W crustal extension. The eventual closure of the Guadalhorce corridor was a consequence of tectonic uplift (López-Garrido and Sanz de Galdeano, 1999).

Lithology and sequence

The Upper Miocene of the Guadalhorce River valley consists mostly of siliciclastics that locally include carbonate and mixed siliciclastic-carbonate sediments. In northernmost exposures near Teba and Peñarrubia (Fig. 2), bioclastic carbonates and mixed siliciclastic-carbonate sediments occur intercalated with marls that onlap a steeply dipping, Jurassic-substrate palaeorelief. Limestone palaeocliffs exhibit borings by bivalves and sponges. Bioclasts within the Miocene carbonates consist of fragments of bryozoans, coralline algae and bivalves, together with lesser amounts of foraminifers, barnacles, echinoids and solitary corals.

The thickest and best-preserved part of the gateway record (stratal thickness, around 400 m) is found in the El Chorro exposure (Fig. 3). Matrix-supported, boulder-bearing, channelized debris-flow conglomerates (single channel-infilling deposits < 3 m thick), changing laterally to lobate (some tens of metres in lateral extent and < 2 m thick) debris-flow conglomerates alternating with sands, occur at the bottom of the sequence at the southeastern and southwestern margins of the outcrop. Some conglomerate clasts exhibit *Lithophaga* borings. Sand layers (up to a few metres thick) contain shallow-marine fossil remains (mostly bivalves). In the centre of the exposure, cross-bedded sands and microconglomerates (ranging in size from granules to pebbles), around 300 m thick, with bioclasts

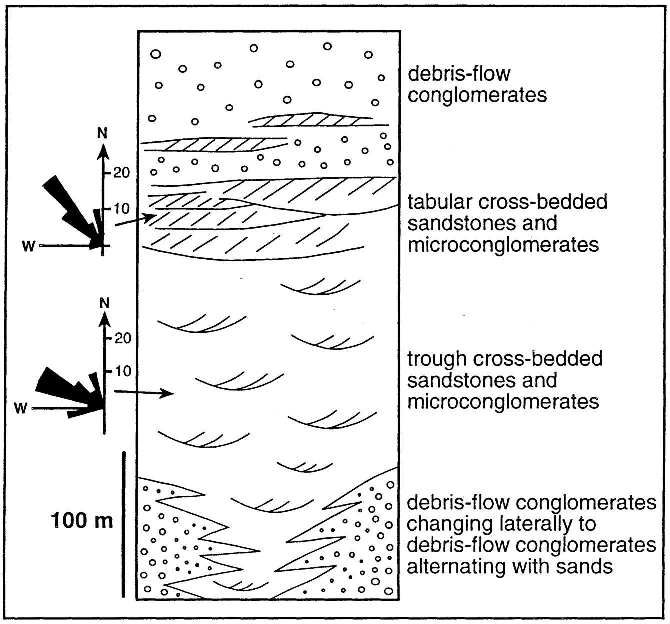

Fig. 3 Stratigraphic scheme of the El Chorro exposure. Palaeocurrent indicators at the left are for the lower and upper intervals of the sandstone/microconglomerate succession, exhibiting large-scale, trough cross-bedding and tabular cross-bedding, respectively.

comprising less than 20% of the grains, occur at the base of the section. These sediments become ubiquitous in the middle part of the sequence. All of these deposits are overlain by matrix-supported, boulder-bearing, debris-flow conglomerates (Fig. 3).

At the northeastern margin of the El Chorro outcrop, channelized, clast-supported (particles up to cobble in size) conglomerates occur. They intercalate with silts and grade laterally to sands with marine fossils. In the southernmost exposures near Alora and Pizarra (Fig. 2), sandstones and debris-flow conglomerates are the most common lithic varieties, with minor bioclasts comprising less than 5% of the rock.

Large-scale sedimentary structures

The ~ 300 m-thick sandstones and microconglomerates comprising the basal and middle part of the sedimentary sequence in the centre of the El Chorro outcrop (Fig. 3) exhibit large-scale sedimentary structures (Fig. 4). Differences in the sedimentary structures divide the sandstone/microconglomerate body into a lower interval and an upper interval. In the lower interval, sets of trough-cross-beds 10–20 m thick and < 100 m long, with irregular boundary surfaces, are ubiquitous. In contrast, persistent sets of tabular cross-bedding, up to 800 m in set length and 30 m in set thickness (Fig. 5), with laterally extensive, gently upward-curved boundary surfaces, occur in the upper interval. Palaeocurrent determinations made on both the lower and upper intervals indicate a northwestward flow, parallel to the margins of the gateway (Fig. 3). Despite the very significant set sizes and the extent to which the sets can be traced downcurrent, no reactivation surfaces have been identified within the cross-bedding, except for a few located in the upper part of the tabular cross-bedded interval (Fig. 4).

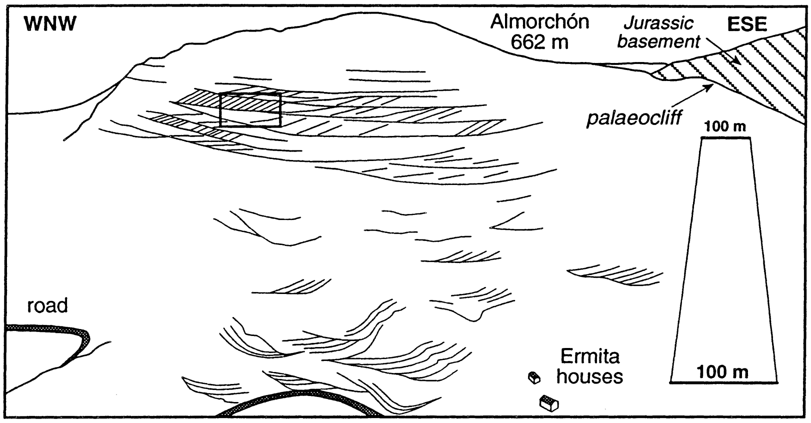

Fig. 4 Interpretation from a photo-mosaic of the El Chorro exposure. This WNW–ESE section, located in the middle of the outcrop, is parallel to the trend of the gateway. Note the ubiquitous occurrence of major unidirectional cross-beds (trough cross-beds and overlying tabular cross-beds) indicative of Mediterranean bottom currents flowing out towards the Atlantic. Major boundary surfaces between cross-bedded sets also clearly stand out. They are very irregular and deeply erosional in the lower interval, and slightly curved, convex-upwards in the upper one. Reactivation surfaces within sets of cross-bedding, with a lateral spacing of some tens of metres, are present only in the uppermost part of the tabular cross-bedded interval. Set reversals at the bottom part of the figure, left of the Ermita houses, are apparent (they relate to the trough geometry of the cross-bedding in the lower interval). Because of the difference in horizontal scales from bottom to top, there is some distortion of the figure. Inset shows location of Fig. 5.

Sedimentological interpretation: 'a major gateway'

Palaeogeographic reconstruction

Miocene sediments of the Guadalhorce valley accumulated in a NW–SE-trending strait that narrowed slightly in its central part. Sea cliffs of Jurassic limestone, which were intensely bored by bivalves and sponges, bordered this central part of the gateway at its eastern side, and these ancient sea cliffs persist as features in the present-day landscape (Figs 6 and 7). Conglomeratic sediments, up to 200 m in thickness, derived from erosion of the nearby emergent land, entered the linear gateway from both its eastern and western margins and locally resulted in fan deltas and coalescent fan-delta systems (Fig. 2). Channelized debris-flow conglomerates represent the inner-fan deposits,

Fig. 5 View of the tabular cross-bedding exhibited by the sandstones/microconglomerates upper interval at the El Chorro exposure. See precise position in Fig. 4 (inset). The picture, of a vertical wall, was taken at ≈1.5 km distance, using a telephoto lens. Scale bar is 10 m.

Fig. 6 Eastern side of the El Chorro exposure. Horizontal Miocene layers abut abruptly against vertical Jurassic limestone strata. This very clear, NW–SE aligned contact corresponds to a palaeocliff wall, marking the eastern margin of the Guadalhorce gateway.

while lobate debris-flow conglomerates alternating with sands were deposited in mid-fan areas. Part of these latter deposits, together with the outer-fan siliciclastic sediments, were re-mobilized along the corridor's length and mixed with minor amounts of autochthonous and parautochthonous bioclastic constituents to form the bulk of the sandstone/microconglomerate sedimentary prism cropping out in the more central parts of the gateway. Huge, unidirectional sedimentary structures in the latter deposits indicate northwestward transport of sediments. The topmost debris-flow conglomerates correspond to the final infilling stage of the gateway.

A small delta system developed on the northeastern side of the corridor (Fig. 2), where conglomerates, sands and silts accumulated. Carbonate sediments of the Teba and Peñarrubia exposures formed within a sheltered embayment at the northwestern end of the corridor.

Significance of the large-scale sedimentary structures

Interpretation of the hydrodynamic characteristics of the corridor is necessarily based on the large-scale sedimentary structures. Unidirectional cross-beds, with sets < 100 m in length and 7–9 m in thickness, similar in shape and dimensions to the sedimentary structures occurring within the lower sandstone/microconglomerate interval of the Guadalhorce valley, have been described by Anastas *et al.* (1997) from coarse-grained calcarenites of Oligocene–earliest Miocene age in New Zealand. These cross-beds are the result of the progradation of dunes within a 50–100-km-wide seaway with current velocities of 0.5–1.3 m s^{-1} and water depths of 40–60 m. The range of water depths in which such dunes accumulated can be estimated using maximum set thickness as a proxy for dune height (Anastas *et al.*, 1997). In modern settings, dune height (H) and water depth (D) are related by: $H = 0.17D$ (Rubin and McCulloch, 1980; Dalrymple and Rhodes, 1995). Applying this formula to the Guadalhorce valley structures yields water depths of approximately 120 m for the 20-m-thick dunes of the lower sandstone/microconglomerate interval. Inasmuch as the typical set-thickness within the Guadalhorce corridor is 10–20 m, the range of water depth within which the dunes accumulated can be computed as being at least 60–120 m.

Tabular cross-beds within the upper sandstone/microconglomerate interval of the Guadalhorce valley are similar – both in lithology and size – to those exhibited by a present-day sand ridge occurring on the KwaZulu–Natal outer shelf (SE Africa) at depths of 50–70 m. The internal structure of this sand ridge has been interpreted by Ramsay *et al.* (1996) from shallow-penetration seismic profiles. In the case of the African example, the sand ridge is ascribed to a geostrophic current flowing southeastwards, parallel to the shoreline, with current velocities of approximately 1.5 m s^{-1}.

All of the large-scale sedimentary structures within the Guadalhorce corridor are unidirectional, traction-current structures indicative of northwesterly flow (Fig. 3). As no evidence was found for tidal activity along the corridor, a bottom-density current stemming from the Mediterrranean higher-salinity waters is considered responsible for the formation of these structures. As indicated by the heights

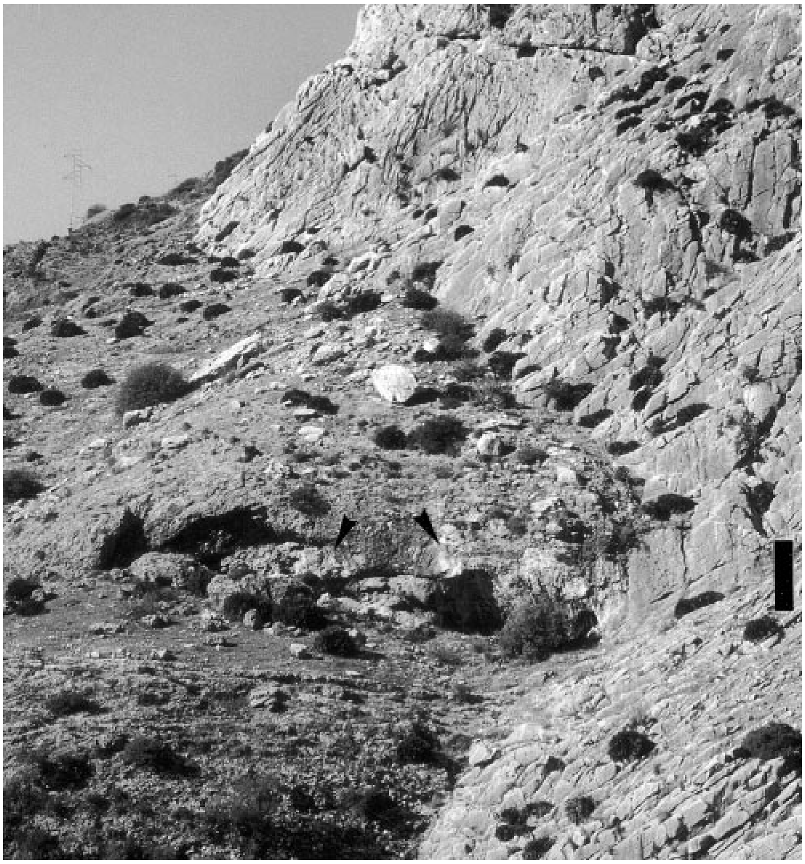

Fig. 7 Closer view of the palaeocliff at the eastern margin of the Guadalhorce gateway (El Chorro exposure). Limestone blocks (arrowheads point to some of them), fallen from the cliff wall and heavily bored by bivalves and sponges, stand out embedded within the Miocene sandstone/microconglomerate sediments. Scale bar is 2 m.

of dunes, current velocities are judged to have been approximately 1.0–1.5 m s^{-1}. This figure could be even higher considering that, in the Guadalhorce corridor, around 30% of the sediment was very coarse, up to pebble-grade in size. The scarcity of reactivation surfaces within sets of cross-bedding implies that the currents generating the sets were not only of high velocity, but also relatively continuous and steady. These bottom currents fashioned giant dunes and ridges at water depths of 50–120 m in a strait that was only 2–3 km wide in its central part (Fig. 2). Tectonic subsidence during deposition of the cross-bedded units kept gateway depth within this range. Assessments of palaeocurrents indicate a slightly greater dispersal pattern for dunes in the lower interval, which might explain the more irregular shapes of these dunes and the occurrence of trough cross-beds instead of tabular cross-beds.

Additional published accounts of both present-day and ancient gateways have invoked strong bottom currents producing large-scale cross-stratification. Collins *et al.* (1996), for example, envisioned an Upper Miocene (~ 6 Ma) jet of bathyal water within the Panama strait that flowed from the Pacific into the Caribbean and thereby produced a large wedge of cross-laminated sandstone and coarse-grained coquina.

Within the modern Straits of Gibraltar (which is ~ 14 km wide at its narrowest point), warm (> 12 °C), dense, saline (> 36.2‰) Mediterranean water flows out at depths between ~ 200 and 700 m, with velocities of 1.8–2.5 m s^{-1} (Kenyon and Belderson, 1973; Ambar and Howe, 1979; Nelson *et al.*, 1999), leaving behind a scoured basement with sparse accumulations of very coarse-grained sediments (López-Galindo *et al.*, 1999; Rodero, 1999).

Significance and implications

The Miocene Guadalhorce gateway was the last Atlantic–Mediterranean, Betic connection. The Northbetic Straits, which connected the Atlantic Guadalquivir basin with the Mediterranean via the Prebetic area of Alicante (northeasternmost part of the Betic Cordillera), closed at the end of the Middle Miocene. The last marine sediments to be found in the Prebetic area of Alicante are middle Miocene in age. Younger Miocene deposits in this region are continental in origin (Esteban *et al.*, 1996). The only other possible Atlantic–Mediterranean Betic connection – that of the present Guadix-Baza basin within the central part of the Betic Cordillera – had ceased to exist by the late Tortonian (~ 8 Ma) (Soria *et al.*, 1999).

The Guadalhorce gateway, the only Messinian Betic strait, is believed to have been coeval with the Rifian corridors of northern Morocco (Fig. 8), which were also important Atlantic–Mediterranean passages during the Tortonian and Messinian (Benson *et al.*, 1991; Esteban *et al.*, 1996). Patterns of circulation within the Guadalhorce gateway, characterized by bottom currents flowing from the Mediterranean into the Atlantic, are in accordance with the 'siphon' model proposed by Benson *et al.* (1991). According to these authors, during the early Messinian, Atlantic waters entered the Mediterranean through Rifian corridors in northern Morocco, while higher salinity Mediterranean water flowed out through a Betic discharge channel into the Atlantic.

Following the closure of the Guadalhorce gateway, Atlantic–Mediterranean communication was restricted to the Rifian straits in northern Morocco (Esteban *et al.*, 1996). The early Messinian age of this event suggests that the closure of the Guadalhorce gateway was coeval with the onset of western Mediterranean water-mass stratification, contemporaneous with Messinian reef development (Martín and Braga, 1994; Martín *et al.*, 1999; Sánchez-Almazo *et al.*, in press). This palaeogeographic restriction of the Mediterranean, which has been constrained by the stable isotope record in the Mediterranean Messinian (Vergnaud-Grazzini, 1985; Glaçon *et al.*, 1990), led to reduced water circulation,

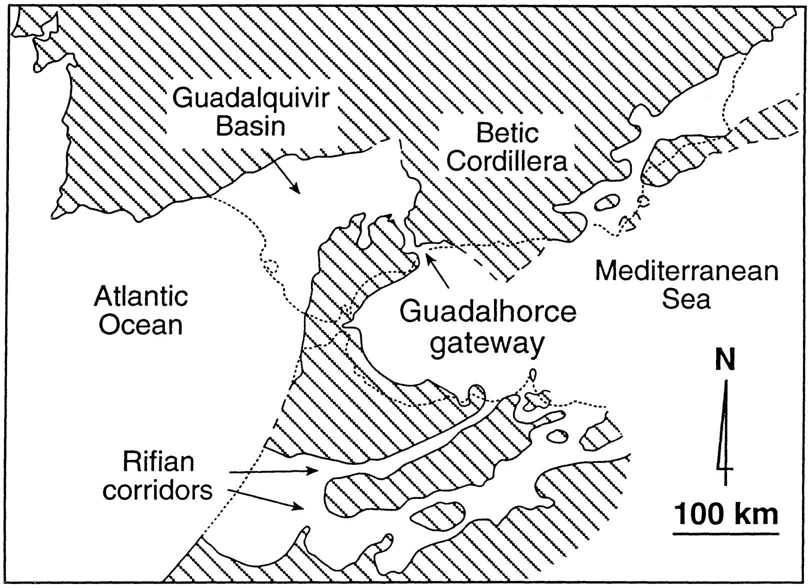

Fig. 8 Western Mediterranean palaeogeography during the early Messinian (modified from Esteban *et al.*, 1996). Note the position of the Guadalhorce gateway cutting across the central part of the Betic Cordillera. Present land margins of southern Iberia and north Africa are shown with dotted lines.

increasing the residence time of bottom-water masses and promoting widespread disaerobic bottoms. Later closing of the Rif straits, at around 6 Ma (Krijgsman *et al.*, 1999), gave way to the complete isolation and subsequent desiccation of the Mediterranean, which resulted in the precipitation of extensive evaporites within the central and deeper parts of the Mediterranean (Hsü *et al.*, 1977).

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