Geo-Marine Letters (1992) 12:165–172

Geo-Marine Letters

Stratigraphic and Tectonic Evolution of the Western Alboran Sea: Late Miocene to Recent

A. C. Campillo,[1] A. Maldonado,[1] and A. Mauffret[2]

[1]Instituto de Ciencias del Mar, CSIC, Paseo Nacional s/n, 08039 Barcelona, Spain, and [2]Département de Géodynamique, Tectonique et Environement/CNRS, Université Pierre et Marie Curie, 75252 Paris CEDEX 05, France

Manuscript received 29 July 1991; revision received 12 December 1991

Abstract. The western Alboran Sea contains three morphostructural domains: continental margins, structural highs, and basins, some with diapirs. Seven sequences from Tortonian to upper Quaternary, identified on airgun profiles, record a distinct set of depositional events. The tectonic evolution was influenced by the relative movement of the African and Iberian plates. Connections through the Atlantic/Mediterranean gateways and global sea level oscillations are recorded as major unconformities in the depositional record. A Neogene change in tectonic character from transtensional to transpressional regimes is postulated on the basis of changes in the regional stress field orientation.

Introduction

Inquiries concerning the origin of the western Alboran Sea concentrate on the geodynamic evolution and detailed seismic stratigraphy, largely influenced by the tectonic events and the development of the Atlantic–Mediterranean gateway (Weijermars 1988). Seismic reflection profiles of the Alboran Sea show that its western sector contains the largest basin and probably the thickest and oldest depositional sequences (Mulder and Parry 1977; Megías 1982). This basin, created under a generalized compressional regime, underwent an important subsidence after the early Miocene as shown by its several kilometers thick Neogene and Quaternary deposits (Le Pichon and others 1972). The Late Miocene to Recent stratigraphy of this area is based, actually, on results from DSDP Site 121 (Ryan and others 1973), although this drill-site has been the subject of several controversies concerning the identification of the upper Miocene units (Olivet and others 1973; Auzende and others 1975; Pastouret and others 1975; Montenat 1977). The base of this drill-site was initially identified as Tortonian but lately reinterpreted as Messinian.

Furthermore, the Late Miocene paleoceanography in relation to the Atlantic/Mediterranean gateway and to the Mediterranean salinity crisis is not well understood, because different studies propose conflicting interpretations, such as the presence of thick evaporite deposits in the western Alboran basin (Auzende and others 1975; Dillon and others 1980).

We concentrate on the interpretation of the stratigraphic and tectonic evolution of the western Alboran Sea, particularly from the Late Miocene to present (Fig. 1A). This work uses recently collected airgun reflection profiles to provide a detailed definition of depositional sequences and tectonic events, not previously available from deep-penetration seismic surveys. A new seismic stratigraphy is proposed on the basis of the correlation of these profiles with lithologic units defined on DSDP Site 121 and the identification of key stratigraphic horizons of regional distribution.

Methods

Three cruises were conducted aboard B/O García del Cid during 1989–1990 (GC-89-1, GC-90-1, GC-90-2) collecting single-channel airgun seismic reflection profiles (Fig. 1B). Different airgun sources were deployed, from 80 to 160 in^3 (13 to 26 deciliters) and recorded in two different hydrophone arrays (80 and 120 element SIG hydrophones). More than 2,000 km of new seismic lines were obtained on analog records at 1, 2, and 4 sec (two-way travel time). All seismic data were processed onboard and represented in analog format. Navigation was by NAVSTAR G.P.S. and Transit satellites.

About 400 km of single channel, deep penetration flexotir seismic profiles from Polymede I, and more than 200 km from Geomede cruises were interpreted (Fig. 1B). Seismic profile interpretations of Atlante and Gibraltar II cruises were also utilized. The abundance of research cruises that collected seismic data are compiled in Fig. 1B.

Morphostructure and Seismic Stratigraphy

The western sector of the Alboran Sea is limited to the west by the arcuate orogen of the Rif Mountains and Betic Cordilleras, which are incised in the arc axis by the Strait of Gibraltar (Andrieux and others 1971; Horvarth and Berckhemer 1982). To the east, the Alboran Sea opens to the

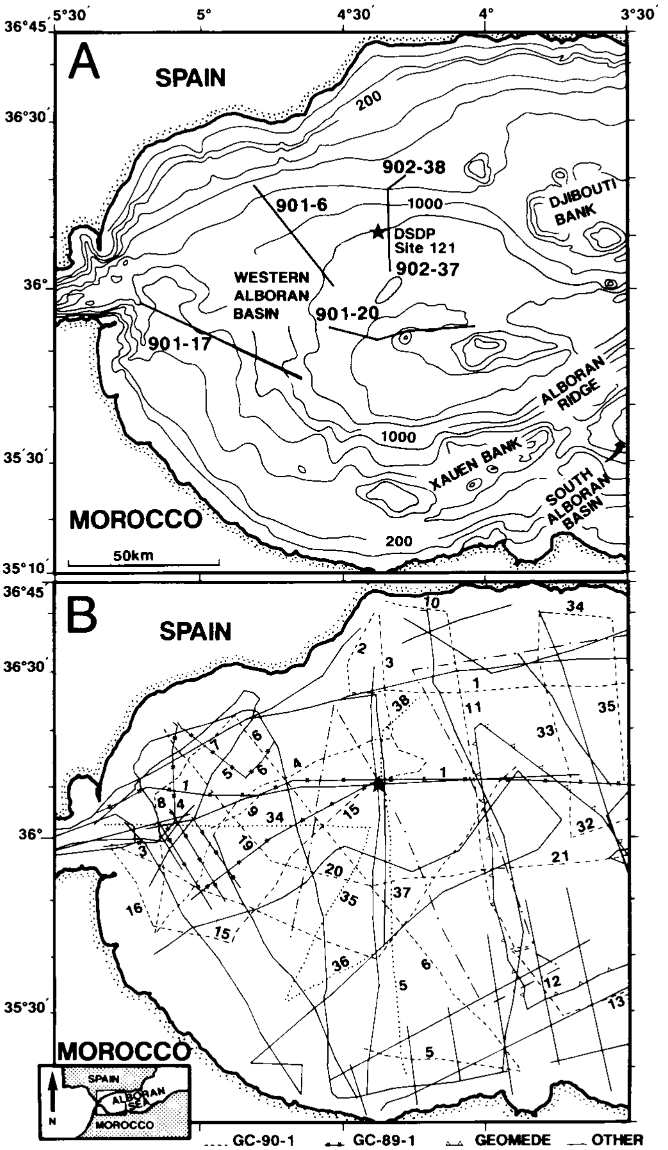

Figure 1. Western Alboran Sea. A: Bathymetric chart showing the location of the seismic profiles illustrated in Figures 3–5. Soundings in meters. Base chart IOC-UNESCO (1981). B: Seismic profiles gathered during various cruises. Profiles Shell 1975 from Mulder and Parry (1977).

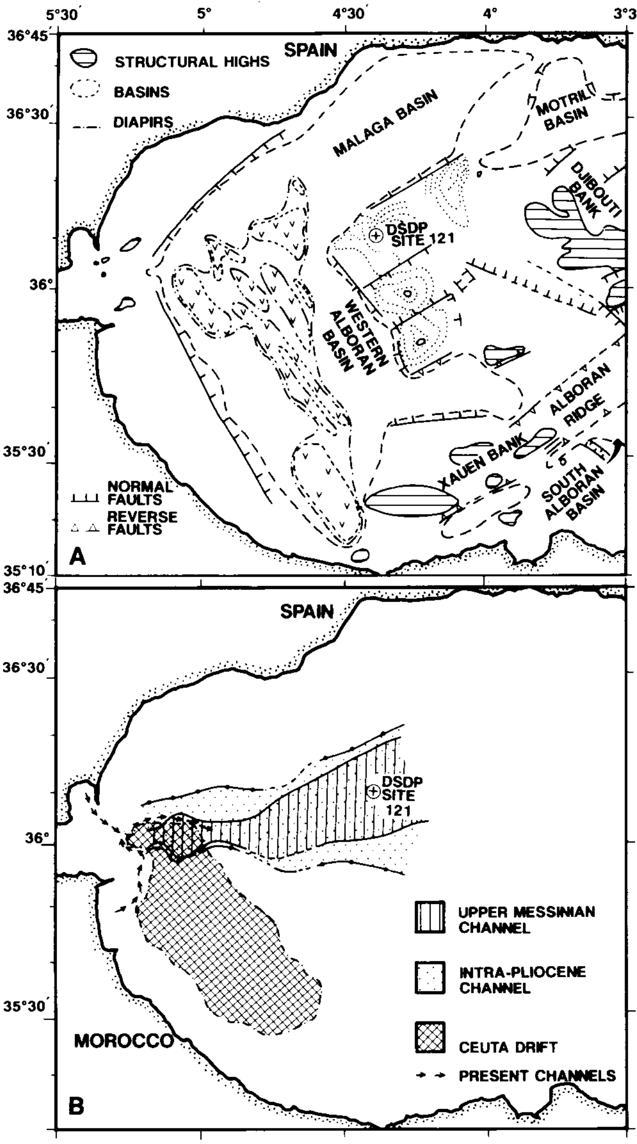

Figure 2. Morphostructural chart of the western Alboran Sea. A: Main morphostructural elements. B: Ceuta Drift and upper Messinian and intra Pliocene channels. Explanation in text.

Algerian–Balearic basin plain, limited by the 2,000 m isobath. The western end of the Alboran Ridge is the most prominent feature, composed of a series of seamounts and intervening depressions oriented in an east-northeast direction (Fig. 1A). The western Alboran Basin has a subdued, gentle sloping to subhorizontal bottom topography in the center with water depths of 1,400–1,500 m. Several irregular submarine banks were also observed between the Spanish margin and the Alboran Ridge (Fig. 1A).

Morphostructural Domains

Three main morphostructural domains are differentiated: (1) the continental margins of Spain and Morocco, (2) the western Alboran, Málaga, and Motril basins, and (3) the structural highs of the Alboran Ridge and the Djibouti and Xauen banks. Another structural high of the basement is called DSDP Site 121 High (Figs. 1A and 2A).

The Spanish continental margin is characterized by gentle relief, with a gradual transition from shelf to slope and to base-of-slope provinces. The deposits above the structural blocks of the acoustic basement are thick and generally not disrupted by faulting (Fig. 3A). The Moroccan continental margin shows, in contrast, two different styles. In the western, north-northwest oriented sector, the proximal continental margin is mostly characterized by a narrow and rather sediment-starved continental shelf, with outcrops of the Internal Rifean zones (Tesson and others 1987). Above the structural blocks of the basement, the slope and base-of-slope are occupied by thick depositional units not affected by faulting (Fig. 3B). The other sectors of the continental margin of Morocco and the Alboran Ridge are characterized by structural blocks of the basement with a very irregular

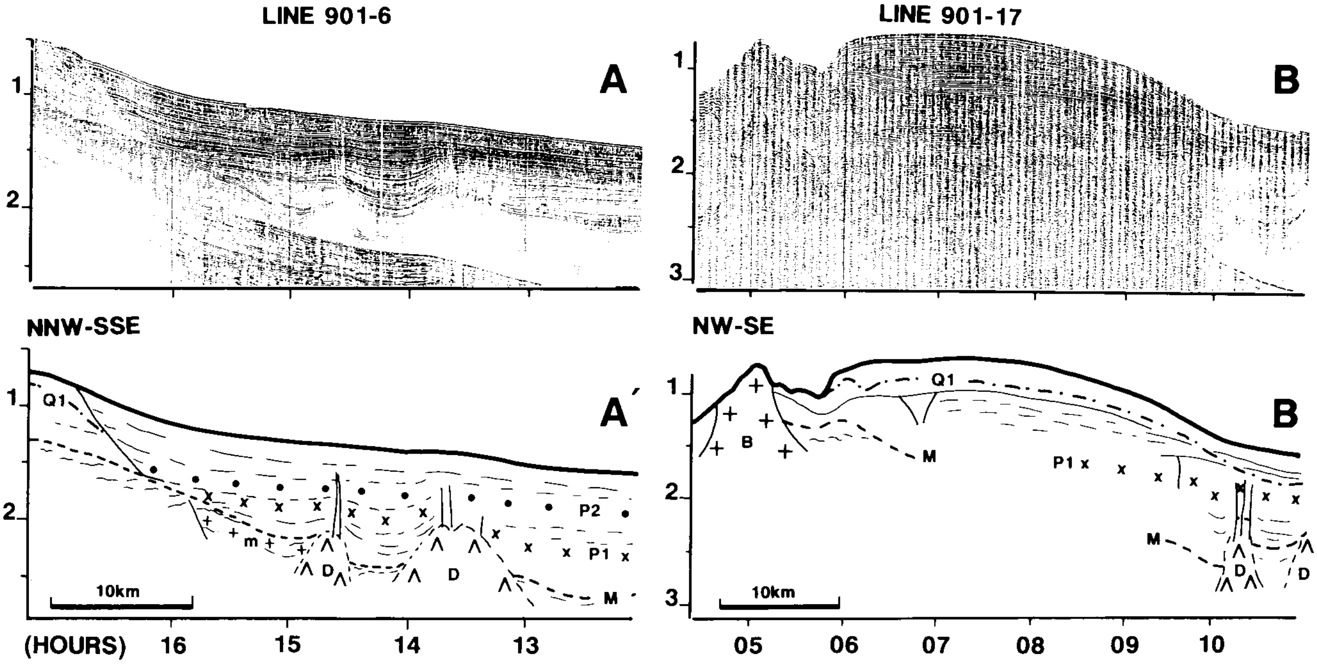

Figure 3. Representative seismic profiles showing the main morphostructural elements of the western Alboran Sea. A: Spanish margin. B: Margin off Morocco showing the Ceuta Drift. Key horizons: T, top of Tortonian sequence; m, top of lower Messinian sequence; M, Messinian unconformity; P_1, top of lower Pliocene sequence; P_2, top of upper Pliocene sequence; Q_1, top of lower Quaternary sequence; D, diapirs; B, basement. Location in Figure 1A.

distribution of deposits, which are affected by faulting of the most recent units (Campos and others 1992, their Fig. 3A; Maldonado and others 1992, their Fig. 2B).

The west Mediterranean basins are deep depressions of the basement, bounded by faults and characterized by thick depositional units of Miocene to Recent deposits. The western Alboran Basin is an elongated structural depression oriented north-northwest and approximately 130 km long and 55 km wide that occupies the deepest sector (Fig. 2A). The axis of the basin contains diapiric walls with their crest subparallel to the direction of the depression elongation, except in the northern sector where the diapirs are more irregular. The Málaga Basin has a predominantly east-northeast orientation and is largely confined on the Spanish continental margin (Figs. 1A and 2A). To the east of the Strait of Gibraltar these two basins are connected and very thick depositional sequences are observed in multichannel seismic profiles (Mulder and Parry 1977; Megías 1982).

The structural highs, including the Alboran Ridge, correspond to faulted blocks of the basement with a reduced or absent sedimentary cover (Fig. 2A). A large part of this basement belongs to formations of the Betic and Rif Internal Zones sampled at DSDP Site 121, and volcanic rocks that may outcrop locally as seamounts (Olivet and others 1973; Ryan and others 1973; Auzende 1978). The structural highs are bounded by faults that show a vertical offset of reflectors. Most faults are oriented east-northeast or north-northwest, but northwest, northeast, east, and north trends are also observed locally (Fig. 2A). The vertical offset of reflectors shows a predominantly normal component, but some faults may have changed over time to a reverse component, developing structural inversions. The transcurrent movements of these faults cannot be evaluated from seismic reflection profiles. Some of the most important faults are, however, the offshore extension of inland faults where significant strike–slip components have been recognized (Weijermars 1987; Leblanc, 1990).

Seismic Stratigraphy

Seven seismic sequences are identified in single-channel airgun seismic profiles ranging in age from the Late Miocene to Recent (Figs. 3–5).

Sequence 1, at the top, is characterized by continuous and parallel reflectors with high acoustic impedance, limited at the base by a paraconformity in the basins and unconformity toward the margins (Q_1 horizon; Figs. 3–5). The parallel reflectors, which form the bulk of this unit in the basins, contain locally channelized and wedge lobe reflector patterns toward the margins, with a variety of seismic facies indicative of high energy deposits. Thicknesses range from 0.2 sec (two-way travel time) or absence in the margins, to more than 0.7 sec in the basins. The reflectors mimic the sea bottom morphology, except where they are incised by canyons. This sequence mostly represents basin ponding by hemipelagic deposits, which are locally interrupted at the margins by gravity flows and turbidites derived from river sources. The westernmost continental margin off Morocco shows a mounded geometry and facies characteristics indicative of drift deposits developed by bottom currents (Fig. 3B). This sequence is situated within lithologic Unit 1 of DSDP Site 121 attributed to the Quaternary (Fig. 4). The lower boundary cannot be precisely dated, due to poor recovery at this drill-site and, compared with the underlying unit, the absence of major lithologic or seismic changes in the basin.

Sequence 2 is best developed at the continental margins, bounded by an unconformity at the top (Q_1 horizon) and

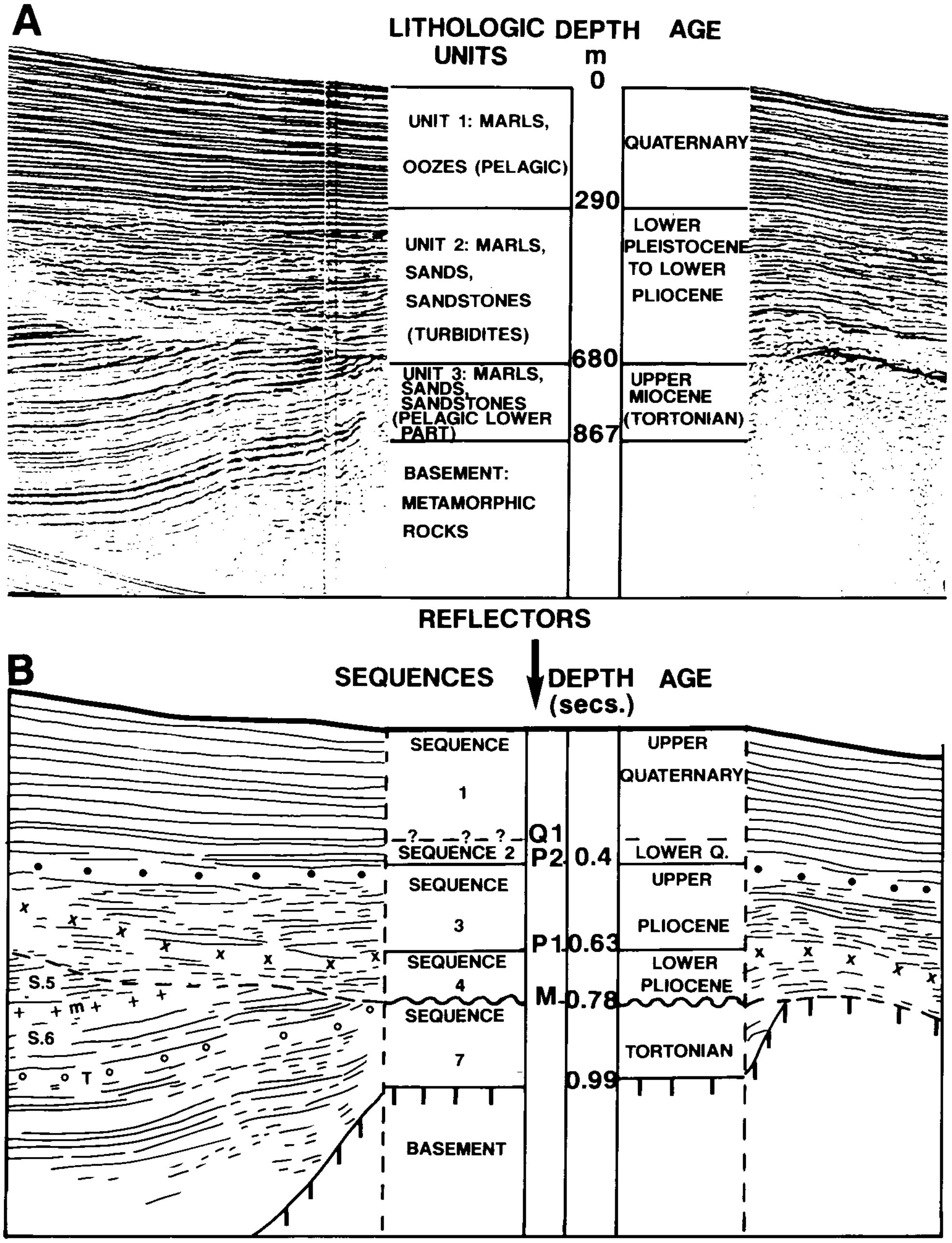

Figure 4. Correlation between lithologic units from (A) DSDP Site 121 after Ryan and others (1973) and the seismic stratigraphy (B) of a representative single-channel airgun seismic profile (Line 902-37), also illustrated in Figure 5A. Location in Figure 1A. Explanation in text.

onlap terminations over the underlying deposits (P_2 horizon). The seismic reflectors depict sigmoid and complex sigmoid progradations over the margins and continuous and parallel reflectors in the basins. Thicknesses range from 0.6 sec on the continental slope (where it is best developed) to 0.2 sec in the basins. On the basis of the results of DSDP Site 121, the bottom of this sequence is tentatively correlated with the transition between lithologic Unit 1 (pelagic) and lithologic Unit 2 (turbiditic), dated at about the Pliocene/Quaternary boundary (Fig. 4).

Sequence 3 (between the P_2 and P_1 horizons) is best characterized by the presence of channelized facies and short discontinuous wavy reflectors (Figs. 3 and 5). Facies with parallel reflectors are also observed, but the reflectors are more widely spaced than in overlying sequences. The unconformity at the bottom of Sequence 3 locally has a strong erosive character and fills deeply incised channels, as illustrated by a large erosive channel trending eastward from the Strait of Gibraltar (Figs. 2B and 5B). This sequence is mainly restricted to the basins and distal sectors of the continental margins, although the thickness distribution (0.1 to 0.5 sec) varies due to the erosive character of the base. A suite of erosive events, high-energy channelized turbidite and hemipelagic settling processes are recorded, which show significant vertical and lateral changes (Figs. 3 and 5). Cores of lithologic Unit 2 at DSDP Site 121 reveal the presence of turbidites and sands, which may correspond to a channelized facies of Sequence 3 in airgun records (Figs. 4 and 5). The lower boundary of Sequence 3 clearly lies within this turbiditic Unit 2 of Pliocene age. In contrast, previous correlations of seismic reflectors with DSDP Site 121 have misattributed the base of Sequence 3 to the

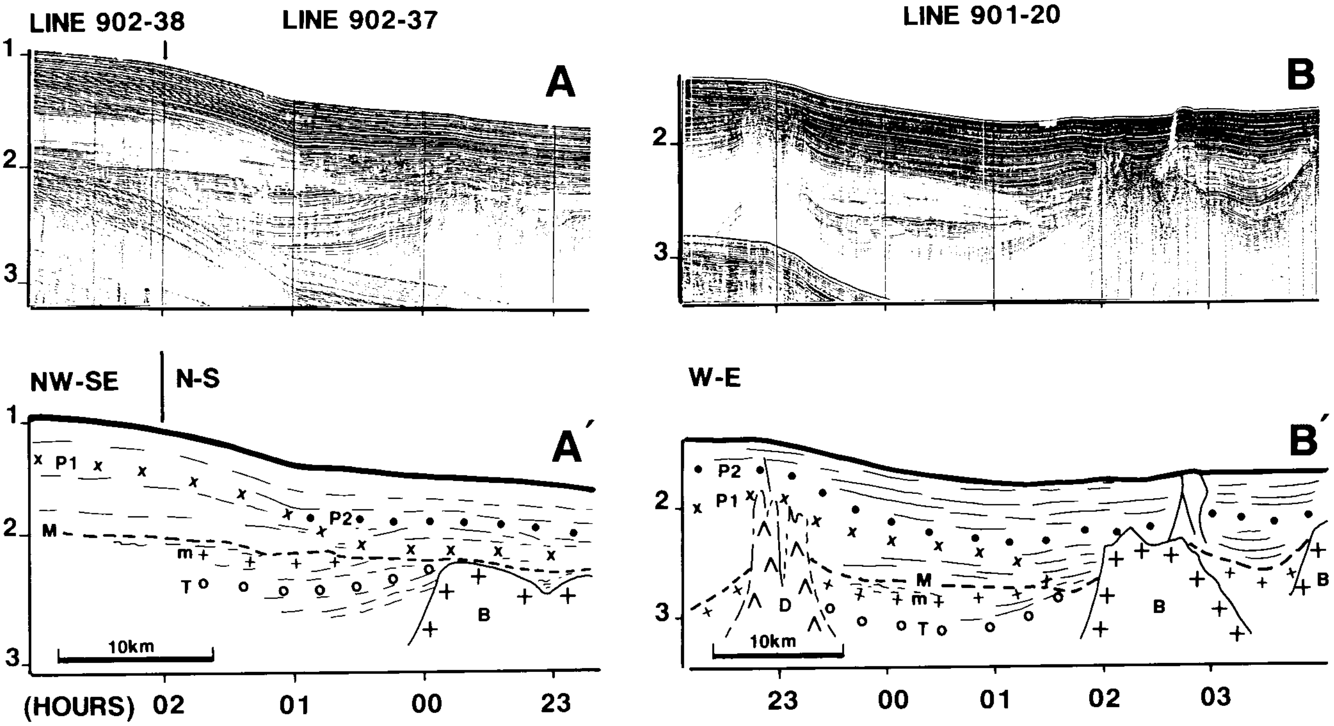

Figure 5. Representative seismic profiles of the study area. A: Spanish margin, Málaga Basin, and DSDP Site 121 structural high. B: western Alboran Basin and DSDP Site 121 structural high. Key horizons as in Figure 3. Location in Figure 1A. Explanation in text.

Messinian unconformity (Mulder and Parry 1977), probably due to the channelized character of the base and the reduced resolution of deep-penetration seismic profiles.

Sequence 4 has a predominantly transparent character in airgun profiles (Figs. 3 and 5). Locally, strong parallel reflectors are also observed, but the continuity is low in comparison to the overlying units. The unconformity at the bottom of this sequence (M horizon) has a strong erosive character and an irregular morphology, although the vertical relief is less prominent than in the unconformity at the top (P_1 horizon; Fig. 5A and B). Sequence 4 is best developed in the basins, with a very irregular thickness distribution due to the erosive character of the two bounding horizons. It is also observed locally in proximal sectors of the continental margins, filling depressions among the structural blocks (Figs. 3 and 5). It shows a basinward transition, from high energy and probably shallow deposits in the proximal margin grading to ponding and distal turbidites in the basins. We correlate the unconformity at the base of this sequence with the M reflector of the Messinian event (Ryan and others 1973). Sequence 4 corresponds, consequently, to the lower Pliocene, which was almost totally eroded at DSDP Site 121 as shown by the airgun records (Figs. 4 and 5A).

Sequence 5 is represented by very irregular, discontinuous reflectors of high acoustic impedance and numerous internal unconformities (Fig. 5). The distribution of this sequence is controlled by the structure of the basement and the depth of erosion of the M reflector at the top. The bottom boundary (m horizon) onlaps the basin margins and structural highs. Sequence 5 shows locally a tilting of the reflectors and angular unconformity below the overlying deposits. Vertical faulting is also observed, particularly at the continental margins. This sequence is thin in airgun profiles, 0.2–0.3 sec, and normally absent in the continental margins and below the erosive channel in the basin (Figs. 2B and 5B). The internal reflectors of this sequence seem to represent thin evaporites and reef deposits similar to those exposed in the Messinian facies of southeastern Spain (Weijermars and others 1985; Dabrio and others 1985; Montenat and others 1987). Thick evaporitic or salt deposits of the type of the Algero-Balearic basin, inferred in some previous studies (Auzende and others 1975; Dillon and others 1980), are not observed, not even in the deepest sectors of the western Alboran Basin.

The age of Sequence 5 is problematic, as it was probably not present at DSDP Site 121, located within the basin channel (Fig. 4). In addition, the precise location of the Pliocene/Miocene unconformity, and the occurrence of Messinian and Tortonian deposits in this borehole are also controversial (Ryan and others 1973; Auzende and others 1975; Montenat and others 1975; Pastouret and others 1975). We attributed Sequence 5 to the upper Messinian on the basis of its stratigraphic position and seismic characteristics, in agreement with the interpretation of Ryan and others (1973).

The deposits below Sequence 5 are poorly represented because of the limited penetration of single-channel profiles. Sequence 6 is represented by parallel reflectors of low acoustic impedance, with a thin transparent layer at the top. This sequence shows a local angular unconformity with the overlying deposits (m horizon) and apparent conformity at the bottom (T horizon, Figs. 4 and 5). The thickness observed is rather uniform (0.2 sec). Sequence 6 represents basin ponding by pelagic deposits and it is attributed to the lower Messinian on the basis of correlation with the stratigraphy of the internal basins of southeastern Spain (Dabrio and others 1985; Montenat and others 1987). According to Montenat and others (1975), there are evidences for the presence of Messinian facies at DSDP Site 121, although the airgun records show that Sequence 6 was eroded there (Figs. 4 and 5).

Sequence 7 (below the T horizon) is only observed in our airgun records in the proximity of structural highs and basin diapirs (Figs. 3–5). This sequence is represented by an alternation of parallel reflectors and transparent beds with wavy, discontinuous reflectors (Fig. 4). This facies corresponds to an alternation of hemipelagic ponding deposits and turbidites that record a cyclic pattern of low and high terrigenous influx to the basin. Sequence 7 was dated above the metamorphic basement as Tortonian at DSDP Site 121 (Fig. 4).

Two more acoustic units are differentiated in the airgun records. The nucleus of the diapirs appears as transparent facies deeply rooted below Sequence 7 (Figs. 3 and 5). These facies are thought to be undercompacted shales with excess pore-pressure resulting from sediment overburden, which facilitates density inversion and the development of diapiric structures. On multichannel seismic profiles these facies are dated as lower Miocene (Comas and others 1992). The acoustic basement is represented either by metamorphic rocks of the Alboran Domain, as at DSDP Site 121, or by volcanic rocks that outcrop locally in submarine banks (Olivet and others 1973).

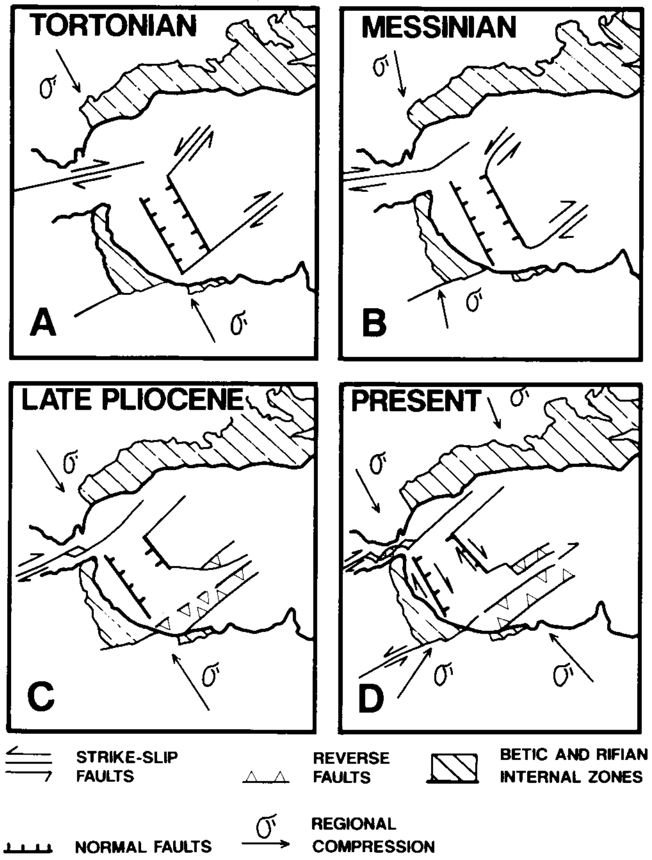

Figure 6. Simplified structural sketches of the western Alboran Sea evolution, Late Miocene to Recent. See explanation in text. Reconstruction of relative positions of Africa and Iberia from Srivastava and others (1990).

Geodynamic Evolution

Early Miocene

For this period, deep-penetration seismic profiles show that the oldest deposits infilling the basins are Early Miocene in age (Comas and others 1992), probably between Early Aquitanian and Late Burdigalian (22–14 m.y.a.). The oblique convergence of the African and Iberian plates during this time along irregular plate boundaries may have produced significant boundary-parallel displacements and synchronous development of contractional fault systems, similar to those formed by the tectonic escape in the Alpine and Himalayan system (Laubscher 1988). A model of orogenic float can be postulated for the development of the western Alboran Basin, where a major decollement separates the sedimentary and Alboran Domain units mechanically from the underlying continental lithosphere (e.g. Oldow and others 1990). Such a major decollement system individualizes the complex structures of the orogenic float and favors longitudinal transport of terrains. We endorse the proposal that the initial development may have resulted from oblique lateral transport of terrains along strike–slip faults, within the transpressional orogenic float.

Tortonian to Recent

The evolution from the Tortonian to Recent is summarized in four representative time sketches (Fig. 6). The relative positions of Iberia and Africa for this reconstruction are based in the kinematic of Iberia, recently developed by Srivastava and others (1990). Because the absolute sense of motions along faults cannot be defined in seismic profiles, we also adopt the stress fields established from land studies (e.g. Montenat and others 1987; Philip 1987; De Larouzière and others 1988; Sanz de Galdeano 1990). The discrepancies that may be observed locally between the generalized stress field for each epoch and the proposed movements along faults, however, should be attributed to significant regional variations of the same stress field (e.g. Philip 1987).

Before the Tortonian, the main western Alboran basins were largely developed as small, deep, faulted depressions filled with sediments while a regional subsidence was active. The Tortonian deposits (Sequence 7) are largely transgressive, as depositional sequences onlap the margins and structural highs, whereas the basins were ponded throughout with a cyclic alternation of hemipelagic and turbiditic facies. Normal faulting was still active along the eastern and western borders of the western Alboran Basin (Fig. 3A), but coeval movements with predominant transcurrent components are proposed along the southern and northern borders (Fig. 6A).

The Messinian deposits (Sequences 5 and 6) record compressional tectonics, particularly along the margins and structural highs where angular unconformities are observed below the overlying Pliocene sequence (Figs. 3 and 5). The roughly north–south stress field during this epoch facilitated relative sea level lowering as a result of intraplate stresses (e.g. Cloetingh 1988), and together with a global sea level lowering (Haq and others 1987) associated with a great expansion of the Antarctic ice sheet (Weijermars 1988), resulted in the closure of the Betic and Rif straits, which led to the isolation of the Mediterranean from the Atlantic Ocean and the Messinian event (Fig. 6B). This stress field also allowed transcurrent movements and extension in an east–west to east-southeast–west-northwest direction at the end of the Messinian.

During the Early Pliocene (Sequence 4), the stress field was also roughly oriented in a north–south direction (Philip 1987; De Larouzière and others 1988). The transtensional regime in the Strait of Gibraltar facilitated the development of small asymmetrical pull-apart basins along the axis and induced the reopening of the connection with the Atlantic Ocean. During this time the western Alboran Basin continued the extension within a generalized transtensive regime.

The stress field changed during the Late Pliocene to the north-northwest–south-southeast direction (Fig. 6C). A relative lowering of sea level was observed, as the depositional sequences (Sequence 3) were shifted basinward and ponded the basins. Strike–slip movements were active along the Strait of Gibraltar, developing small pull-apart basins that propagated toward the west and filled with relatively thick depositional sequences. Along the Alboran Ridge the strike–slip systems were blocked with the development of positive flower structures (e.g. Campos and others 1992, their Fig. 4).

The regional stress field in the western Alboran Sea at present is relatively well established. The orientation of the stress varies between north-northwest–south-southeast and north-northwest–south-southwest (Philip 1987). During the most recent epoch, the Alboran Ridge has been characterized by a predominantly compressive regime and development of structural inversions. The bending of the stress field around the Strait of Gibraltar and the orientation of faults in relation to the local stress also facilitated horizontal movements at this time (Fig. 6D).

Conclusions

The basins of the western Alboran Sea were developed under transtensive tectonics regime that evolved to transpressive within a generalized regime of transcurrent, continental collision. The anisotropy of the lithosphere and local discontinuities created by individual structural blocks have facilitated variations in the distribution of the stress field and tectonic regime (Philips 1987; Mauffret and others 1992). During Tortonian time, the western Alboran Basin expanded and onlapped the margins under a generalized northwest–southeast compressive regime. The stress field during Messinian time was roughly north–south and coupled with a low global sea level stand, severed the Atlantic/Mediterranean connections through the Rif and Betic straits (Fig. 6). The upper Messinian sequence records a drastic change in the sedimentary environment with subaereal erosion, as well as restricted and shallow marine facies, although no salt or thick evaporitic deposits have been observed (Fig. 4). After the Messinian, the tectonism in the Strait of Gibraltar, with transcurrent movements, reopened the Atlantic/Mediterranean gateway and developed a deep canyon entrenched eastward from the Strait of Gibraltar into the western Alboran Basin.

The Early Pliocene is characterized by onlap and ponding of the continental margins and basins, respectively. During the Late Pliocene there was a transpressive regime along east-northeast structures that was perpendicularly oriented to the stress, for example the Alboran Ridge, and a basinward shift of depocenters, which reflect the global sea level lowering and tectonic influence. An evolution similar to the Pliocene is observed during the Quaternary, with onlap and agradation of the continental margins in the lower Quaternary sequence and basinward migration of depocenters and basin ponding during the upper Quaternary sequence.

Acknowledgments. We thank the officers and crew of the B.O. García del Cid for their assistance at sea. A.C.C. thanks the scientific team of "Groupe d'Etude de la Marge Continentale et de l'Ocean" of the "Université Pierre et Marie Curie, Paris VI," for discussions and help during her stay in Paris. Critical comments by M. Farrán, F. Sàbat, R. Weijermars, and P. Santanach are gratefully recognized. This research was sponsored by the "Comisión Interministerial de Ciencia y Tecnología" (CICYT, Recursos Geológicos Project GEO89-0829) and a CSIC/CNRS PICS Project.

References

Andrieux, J., Fonboté, J.M., and Mattauer, M., 1971. Sur un modèle explicatif de l'Arc de Gibraltar. *Earth and Planetary Science Letters* **12:**191–198.

Auzende, J.M., 1978. Histoire tertiaire de la Méditerranée occidentale. Thèse d'Etat, Paris. 130 pp.

Auzende, J.M., Rehault, J.P., Pastouret, L., Szep, B., and Olivet, J.L., 1975. Les bassins sédimentaires de la mer d'Alboran. *Bulletin de la Société Géologique de France* **17:**98–107.

Campos, J., Maldonado, A., and Campillo, A.C., 1992. Post-Messinian evolutional patterns of the central Alboran Sea. *Geo-Marine Letters* **12:**173–178.

Cloetingh, S., 1988. Intraplate stresses: A new element in basin analysis. In: Kleinspehn, K. and Paola, C. (Eds.), New perspectives in basin analysis. Springer-Verlag, New York. 205–230.

Comas, M.C., García-Dueñas, V., and Jurado, M.J., 1992. Neogene tectonic evolution of the Alboran Sea from MCS data. *Geo-Marine Letters* **12:**157–164.

Dabrio, C.J., Martin, J.M., and Megías, A.G., 1985. The tectosedimentary evolution of Miopliocene reefs in the province of Almería (SE Spain). 6th European Regional Meeting Excursion Guide-book. 271–305.

De Larouzière, F.D., Bolze, J., Bordet, P., Hernandez, J., Montenat, C., and Ott d'Estevou, P., 1988. The Betic segment of the lithospheric trans-Alboran shear zone during the Late Miocene. *Tectonophysics* **152:**41–52.

Dillon, W.P., Robb, S.M., Gary Greene, M., and Lucena, J.C., 1980. Evolution of the continental margin of southern Spain and the Alboran Sea. *Marine Geology* **36:**205–226.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. *Science* **235:**1156–1167.

Horvarth, F. and Berckhemer, H., 1982. Mediterranean back-arc basin. In: Berckhemer, H. and Hsü, K. (Eds.), Alpine Mediterranean geodynamics. American Geophysical Union **7:**141–173.

IOC-UNESCO, 1981. International Bathymetric Chart of the Mediterranean Sea, Scale 1:1.000.000. Ministry of Defense, Leningrad. Sheet No. 6.

Laubscher, H., 1988. Material balance in Alpine orogeny. *Geological Society of America Bulletin* **100:**1313–1328.

Leblanc, D., 1990. Tectonic adaptation of the external zones around the curved core of an orogen: the Gibraltar Arc. *Journal of Structural Geology* **12:**1013–1018.

Le Pichon, X., Pautot, G., and Weill, J.P., 1972. Opening of the Alboran Sea. *Nature Physical Science* **236:**83–85.

Maldonado, A., Campillo, A.C., Mauffret, A., Alonso, B., Woodside, J.M., and Campos, J., 1992. Alboran Sea Late Cenozoic tectonic and stratigraphic evolution. *Geo-Marine Letters* **12:**179–186.

Mauffret, A., Maldonado, A., and Campillo, A.C., 1992. Tectonic framework of the eastern Alboran and western Algerian basins, western Mediterranean. *Geo-Marine Letters* **12:**104–110.

Megías, A.G., 1982. La evolución del Mar de Alborán y cadenas Bético-Maghrébides durante el Neógeno. Quinto Congreso Latinoamericano de Geología, Actas II. 329–340.

Montenat, C., 1977. L'historie tectonique récente (Tortonien à Quaternaire) de l'Arc de Gibraltar et des bordures de la mer d'Alboran. I. Chronologie et principaux événements de l'histoire paléogéographique du Néogène Récent. *Bulletin de la Société Géologique de France* **19:**577–583.

Montenat, C., Bizon, G., and Bizon, J.J., 1975. Remarques sur le Néogène du forage JOIDES 121 in mer d'Alboran (Méditerranée occidentale). *Bulletin de la Société Géologique de France* **18:**45–51.

Montenat, C., Ott d'Estevou, P., and Masse, P., 1987. Tectonic sedimentary characters of the Betic Neogene basins evolving in a crustal transcurrent shear zone (SE Spain). *Bulletin des Centres Recherches Exploration Production. Elf-Aquitaine* **11(1):**1–22.

Mulder, C.J. and Parry, G.R., 1977. Late Tertiary evolution of the Alboran Sea at the eastern entrance of the Strait of Gibraltar. In: Biju-Duval, B., and Montadert, L. (Eds.), International Symposium of the Structural History of the Mediterranean Basins, Split (Yugoslavia) 1976. Editions Technip, Paris. 401–410.

Oldow, J.S., Bally, A.W., and Avé Lallemat, H.G., 1990. Transpression, orogenic float, and lithospheric balance. *Geology* **18:**991–994.

Olivet, J.L., Pautot, G., and Auzende, J.M., 1973. Alboran Sea structural framework. In: Ryan, W.B.F., Hsü, K.J., and others (Eds.), Initial Reports of the Deep Sea Drilling Project, volume 13(2). 1417–1430.

Pastouret, L., Olivet, J.L., Auzende, J.M., and Rehault, J.P., 1975. Remarques complémentaires sur le Néogène de la mer d'Alboran. *Bulletin de la Société Géologique de France* **17:**1168–1171.

Philip, H., 1987. Plio-Quaternary evolution of the stress field in the Mediterranean zones of subduction and collision. *Annales Geophysicae* **5B:**301–320.

Ryan, W.B.F., Hsü, K.J., Cita, M.B., Dumitricia, P., Lort, J., Maync, W., Nesteroff, W.D., Pautot, G., Stradner, H., and Wezel, F.C., 1973. Western Alboran Basin-Site 121. In: Ryan W.B.F., Hsü, K.J., and others (Eds.), Initial Reports of the Deep Sea Drilling Project, volume 13(2). 43–89.

Sanz de Galdeano, C., 1990. Geologic evolution of the Betic Cordilleras in the western Mediterranean, Miocene to the present. *Tectonophysics* **172:**107–119.

Srivastava, S.P., Roest, W.R., Kovacs, L.C., Oakey, G., Lévesque, S., Verhoef, J., and Macnab, R., 1990. Motion of Iberia since Late Jurassic: Results from detailed aeromagnetic measurements in the Newfoundland Basin. In: Boillot, G. and Fontboté, J.M. (Eds.), Alpine evolution of Iberia and its continental margins. *Tectonophysics* **184:**229–260.

Tesson, M., Gensous, B., and Labraimi, M., 1987. Seismic analysis of the southern margin of the Alboran Sea. *Journal of African Earth Sciences* **6:**813–821.

Weijermars, R., 1987. The Palomares brittle-ductile shear zone of southern Spain. *Journal of Structural Geology* **9:**139–157.

Weijermars, R., 1988. Neogene tectonics in the western Mediterranean may have caused the Messinian salinity crisis and an associated glacial event. *Tectonophysics* **148:**211–219.

Weijermars, R., Roep, Th.B., van den Eeckhout, B., Postma, G., and Kleverlaan, K., 1985. Uplift history of a Betic fold nappe inferred from Neogene-Quaternary sedimentation and tectonics (in the Sierra Alhamilla and Almería, Sorbas and Tabernas Basins of the Betic Cordilleras, SE Spain). *Geologie en Mijnbouw* **64:**397–411.