



MIOCENE ATLANTIC-MEDITERRANEAN SEAWAYS IN THE BETIC CORDILLERA (SOUTHERN SPAIN)

Los estrechos Miocenos Atlántico-Mediterráneos de la Cordillera Bética (S de España)

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Abstract: *The link between the Mediterranean Sea and the Atlantic Ocean through the Betic Cordillera (southern Spain) was reduced to a few seaways in the Miocene as the mountain belt uplifted during the Alpine orogeny. The North-Betic Strait, located in the Prebetic Zone, was the first one to close in the Early Late Miocene. During the Tortonian, there were connections through the Granada-Guadalquivir basins (Zagra Strait) and the Guadix-Guadalquivir basins (Dehesas de Guadix Strait). Only one corridor, the Guadalhorce Strait, existed in the early Messinian through the Guadalquivir and Málaga basins. The closing of the youngest straits (Dehesas de Guadix and Guadalhorce Straits) brought about profound paleoceanographic changes, leading to an increase of Mediterranean restriction and water-mass stratification. All these straits were several kilometers wide, and a few tens to c. 100 m deep. The strait deposits (up to 400 m thick) consist of siliciclastics and siliciclastics-carbonates. Giant dunes (up to 30 m high and 800 m long), exhibiting internal giant cross-bedding, are characteristic features of these ancient seaways. In the North-Betic and Zagra straits the dunes were moved by tides and in the Dehesas de Guadix and Guadalhorce straits by bottom density currents flowing from the Mediterranean towards the Atlantic.*

Key words: *Atlantic-Mediterranean seaways, Betic Cordillera, Neogene basins, Giant dunes, Giant cross-bedding.*

Resumen: *Las conexiones Atlántico-Mediterráneo, en el Mioceno, a través de la Cordillera Bética (S de España), fueron progresivamente reduciéndose a unos pocos estrechos conforme ésta se fue levantando durante la Orogenia Alpina. El Estrecho Nordbético, localizado en la Zona Prebética (parte más externa de la Cordillera Bética) fue el primero en cerrarse en el Tortoniano inferior. A lo largo del Tortoniano las conexiones fueron a través de las cuencas de Granada y del Guadalquivir (Estrecho de Zagra) y de las cuencas de Guadix y del Guadalquivir (Estrecho de Dehesas de Guadix). El último estrecho en desarrollarse, en el Messiniense inferior, fue el del Guadalhorce. La conexión Atlántico-Mediterránea fue, en este caso, a través de las cuencas de Málaga y la del Guadalquivir. El cierre de los estrechos más modernos (Dehesas de Guadix y Guadalhorce) indujo cambios paleoceanográficos profundos en el Mediterráneo, con aumento significativo de su nivel de restricción y de estratificación de sus aguas. Estos estrechos tenían unos pocos kilómetros de anchura y profundidades entre unas pocas decenas de metros y algo más de 100 m. Los sedimentos de los estrechos son siliciclásticos y mezclas de siliciclásticos y carbonatos bioclásticos, con potencias de hasta 400 m. El tamaño de grano del sedimento es de arena y conglomerado, este último con clastos de centimétricos a decimétricos. Los bioclastos son predominantemente fragmentos de algas rojas, briozoos y bivalvos. La presencia de dunas gigantes es una característica distintiva, omnipresente en estos antiguos estrechos. Las mayores dunas preservadas alcanzan los 30 m de altura y se extienden lateralmente unos 800 m. Los dispositivos internos de capas cruzadas alcanzan los 15° de buzamiento. En el Estrecho Nordbético la estratificación cruzada de gran escala es resultado de la migración de grandes dunas movidas por las mareas. En él son frecuentes los ejemplos de dunas compuestas que muestran estratificación cruzada con doble sentido y abundantes superficies de reactivación. En el Estrecho de Zagra la marea fue de nuevo el agente dominante, con predominio de las grandes estructuras hacia el sureste, en su parte septentrional, y bidireccionales (noroeste y sureste), en su zona meridional. En los Estrechos de Dehesas de Guadix y del*



Guadalhorce la estratificación cruzada de gran escala es unidireccional. En estos dos últimos casos, las responsables del desplazamiento de las dunas fueron las corrientes de fondo mediterráneas, más salinas y de más alta densidad, en su salida hacia el Atlántico.

Palabras clave: Estrechos Atlántico-Mediterráneos, Cordillera Bética, Cuencas Neógenas, Dunas gigantes, Megaestratificación cruzada.

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Straits are narrow corridors of tectonic origin connecting seas and/or oceans. As gateways for the exchange of water masses between basins, they can be key areas for energy transfer at a global scale, influencing climate on small and large timescales. Straits can be important topographic constraints for water flow and can impose strong thermohaline differences in the interconnected basins. This is true of the Gibraltar Straits connecting the open Atlantic with the Mediterranean Sea, a semi-enclosed sea with negative water and heat-flux budgets, which are offset by water inflow from the open ocean (Bethoux, 1979). Evaporation exceeds fresh water input into the sea, promoting the formation of deep water with high salinity. This water flows out through the Gibraltar Straits in depth, below the Atlantic water flowing into the Mediterranean basin (Wüst, 1961). Despite the crucial influence of the Gibraltar Straits in the oceanography and the very existence of the Mediterranean Sea, this seaway is relatively young in geological terms, as it opened in the Pliocene (Hsü et al., 1973, 1977). Before the establishment of the Strait of Gibraltar as the single narrow link, the connections of the Atlantic and the Mediterranean underwent a complex evolution, governed

mainly by the uplift of the Betic-Rif orogen (Martín et al., 2010).

The location, dynamics, and evolution of these ancient connections had profound paleoceanographic implications, and unraveling the record of these seaways is crucial for understanding the paleoceanography of both the Mediterranean Sea and the northern Atlantic Ocean (i.e. Pérez-Asensio et al., 2012). In this paper, the sedimentary record and evolution of the straits connecting these two major basins through the Betic Cordillera during the Miocene are reviewed. The sedimentological features characteristic of ancient straits and their driving mechanisms are discussed together with the main consequences of successive closures for the paleoceanography of the western Mediterranean and nearby Atlantic areas.

Geological setting

The Betic Cordillera, which constitutes the westernmost segment of the European Alpine Belt, resulted from the convergence of the African and European plates during the Alpine orogeny. Two major domains can be differentiated:

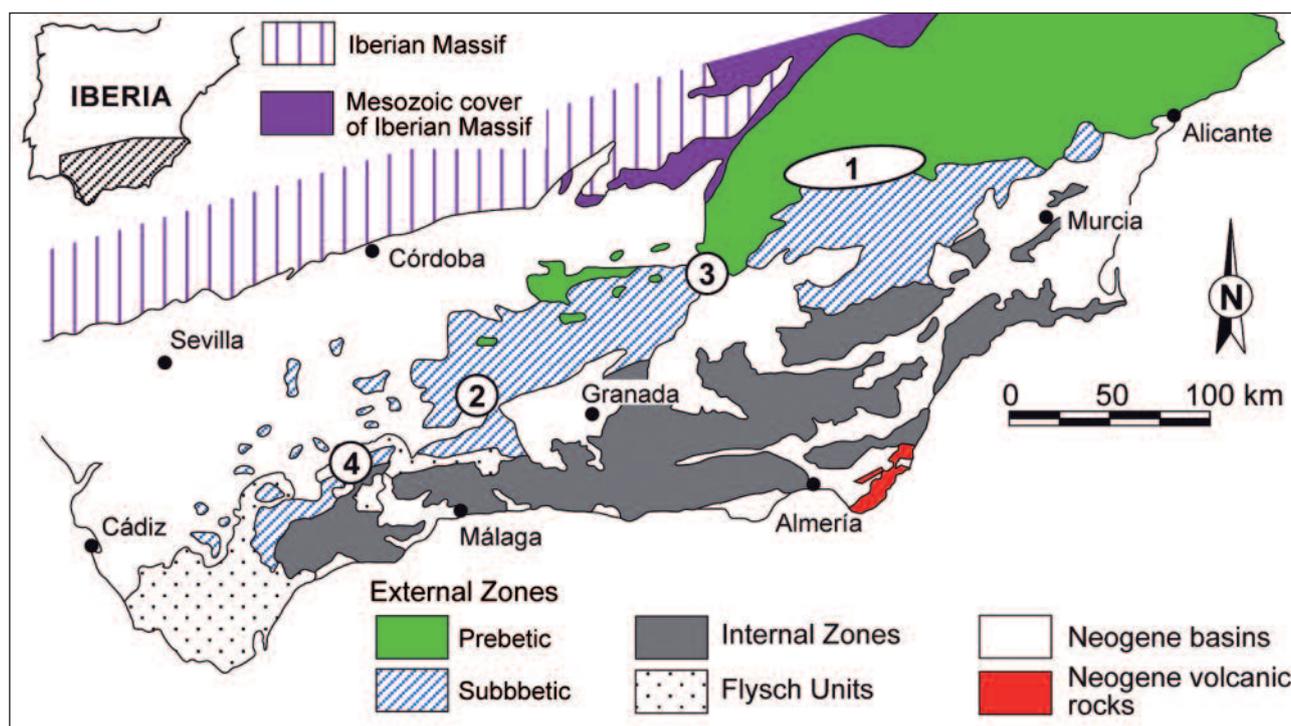


Fig. 1.- Simplified geological map of the Betic Cordillera. The position of the successive Betic straits is marked. 1: North-Betic Strait; 2: Zagra Strait; 3: Dehesas de Guadix Strait; 4: Guadalhorce Strait.

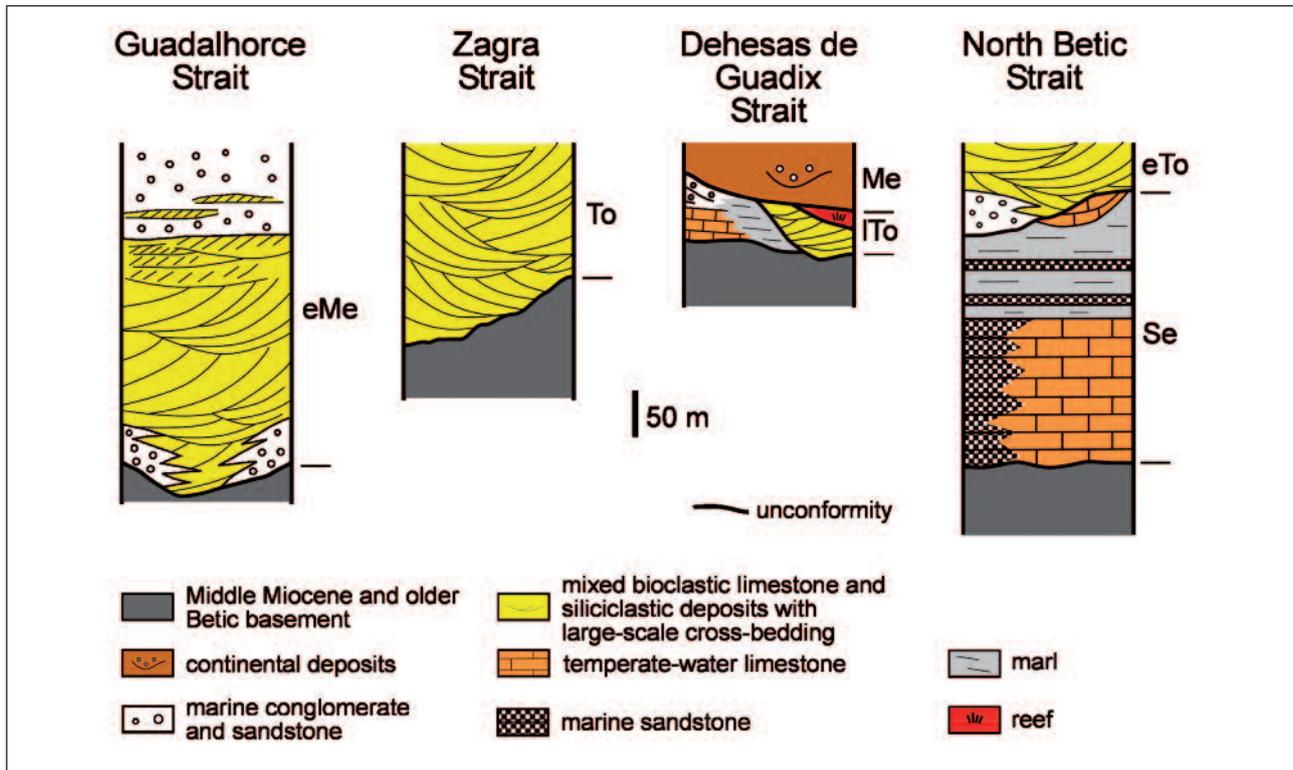


Fig. 2.- Schematic stratigraphic sequences of the study localities. Strait deposits exhibit ubiquitous, large-scale cross-bedding, pointing in opposite directions in the cases of the North Betic and the Zagra Straits and in the same direction in the cases of the Dehesas de Guadix and the Guadalhorce Straits. Se: Serravallian; eTo: early Tortonian; To: Tortonian; ITo: late Tortonian; eMe: early Messinian; Me: Messinian.

the External Zones to the north, and the Internal Zones to the south. Within the External Zones, the Prebetic Zone constitutes the northernmost part and the Subbetic Zone the distal one of the southern margin of the Variscan Iberian Massif (García Hernández et al., 1980; Vera, 2004) (Fig. 1).

The Betic Cordillera, lying just between the Atlantic Ocean and the Mediterranean Sea, started to uplift in the Middle Miocene as result of the Alpine collision. First, only certain minor reliefs emerged as small, isolated islands. In Late Miocene, the paleogeography evolved into irregularly trending, interconnected, intermontane marine basins as the emerging reliefs expanded in size and fused together. Some of these basins opened directly to the Atlantic Ocean and others to the Mediterranean Sea (Braga et al., 2003). In the initial stages, numerous marine passages formed between the Atlantic-linked and the Mediterranean-linked basins. These seaways were, however, progressively confined and reduced in number during the uplifting until they finally disappeared.

The Betic straits

The following description outlines the most significant characteristics of the successive Betic straits (see Fig. 1 for location).

The North-Betic Strait

This was long considered the only communication between the Atlantic Ocean and the Mediterranean Sea

through the Betic Cordillera (Hsü et al., 1973, 1977; Benson et al., 1991). Strait-sediment outcrops appear in the western part of the Prebetic Zone, in an ENE-SSW trending belt that extends laterally for some 90 km with a maximum width of 18 km. Strait deposits, as a whole, reach a thickness of around 100 m (Fig. 2). The sediments are a mixture of carbonates and siliciclastics, with a predominance of the carbonate components. The carbonates are bioclastic, coarse-grained calcarenites to fine-grained calcirudites and contain abundant remains of bivalves, bryozoans, and coralline red algae. Locally, some delta-fan conglomerates also occur, located along the edges of the former strait (Martín et al., 2009).

This strait connected the Atlantic Ocean and the Mediterranean Sea via the Prebetic Zone and the Guadalquivir Basin. It developed as a result of the progressive confinement created by the overthrusting Subbetic nappes as they moved north and approached the Prebetic platform (Meijninge and Vissers, 2007). In its early stage, in Serravallian times, it was a relatively open marine pass bordered on the south by an extensive, wave-dominated carbonate platform (Braga et al., 2010). In its final stage, in the Early Late Miocene, it transformed into a major tidal passage, with huge sediment dunes being moved along its bottom by strong tidal currents and developing giant cross-bedding as result of their migration (Martín et al., 2009). The biggest dunes (up to 20 m high and c. 100 m long) occurred at its westernmost end. There, cross-bedded sets point persistently westwards, towards the Atlantic. This westernmost part was also the deepest area, estimated at

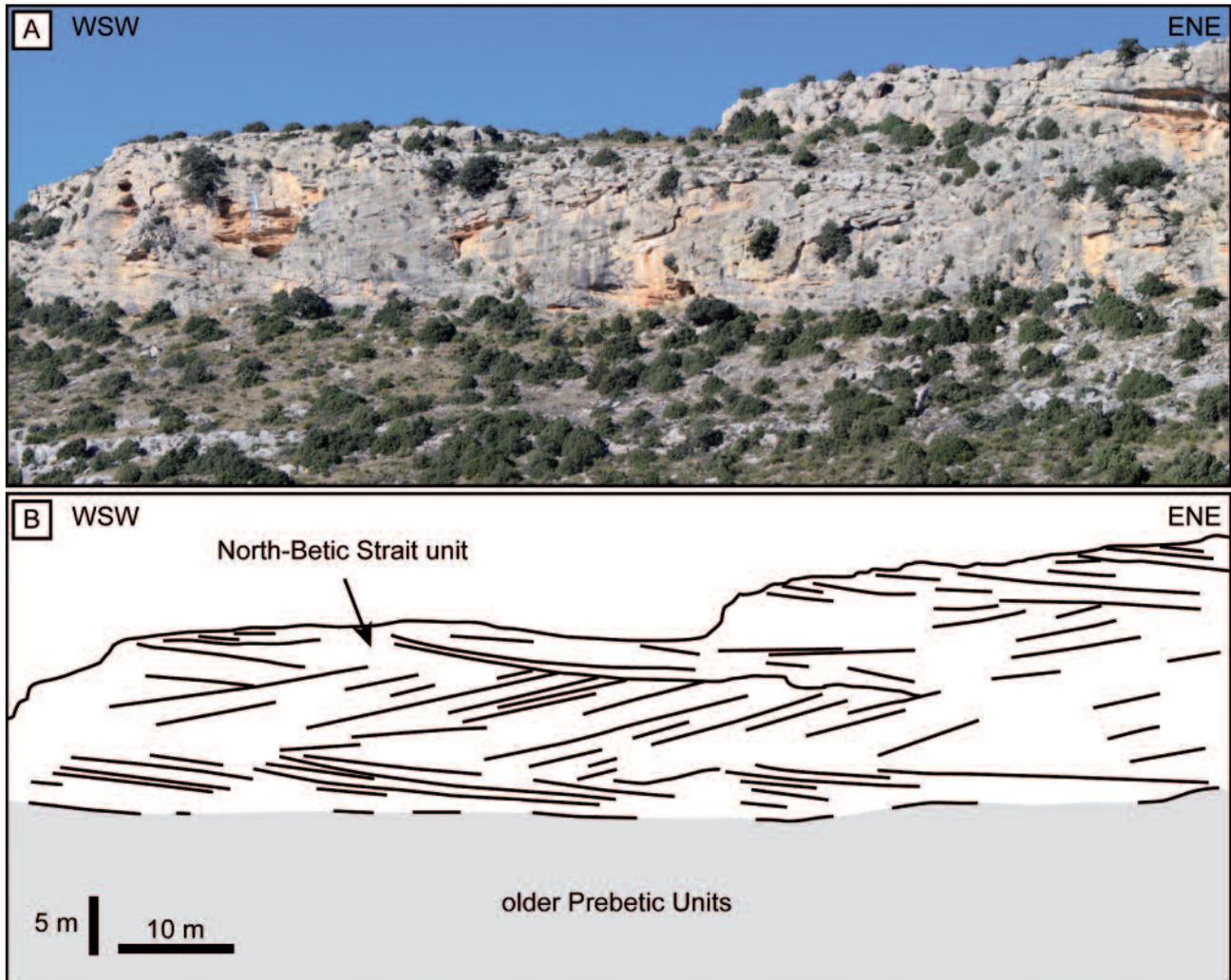


Fig. 3.- Composite structures exhibiting reverse, large-scale cross-bedding are common features in the North-Betic Strait deposits

around 90 m (following Allen's 1984 formula applied to the recorded dune high). In the middle part of the strait the cross-bedding pointed both to the east and west, towards the Mediterranean and the Atlantic, respectively. In this middle part, composite dunes with abundant internal reactivation surfaces were common features (Fig. 3). The dunes were smaller (up to 15 m high and some tens of meters long) with an estimated water depth in this case of around 70 m. In its easternmost part, only small dunes (up to 5 m high and a few tens of meters long) developed, with the cross-bedding pointing eastwards. This was also the shallowest area (c. 30 m deep) (Martín et al., 2009).

The Zagra Strait

The Atlantic-Mediterranean communication was in this case through the northwestern part of the Granada Basin, at Zagra, just north of Loja. Strait deposits occurred along a WNW-ESE (approximately N110°E) trending belt, with a minimum width of 4 km. The sediments are bioclastic sands (bioclasts are mainly from bryozoans and bivalves) and conglomerates, displaying large-scale cross-bedding (Fig. 2). They are presumably Tortonian in age (Rodríguez-Fernández, 1982), although not precise dating has been achieved. At the studied outcrops, strait sediments lie

unconformably on top of Serravallian marls and older deposits.

In the westernmost outcrops (Fuentes de Cesna) a bioclastic sandstone sequence, up to 215 m thick, appears, which locally has intercalated thin (1 m thick) conglomerate beds. Giant trough cross-bedding is the dominant sedimentary structure. Individual troughs are up to 25 m high and several hundred meters long. Small- and medium-scale trough cross-bedding, generated by the migration of dunes up to 2 m high and several tens of meters of wavelength, is also widespread. Most cross-bedded sets point to the SE, ranging from N100°E to N180°E, with a predominant N140°E to N170°E direction. Slumped giant dunes, displaced to the SE, occur at the base of the sequence (Fig. 4). In the middle and upper part of the section the giant dunes are smaller in size (up to 15 m high and 100 m long). In this part of the section, some local, major and minor N-NW (N35°W to N10°E) dipping cross-bedded units appear as well.

In the easternmost outcrops (Ventorros de San José and Zagra) the stratigraphic sequence is up to 130 m thick. Strait sediments are slightly calcareous (bioclastic) sandstones and fine- to medium-grained conglomerates, exhibiting large-scale (up to 25 m high and 150 m long) trough cross-bedding, as well as minor, small- to middle-

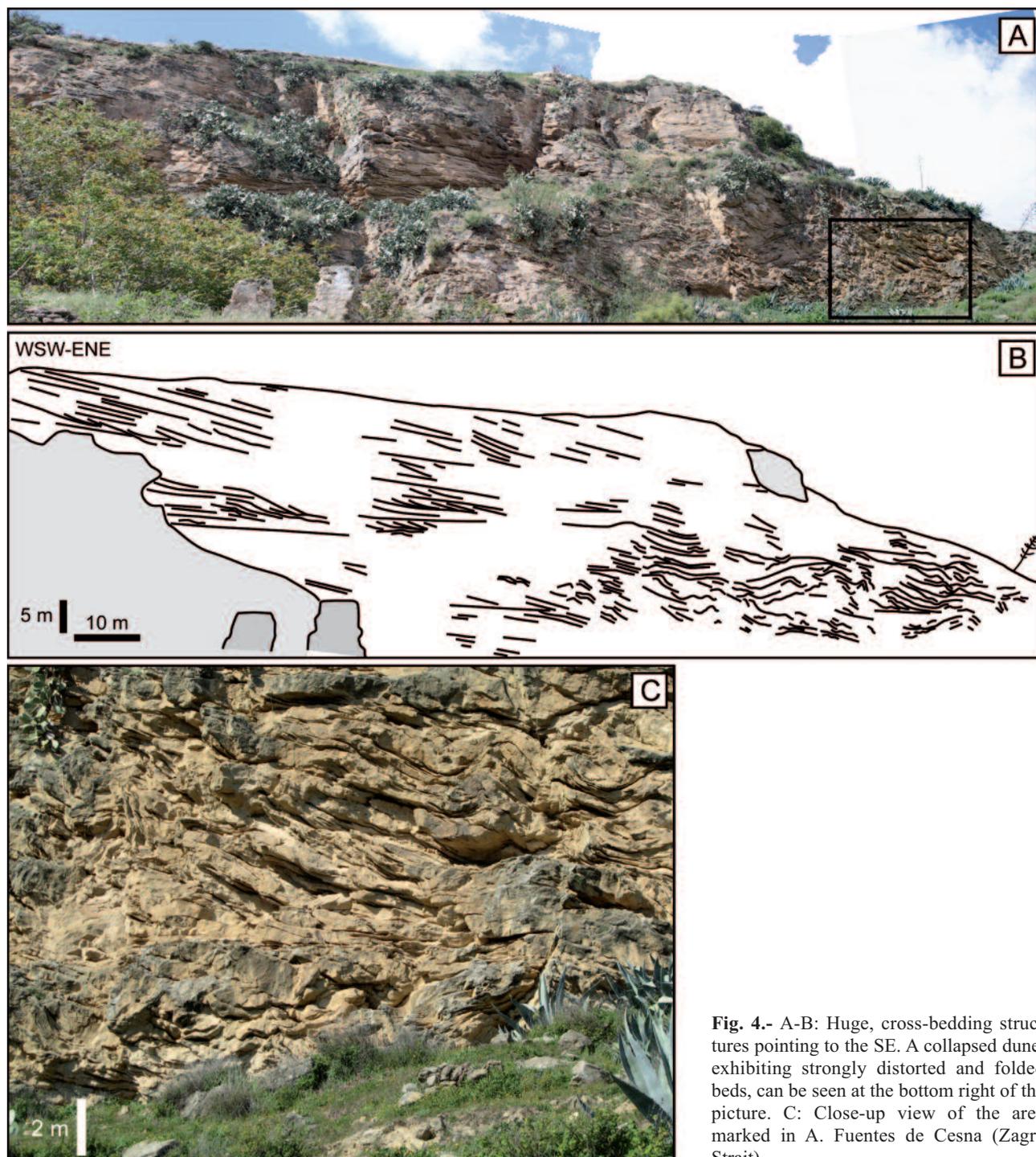


Fig. 4.- A-B: Huge, cross-bedding structures pointing to the SE. A collapsed dune, exhibiting strongly distorted and folded beds, can be seen at the bottom right of the picture. C: Close-up view of the area marked in A. Fuentes de Cesna (Zagra Strait).

scale trough cross-bedding. Both N-NW (N75°W to N10°E) dipping and S-SE dipping (N160°E to N200°E) cross-bedded sets are frequent (Fig. 5).

The above-mentioned data suggest that the Zagra Seaway was a tide-controlled strait, with Mediterranean-directed flows dominating its western, Atlantic side while bidirectional, Atlantic- and Mediterranean-directed flows predominated on its eastern, Mediterranean side.

The Dehesas de Guadix Strait

This N-S elongated strait communicated the Atlantic-linked Guadalquivir Basin with the Mediterranean-linked

Guadix Basin (Soria et al., 1999; Betzler et al., 2006). A late Tortonian age (8.5-7.8 Ma) is well-constrained for this strait in which two phases of development can be clearly distinguished. In its early stage of evolution it was a relatively open marine passage (around 12-15 km wide). Conglomerates/sandstones and calcarenites (calcirudites) were deposited on its edges, while marls accumulated in its central, deeper parts (Fig. 2). It evolved into a narrow (no more than 2 km wide), confined strait before closing. At this final evolutionary stage, strong bottom currents flowing from the Mediterranean to the Atlantic moved huge bioclastic sand and conglomerate dunes, displaying internally large-scale cross-bedding (Betzler et al., 2006) (Fig.

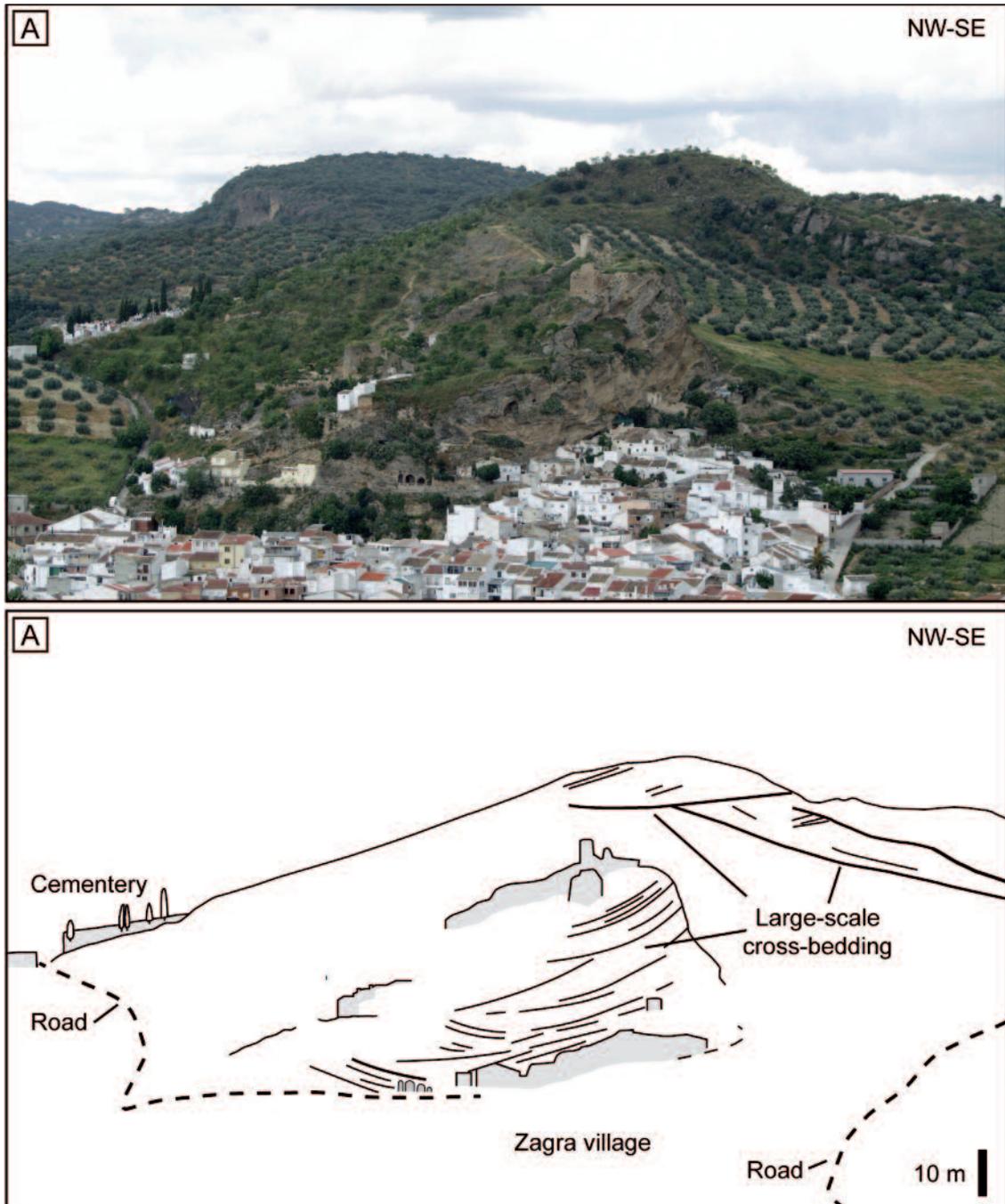


Fig. 5.- S-SE and N-NW dipping giant trough cross-bedding units are ubiquitous in the Zagra Strait.

6). The thickness of the deposit as a whole was almost 100 m. Bioclast remains were mainly from bivalves, brachiopods, and bryozoans. Cross-bedded sets were up to 15 m high and 70 m long. Estimated paleodepths, considering the inferred dune high and using formula of Allen (1984) and Rubin and McCulloch (1980), were 70 and 90 m, respectively. The estimated water flow was $0.145 \text{ km}^3/\text{s}$ (assuming water-current velocities of around 0.8 m/s) (Betzler et al., 2006). In this strait, contemporaneous with the Mediterranean bottom currents, there were Atlantic, counter-clockwise surface currents flowing southwards, into the Guadix Basin (Puga-Bernabéu et al., 2010).

This Guadix Basin remained connected to the Mediterranean Sea between 7.8 and 7.4 Ma, after the Dehesas de

Guadix Strait closed 7.8 Ma ago. During this interval, some coral reef growth took place on the basin margins.

The Guadalhorce Strait

This was the last Betic Strait. The Atlantic-Mediterranean communication was in this case through the Atlantic-linked Guadalquivir Basin and the Mediterranean-linked Málaga Basin (Orueta, 1917). This NNW-SSE trending strait was normal-fault controlled (López Garrido and Sanz de Galdeano, 1999). Strait sediments, early Messinian in age, occurred along a 30-km-long trending belt located NE of Málaga. The maximum strait width was around 5 km. In its narrowest area (only 2 km wide) it was



Fig. 6.- Unidirectional, giant cross-bedding is the most outstanding feature in the Dehesas de Guadix Strait. Man in the picture (encircled) is 1.85 m tall.

limited by vertical cliffs, sculpted in the Jurassic limestone basement, which can still be identified as prominent features in the present-day landscape (Martín et al., 2001) (Fig. 7).

The thickness of the sedimentary sequence as a whole is around 400 m. At the base of the sequence lie fan-delta deposits consisting of debris-flow conglomerates and sandstones. These are overlain by a thick body of locally bioclastic sandstones and micro-conglomerates, exhibiting ubiquitous large-scale cross-bedding. Bioclasts are mainly from bryozoans, coralline red algae, and bivalves. Clast-supported conglomerates appear on top (Fig. 2). Large-scale (up to 20 m high and 100 m in length) trough cross-bedding is widespread in the lower part of the sandstone/microconglomerate deposits. Large-scale tabular cross-bedding characterizes the upper part. In this latter case, individual bed sets can be up to 30 m thick, extending laterally for almost 1 km. By comparison with present-day examples of similar characteristics (Rubin and McCulloch, 1980; Dalrymple and Rhodes, 1995; Ramsay et al., 1996), current velocities of 1-1.5 m/s have been estimated for the formation and mobilization of the dunes responsible for the generation of the trough cross-bedding and the tabular cross-bedded sets. Inferred depositional depths (calculated considering preserved dune heights) range between 60 and 120 m. All the cross-bedding structures dip to the N-NW. This indicates the existence of strong and persistent bottom currents flowing from the Mediterranean to the Atlantic (Martín et al., 2001).

The Guadalhorce paleo-current pattern is consistent with the siphon model proposed by Benson et al. (1991) for the early Messinian. According to these authors, Atlantic water entered the Mediterranean through the Rifian straits and Mediterranean outflow was through a Betic Strait. Nevertheless, these authors were mistaken in considering the North-Betic Strait, rather than the Guadalhorce Strait, as the Betic outflow channel. This scenario is now beyond question since the North-Betic Strait was already closed during Messinian times (see above).

The Atlantic Ocean-Mediterranean Sea connections

The history of the strait connections between the Atlantic Ocean and the Mediterranean Sea within the Betic Cordillera during the Late Miocene is complex (Esteban et al., 1996; Martín et al., 2010) and can be summarized as follows (Fig. 8). The first strait to be differentiated was the North-Betic Strait (Martín et al., 2009), located in the north-eastern part of the Cordillera, between the Prebetic platform and the reliefs formed to the south by the northward-overthrust Subbetic nappes. This Atlantic-Mediterranean communication was closed in the early Tortonian. In the central part of the cordillera, as the emerging reliefs linked to the Subbetic nappes expanded and fused together, two new straits developed in the Tortonian: Zagra Strait (this paper), situated on the northern edge of the Granada Basin, and Dehesas de Guadix Strait (Betzler et al., 2006), located in the northern part of the Guadix Basin.



Fig. 7.- Aerial view of the Guadalhorce Corridor: Horizontal to gently dipping layers of the Messinian strait-infilling stand out in the centre of the picture. The Miocene beds are limited by Jurassic limestones (upper part of the picture) and by Paleozoic schists (bottom part of the picture).

The Guadalhorce Strait (Martín et al., 2001), placed more to the southwest, north of Málaga at the contact area between the External and the Internal Zones of the Cordillera, formed and closed in the early Messinian. The Gibraltar Straits, the westernmost and youngest Atlantic-Mediterranean marine pass, resulted from the opening of a new sea corridor in the middle of a former emergent area, at the beginning of the Pliocene (Hsü et al., 1973, 1977; Comas et al., 1999).

The Rifian straits (Benson et al., 1991), located in northern Morocco, represent the other major Miocene connection between the Atlantic Ocean and the Mediterranean Sea (Fig. 8). These straits formed in the late Tortonian, approximately 8 Ma ago (Krijgsman et al., 1999; Barbieri and Ori, 2000) and remained as the only Messinian Atlantic-Mediterranean seaways, after the Betic Guadalhorce Corridor closed in the early Messinian (Krijgsman et al., 1999; Martín et al., 2001).

Discussion

Huge volumes of sea water, of different characteristics, are constantly mobilized and interchanged in straits, which may imply major ecological, sedimentological, and climatic changes. In the case of the Betic straits, as the

marine passages between the Atlantic Ocean and the Mediterranean Sea reduced in number and were progressively confined, a major change took place from tide-dominated straits to density current-dominated straits. In the final stages of this Miocene evolution, the role played by some of these ancient straits was extremely important and their final disappearance brought about far-reaching paleoceanographic changes that raised the level of restriction of the entire Mediterranean basin. In this respect, the closing of the Dehesas de Guadix Strait, at 7.8 Ma (Betzler et al., 2006), was concomitant to a significant fall in the Mediterranean bottom-water, oxygen levels that took place at around 7.9 Ma (Seidenkrantz et al., 2000; Kouwenhoven et al., 2003). The return to normal conditions, at around 7.6 Ma, coincides with the maximum flooding event in the Rifian Straits (Krijgsman et al., 1999; Barbieri and Ori, 2000).

Similarly, the closing of the Guadalhorce Strait at around 6.2 Ma (Pérez-Asensio et al., 2012) limited the Atlantic-Mediterranean communications to the Rifian straits in northern Morocco. This led to an increase in Mediterranean-water, residence time, and subsequently to a Mediterranean restriction, resulting in the development of water-mass stratification (Martín et al., 2001). These deductions are supported by the available paleontological and

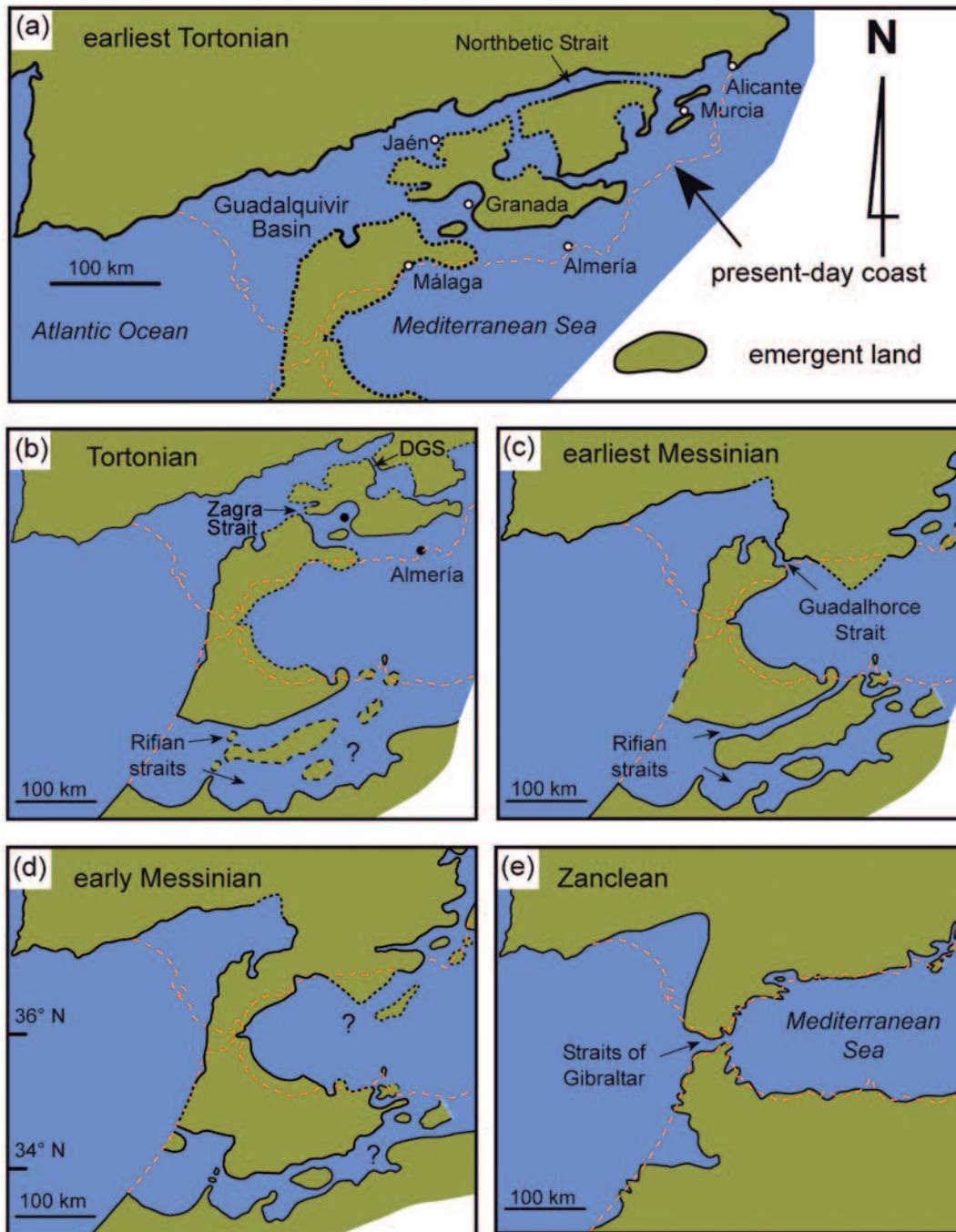


Fig. 8.- Paleogeographic maps showing the changes in the Atlantic–Mediterranean connections from the Tortonian to the Pliocene, and the location of the successive Betic straits (modified from Martín et al., 2010). The North-Betic and Zagra straits were tide-dominated, and are early Tortonian and Tortonian in age respectively. In the Dehesas de Guadix (DGS) and Guadalhorce straits strong Mediterranean-linked, bottom density currents flowed persistently towards the Atlantic Ocean. These two latter straits are late Tortonian and early Messinian in age, respectively.

geochemical (stable isotope) data from studies conducted in the Mediterranean sediments deposited immediately prior to the Messinian Salinity Crisis (Vergnaud-Grazzini, 1985; Glaçon et al., 1990; Kouwenhoven et al., 2003).

The disappearance of this strait also had important paleobiogeographical implications for the emerged areas. In this respect, the presence of continental African mammals in some localities of eastern Spain in the pre-evaporitic Messinian, at around 6.2 Ma, prior to the Messinian Salinity Crisis, is linked by Gibert et al. (2013)

to the closing of the Guadalhorce Strait and the existence of some ephemeral land bridges across the Rifian straits during some of the Late Miocene glacial intervals.

Most of the above-described Miocene Betic strait examples have certain common features. They formed as result of the progressive confinement of the communication passages between Atlantic-linked and Mediterranean-linked basins. Their evolution has two significant stages, as they were first relatively open marine passages that then narrowed significantly before closing. In the final stage,

confined flows generated strong currents that eroded and/or transported a significant amount of sediment along the sea bottom (Betzler et al., 2006; Martín et al., 2009).

The presence of giant cross-stratification is a distinctive feature in the sediments of all these ancient straits (see Figs 2 to 6). This giant cross-bedding was generated by the migration of large dunes built up and mobilized by strong currents. Due to the high energy levels of the currents, the sediment grain size was frequently coarser than sand (up to pebble in size; Martín et al., 2001, 2009; Betzler et al., 2006).

Ancient seaways are sedimentologically characterized by the existence of persistent and ubiquitous giant cross-bedding, as shown in the Betic strait examples studied here (Martín et al., 2001, 2009; Betzler et al., 2006). A comparable situation has been reported from the Strait of Panama (Collins et al., 1996) where, around 6 Ma ago, a strong bottom current flowing from the Pacific into the Caribbean accumulated a thick and extensive, bioclastic and sandy cross-bedded deposit. In the Calabrian Arc, a thick (up to 120 m thick) sequence of siliciclastic sands exhibiting large-scale cross-bedding accumulated on both sides of a series of tide-dominated straits, Tortonian to Plio-Pleistocene in age (Longhitano et al., 2012; Longhitano, 2013). On a smaller scale, Dabrio (1986-1987) referred to a Pliocene calcarenitic deposit in SE Spain, exhibiting large-scale cross-bedding, resulting from the E-W migration of sandwaves moved by wind-induced currents along a narrow pass between two small islands.

In present-day straits, currents commonly flow in one direction (Defant, 1961). When they are regulated by tidal cyclicity the strait is qualified as tidal (Pratt, 1990). Megadunes develop at the strait bottom, independently of the current origin (i.e. tides or density gradients), with current velocities between 0.7 and 1.5 m/s (Berné, 1991; Longhitano, 2013). Their migration results in the generation of giant cross-bedding. Stronger currents, however, encourage scouring and by-pass situations, as in the present-day Strait of Gibraltar, where the MOW (Mediterranean Outflow Water) bottom-current velocity is higher than 2 m/s (Ambar and Howe, 1979) and there is no significant sediment deposition. Nevertheless, the MOW current velocity diminishes quickly as it flows westwards, within the Gulf of Cádiz. Dunes up to 10 m high and 75 m in length formed there, inside some submarine valleys, with current velocities of 0.8 m/s (Nelson et al., 1993). In modern tidal straits, such as the Messina (Ferranti et al., 2008), San Francisco (Barnard et al., 2006) and Cook (Lamarque et al., 2011) straits, currents flow axially to the seaway, having reversal directions and phase differences between the two interlinked basins (Longhitano, 2013). Tidal currents distribute sediments, producing a bedload parting which promotes the transport of bed material from the shallow and confined central (erosional) part (where current velocities exceed 2 m/s), towards either side of the strait after flow expansion (Harris et al., 1995; Reynaud and Dalrymple, 2012). As a result, most sediment accumulates in the so-called "dune-bedded strait zone", at both sides of the central zone, due to the rapid deceleration of the tidal cur-

rents. In this zone, medium- to very large-scale tidal dunes occur (Longhitano, 2013).

Conclusions

In the late Miocene, the positions of the Atlantic - Mediterranean seaways changed through time as the Betic and Rifian reliefs were being uplifted. Within the Betic Cordillera a series of straits first differentiated and then were closed.

The oldest one is the North-Betic Strait, which is early Tortonian in age. It formed in the southern Prebetic zone and connected the Atlantic-linked Guadalquivir Basin with the Mediterranean Sea through the Prebetic area. In this strait, huge dunes up to 20 m high formed and were displaced by strong tidal currents.

Two straits, located more to the south, differentiated within the Subbetic Zone in the course of the Tortonian. The westernmost one was the Zagra Strait and the easternmost one the Dehesas de Guadix Strait. The Zagra Strait linked the Atlantic Guadalquivir Basin with the Mediterranean Granada Basin. This strait was trending WNW-ESE and had a minimum width of 4 km. Strong tidal currents moved giant dunes along its bottom. Mediterranean-directed flows predominated at its westernmost entrance (Atlantic side) and both Atlantic- and Mediterranean-directed flows at its easternmost end (Mediterranean side).

In the case of the Dehesas de Guadix Strait, the Atlantic-Mediterranean communication was through the Guadalquivir and Guadix basins. In this strait, strong, N-S directed currents, flowing from the Mediterranean to the Atlantic, mobilized giant dunes, up to 15 m high, at its bottom. At the same time, weaker surface currents, flowing from the Atlantic to the Mediterranean, entered the Guadix Basin. The closing of this strait was concomitant to a significant decrease in the Mediterranean bottom-water oxygen-levels that occurred at around 7.9 Ma.

The Guadalhorce Strait, early Messinian in age, is the last Betic Strait. In this NNW-SSE trending strait the Atlantic-Mediterranean communication was via the Atlantic-linked Guadalquivir Basin and the Mediterranean-linked Málaga Basin. The maximum strait width was around 5 km, with a depth range between 60 and 120 m. In this case, migration of bottom dunes, moved by strong bottom currents flowing N-NW (from the Mediterranean to the Atlantic), resulted in the development of giant cross-bedding with cross-bedded sets up to 30 m thick, extending laterally for almost 1 km. The closing of the Guadalhorce Strait at around 6.2 Ma limited the Atlantic-Mediterranean communications to the Rifian straits in northern Morocco and led to an increase of the Mediterranean restriction, resulting in seawater stratification.

The presence of giant cross-stratification is a distinctive feature in the sediments of these ancient straits. This giant cross-bedding, bidirectional or unidirectional, was generated by the migration of the dunes moved either by tides or by density currents respectively. Ancient seaways are thus sedimentologically characterized by the presence of this persistent and ubiquitous giant cross-bedding. Submarine

dunes, comparable in size, abound in present-day straits, moved by strong bottom currents with velocities ranging from 0.7 to 1.5 m/s.

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