MIOCENE ATLANTIC-MEDITERRANEAN BETIC STRAITS (SOUTHERN SPAIN)

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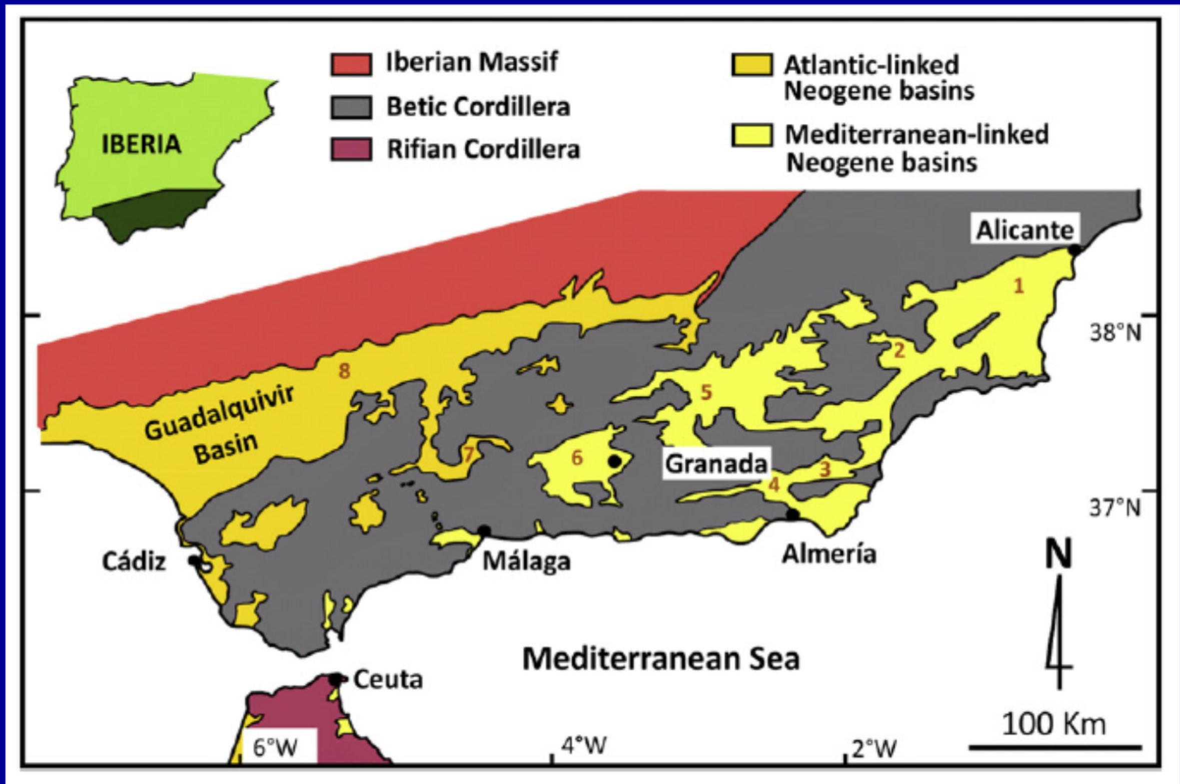
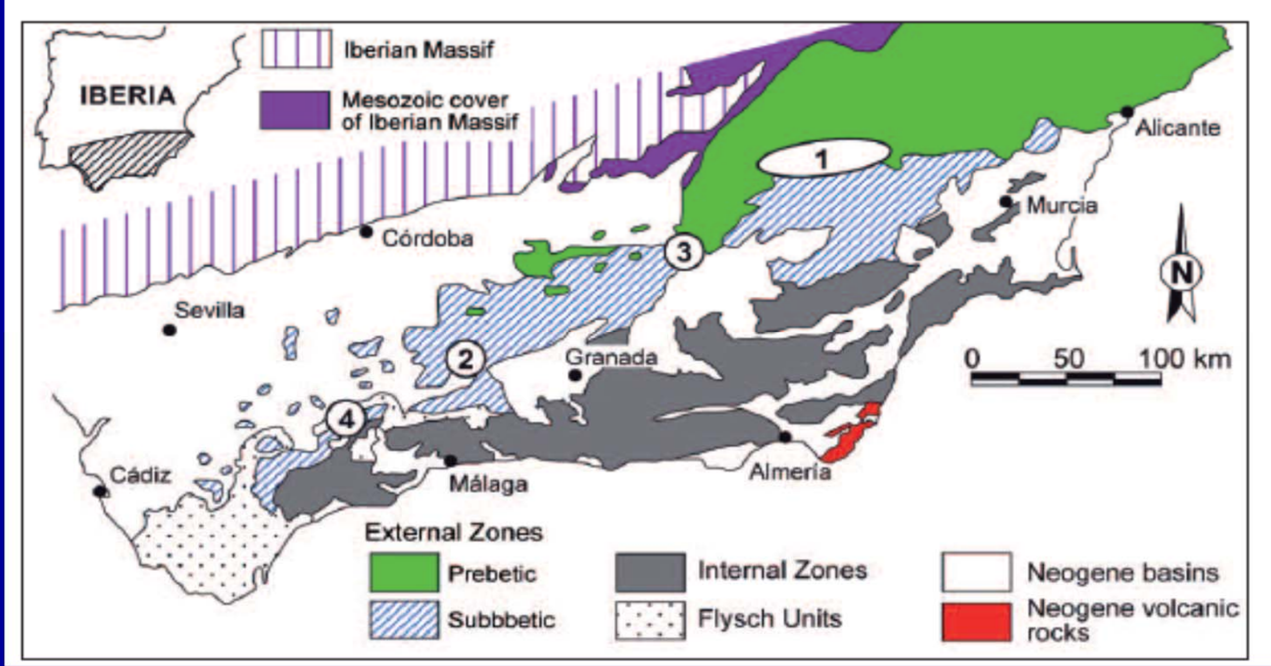
NEOGENE BASINS IN THE BETIC CORDILLERA



Two types: Atlantic-linked and Mediterranean-linked basins

THE CONNECTIONS BETWEEN THE ATLANTIC-LINKED AND THE MEDITERRANEAN-LINKED BASINS: THE BETIC STRAITS

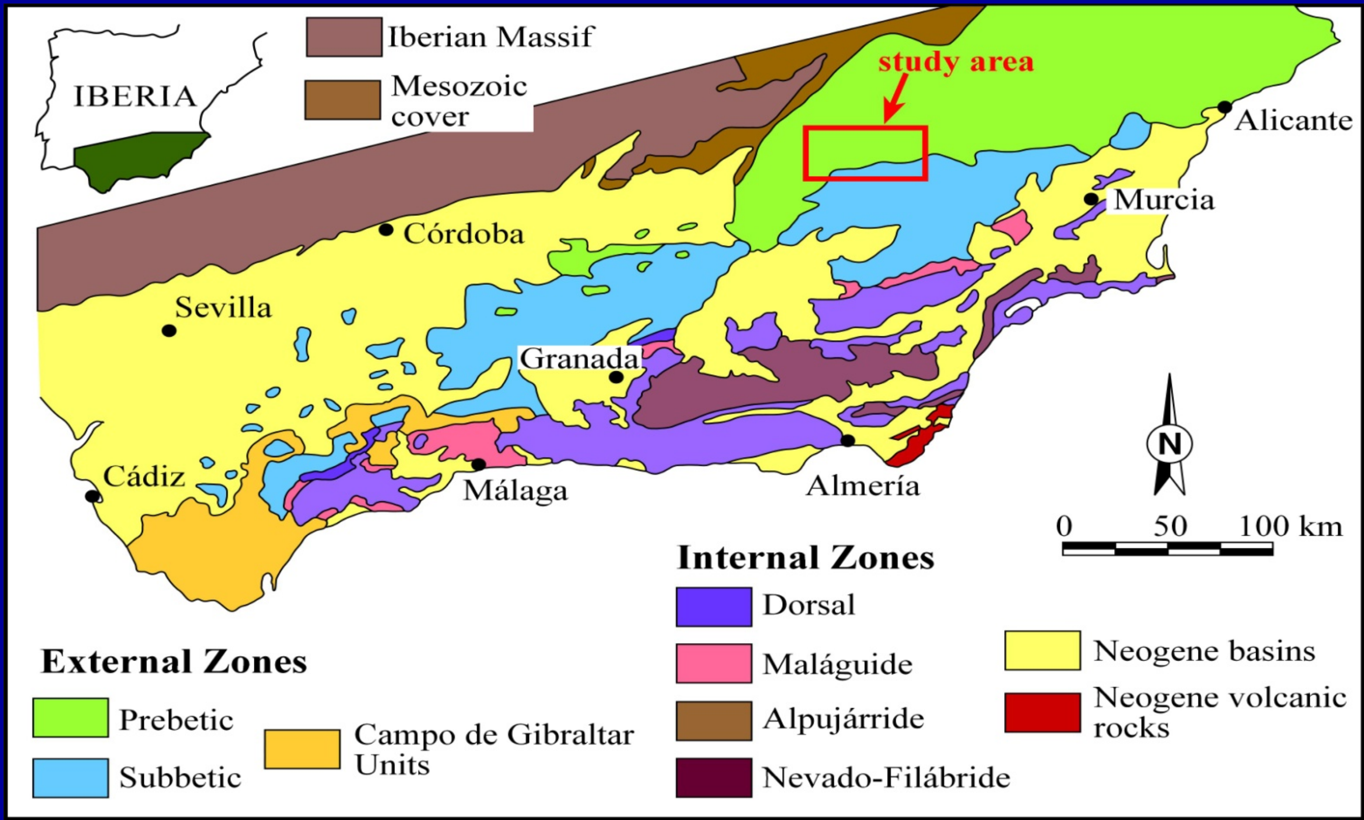
The link between the Mediterranean Sea and the Atlantic Ocean through the Betic Cordillera (southern Spain) was reduced to a few seaways in the Miocene as the mountain belt uplifted during the Alpine orogeny



Strait location 1: North-Betic Strait (early Tortonian); 2: Zagra Strait (Tortonian) ; 3: Dehesas de Guadix Strait (late Tortonian); 4: Guadalhorce Strait (early Messinian)

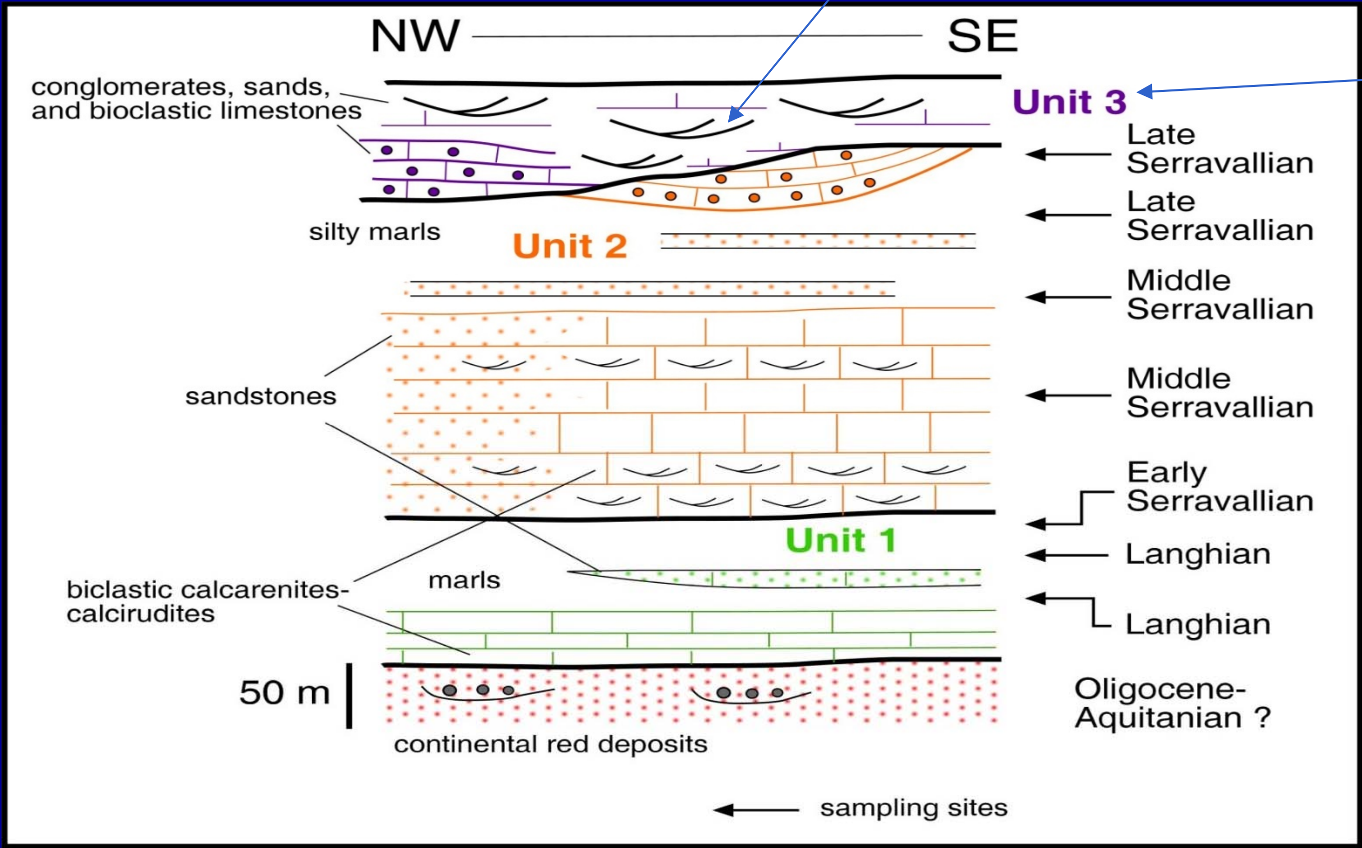
THE NORTH-BETIC STRAIT

The North-Betic Strait was considered for a long time as the main way of communication between the Atlantic Ocean and the Mediterranean Sea during the Miocene although its precise situation and age were unknown. It was thought to be located somewhere in the Prebetic Zone (outermost part of the Betic Cordillera)



THE MIOCENE RECORD OF THE WESTERN PREBETIC

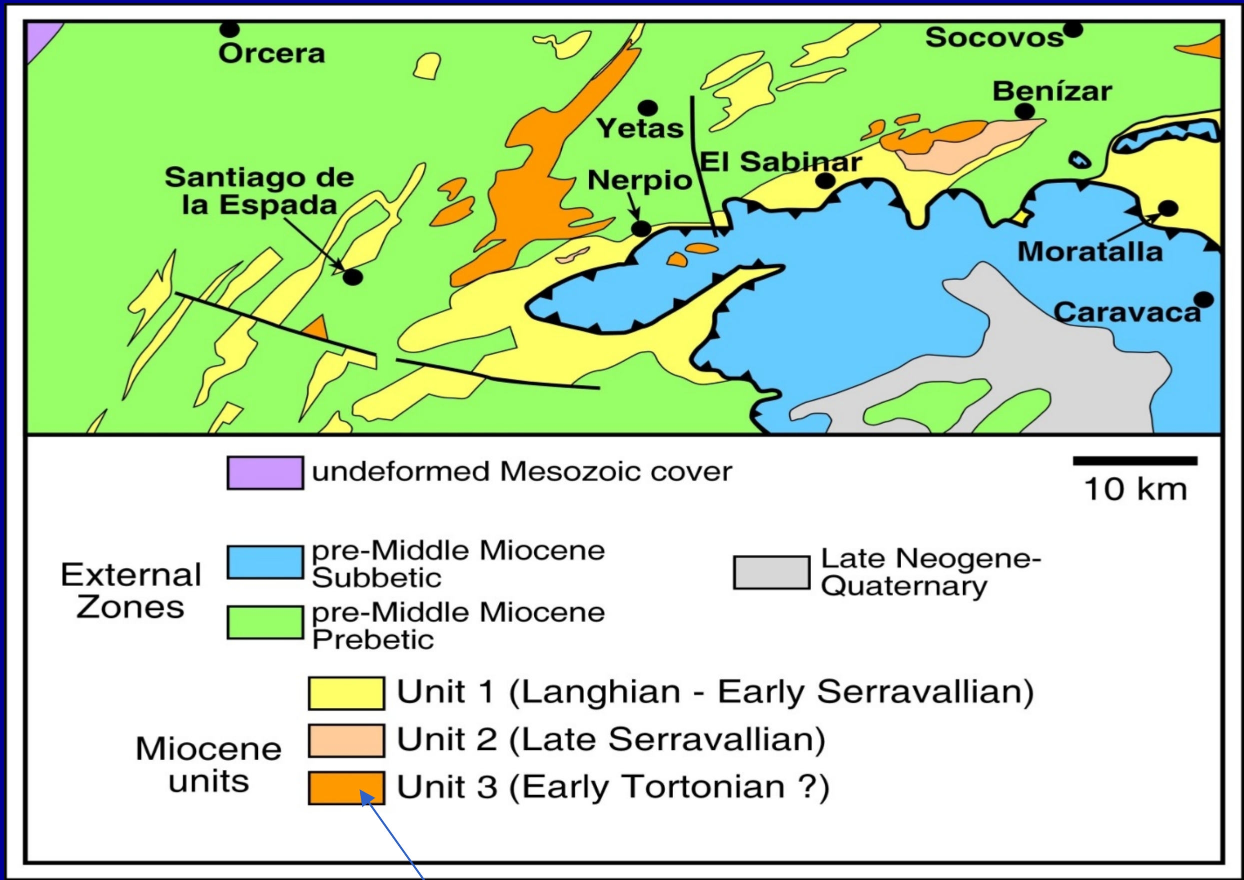
In the western Prebetic the Miocene record comprises several marine units separated by unconformities. The topmost, last marine unit exhibits giant, cross-bedded structures



This unit (Unit 3) is thought to represent the North-Betic Strait deposits

THE NORTH-BETIC STRAIT UNIT

Outcrop distribution



The cross bedded unit (Unit 3) can be traced along a narrow east-west (E-NE/W-SW) trending band for almost one hundred kilometres

THE NORTH-BETIC STRAIT UNIT

Its erosional base

The cross-bedded unit lies unconformably on top of deeply-eroded materials ranging in age from Triassic to Middle Miocene and belonging to both the Prebetic and Subbetic Zones of the Betic Cordillera

THE NORTH-BETIC STRAIT UNIT: LITHOLOGIES

The predominant lithologies are bioclastic carbonates and mixed siliciclastics-carbonates

Carbonates range from calcarenites to medium-grained calcirudites. Bioclasts are mainly from coralline algae, bryozoans and bivalves

Terrigeneous clasts are of quartzites and carbonates (limestones and dolomites). Siliciclastic content may reach up to 30%

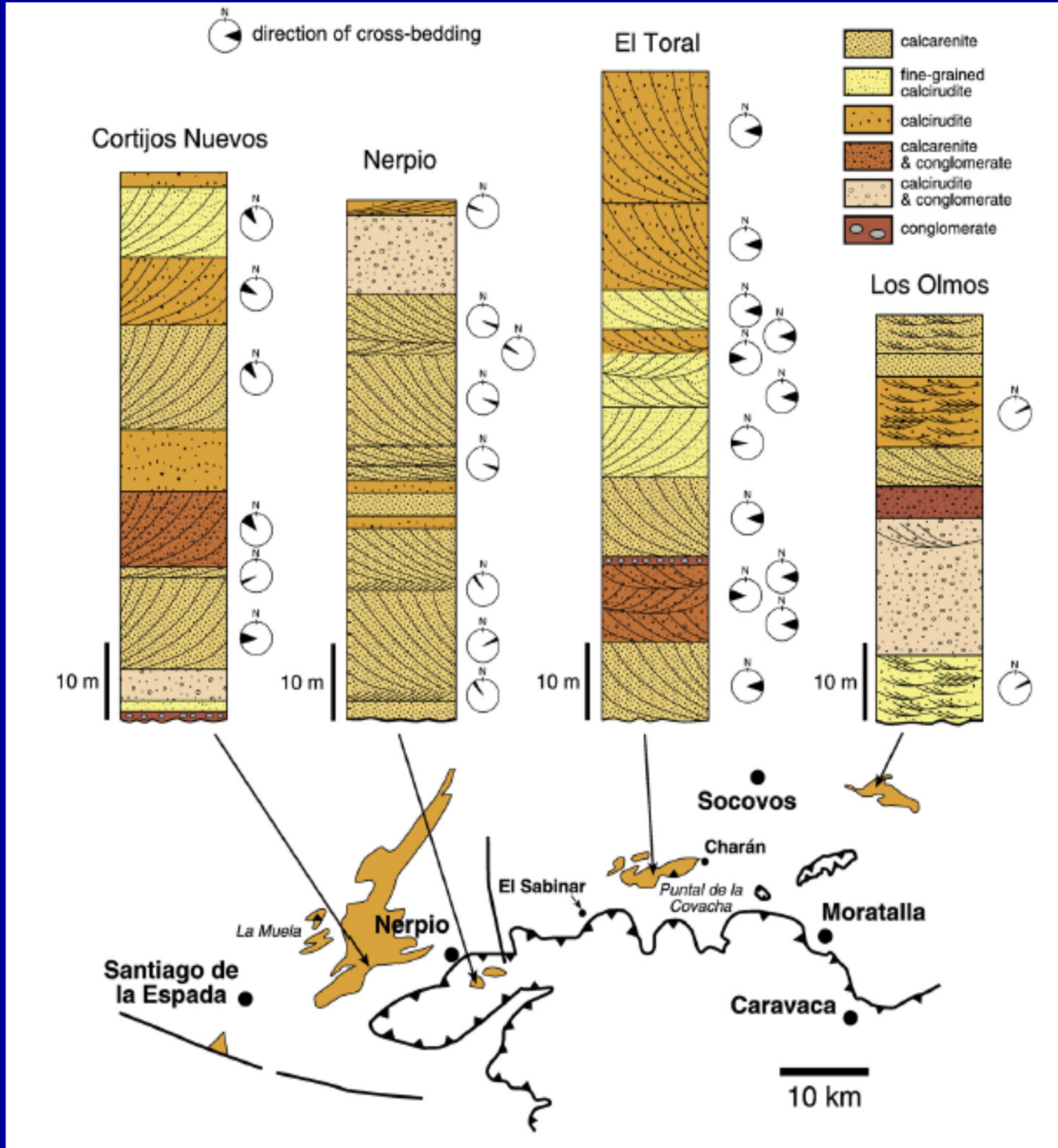
Conglomerates may also appear locally

They correspond to fan-delta deposits, up to 80 m thick, located at the strait margin

THE NORTH-BETIC STRAIT UNIT

Selected sections

Four sections (Los Olmos, El Toral, Nerpio and Cortijos Nuevos sections), along a NE-SW transect, were selected. Further observations were made in the westernmost outcrops (Santiago de la Espada area). All the strait deposit exhibit ubiquiteous, large-scale cross bedding



THE NORTH-BETIC STRAIT DEPOSITS
SEDIMENTARY STRUCTURES

In the eastern outcrops cross-bedded structures, pointing to the East, are up to 5 m high and a few tens of metres in lenght. They locally exhibit herringbone cross-stratification

In the central outcrops the giant cross-bedded structures point both to the East and to the West. Single troughs are up to 15 m high and some tens of metres in lenght

Western outcrops. Giant, cross-bedded structures point to the W-NW

In the westernmost outcrops, giant cross-bedded structures, pointing to the W-SW, are up to 20 m high and a few hundreds of metres in lenght

THE NORTH-BETIC STRAIT

Genesis of the giant cross-bedding

The giant cross-bedding was generated by migration of large-scale dunes moved by tides. Similar structures are found in Present-day, tide-dominated channels (Berné, 1991), with current velocities of up to 1.5 m/s

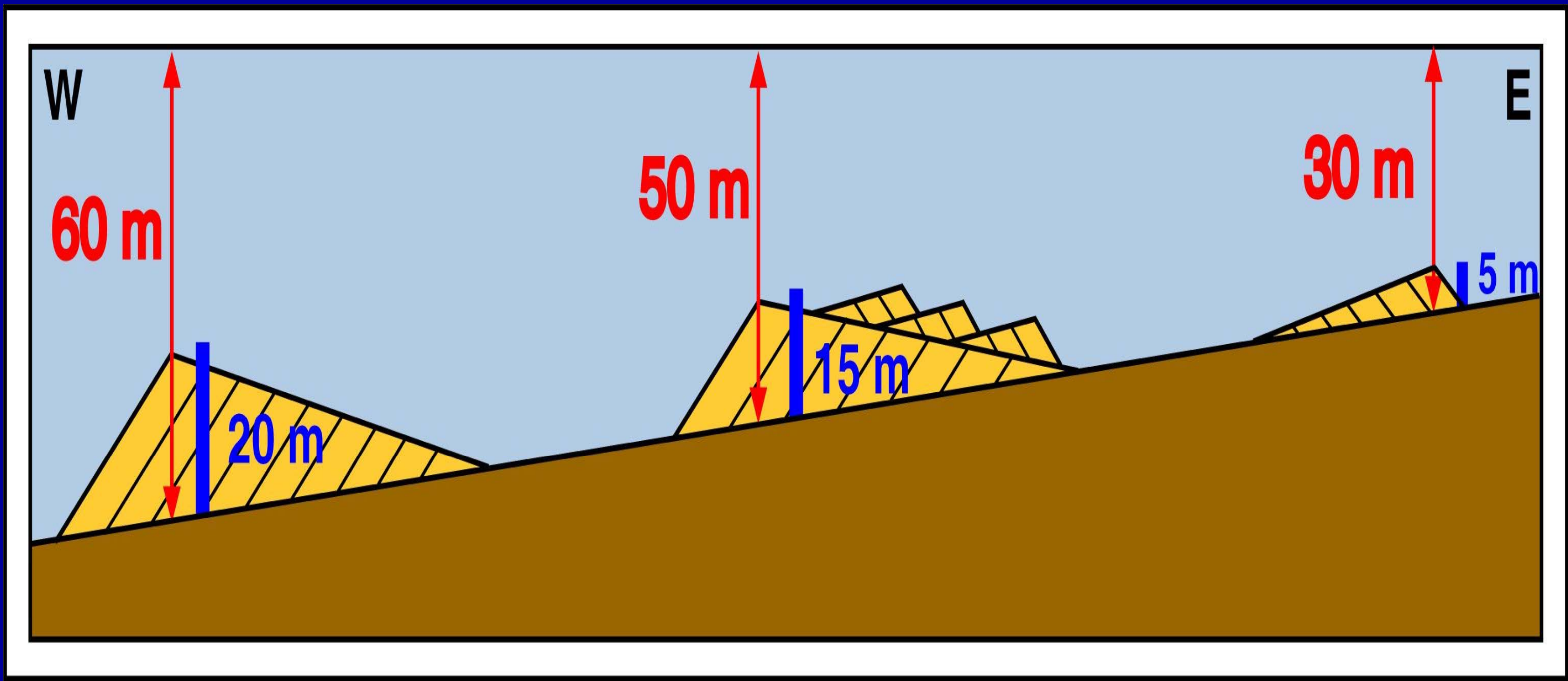
Cross-bedding distribution

The cross-bedding distribution is similar to that observed in some Present-day tidal channels which show a flood-dominated shallower area, an intermediate flood/ebb area and a deeper ebb-dominated zone. The ebb currents generated the largest cross-bedding

Depositional depth

In modern settings a relationship exists between height of dunes and depositional depth. According to Rubin and McCulloch (1980) and Dalrymple and Rhodes (1995), H = 0.17 D (H = height of the dune; D = depositional depth), which means a depositional depth of approximately 30 m for the 5 m high dunes, 90 m for the 15 m high, and 120 m for the 20 m high respectively

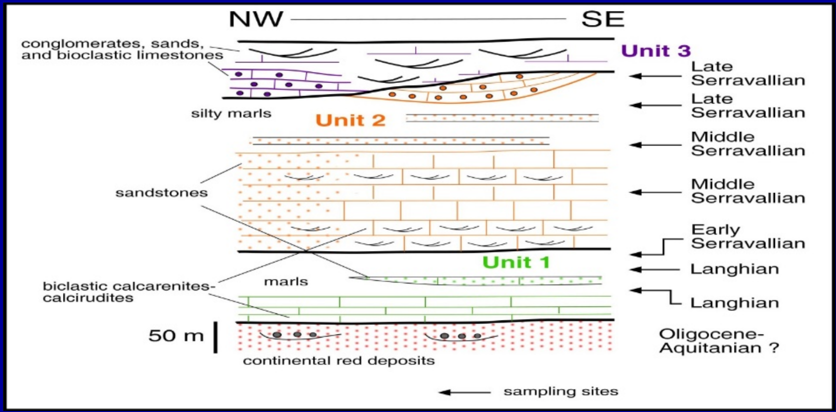
Following Berné's (1991) proposed equation (H = 0.50 D – 10.2), significantly smaller values would result for the highest dunes (30 m for the 5 m high dunes as before, but 50 m only for the 15 m high, and 60 m for the 20 m high respectively). These latter figures seem to be more in accordance with what is observed in recent tidal environments



The North-Betic Strait shallowed to the East and deepened to the West

BASIN EVOLUTION AND DIFFERENTIATION OF THE NORTH-BETIC STRAIT

The Miocene record of the western Prebetic Zone revisited

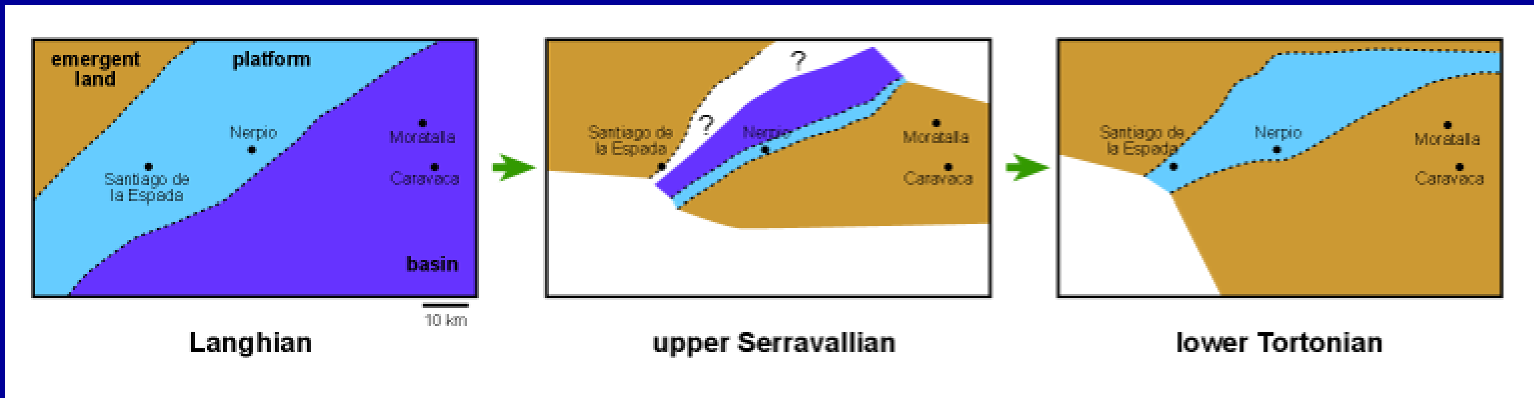


Unit 3 (presumably lower Tortonian in age) corresponds to the last marine deposits found in the area, which accumulated within the North-Betic Strait

Unit 2 (Serravalian in age) is made up of marine carbonate and detrital rocks, linked to a southern relief formed as a result of the uplifting of the NW overthrusted Subbetic-nappes

Unit 1 (Langhian in age), with platform deposits to the N-NW and basinal deposits to the S-SE, represents the last Prebetic materials linked to a northern emerged area

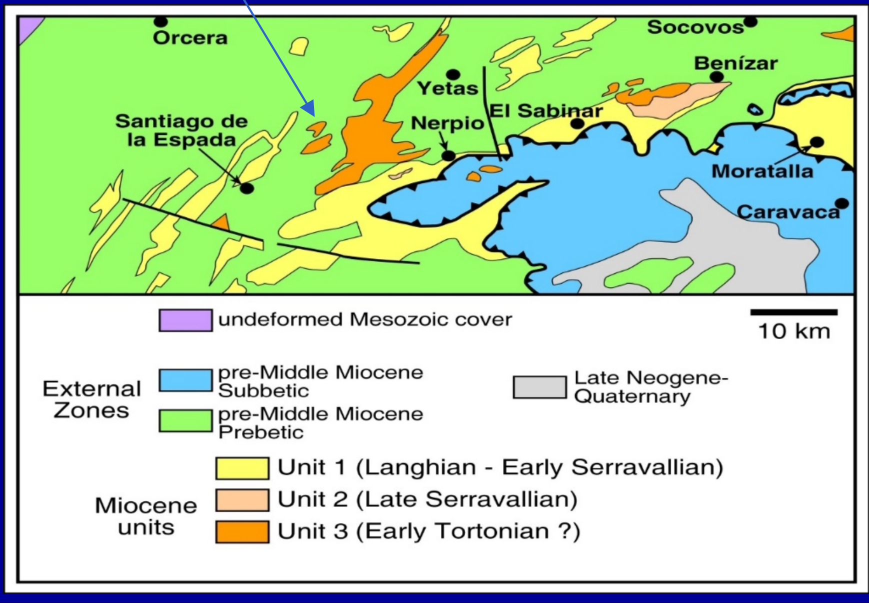
The evolution towards the formation of the North-Betic Strait can be divided into a series of steps. The palaeogeography evolved from a southern-facing platform, marginal to a northern relief, to a wide-open marine passage limited by a southern platform (Braga et al., 2010) and, finally, to a tidal-dominated strait (Martín et al., 2009). This strait was at least 85 km long and reached up to 18 km at its widest point



THE CLOSING OF THE NORTH-BETIC STRAIT

The closing of the North-Betic Strait is recorded by the presence of some lagoonal, silty deposits, covered by a stromatolite layer and crowned by a red soil, found on top of the La Muela outcrop, NE of Santiago de la Espada

La Muela outcrop



red soil

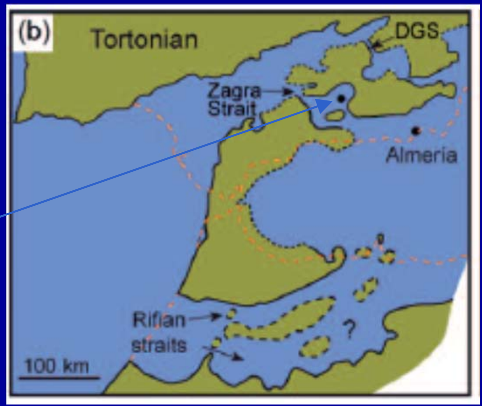
stromatolite bed

silty marls

THE ZAGRA STRAIT

In this Tortonian Strait the Atlantic-Mediterranean communication was through the NW of the Granada Basin

Granada Basin



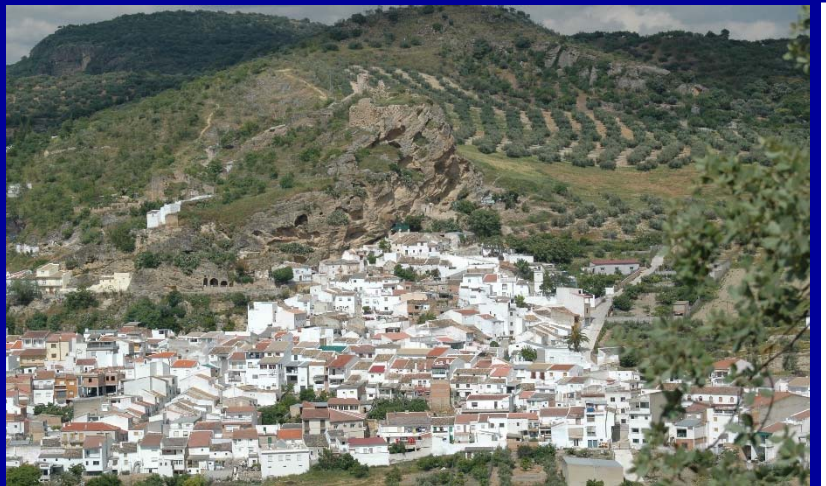
Strait deposits occur along a N110°E trending belt, with a minimum width of 4 km

Strait sediments (up to ~ 200 m thick) lie unconformably on top of Serravallian marls and older deposits

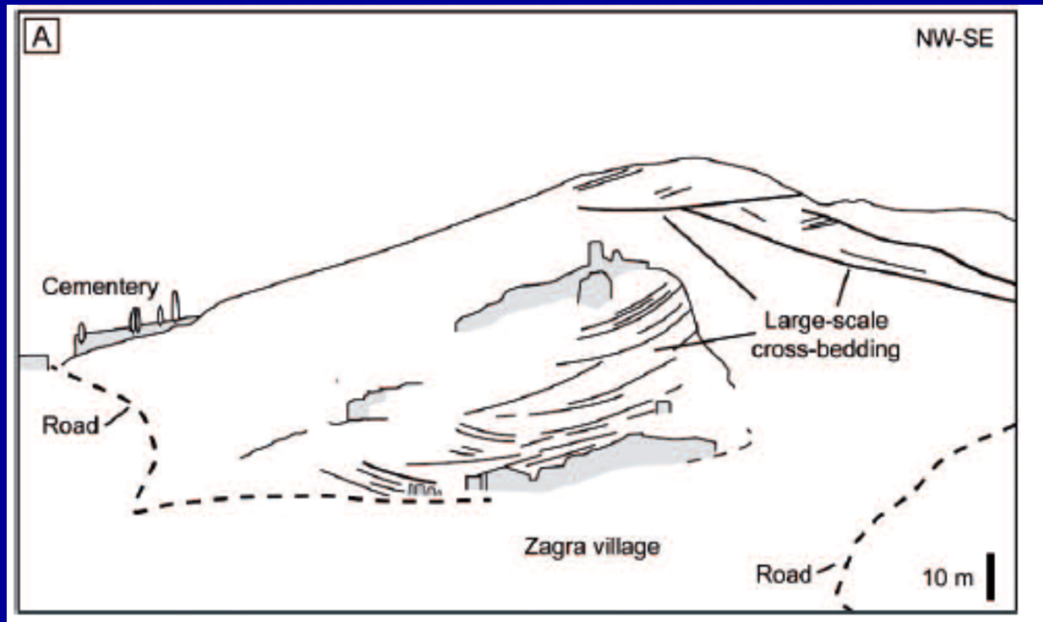
Strait sediments are bioclastic sands (bioclasts are mainly from bryozoans and bivalves) and conglomerates, displaying large-scale cross-bedding

THE ZAGRA STRAIT DEPOSITS: SEDIMENTARY STRUCTURES

In the westernmost outcrops (former Atlantic Ocean side) giant trough cross-bedding (up to 25 m high and several 100 m long), pointing to the SE, is the dominant sedimentary structure. Slumped (to the SE) giant dunes occur at the base of the sequence



In the easternmost outcrops (former Mediterranean Sea side) both N-NW dipping and S-SE dipping, large-scale (up to 25 m high and 150 m long) trough cross-bedded sets are frequent



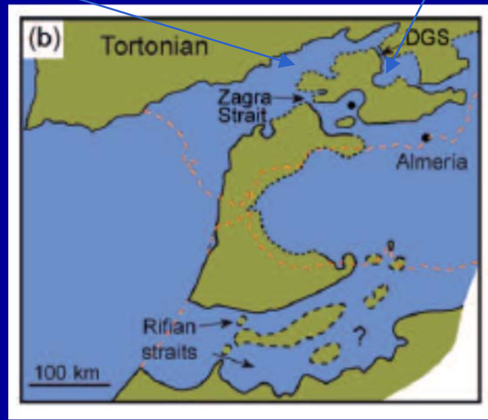
The Zagra seaway was a tide-dominated strait, with Mediterranean-directed flow dominating its western, Atlantic side, while bidirectional, Atlantic- and Mediterranean-directed flows predominated on its eastern, Mediterranean side

THE DEHESAS DE GUADIX STRAIT

The “Dehesas de Guadix” Corridor was a narrow (~ 2 km wide), Late-Tortonian N-S trending strait connecting the Atlantic Ocean and the Mediterranean Sea via the Guadalquivir and Guadix basins

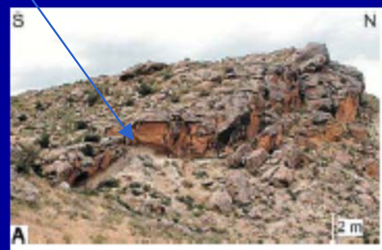
Guadalquivir Basin

Guadix Basin



DGS: Dehesas de Guadix Strait

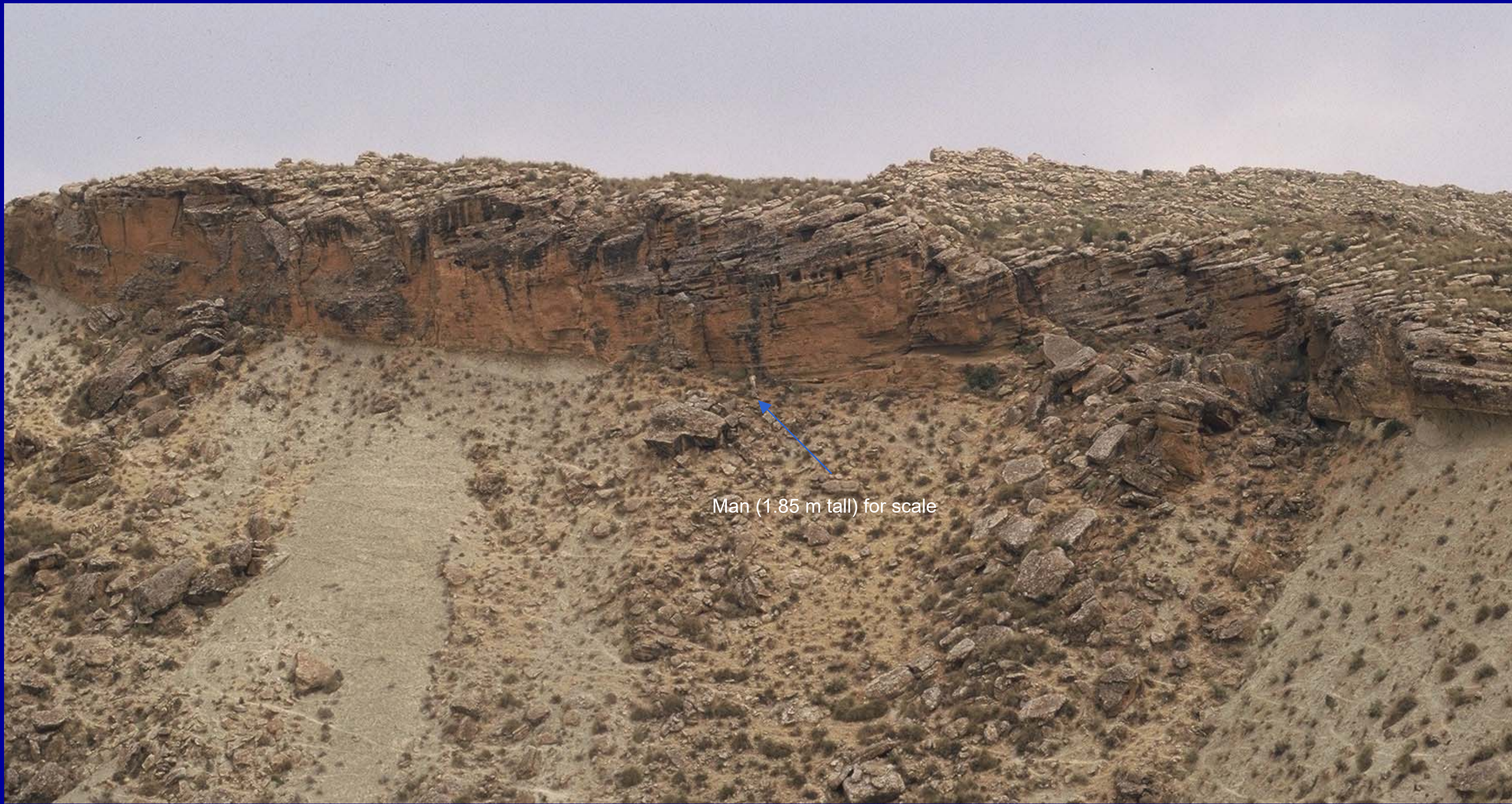
Strait sediments lie unconformably on top of Middle Miocene and upper Tortonian marls



Strait deposits are up to ~ 100 m thick

THE “DEHESAS DE GUADIX” STRAIT DEPOSITS SEDIMENTARY STRUCTURES

Sediments are bioclastic sands and conglomerates (bioclasts are mainly from bivalves, brachiopods, and bryozoans), displaying unidirectional, large-scale cross-bedding. Strong bottom currents flowing from the Mediterranean Sea to the Atlantic Ocean moved giant dunes, resulting in the development of unidirectional, North-dipping (Atlantic-dipping) large-scale cross-bedding. Cross-bedded sets were up to 15 m high and 70 m long. Estimated paleodepths were 70 to 90 m

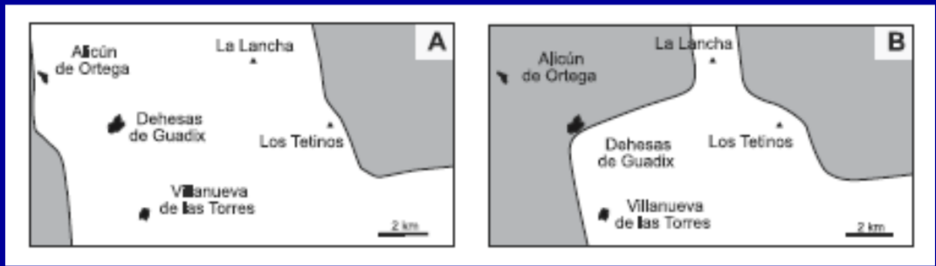


BASIN EVOLUTION AND DIFFERENTIATION OF THE DEHESAS DE GUADIX STRAIT

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). It evolved into a narrow (no more than 2 km wide), confined strait before closing

The 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

PALAEOGEOGRAPHICAL EVOLUTION



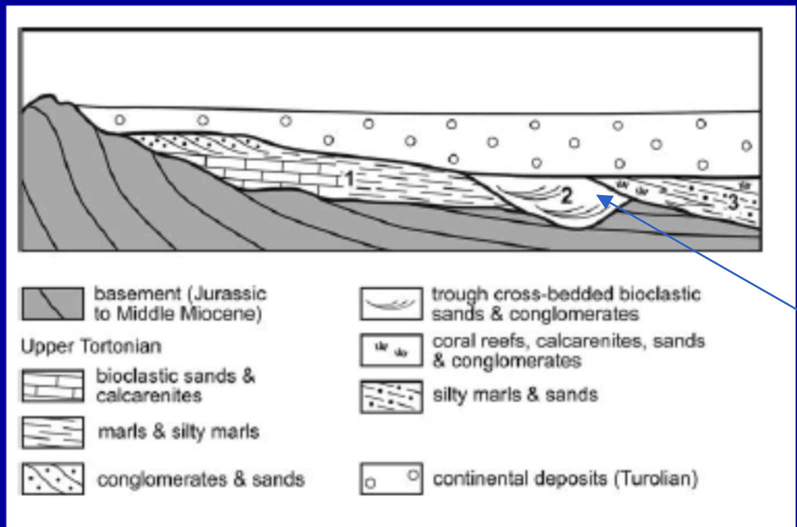
Unit 1

Unit 2

Coral reef

Unit 3

During this interval, some coral reef growth took place on the basin margins



Strait deposits

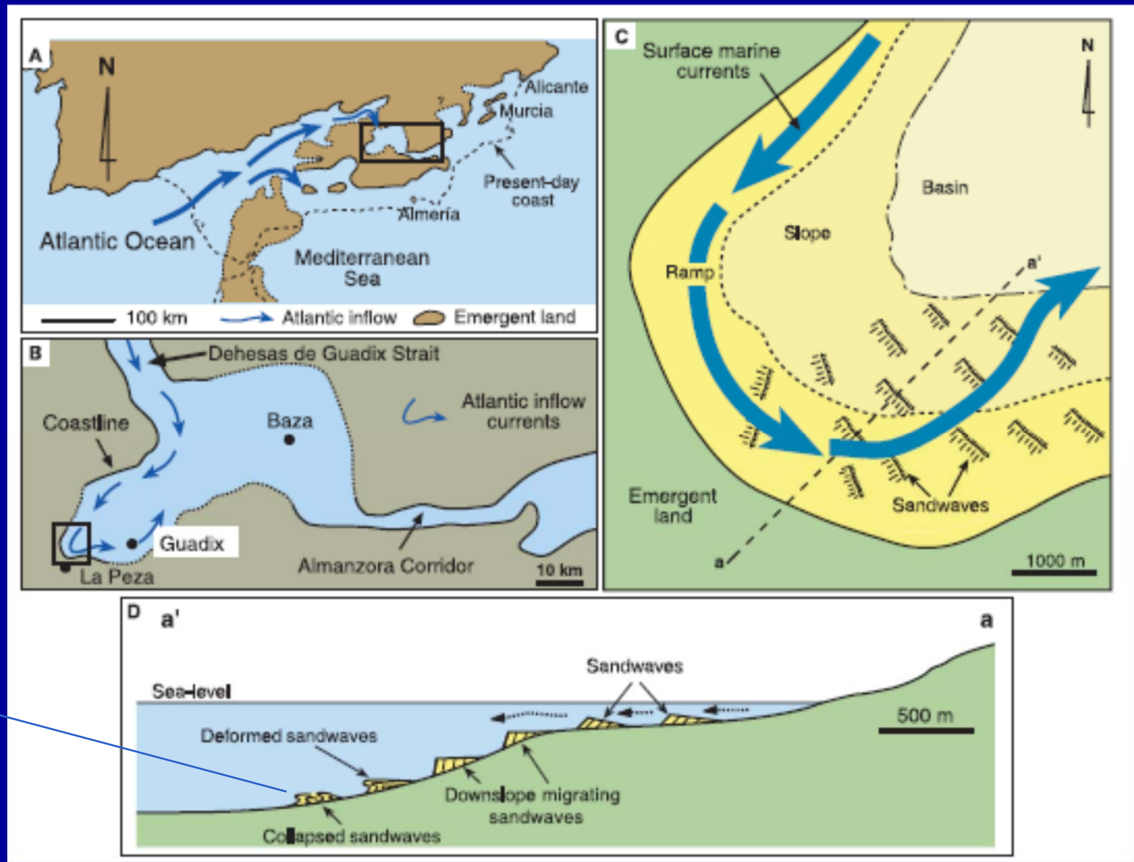
Strait deposits: cross-bedded strata dipping to the North

Reef slopes dipping to the South

THE DEHESAS DE GUADIX STRAIT
THE SURFICIAL WATER-CIRCULATION PATTERN

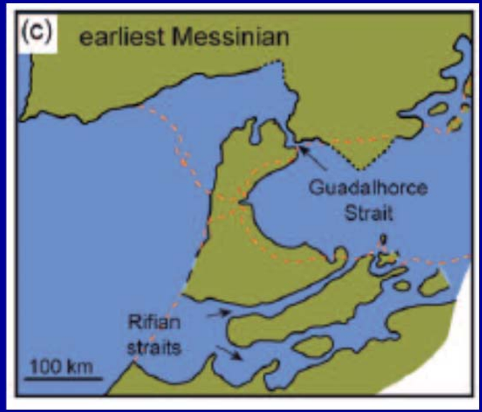
In the “Dehesas de Guadix” Strait, contemporaneous with the Mediterranean bottom currents, there were Atlantic, counter-clockwise surface currents flowing southwards, into the Guadix Basin (Puga et al., 2010)

In relation with this circulation pattern and within the Guadix Basin a downslope-migrating sandwave field developed in its southern margin, with sandwaves moving progressively down the ramp to the ramp-slope, where they destabilized, folded and occasionally collapsed

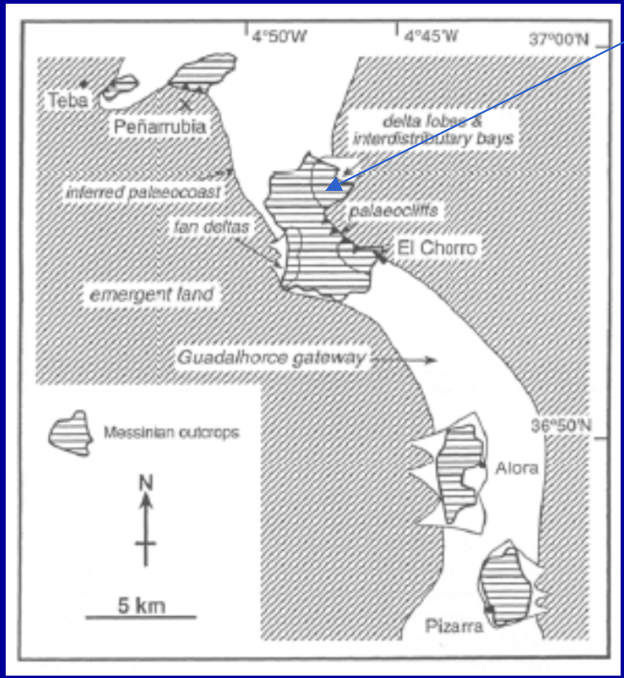


THE GUADALHORCE STRAIT

The Guadalhorce Corridor was a Late Miocene (early Messinian) strait connecting the Atlantic Ocean and the Mediterranean Sea via the Guadalquivir and Málaga basins



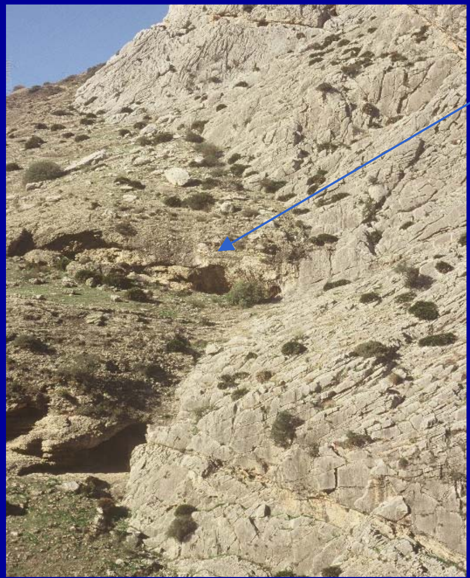
Palaeogeographical map and strait deposits



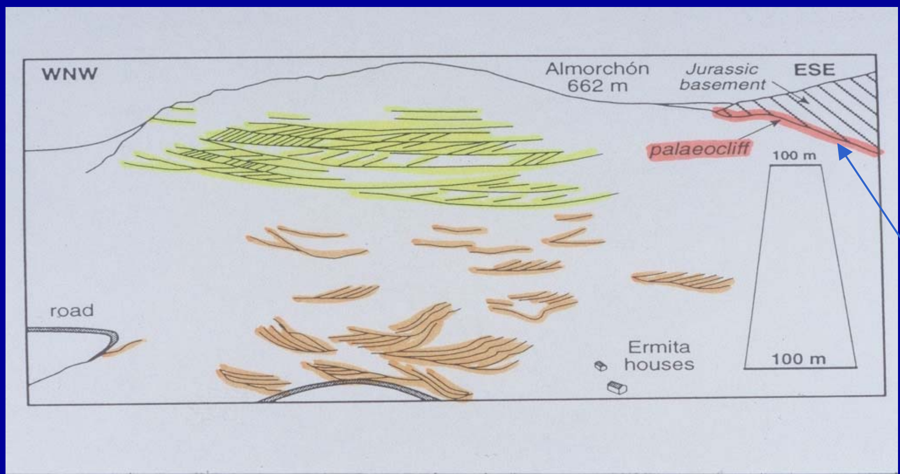
The Guadalhorce Corridor was a 30 km long and up to 5 km wide, NNW-SSE trending strait

Horizontal to gently dipping layers of the Messinian strait-infilling stand out in the centre of the picture. The Miocene beds are limited by Paleozoic schists (seen at the foreground) and Jurassic limestones (seen at the background)

MAJOR FEATURES OF THE GUADALHORCE STRAIT PALAEOCLIFFS



Limestone blocks, fallen from the cliff wall, stand out embedded within the Miocene sediments

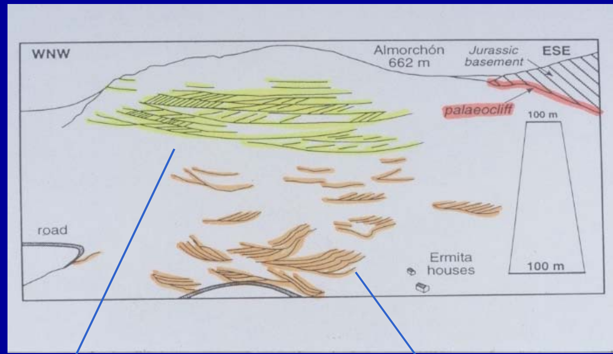


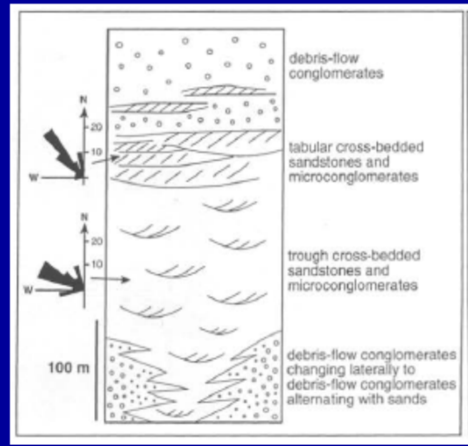
Horizontal Miocene layers abut abruptly against vertical Jurassic limestone strata. This NW-SE aligned contact corresponds to a palaeocliff-wall, marking the eastern margin of the Guadalhorce gateway

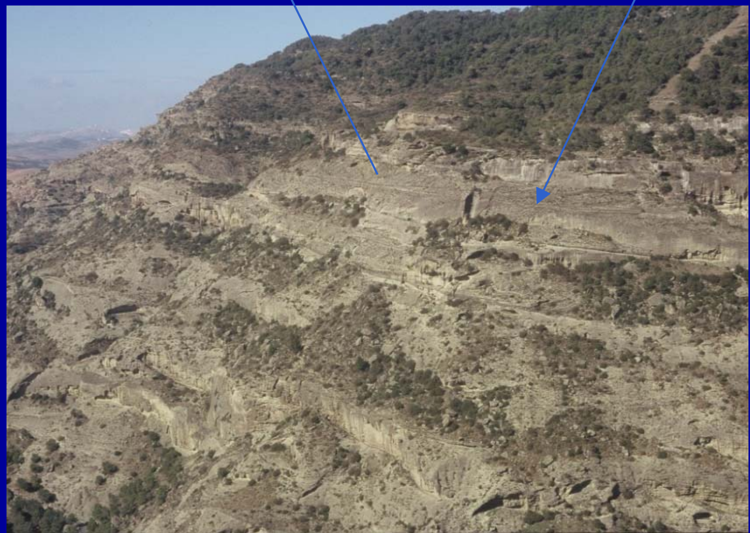
THE GUADALHORCE STRAIT SEDIMENTARY STRUCTURES

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



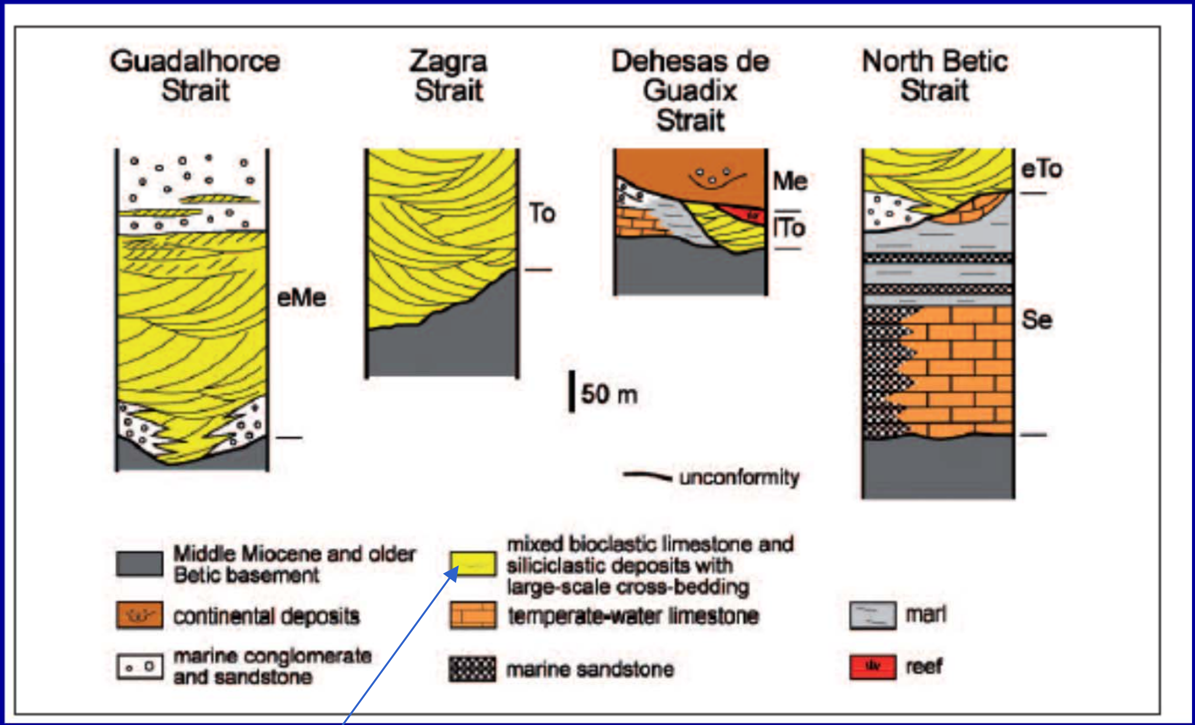




Large-scale (up to 20 m high and 100 m in length) trough cross-bedding is widespread in the lower part of the strait sequence. Large-scale tabular cross-bedding characterizes the upper part. In this latter case, individual bed sets can be up to 30 m thick, extending laterally for almost 1 km. Current velocities of 1-1.5 m/s have been estimated for the formation and mobilization of the submarine dunes. Inferred depositional depths range between 60 and 120 m

HOW TO RECOGNIZE ANCIENT STRAITS?

Huge, cross-bedded structures are characteristic features in the sedimentary record of these ancient straits



Strait deposits

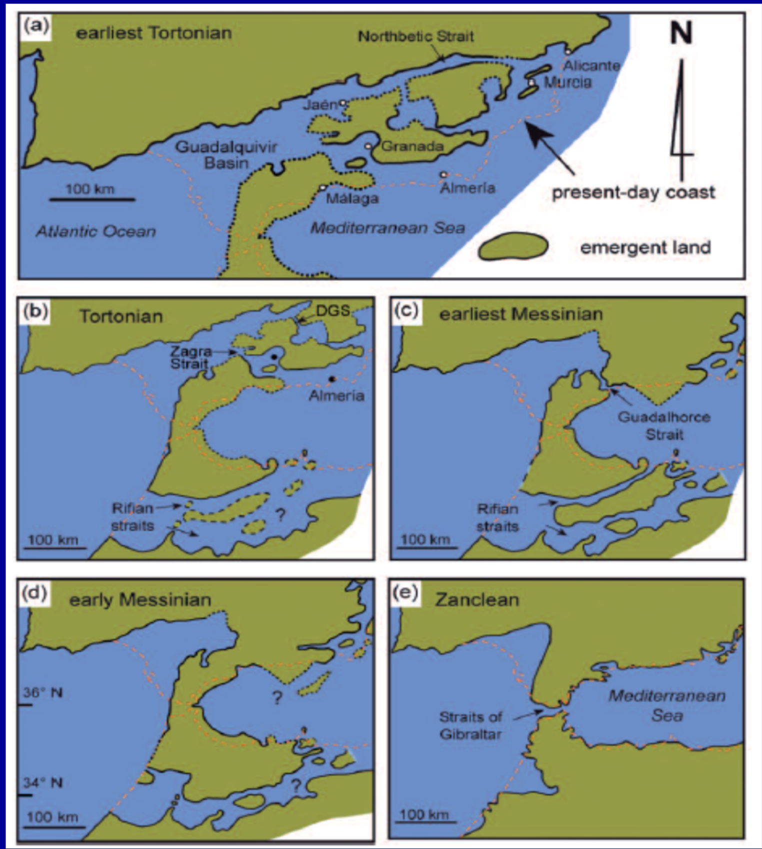
Sediment ages
Se: Serravalian; eTo: early Tortonian; To: Tortonian; lTo: late Tortonian; eMe: early Messinian; Me: Messinian

The North-Betic and Zagra Straits were tide dominated; the Dehesas de Guadix and Guadalhorce Straits were current dominated. In the latter two cases, bottom currents flowing from the Mediterranean Sea to the Atlantic Ocean moved giant dunes on the sea floor generating the large-scale (giant) cross bedding

EVOLUTION OF THE ATLANTIC-MEDITERRANEAN CONNECTIONS

The northern Betic connections: In the early Tortonian, a narrow passage, the North-Betic Strait (Martín et al., 2009), existed North of the Cordillera, limited by an emerged southern relief. In the late Tortonian, the Betic Atlantic-Mediterranean connections were through the Dehesas de Guadix Corridor (DGS) (Betzler et al., 2006) and the Zagra (Martín et al., 2014) Straits. The Guadalhorce Strait (Martín et al., 2001) formed and closed in the early Messinian

The southern Rifian connections: The Rifian Straits, located in northern Morocco, represent the other major Miocene connection between the Atlantic Ocean and the Mediterranean Sea. 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 (Esteban et al., 1996), after the Betic Guadalhorce Corridor closed (at ~ 6.2 Ma ago; Pérez-Asensio et al., 2012) in the early Messinian



The Gibraltar Straits 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)

PALAEOCEANOGRAPHICAL IMPLICATIONS

The closing of the Dehesas de Guadix Strait, at 7.8 Ma, 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)

The closing of the Guadalhorce Strait at around 6.2 Ma 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. Available paleontological and geochemical (stable isotope) data from Mediterranean sediments deposited immediately prior to the Messinian Salinity Crisis (Vergnaud-Grazzini, 1985; Glaçon et al., 1990; Kouwenhoven et al., 2003) support this assumption

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