Comas, M.C., Zahn, R., Klaus, A., et al., 1996
Proceedings of the Ocean Drilling Program, Initial Reports, Vol. 161

1. INTRODUCTION[1]

Shipboard Scientific Party[2]

From the early days of scientific drilling, the Mediterranean has attracted the interest of the earth science community. In 1970, the first expedition of *Glomar Challenger* (Leg 13) to the Mediterranean investigated the "Messinian Salinity Crisis," which had led to the deposition of well-known evaporitic sequences. Important results of Leg 13 were documentation of these basin-wide Messinian evaporites and the discovery that the classical seismic "M"-reflector, which had long been known as a coherent reflector across the entire Mediterranean, corresponds to a terminal Messinian unconformity, representing the rapid transition from restricted to open-marine conditions. Legs 42 (1975) and 107 (1985) cored partially complete Pliocene–Pleistocene sequences and "basement rocks" at 15 sites in the eastern and western Mediterranean, providing a strong foundation for understanding the pre-Messinian environmental history and the tectonic evolution of the Mediterranean.

Western Mediterranean Leg 161 was the second in a two-leg ODP program to address both tectonic and paleoceanographic objectives in the Mediterranean Sea. Part of the drilling strategy was built on the results from the earlier Mediterranean drilling cruises, and, in fact, some sites drilled during Legs 160 and 161 re-occupied sites that had been drilled previously during Legs 13, 42, and 107. During Leg 161, the *JOIDES Resolution* drilled a transect of six sites across the western Mediterranean (Fig. 1), from the Tyrrhenian Sea to the Alboran Sea immediately east of the Strait of Gibraltar. Sites 974 and 975 in the Tyrrhenian Sea and on the Menorca Rise were dedicated to paleoceanographic objectives. Sites 976, 977, 978, and 979 in the Alboran Sea focused mainly on tectonic goals, but included paleoceanographic objectives. The Alboran Sea is a key location for understanding the Messinian salinity crisis and the influence of the Atlantic-Mediterranean gateways on Mediterranean paleoceanography.

The paleoceanographic program during Leg 161 concentrated on reconstructing the Atlantic-Mediterranean water exchange and the paleoceanography of the western Mediterranean during the late Cenozoic. The Leg 161 drill sites were part of a trans-Mediterranean paleoceanographic transect that included 16 drilling sites across the Mediterranean. The paleoceanographic programs of Legs 160 and 161 were closely connected. The combined results will allow us eventually to decipher the paleoceanography that led to the deposition of sapropels in the eastern Mediterranean.

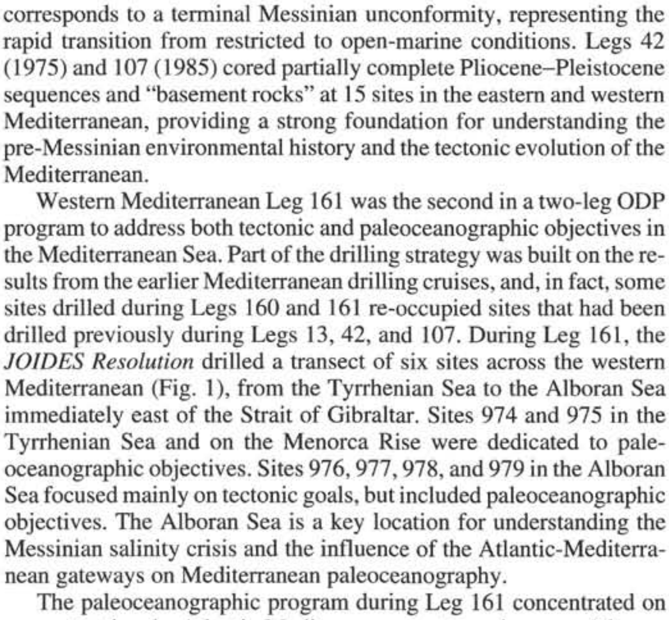

Figure 1. Sites drilled in the western Mediterranean during Leg 161. AB = Alboran Basin, SB = South Balearic Basin, LS = Ligurian Sea.

Within the western Mediterranean, the Alboran Sea basin was chosen as the optimum area to conduct studies of convergent plate-tectonic boundaries, especially those involving the origin of extensional basins in collisional settings. Among the Mediterranean convergent boundaries, the collision between the Eurasian and African plates at the westernmost Mediterranean Sea has resulted in a broad region of distributed deformation rather than a discrete plate boundary. This broad region comprises the Betic, Rif, and Tell Chains linked across the Gibraltar Arc and includes the extensional basins that form the Alboran and South Balearic Seas (Fig. 2). The apparent paradox of extensional basin formation and crustal stretching during the convergence of the Eurasian and African plates has been a longstanding problem in Mediterranean tectonics.

Extended continental crust forms the floor of the Neogene Alboran Sea basin, and the basin is surrounded by a compressional thrust belt that was tectonically active during the extension. It closely resembles the northern Tyrrhenian Sea or the Panonnian Basin, in that there is no geological or geophysical evidence that oceanic lithosphere subduction was associated with the extension in the basin. Extension directions in the Alboran Basin, and those of the coeval thrusting in the surrounding arcuate mountain front, are not clearly related to the Eurasian-African relative plate motion.

The prime tectonic objectives in drilling at the Alboran Sea sites were to determine the response of the crust to compressional and extensional forces and to better understand the kinematics and deformation of the Mediterranean continental lithosphere. The continental rift system that led to the development of the Alboran Basin also provided an opportunity to examine the nature of brittle and ductile deformation of the crust, the role of magmatism in rifting processes, and the role of the upper mantle in crustal modification and lithosphere evolution. The young and tectonically active Alboran Sea is a Mediterranean laboratory where these tectonic processes can be investigated.

Alboran Sea drilling results are expected to have immediate applications in establishing geodynamic models on the origin and evolution of Mediterranean-type backarc extensional basins.

AN EXTENSIONAL BASIN IN A COLLISIONAL SETTING: THE ALBORAN SEA

The Scientific Problem

Continent-continent collision zones at convergent plate boundaries are optimum sites for extensional basins to form. In the Mediterranean, extensional basins developed on the sites of orogens that were created during the Cretaceous-to-Paleogene collision of the Eurasian and African plates (Fig. 2). These basins began to form in regions with thickened continental crust, and they developed by ex-

[1] Comas, M.C., Zahn, R., Klaus, A., et al., 1996. *Proc. ODP, Init. Repts.,* 161: College Station, TX (Ocean Drilling Program).

[2] Shipboard Scientific Party is given in the list preceding the Table of Contents.

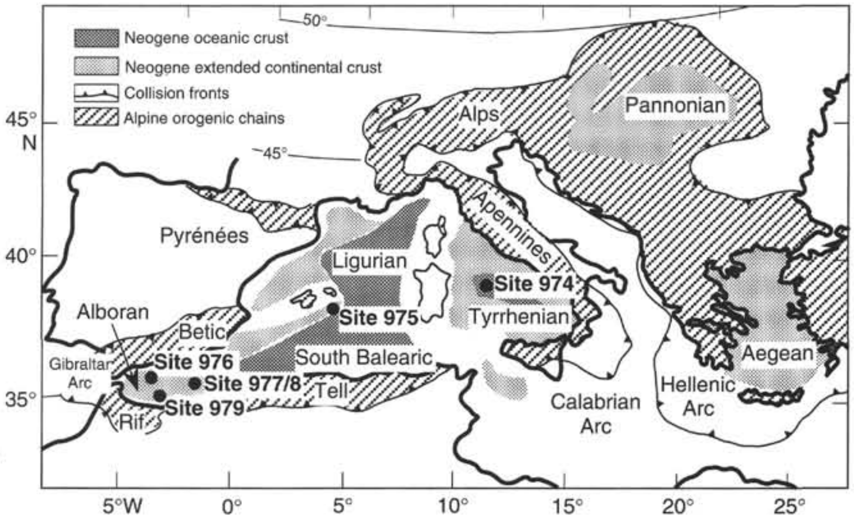

Figure 2. Tectonic map of Mediterranean basins and mountain belts (based on data from various sources). Location of Leg 161 drill sites is shown.

tensional processes behind highly arcuate thrust belts. So far, there is no evidence for the existence of oceanic lithosphere during the Cenozoic, so this crustal stretching was not associated with subduction of oceanic lithosphere. The tectonic history of these basins suggests that the continental collision closely predates the onset of crustal thinning in the region and that the thrust belts surrounding the basins were active during the basins' evolution. Within the basins, synrift sediments rest on highly attenuated continental crust, and calc-alkaline-to-acid volcanism appears to have been associated with the extension. These attributes characterize the Mediterranean "backarc" basins, of which the South Balearic and Alboran Basins are classic examples (Horvath and Berckhemer, 1982).

There is no general agreement about the causes of extension in these basins, nor has the rapid evolution of the collisional zone into regions of extension, adjacent contraction, and arc migration been adequately explained. The origin of the Alboran Sea and other Mediterranean backarc basins has been an extremely controversial subject. Some authors have emphasized the role of anomalous mantle diapirism (Weijermars, 1985; Wezel, 1985), whereas others emphasize subduction similar to that of western Pacific backarc basin models (Biju-Duval et al., 1978; Rehault et al., 1984; Dercourt et al., 1986; Malinverno and Ryan, 1986; Kastens et al., 1987). Others again envisage subduction with detachment and sinking of a lithospheric slab (De Jong, 1991; Zeck et al., 1992; Royden, 1993).

Removal or detachment of the lithosphere mantle either by delamination (Bird, 1979) or by convection (Houseman et al., 1981) is argued currently to explain lithosphere thinning and subsequent development of extensional basins on collisional orogens.

To explain extensional basins that are superimposed on continental collision sutures, Channell and Mareschal (1989) proposed collision-induced delamination ("subduction") of continental mantle lithosphere to explain the rapid evolution of the collision suture into a zone of rifting and the development of adjacent regions of compression and extension. Their model for the Tyrrhenian Basin-Calabrian Arc suggests that asymmetric lithosphere thickening generates asymmetrical mantle flow, causing extension and adjacent contraction.

Convective removal of a cool and dense lithosphere root (Platt and Vissers, 1989; Platt and England, 1994) and asymmetric delamination (peeling off) of the subcrustal lithosphere (Morley, 1992; García-Dueñas et al., 1992; Comas et al., 1993) have recently been discussed as alternative processes responsible for the origin of the Alboran Basin. Both models involve removal of a subcrustal lithospheric slab and replacement by asthenosphere material, and they also predict high geothermal gradients, similar thermal structure, and a comparable pattern of crustal thinning. Consequently, on the basis of these parameters alone, it would be difficult to discriminate between these two models.

A migrating locus of extension, as postulated by the delamination model, vs. a static locus as favored in the extensional-collapse model, is the main difference between these most widely accepted concepts. According to the asymmetric subcrustal lithosphere delamination model, a migrating locus of extension resulted in a distinct migration of the arcuate mountain front. The delamination model as proposed for the Alboran Basin (Fig. 3) fits with the westward migration of the Alboran Domain and the Gibraltar Arc and relates the initial crustal thinning in the Alboran Basin to the origin of the South Balearic Basin (Balanyá and García-Dueñas, 1987; Comas et al., 1993). The concept of convective removal of a lithosphere root implies a static locus of extension at the site of the collisional ridge. This alternative model suggests a radial-symmetrical emplacement of thrust-nappes around the Alboran Sea basin (Platt and Vissers, 1989) and signifies that thermal subsidence largely controlled the evolution of the Alboran Sea basin.

Leg 161 drilling results will unequivocally resolve neither the stalemate regarding the kinematics of deformation of the lithosphere nor the dynamics of the processes that formed the Alboran Basin. However, drilling data will provide accurate information about key parameters with which we can test the validity of competing genetic hypotheses. These parameters include the stratigraphic record, basin geometry, timing and amount of deformation, subsidence rates, and the nature of the basin's basement. To maximize the significance of Leg 161 results, it will be important to integrate geological and geophysical data and results, not only from the Alboran Basin itself, but also from the orogenic belt, the Betic and Rif Chains, that surrounds the Alboran Basin.

Geological and Geophysical Background

Tectonics

The Alboran Sea basin lies within a Miocene arc-shaped orogenic belt formed by the Betic (Southern Spain) and Maghrebian (Rif and Tell, in Morocco) Chains (Fig. 4). The internal domains of both chains, including alpine metamorphic and non-metamorphic complexes, have north-south continuity across the Gibraltar Arc and below the Alboran Sea, forming the basement of the Alboran Basin. The whole system is bounded to the north and south by the Iberian and African continental forelands, respectively, to the east by the oceanic Balearic Basin, and to the west by the Atlantic Ocean.

The complexities of the Betic-Rif orogenic belt and its geodynamic evolution result from its position between two large plates, which,

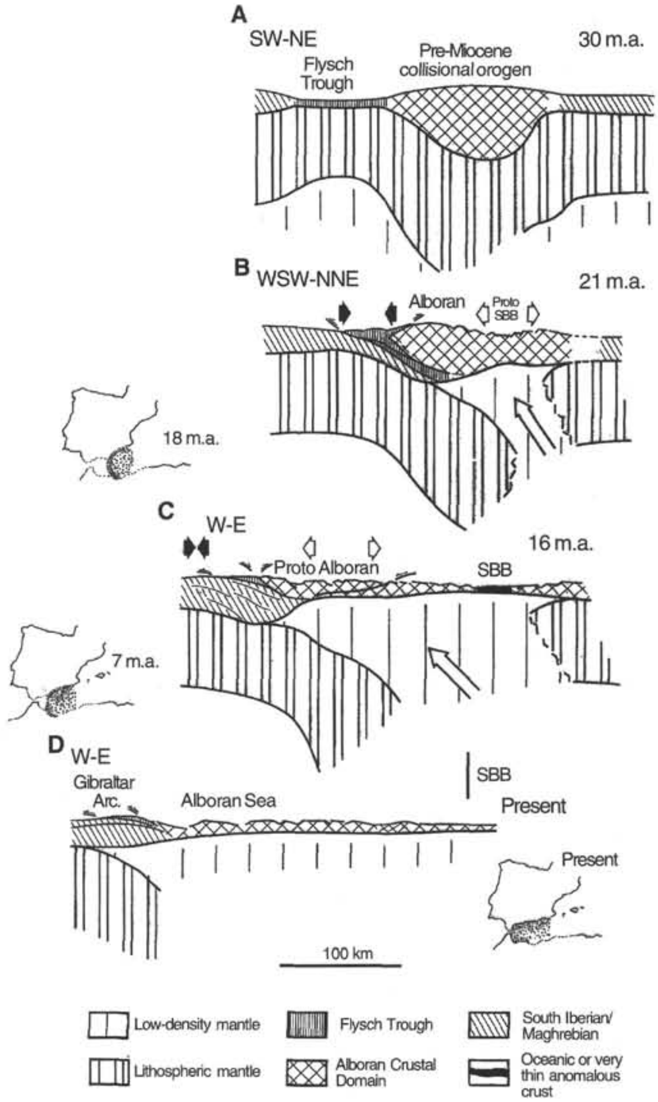

Figure 3. **A–D.** Working hypothesis for the origin of the Alboran Basin, considering initial asymmetric lithosphere thickness (offset) in the former collisional orogen, and subsequent delamination of the lithospheric mantle. Note that this model implies that the onset of Miocene extension in the Alboran Basin was synchronous with the foreland propagation of the Gibraltar Arc thrust-front (B), and that the locus of the extension migrated from the South Balearic to the "proto"-Alboran Basin contemporaneously (B to C). Proposed position for the Gibraltar Arc mountain front at 18 and 7 Ma is shown. Note change of orientation from section A to D.

from the Mesozoic, have undergone variable relative movements. Several kinematic models have been proposed for the motion of Africa relative to Europe (Olivet et al., 1984; Srivastava et al., 1990). Neogene plate-tectonic restoration of the western Mediterranean (Dewey et al., 1989) suggests that this part of the African/European plate boundary underwent 250 km of approximately north-south convergence from mid-Oligocene to late Miocene times, followed by ~50 km of west-northwest–directed oblique convergence since the late Miocene.

The complexes and large paleogeographic elements that form the Betic and Rif Chains and the Gibraltar Arc belong to different crustal

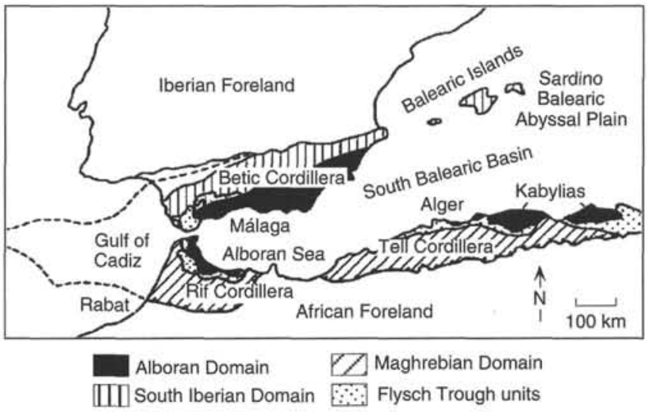

Figure 4. The Alpine Chains surrounding the Alboran Sea and general tectonic subdivision of crustal domains (from Balanyá and García-Dueñas, 1987). Onshore distribution of these domains indicates that the continental basement beneath the Alboran Sea belongs to the Alboran Crustal Domain.

domains (Fig. 4), which were well delimited at the beginning of the Neogene:

1. The South Iberian and Maghrebian Domains (External Zones of the Betic and Rif Chains, respectively) correspond to the Mesozoic paleomargins of the Iberian and African plates. They are composed of non-metamorphosed Mesozoic and Tertiary units overlying Iberia's Hercynian basement. During the Mesozoic, these domains were separated by the Newfoundland-Azores-Gibraltar transform fault (Olivet et al., 1984; Srivastava et al., 1990).
2. The Flysch Complex, allochthonous units that have remarkable continuity in the Maghreb, deposited in a trough over oceanic or very thin continental crust (Dercourt et al., 1986).
3. The Alboran Crustal Domain (Betic-Rifean Internal Zones) composed of a syn- and post-metamorphic, pre-Miocene polyphase thrust-stack that includes three nappe complexes: the Nevado-Filabride, Alpujarride, and Malaguide. The Alpine metamorphic-facies assemblages in the Alpujarride and Nevado-Filabride complexes evolved from high pressure/low temperature to low pressure/high temperature conditions, or at least to isothermal pressure decrease, in both complexes (Bakker et al., 1989; Goffé et al., 1989; Tubía and Gil-Ibarguchi, 1991; Balanyá et al., 1993). In contrast, the Malaguide units have undergone only very low-grade Alpine metamorphism (Chalouan and Michard, 1990).

The high-pressure mineral assemblages of the Alpujarride and Nevado Filabride complexes are the result of crustal stacking and substantial crustal thickening in the Betic and Rif Chains, caused by the pre-Miocene convergence (Bakker et al., 1989; Goffé et al., 1989; Tubía and Gil-Ibarguchi, 1991). The Ronda peridotite massif, the largest known surface exposure of lithospheric mantle, is a thrust sheet within the Alpujarride complex (Lundeen, 1978; Tubía and Cuevas, 1986; Torné et al., 1992; Davies et al., 1993).

The Gibraltar Arc (Figs. 4, 5) is considered a result of an early to middle Miocene westward overthrusting of the Alboran Crustal Domain onto the Iberian and Maghrebian continental crust. This westward thrust postdates the Alboran Domain polyphase thrust-stack (Balanyá and García-Dueñas, 1987; 1988; Morel, 1989; García-Dueñas et al., 1992; Royden, 1993). During the westward migration

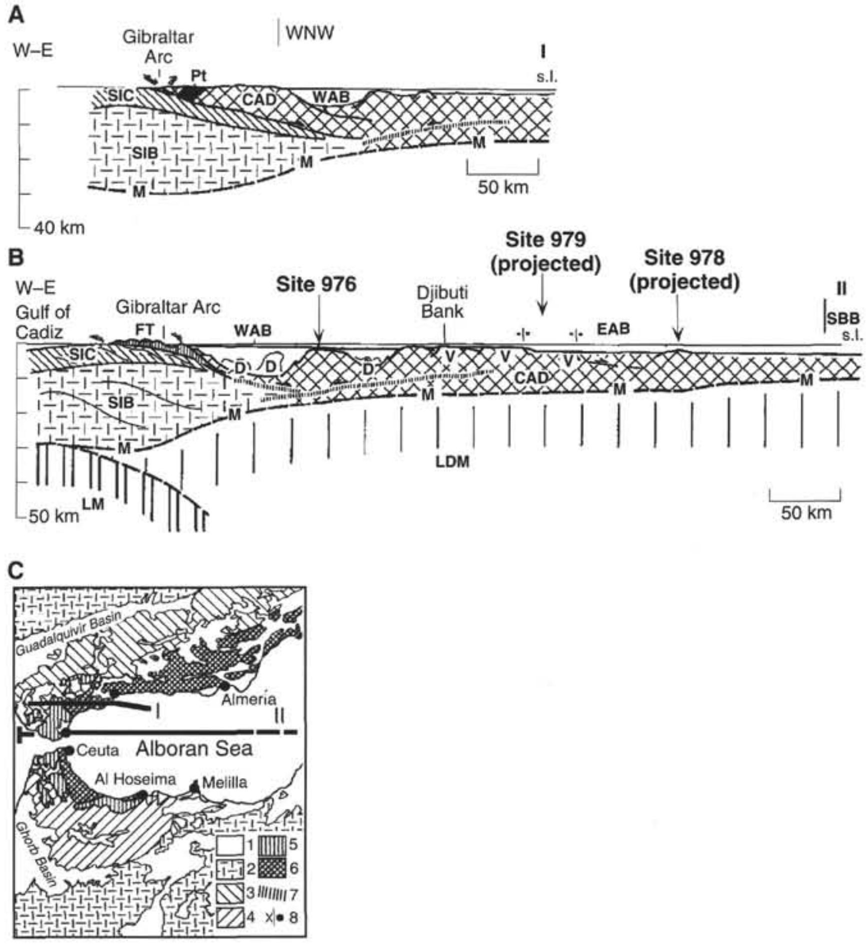

Figure 5. **A, B.** Schematic true-scale crustal sections across the Gibraltar Arc and the Alboran Sea basin to illustrate the large-scale east-west structure of the basin and its location on a convergent orogenic setting. According to this section, the basement beneath the Alboran Sea would correspond to the hanging wall of a major crustal extensional detachment. Note that the slab of Ronda peridotites is also placed on the hanging wall of the extensional detachment (García-Dueñas et al., 1992; Comas et al., 1993). Note that this cross section is the same as cross-section D in Figure 3. Crustal thickness from Banda and Ansorge (1980) and supposed position of ductile extensional detachments within the Crustal Alboran Domain. CAD = Crustal Alboran Domain, D = mud diapirs, FT = Flysch Trough units, LM = lithosphere mantle, LDM = low-density mantle, M = Moho, Pt = Ronda peridotites, SIB = South-Iberian paleomargin basement, SIC = South-Iberian paleomargin cover, V = volcanic rocks in the CAD, EAB = Eastern Alboran Basin, SBB = South Balearic Basin, WAB = Western Alboran Basin, s.l. = sea level. **C.** Structural map of chains surrounding the Alboran Sea. I and II indicate locations of profiles A and B. 1 = Miocene to Holocene sediments, 2 = South-Iberian and Maghrebian paleomargin basements, 3 = South-Iberian paleomargin cover, 4 = Maghrebian paleomargin cover, 5 = Flysch Trough units, 6 = Crustal Alboran Domain, 7 = ductile extensional detachments, 8 = strike-slip faults.

of the Gibraltar thrust front, shortening and crustal thickening occurred along the Gibraltar Arc, while crustal thinning and tectonic subsidence began in the Alboran Basin behind the arc (García-Dueñas et al., 1992; Comas et al., 1992).

Extensional detachment and fault-bounded Miocene sedimentary basins exposed on land are superimposed onto the continental collision structures (Platt, 1986; Balanyá and García-Dueñas, 1987; Platt and Vissers, 1989; Galindo et al., 1989; García-Dueñas and Balanyá, 1991; García-Dueñas et al., 1992; Monié et al., 1991; Morley, 1992). This extensional phase was accompanied by distinctive low-pressure/high-temperature metamorphic events (Torres-Roldán, 1979; Zeck et al., 1992), which have early Miocene radiometric ages (Zeck et al., 1989; Monié et al., 1994). The crustal thinning over much of the region (see below) is likely to be a result of this phase of extension.

Shortening and crustal thickening during the early Miocene (Aquitanian) Gibraltar Arc was mainly coeval with the extension in the internal parts of the system, which continued until the middle Miocene–early Tortonian. Shortening directions vary from northwest in the Betic Cordillera (Banks and Warburton, 1991), to west in the Gibraltar Arc region (Balanyá and García-Dueñas, 1987; 1988), to west-southwest in the Rif Cordillera (Frizon de Lamotte, 1987).

We suggest that, during the early to middle Miocene, the migration of the arcuate mountain front was nearly coeval with extension in the inner part of the Gibraltar Arc, creating crustal attenuation and basinal extension in the Alboran Domain. The Alboran Basin was formed by extension from the early Miocene onward, whereas outside the basin the arc-thrusting processes continued. Schematic true-scale sections across the Alboran Sea and adjacent mountain belts are shown in Figures 5 and 6 to illustrate the position of the Alboran Basin within the convergent orogenic belt.

The Alboran Basin

The Alboran Sea is ~400 km long, 200 km wide, and has narrow shelf and slope physiographies (Fig. 7). In contrast to the adjacent deeper South Balearic Basin, its maximum depth is <2,000 m and it exhibits a complex seafloor morphology, with several sub-basins, ridges, and seamounts. The Alboran Ridge and the Alboran Trough are the more prominent linear structures that extend 180 km and trend obliquely (northeast to southwest) across the Alboran Sea. The Alboran Ridge locally emerges above sea level to form the small Alborán Island. The three main sub-basins, separated by the northeast-to-southwest–trending Alboran Ridge, are the Western, the Eastern, and the Southern Alboran Basins (Fig. 5).

The Alboran Basin contains one of the most impressive accumulations of Neogene and Quaternary deposits within the western Mediterranean. Seismic data indicate up to 7-km-thick sedimentary sequences that fill grabens or half-grabens. The sedimentary cover of the Alboran Sea has been documented in many papers based on seismic reflection data (Pastouret et al., 1975; Auzende et al., 1975; Mulder and Parry, 1977; Dillon et al., 1980; Kazakov et al., 1982; Gensous et al., 1986; Mauffret et al., 1987; Maldonado et al., 1992; Comas et al., 1992; Watts et al., 1993). However, stratigraphic studies of the deep-basin deposits are only known from DSDP Site 121 results (Ryan, Hsü, et al., 1973). Commercial exploration wells provide information on sedimentary sequences that fill basins along the

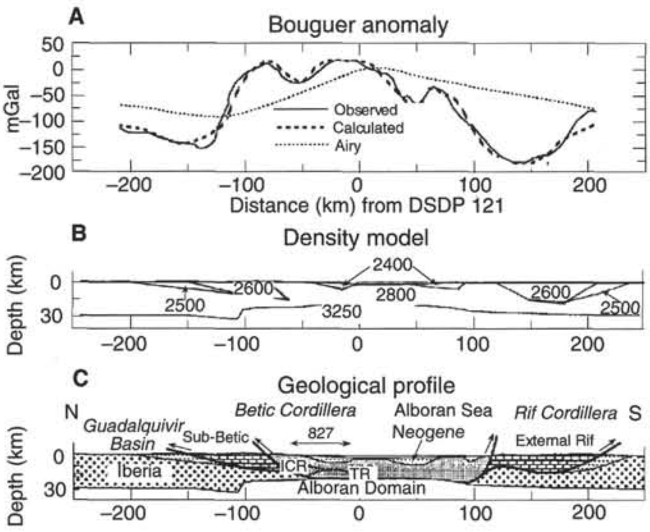

Figure 6. Bouguer anomaly and schematic true-scale section across the Alboran Sea basin and adjacent mountain belts. **A.** Bouguer anomaly. **B.** Density model, assumed densities in kg/m^3. **C.** North-south geological cross section. (ICR = intra-crustal reflector, TRLC = top of reflective lower crust; from Watts et al., 1993).

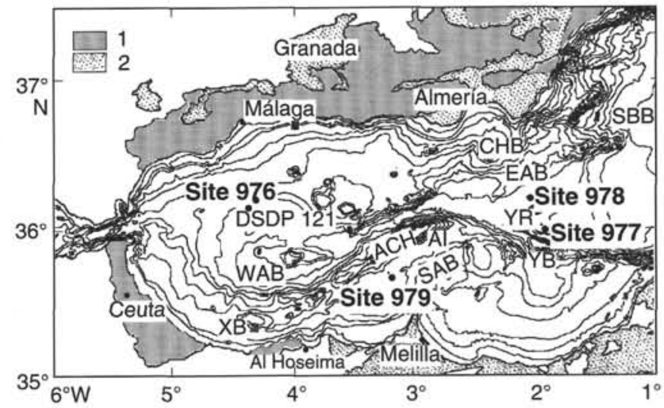

Figure 7. Bathymetric map of the Alboran Sea showing position of Leg 161 sites. Contour lines in m. Map onshore: 1 = Miocene marine sediments, 2 = Alboran Domain, ACH = Alboran Channel, AI = Alborán Island, CHB = Chella Bank, EAB = Eastern Alboran Basin, SAB = South Alboran Basin, SBB = South Balearic Basin, WAB = West Alboran Basin, XB = Xauen Bank, YB = Yusuf Basin, YR = Yusuf Ridge.

Spanish continental shelf. These well data show that beneath the shelf early Miocene to Pleistocene deposits are ~3.5 km thick. Wireline log interpretation, as well as analysis and correlation throughout a dense grid of multichannel seismic reflection lines, identified six lithoseismic units within the sedimentary cover of the Alboran Sea (Fig. 8). The major characteristics of these sequences as defined by Comas et al. (1992) and Jurado and Comas (1992) are:

1. The early- to late-Miocene sedimentary sequence beneath the Spanish shelf, which contains distal marine-facies, suggesting that, during the Miocene, the Alboran Sea coastline was located farther to the north.
2. The lack of well-developed Messinian evaporitic series within deposits of the Alboran Basin. The Messinian deposits are formed by marine or shallow carbonate facies; gypsum and anhydrite intervals are occasionally present.
3. Volcanic and volcaniclastic levels intercalate throughout the middle and late Miocene sequence and, in correlation with seismic data, seem to be widespread across the entire Alboran Basin.
4. The lowermost sediments that directly overlay the basement are late Aquitanian–Burdigalian? in age (seismic Unit VI; Fig. 8). They correspond to the first marine deposits in the basin and are formed of olistostromes that contain clastic material and overpressured shales. This seismic unit is correlated with on-shore complexes composed of clays and detrital deposits containing olistostromes.
5. The large diapiric bodies observed in the Western Alboran Basin that originate from early- to middle-Miocene sediments (seismic Units VI and V; Fig. 8) are formed of undercompacted shales, contradicting earlier literature that inferred that these diapirs were formed by "Messinian salt" (Auzende et al., 1975, among others).
6. Major interregional unconformities occur at the top of Burdigalian sediments (top of seismic Unit VI), within early late-Tortonian sediments (at the base of seismic Unit III) and at the base of the Pliocene (top of the Messinian Unit II). This last reflector corresponds with the "M"-reflector recognized elsewhere in the Mediterranean (Ryan, Hsü, et al., 1973).

Marine Neogene sequences, similar to those of the Alboran Sea basin fill, crop out in the Betic and Rif Chains around the Alboran Sea (Fig. 7) (Aït Brahim and Chotin, 1989; Montenant et al., 1987). It should be emphasized that in the Miocene the Alboran Basin extended north and south, beyond the present limits of the Alboran Sea.

Basement and Crustal Structure

Multichannel seismic reflection profiles and dredge data show that the Alboran Basin acoustic basement is heterogeneous. Broad areas of the top of the acoustic basement east of 4°W appear to be formed of volcanic rocks, based on dredges of volcanic seamounts (Giermann et al. 1968; Maufret et al., 1987). In addition, metamorphic rocks belonging to metamorphic complexes in the surrounding Betic and Rif Chains have been recovered from commercial wells near the Alboran Sea coastline (Fig. 8; Comas et al., 1992). DSDP Site 121 results (Ryan, Hsü, et al., 1973; Kornprobst, 1973; Steiger and Frick, 1973) also suggest that the crust in the Western Alboran Basin is composed of metamorphic rocks. These data suggest that the Alboran Basin is likely floored by the Alboran Crustal Domain (Internal Zones of the surrounding chains), that is disrupted and extended from the former convergent orogenic belt.

Seismic refraction data and gravity modeling show that the crust thins from about 35 km beneath the Internal Zones of the Betic and Rif Chains to about 15–20 km beneath the central Alboran Sea (Hatzfeld, 1978; Banda and Ansorge, 1980; Torné and Banda, 1992; Banda et al., 1993; Watts et al., 1993). Available data suggest that this crust thinned considerably from a continental crust that was previously thickened by collisional stacking. Bouguer gravity anomaly data are consistent with the magnitude of crustal thinning inferred from the seismic refraction data (Fig. 6A; Watts et al., 1993). Aeromagnetic anomaly maps (Galdeano et al., 1974) suggest a pattern of volcanic ridges within the basin. A density model for the Alboran Basin and surrounding chains is shown in Figure 6B.

The mantle beneath the Alboran Sea shows anomalously low seismic velocities, around 7.6–7.9 km/s, at a relatively shallow depth (Banda et al., 1993). Two earthquakes at ~600 km beneath Granada indicate the presence of a detached fragment of sinking lithosphere (Grimson and Chen, 1986). Distinct positive gravimetry anomalies along the coast (i.e., Bonini et al., 1973) suggest that mantle material locally approaches the surface. These anomalies appear to be associated with the Ronda and Beni-Busera mantle peridotite outcrops. The

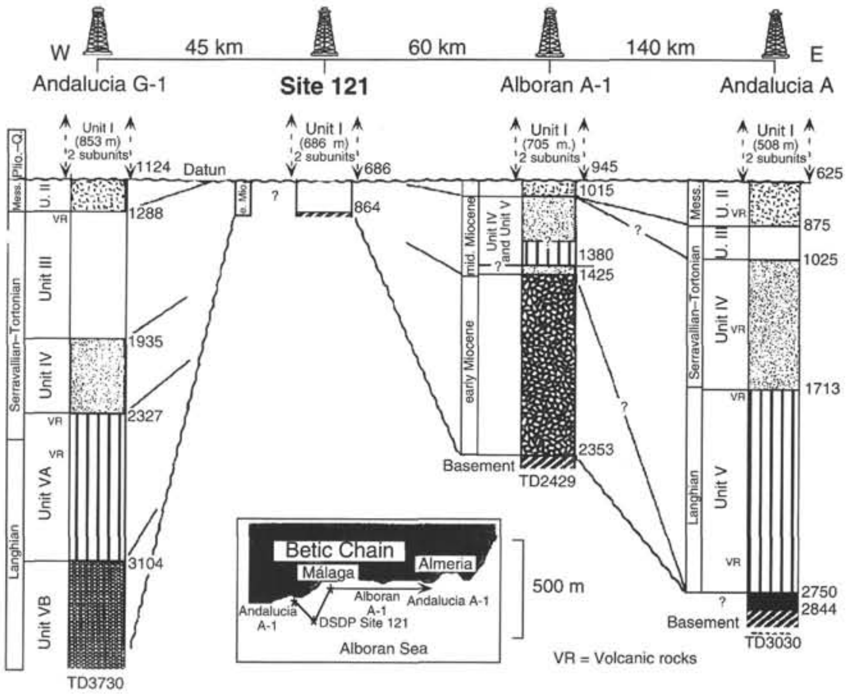

Figure 8. The sedimentary cover and lithoseismic units identified in the northern Alboran Sea. Correlation between commercial wells on the Spanish continental shelf and DSDP Site 121, based on MCS and logging data (from Comas et al., 1992 and Jurado and Comas, 1992).

origin and significance of these peridotite bodies is the subject of considerable debate. They have been interpreted as deep-rooted bodies (Bonini at al., 1973; Weijermars, 1985; Doblas and Oyarzun, 1989), but field evidence suggests that they form an allochthonous sheet of mantle rocks interleaved with crustal rocks (Lundeen, 1978; Dickey et al., 1979; Tubía and Cuevas, 1986; Balanyá and García-Dueñas, 1991). Recent gravity modeling of the Ronda peridotites supports this interpretation (Torné et al., 1992).

Heat-flow survey results in the Alboran Basin provide information regarding the character of the lithosphere beneath the Alboran Sea. Results of a modeling approach that combines heat-flow data, crustal structure, and elevation suggest a dramatic decrease in lithosphere thickness from the Western Alboran Basin (60–80 km) to the Eastern Alboran Basin (30–40 km). This suggests a crustal thickness of about 21 km in the Western Alboran Basin, decreasing to a thickness of no more than 11.5 km in the easternmost Alboran Sea (Polyak et al., in press).

The above-mentioned geological and geophysical data are consistent with a Neogene basin generated by rifting, extension, and subsidence.

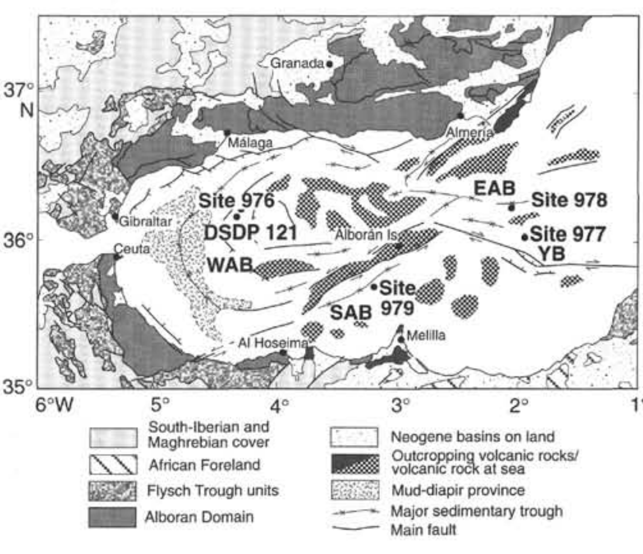

Figure 9. Structural sketch of the Alboran Sea, based on interpretation of MCS profiles and the surrounding Betic and Rif Chains (from Comas et al., 1993). Position of Leg 161 drill sites and DSDP Site 121 within the structural setting is shown. EAB = Eastern Alboran Basin, SAB = Southern Alboran Basin, WAB = Western Alboran Basin, YB = Yusuf Basin.

Tectonic Evolution of the Basin

The tectonic pattern of the Alboran Sea basin (Fig. 9) shows structures developed during various tectonic stages of basin evolution. Earlier structures are extensional grabens generated by several rifting episodes; developed from the late Aquitanian (22 Ma) to the early Tortonian (10 Ma). The Miocene episode of crustal thinning was partially coeval with the westward displacement of the Alboran Crustal Domain and the concurrent opening of the western Mediterranean (García-Dueñas et al., 1992). Subsequent tectonic subsidence probably led to an initial eastward transgression that deposited Aquitanian–Burdigalian seismic Unit VI (Comas et al., 1992; 1993; in press). Onshore geologic data also indicate that sequences that are equivalent to seismic Unit VI were probably the first transgressive deposits postdating initial extensional faulting of the Betic metamorphic complexes. The first stages of crustal stretching (which led to the Aquitanian transgression) are not well recognized in existing seismic data. However, two main rifting episodes, of Burdigalian–Langhian (~17–15 Ma) and Serravallian–early Tortonian (~14–10 Ma) ages, can be easily recognized. The direction of extension during this rifting may be deduced from the fault-related mid-Miocene deposition centers. A predominant east-northeast–west-southwest extension direction is well identified from mid-Miocene extensional structures in the Western Alboran Basin (Comas et al., 1993). As a whole, directions of extension and rifting episodes recognized offshore are consistent with those recognized onshore (García-Dueñas and Martínez-Martínez, 1988; Galindo et al., 1989, García-Dueñas et al., 1992, Crespo-Blanc et al., 1994).

Late Serravallian to Tortonian alkaline and calc-alkaline volcanic rocks (Bellon et al., 1983; Hernandez et al., 1987) are exposed onshore and have been detected offshore (Comas et al., 1992). These magmatic events (first occurrences: leucogranites at 22 Ma, ryolitic tuffites at 22–19 Ma), as well as the extensive mud diapirism recognized beneath the western Alboran Sea, have likely resulted from these extensional processes.

Seismic data indicate that the extensional evolution of the Alboran Basin was abruptly interrupted in the late Tortonian by an episode of contraction that created folding, strike-slip faults, and the inversion of previous normal faults (Comas et al., 1992; Bourgois et al., 1992; Woodside and Maldonado, 1992). Numerous onshore observations in the areas close to the Alboran Sea indicate a north-northeast compression during the late Tortonian–Messinian, changing to north-northwest compression during the Pliocene and Pleistocene (Ott d'Estevou and Montenat, 1992; Aït Brahim and Chotin, 1989; Morel, 1989). These directions agree with the east-west trend of late Tortonian–Pliocene folds seen in seismic lines (Comas et al., 1992). During and after folding, approximately northwest and northeast directed conjugate strike-slip faults were active. The Alboran Basin was broken into sub-basins by transverse ridges during this tectonic event. Pull-apart basins bear witness to recent compressional conditions (Mauffret et al., 1987). Structural inversion, folding, and strike-slip faulting resulted in a north-south shortening and an east-west elongation of the basin. Available data suggest that the Alboran Basin increased in length considerably since the late Miocene and was offset from the adjacent South Balearic Basin by left-lateral displacement (Montenat et al., 1992; de Larouzière et al., 1988).

Messinian lamproites, shoshonitic lavas (4.5–9 Ma), and alkali basalts (1.5–6 Ma) erupted extensively during this compressional stage (Bellon et al. 1983; Hernandez et al., 1987). These volcanic rocks (regionally associated with other calc-alkaline rocks, 7–13 Ma) have been genetically related to a lithospheric trans-Alboran shear zone (de Larouzière et al., 1988).

The later tectonic reorganization of the Alboran Basin started in the late Pliocene and was dominated by normal faulting and oblique strike-slip faults, most of them resulting from reactivation of Miocene faults. A Pliocene–Pleistocene faulting episode was probably related to basin subsidence and the simultaneous uplifting of the Iberian and African coasts. This episode is believed to have influenced the location of the present day coastline (Comas et al., 1992).

THE ODP TRANS-MEDITERRANEAN DRILLING TRANSECT: PALEOCEANOGRAPHIC EVOLUTION AND HISTORY OF SAPROPEL FORMATION IN THE MEDITERRANEAN

The primary paleoceanographic goal during Legs 160 and 161 was to obtain complete Pliocene–Pleistocene sedimentary sequences in a transect across the entire Mediterranean (Fig. 10). This drilling transect was designed to determine Mediterranean-wide circulation patterns during the late Cenozoic with special focus on periods of sapropel deposition.

Recent work has demonstrated that the occurrence of sapropels closely correlates with minima in the Earth's orbital precession cycle, which occur every 21,000 years (Fig. 11; Hilgen, 1991, Lourens, 1994). During these periods, the northern hemisphere receives stronger summer insolation and weaker winter insolation than is received at present. This enhances seasonal and continent-ocean temperature contrasts and promotes stronger monsoonal circulation (Prell and Kutzbach, 1992), which, in turn, trigger higher precipitation over East Africa, thereby enhancing river runoff to the eastern Mediterranean via the Nile River (Rossignol-Strick, 1985). At the same time, precipitation over the northern Mediterranean borderlands increases as atmospheric depressions move across the Mediterranean, respond-

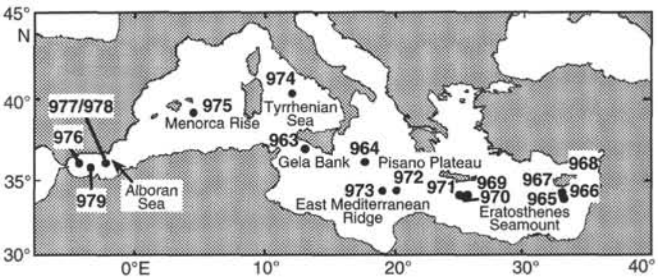

Figure 10. Sites in the eastern and western Mediterranean that were drilled during Legs 160 and 161. The sites were selected along an east-west transect that would allow documentation of Mediterranean-wide hydrographic patterns during Pliocene–Pleistocene times.

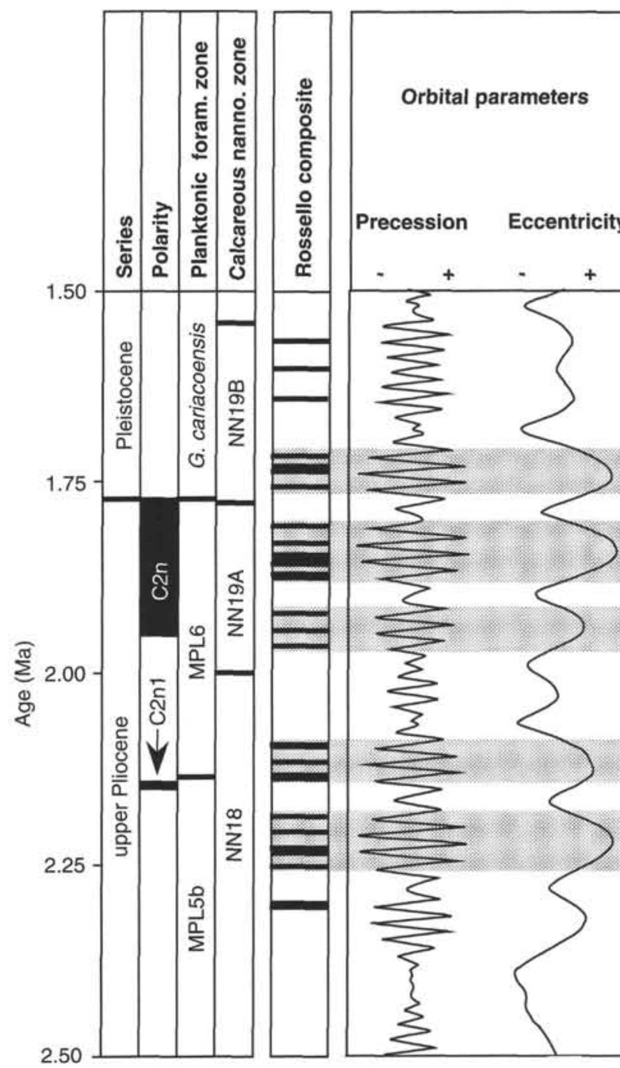

Figure 11. Pliocene–Pleistocene sapropel occurrence in the Vrica, Singa, and Rossello sections (spliced together to the Rossello Composite) in Southern Italy and Sicily (Lourens, 1994). Sapropels correlate with minima in the orbital precession index, sapropel clusters correlate with maxima in the Earth's orbital eccentricity. Polarity time scale is from Cande and Kent (1992), biozones are from Sprovieri (1992, 1993) and Rio et al. (1990). Orbital parameters are from Berger and Loutre (1991).

ing to increased formation of Atlantic lows that stimulate enhanced moisture transport to the east (Rohling and Hilgen, 1991). The combined influence of increased river runoff and precipitation has been postulated to promote the formation of a low-salinity surface layer in the eastern Mediterranean, which would stabilize the upper water column. As a result, surface-water convection would cease and ventilation of the deeper water column would be reduced, depleting deep- and bottom-water oxygen, thus enhancing the preservation of organic matter at the seafloor.

Episodes of bottom-water anoxia in conjunction with post-glacial sea-level rise and freshwater input from the Black Sea during the reestablishment of the marine connection through the Bosporus have been proposed in earlier studies (e.g., Olausson, 1961) to explain the formation of sapropels in the eastern Mediterranean. The anoxia model appeared to be supported by the lack of benthic foraminifers in most sapropels and the lamination of the organic-rich sapropel facies (Rohling et al., 1993). This evidence was used to infer extremely hostile, oxygen-depleted benthic environments that led to a complete extinction of benthic communities during sapropel formation. Further support for the anoxia model was derived from strong negative oxygen-isotope anomalies recorded in planktonic foraminifers that are associated with the sapropels (e.g., Williams et al., 1978; Vergnaud-Grazzini et al., 1986). These anomalies imply the presence of low-salinity excursions in the surface waters, which would have enhanced the surface-deep water density contrast and brought deep convection to a halt.

The anoxia model has been challenged by geochemical evidence that the early-Holocene sapropel (up to 14% organic carbon) in the Black Sea must have formed under well-ventilated, fully-oxic conditions (Calvert, 1990). In addition, no sapropels are forming there at present, even though the modern Black Sea is regarded as the classic-type euxinic basin. Thus, decreased organic matter degradation alone appears unlikely to have promoted the formation of sapropels in the eastern Mediterranean.

An alternative hypothesis postulates that the formation of sapropels correlates with periods of enhanced marine productivity and increased flux of organic matter to the seafloor (Calvert et al., 1992; Lourens et al., 1992; Van Os et al., 1994). This hypothesis is supported by the presence of organic carbon concentrations as high as (or even higher than) those measured for the eastern Mediterranean sapropel, in sediments that accumulate in coastal upwelling regimes where bottom waters are neither anoxic nor stagnant (Zahn and Pedersen, 1991; Lyle et al., 1992; Sancetta et al., 1992). Also, the Mediterranean is an oligotrophic sea where annual primary production is low, ranging from 25–50 g C/m^2 in the open Mediterranean to 60–75 g C/m^2 in some coastal zones (Murdoch and Onuf, 1974; for comparison, primary productivity in coastal upwelling regimes off Peru and northwest Africa reaches values of 250 to >400 g C/m^2/yr; Berger et al., 1994). At this low rate of organic carbon production, sedimentary organic carbon concentrations today would barely reach the elevated levels of organic carbon concentration observed in eastern Mediterranean sapropels, even if all organic carbon was preserved at the seafloor.

If increased productivity was important for the formation of sapropels, then what caused marine productivity to increase at the rhythm of the orbital precession period? Rohling and Gieskes (1989) propose a conceptual model in which enhanced precession-driven freshwater flux would cause the eastern Mediterranean's pycnocline and the associated deep-nutrient maximum to shoal into the euphotic zone, leading to the formation of a deep-chlorophyll maximum, which would have stimulated marine productivity (Fig. 12). This scenario appears to be supported by the observation that abundances of planktonic foraminiferal and nannofloral species, which are associated with deep chlorophyll maxima in today's ocean, are enhanced in most sapropels (Rohling and Gieskes, 1989; Castradori, 1993).

Even though the occurrence of individual sapropel layers is closely correlated to minima in the precession index, they are not evenly distributed through time (Fig. 11). Rather they occur in distinct clusters that correlate with maxima in the Earth's orbital eccentricity occurring at periods of 100,000 years and 400,000 years (Hilgen, 1991). The temporal distribution pattern of sapropels indicates a close correlation with changing external boundary condition (i.e., climate and hydrography). Therefore, it seems plausible to infer that whatever mechanism exerted primary control on the formation of sapropels (basin-wide anoxia or increased biological productivity), its operation must have resulted in distinct changes of the Mediterranean's physical circulation and geochemical cycling.

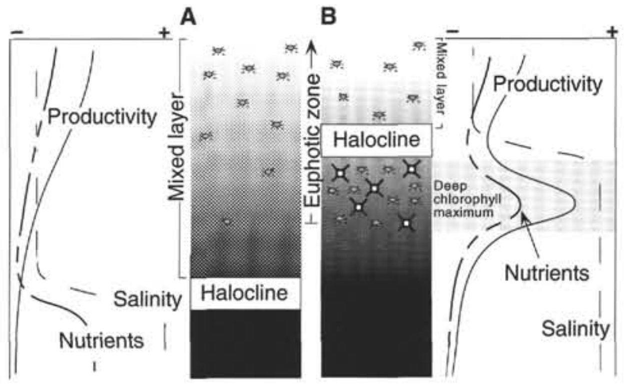

Figure 12. Schematic diagram showing the development of a Deep Chlorophyll Maximum (DCM) in the Mediterranean. **A.** Nutrients are consumed in the mixed layer by marine biota. Organic tissue sinks below the halocline where it is remineralized, leading to the formation of a deep nutrient maximum. The halocline imposes a density barrier that does not allow nutrients to re-enter the mixed layer from below. **B.** During periods of decreased evaporation and/or increased freshwater flux to the Mediterranean, the halocline shoals and the deep nutrient maximum migrates upward into the euphotic zone. This promotes the formation of a DCM at the base of the euphotic zone, thereby stimulating biological productivity and increasing the flux of organic matter to the seafloor. This conceptual model has been proposed by Rohling and Gieskes (1989) to explain sapropel formation during periods of wet climates.

The paleoceanographic drilling program during the previous Leg 160 was devoted to obtaining continuous high-resolution Pliocene–Pleistocene paleoceanographic data from the eastern Mediterranean that contained a detailed record of sapropel deposition. Leg 161 was designed to retrieve time-equivalent sedimentary sequences that would allow documentation of the paleoceanography of the western Mediterranean during the Miocene through Pleistocene and determination of Mediterranean-wide circulation patterns at times of sapropel formation in the eastern Mediterranean.

PALEOCEANOGRAPHY OF THE WESTERN MEDITERRANEAN: THE CURRENT STATE OF IGNORANCE

Mediterranean Hydrography

The hydrography and circulation of the western Mediterranean is primarily driven by inflowing Atlantic surface water and outflow of intermediate waters at depth (Fig. 13; Sparnocchia et al., 1994). The outflow waters are derived from Levantine Intermediate Water (LIW), which forms in the Levantine Basin of the eastern Mediterranean. Salinity of the inflowing Atlantic water increases to the east as evaporation increases. By the time it reaches the Levantine Basin, salinity is about 2‰ higher than that of the inflowing Atlantic water, inducing sinking of surface water and formation of LIW and Eastern Mediterranean Deep Water.

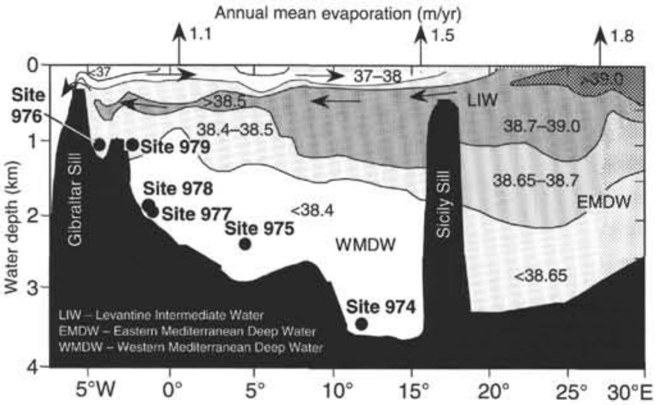

Figure 13. Salinity transect across the Mediterranean showing Leg 161 sites in the western Mediterranean. The salinity pattern indicates the presence of type-water masses, namely Eastern Mediterranean Deep Water, Levantine Intermediate Water, and Western Mediterranean Deep Water. Also shown are annual mean evaporation rates that cause surface salinity to increase to the east.

The east-west gradient in surface salinity is also reflected in the vertical salinity contrast in the western Mediterranean between Modified Atlantic Water in the surface layer and saline LIW at depth (Fig. 14). As the Mediterranean's physical circulation is driven by the excess of evaporation over precipitation and resultant basin-to-basin salinity gradients (Bryden and Kinder, 1991), monitoring hydrographic paleogradients across the Mediterranean is an important objective of paleoceanographic research in the area (e.g., Thunell and Williams, 1989; see below).

Formation of deep water plays only a minor role in the western Mediterranean. It occurs regionally in the Ligurian Sea when dense surface waters sink to greater depth in response to winter cooling and enhanced evaporation caused by dry "mistral" winds (MEDOC Group, 1970; Schott and Leaman, 1991; Leaman, 1994). The shallow sill depths of the Strait of Sicily (330 m) and Strait of Gibraltar (280 m) inhibit exchange of deep waters with the Atlantic and between the Eastern and Western Mediterranean Basins. Interbasin exchange of deep waters occurs only in the event of seasonally more intense intermediate water circulation that may draw deeper waters up and above the sills (Bryden and Kinder 1991; for a detailed discussion of western Mediterranean oceanography see La Violette, 1994).

Atlantic-Mediterranean Water Exchange

An important aspect of paleoceanographic research in the western Mediterranean is the history of water exchange with the Atlantic during late Quaternary glacial-interglacial sea level changes (e.g., Faugères et al., 1984), and its influence on the Mediterranean's hydrography (Vergnaud-Grazzini et al., 1986; Thunell et al., 1987; Thunell and Williams, 1989). Early work on sedimentary facies patterns east and west of the Strait of Gibraltar suggested that current reversals toward an estuarine flow pattern (deep inflow, surface outflow) occurred during post-glacial sea-level rises (Olausson, 1961; Huang and Stanley, 1972). The current reversal would have been driven by an enhanced freshwater flux from melting alpine glaciers and re-establishment of the marine connection between the eastern Mediterranean and the Black Sea at the end of the glacial periods (Kullenberg, 1952; Olausson, 1961). This would have resulted in a positive water balance in the Mediterranean with a subsequent outflow of surface waters to the west.

However, the early evidence supporting this hypothesis was not conclusive (Diester-Haass, 1973; Sonnenfeld, 1974). Subsequent

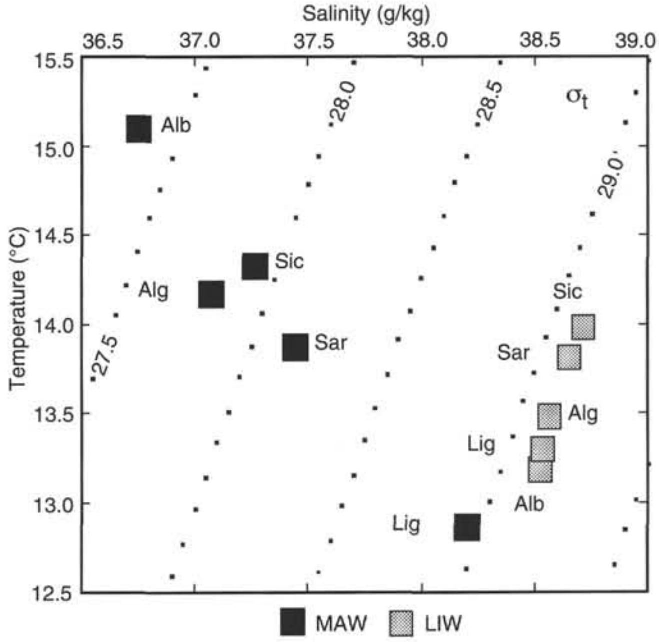

Figure 14. Temperature-salinity (T-S) characteristics of Atlantic waters (MAW = Modified Atlantic Water) and Levantine Intermediate Water (LIW) in the western Mediterranean during winter. T-S values for MAW are 15.11°C and 36.76 PSU in the Alboran Sea (Alb). Surface salinity increases as MAW flows east through the Algerian Basin (Alg) and Sardinian Sea (Sar), and out into the eastern Mediterranean through the Strait of Sicily (Sic). LIW enters the western Mediterranean with T-S values of 13.98°C and 38.70 PSU. The slight salinity decrease of LIW to the west is caused by the admixture of low-salinity waters from above and below. The salinity offset between MAW and LIW is driven by evaporation and freshwater flux across the Mediterranean. Estimating T-S values of past surface and bottom waters in the western Mediterranean may thus yield information on Mediterranean-wide hydrographic and climatic boundary conditions. T-S data are from Sparnocchia et al. (1994).

analysis of foraminiferal, stable-isotope, and trace-element patterns on both sides of the Strait of Gibraltar suggested that the modern current pattern was maintained during the post-glacial sea-level rise (Faugères et al., 1984; Stow et al., 1986; Zahn et al., 1987; Grousset et al., 1988; Vergnaud-Grazzini et al., 1989). According to these studies, deep Mediterranean Outflow Waters (MOW) continued to flow into the North Atlantic during the Last Glacial Maximum (approximately 18,000 ^{14}C ka), when sea level was about 120 m below its present level. At this time, the advection of MOW would have been reduced to 30–50% of its current rate, because of the reduced dimensions of the Strait of Gibraltar (Béthoux, 1984; Bryden and Stommel, 1984; Thunell et al., 1987). During the post-glacial sea-level rise, advection of MOW to the North Atlantic appeared to be sporadically reduced (Zahn et al., 1987; Grousset et al., 1988; Vergnaud-Grazzini et al., 1989), but the flow pattern apparently never was reversed. This contention is supported by similar paleoceanographic evidence from the Strait of Sicily that indicates the modern anti-estuarine flow patterns (i.e., surface flow to the east, deep flow to the west) through the strait persisted during glacial and post-glacial times (Vergnaud-Grazzini et al., 1988).

Alboran Sea Circulation and Biological Productivity

Alternating north-south directions of the Atlantic inflow across the Alboran Sea generate a anticyclonic gyre circulation in the Western and Eastern Alboran Sea. The western gyre is mainly driven by bottom topography and a strong northward component of the Atlantic inflow immediately east of Gibraltar (Kinder and Parrilla, in press). What drives the eastern gyre is not well understood. A strong density front (Almería-Orán front) along its eastern boundary forces the Atlantic inflow to the south where it flows as a strong eastward jet through a narrow zone along the Algerian coast (Tintoré et al., 1995). Geostrophic forcing along this jet stimulates upwelling of deeper, nutrient-enriched waters that increase nutrients regionally in the surface layer. The circulation pattern in the Alboran Sea is driven both by the Atlantic inflow and climate (Tziperman and Malanotte-Rizzoli, 1991; Kinder and Parrilla, in press) and, thus, glacial-interglacial climatic change may alter circulation and nutrient patterns in the Alboran Sea. Glacial-interglacial fluctuations in biological productivity have indeed been inferred from paleoceanographic records in the Alboran Sea (Abrantes, 1988; Vergnaud-Grazzini and Pierre, 1991). They were likely driven by changes of circulation fronts and associated zones of increased biological productivity. Variable concentrations of nutrients contained in the eastward-flowing Atlantic surface current may have also influenced productivity patterns in the western Mediterranean. Monitoring late Cenozoic productivity patterns in the Alboran Sea is, therefore, an important paleoceanographic objective of Leg 161.

Messinian Desiccation

Isolation and desiccation of the Mediterranean during the Messinian is a second major paleoceanographic research objective. It is an important paleoenvironmental event that affected the Mediterranean climate and was potentially important in affecting open-ocean circulation (Ryan, Hsü, et al., 1973; Hsü, Montadert, et al., 1978; Adams et al., 1977; Cita et al., 1985; Cita and McKenzie, 1986; McKenzie et al., 1990). After the Mediterranean's connection to the Indian Ocean in the East was closed during the early Miocene, the Betic and Rif gateways in the west remained the only pathways for water exchange with the open ocean. The combined tectonic and climatic phenomena of rhythmic eustatic sea-level change and alternating phases of tectonic uplift and subsidence of the Gibraltar Arc explain the closure of the Atlantic-Mediterranean gateway and subsequent desiccation of the Mediterranean.

Today, the advection of deep Mediterranean Outflow Water (MOW) constitutes a significant salt contribution to the global ocean (Armi and Farmer, 1985; Zenk and Armi, 1990; Ambar et al., 1992) and potentially contributes to the rate of thermohaline overturn in the northern North Atlantic (Reid, 1979). Even though the influence of MOW on deep-water formation in today's North Atlantic is controversial (Reid, 1979; Bryden and Kinder, 1991), the complete closure of the Atlantic-Mediterranean gateway and subsequent shut-down of salt export to the North Atlantic during the Messinian had a significant effect on the global ocean's thermohaline circulation (Blanc and Duplessy, 1982; Thunell et al., 1987). For instance, a foraminiferal carbon isotope anomaly is observed throughout the world ocean during the Messinian, pointing to a vertical redistribution of carbon within the ocean's carbon reservoir, possibly in conjunction with a slowdown of oceanic overturn (Bender and Keigwin, 1979; Vincent et al., 1980; Keigwin et al., 1987; Thunell et al., 1987). Enhanced dissolution of deep-sea carbonates during the Messinian also suggests diminished deep-ocean ventilation, which would have made deep waters more corrosive (Thierstein and Berger, 1978; Thunell, 1981). To what extent these changes were driven by the cessation of MOW flow to the North Atlantic remains unclear. Documentation of the onset of evaporitic conditions during the Messinian and the re-establishment of the Atlantic-Mediterranean marine connection during the latest Messinian therefore remains a high-priority issue for Mediterranean paleoceanography as well as global circulation studies.

The Mediterranean and Global Glaciation

The response of the Mediterranean Sea to the onset of northern hemisphere glaciation 2.7–3.2 Ma (Shackleton et al., 1984; Raymo et al., 1992; Lourens and Hilgen, 1994) and concomitant sea-level change during the late Pliocene is yet to be determined. Changes of climatic patterns during this period are recorded at open-ocean sites (Raymo et al., 1989; Tiedemann et al., 1994) and in environmental records from the Mediterranean region (Fig. 15). Around 2.4 Ma, the pattern of sapropel deposition in the eastern Mediterranean changed toward less frequent sapropel occurrence and better carbon preservation with increasing water depth (Emeis, Robertson, Richter, et al., 1996). Progressive intensification of glacial boundary conditions during this period may have resulted in an onset of rapid oscillations of monsoonal climates between arid and humid conditions and concomitant oscillations of the freshwater flux to the Mediterranean.

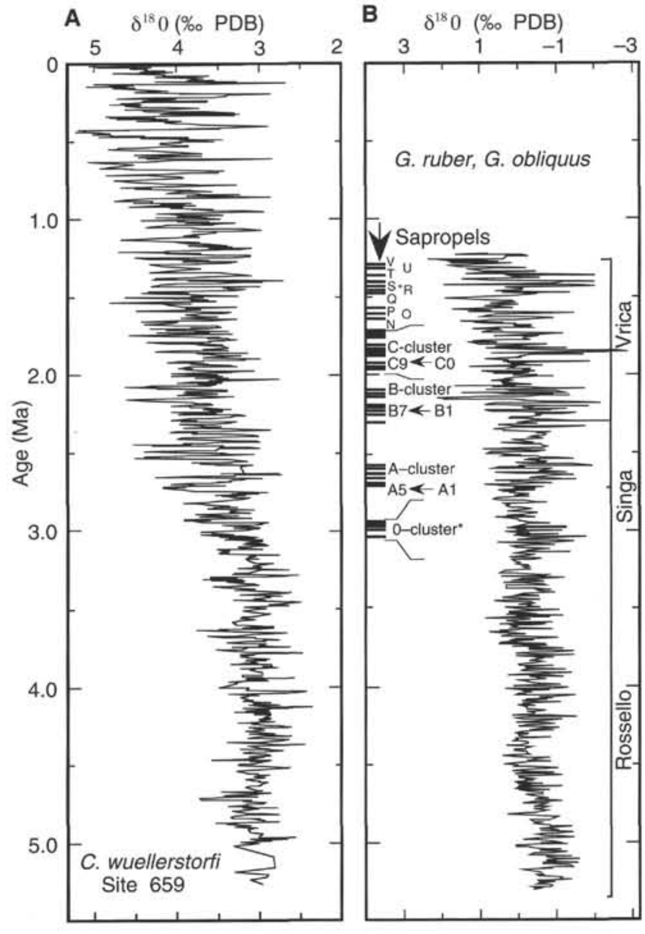

Figure 15. Oxygen isotope records from (**A**) ODP Site 659 in the eastern North Atlantic (Tiedemann et al., 1994) and (**B**) the Mediterranean (Lourens, 1994). The records show an increase in amplitude and a change in trend towards more positive values at ~3.0 Ma, indicating the onset of northern hemisphere glaciation. This is also when sapropels are first observed in land sections in southern Italy and Sicily. The Mediterranean isotope curve is spliced together from data obtained at the Vrica, Singa, and Rossello sections. Isotope amplitudes in the Mediterranean are more than twice the amplitudes seen in the Atlantic record (note different isotope scales). This points to the "concentration" effect of the Mediterranean (i.e., the amplification of climate signals due to the restricted water-mass exchange with the open ocean, in conjunction with a net water loss to evaporation).

Similar changes are documented for the late Quaternary (Gasse et al., 1990; Gasse and van Campo, 1994; Zahn, 1994) and have been proposed to control the formation of sapropels (Rossignol-Strick, 1985; Rohling and Gieskes, 1989; Hilgen, 1991).

Inflowing Atlantic waters contribute to the hydrographic and climatic boundary conditions in the Mediterranean in that their temperature and salinity determine the flux of heat across the Mediterranean and the intensity of water-mass stratification (Bryden and Kinder, 1991; Sparnocchia et al., 1994). The response of water-mass distribution in the North Atlantic to periodic meltwater input is still controversial (Veum et al., 1992; Lehman and Keigwin, 1992; Zahn, 1992), but recent modeling suggests that thermohaline overturn in the northern North Atlantic may not cease but is likely to continue immediately following the injection of meltwaters (Rahmstorf, 1994). That is, the North Atlantic's surface circulation is likely to maintain its general circulation pattern and meltwater signals may be advected into the Mediterranean with inflowing Atlantic waters. If this is true, the Mediterranean may have started to receive North Atlantic meltwater signals as northern hemisphere glaciation and periodic meltwater discharge to the North Atlantic commenced ~3 Ma. These hydrographic anomalies should have left their imprints most distinctly in paleoceanographic proxy records at the westernmost Mediterranean drill sites. Establishing continuous records of paleoceanographic proxies that are linked to water-mass temperature and salinity (Thiede, 1978; Prahl and Wakeham, 1987; Zahn and Mix, 1991) and high-resolution stratigraphy at these sites are thus of primary importance in monitoring the hydrography of inflowing Atlantic waters and their potential links to marine environmental changes in the Mediterranean Sea.

LEG 161 SCIENTIFIC OBJECTIVES AND DRILLING TARGETS IN THE WESTERN MEDITERRANEAN

Leg 161 combined tectonic and paleoceanographic objectives. The tectonic history and paleoceanographic evolution of the western Mediterranean are connected in that paleogeographic variations (e.g., of the Atlantic-Mediterranean gateway) determine water circulation in the western Mediterranean. Thus, even though the tectonic and paleoceanographic objectives are listed separately they complement each other.

The primary paleoceanographic objectives of Leg 161 were:

1. To better understand the timing of sapropel formation in the Tyrrhenian Sea. At the time Leg 161 was being planned, this was the westernmost documented occurrence of sapropels in the Mediterranean.
2. To gain insight into the circulation pattern in the western Mediterranean during periods of sapropel formation in the east, and to determine hydrographic patterns across the entire Mediterranean to better define environmental factors that may have contributed to the formation of sapropels (i.e., basin-wide anoxia vs. biological productivity).
3. To determine environmental patterns during the onset of evaporitic conditions and the re-establishment of open-ocean conditions during the earliest and latest Miocene.
4. To investigate Atlantic-Mediterranean water exchange and its influence on the Mediterranean's hydrography during the onset of northern hemisphere glaciation, about 3.0 Ma. Monitoring hydrographic paleogradients across the Mediterranean as well as vertical paleogradients between surface and deep-water hydrographic proxies was an important objective of Leg 161.

The tectonic objectives of Leg 161 were:

1. To better understand dynamics, kinematics, and deformation of the western Mediterranean continental lithosphere, including (a) the development of extensional basins on former collisional orogens, (b) the dynamics of the collisional ridges resulting in extensional basins surrounded by orogenic belts, and (c) selected compressional processes.
2. To investigate the nature of the crust beneath the Alboran Basin, to develop a lithosphere model for the observed rifting system and establish (a) models for Miocene rifting that constrain the nature of the basement and the geometry of rifting, (b) the magnitude and timing of extensional faulting, (c) the nature of synrift vs. postrift subsidence and the pattern of total tectonic subsidence, and (d) the timing and role of volcanism during extension.
3. To investigate postrift deformation: (a) the Late Miocene to Holocene contractive reorganization of the Alboran Basin, (b) the recent strike-slip tectonics, (c) the role of volcanism, and (d) the recent collapse of the basin.

To address these topics, six sites were selected for drilling in the western Mediterranean (Fig. 1):

(1) Site 974 (proposed Site MedSap 5), Tyrrhenian Sea

This site is a reoccupation of Site 652, which recovered eight sapropels and several volcaniclastic deposits (Kastens, Mascle, Auroux, et al., 1987; Emeis et al., 1991; McCoy and Cornell, 1990). The primary objective of Site 974 was to obtain a continuous Pliocene–Pleistocene record of organic-rich sedimentary events and a comprehensive record of volcaniclastic sedimentation that could be tied into the paleoceanographic and tephrachronologic concepts of the Mediterranean.

(2) Site 975 (proposed Site MedSap 6A), Menorca Rise

This site was chosen for its key position to monitor both the history of inflowing Atlantic waters as they flow to the east and of outflowing Mediterranean waters on their way west to the Alboran Sea. It is a central tiepoint along the trans-Mediterranean drilling transect that was drilled during Legs 160 and 161.

(3) Site 976 (proposed Site Alb 2A), Western Alboran Basin

This site is on a structural high at the southern Spanish margin close to DSDP Site 121. Its primary objective was to penetrate through the Pleistocene–Miocene sediment cover and recover hard-rock samples at least 200 m down into basement to yield information on the origin and extensional tectonic evolution of the Alboran Sea. A primary paleoceanographic objective at this site was to monitor the Atlantic-Mediterranean water exchange during the late Cenozoic.

(4) Sites 977 and 978 (proposed Sites Alb 4A and Alb 4), Eastern Alboran Basin.

The sites lie in small sub-basins south and north of the Al-Mansour Seamount. Sites 977 and 978 were selected in order to drill through a sequence likely representing postrift sediments that may yield information on the subsidence history and later tectonic evolution of the Eastern Alboran Basin. Paleoceanographic queries included the history of the Atlantic-Mediterranean water exchange from the Miocene to the Pleistocene and productivity patterns in the Eastern Alboran Sea in relation to climatically driven circulation changes.

(5) Site 979 (proposed Site Alb 3A), Southern Alboran Basin

The site is on the southern flank of the Alboran Ridge, ~45 km north of Cabo Tres Forcas. The main objective was to penetrate a zone of syn- and post-sedimentary folds on the flank of the ridge, which are depicted in seismic reflection profiles across the site as yielding the age and nature of the folds and associated unconformities. Ultimately, this will provide the database needed to establish the history of subsidence and/or uplifting of the Southern Alboran Basin.

To achieve the paleoceanographic objectives at Sites 974, 975, and 976, APC and XCB coring was performed at up to three offset holes to recover sedimentary sequences that were as complete as possible. Splicing together sections from offset holes may allow voids in one core to be filled by using intact sequences at an offset hole. The deeper sedimentary units and basement were recovered by RCB coring. At Site 976, an offset RCB hole was drilled to retrieve additional cores across the sediment-basement contact and to obtain high-quality logs of this transition. This offset strategy was proven successful in that it allowed us to obtain more complete sedimentary records and better coverage of critical intervals.

REFERENCES

Abrantes, F., 1988. Diatom productivity peak and increased circulation during the latest Quaternary: Alboran Basin (western Mediterranean). *Mar. Micropaleontol.,* 13:79–96.

Adams, C.G., Benson, R.H., Kidd, R.B., Ryan, W.B.F., and Wright, R.C., 1977. The Messinian salinity crisis and evidence of late Miocene eustatic changes in the world ocean. *Nature,* 269:383–386.

Aït Brahim, L., and Chotin, P., 1989. Genése et deformation des bassins néogènes du Rif Central (Maroc) au cours du rapprochement Europa-Africa. *Geodin. Acta* (Paris), 3:295–304.

Ambar, I., Armi, L., Baringer, M.O., Bower, A., Fiúza, A., Johnson, G.C., Käse, R., Kennelly, M., Kunze, E., Lueck, R., Lundberg, P., Martins, C.G., Prater, M.D., Price, J., Rhein, M., Sanford, T., Tokos, K., Verrall, J., and Zenk, W., 1992. Outflows and overflows in the Atlantic and their role in the eastern boundary current system. *Proc. Int. Workshop, Lisbon, October 1–4, 1992.* Grupo de Oceanogr., Dep. de Física, Fac. de Ciências, Univ. de Lisboa.

Armi, L., and Farmer, D., 1985. The internal hydraulics of the Strait of Gibraltar and associated sills and narrows. *Oceanol. Acta,* 8:37–46.

Auzende, J.M., Rehault, J.-P., Pastouret, L., Szep, B., and Olivet, J.-L, 1975. Les basins sèdimentaires de la mer d'Alboran. *Bull Soc. Geol. Fr.,* Ser. 7, XVII, 1:98–107.

Bakker, H.E., De Jong, K., Helmers, H., and Biermann, C., 1989. The geodynamic evolution of the internal zone of the Betic Cordilleras (south-east Spain): a model based on structural analysis and geothermobarometry. *J. Metamorph. Geol.,* 7:359–381.

Balanyá, J.C., Azañón, J.M., Sánchez-Gómez, M., and García-Dueñas, V., 1993. Pervasive ductile extension, isothermal decompression and thinning of the Jubrique Unit in the Paleogene (Alpujarride Complex, western Betics, Spain). *C. R. Acad. Sci. Ser. 2,* 316:1595–1601.

Balanyá, J.C., and García-Dueñas, V., 1987. Les directions structurales dans le Domaine d'Alboran de part et d'autre du Détroit de Gibraltar. *C. R. Acad. Sci. Ser. 2,* 304:929–932.

————, 1988. El cabalgamiento cortical de Gibraltar y la tectónica de Béticas y Rif. *2nd Congr. Geol. España (Simposios),* 35–44.

————, 1991. Estructuración de los Mantos Alpujárrides al Oeste de Málaga (Beticas, Andalucía). *Geogaceta,* 9:26–29.

Banda, E., and Ansorge, J., 1980. Crustal structure under the central and eastern part of the Betic Cordillera. *Geophys. J. R. Astron. Soc.,* 63:515–532.

Banda, E., Gallart, J., García-Dueñas, V., Danobeitia, J., and Makris, J., 1993. Lateral variation of the crust in the Iberia Peninsula: new evidence for the Betic Cordillera. *Tectonophysics,* 221:53–66.

Banks, C.J., and Warburton, J., 1991. Mid-crustal detachment in the Betic system of southern Spain. *Tectonophysics,* 191:275–289.

Bellon, H., Bordet, P., and Montenat, C., 1983. Le magmatisme néogène des Cordillères bétiques (Espagne): cronologie et principaux caractères géochimiques. *Bull. Soc. Geol. Fr.,* Ser. 7, 25:205–218.

Bender, M.L., and Keigwin, L.D., Jr., 1979. Speculations about the upper Miocene change in abyssal Pacific dissolved bicarbonate $\delta^{13}C$. *Earth Planet. Sci. Lett.,* 45:383–393.

Berger, A.L., and Loutre, M.F., 1991. Insolation values for the climate of the last 10 million years. *Quat. Sci. Rev.,* 10:297–317.

Berger, W.H., Herguera, J.C., Lange, C.B., and Schneider, R., 1994. Paleoproductivity: flux proxies versus nutrient proxies and other problems concerning the Quaternary productivity record. *In* Zahn, R., Pederson, T., Kaminski, M., and Labeyrie, L. (Eds.), *Carbon Cycling of the Glacial Ocean: Constraints on the Ocean's Role in Global Change: Quantitative Approaches in Paleoceanography:* Berlin (Springer-Verlag), NATO ASI Ser. I, 17:385–412.

Béthoux, J.P., 1984. Paléo-hydrologie de la Méditerranée au cours derniers 20000 ans. *Oceanol. Acta,* 7:43–48.

Biju-Duval, B., Letouzey, J., and Montadert, L., 1978. Structure and evolution of the Mediterranean basins. *In* Hsü, K.J., Montadert, L., et al., *Init. Repts. DSDP,* 42 (Pt. 1): Washington (U.S. Govt. Printing Office), 951–984.

Bird, P., 1979. Continental delamination and the Colorado Plateau. *J. Geophys. Res.,* 84:7561–7571.

Blanc, P.L., and Duplessy, J.-C., 1982. The deep-water circulation during the Neogene and the impact of the Messinian salinity crisis. *Deep-Sea Res., Part A,* 29:1391–1414.

Bonini, W.E., Loomis, T.P., and Robertson J.D., 1973. Gravity anomalies, ultramafic intrusions, and the tectonic of the region around the Straits of Gibraltar. *J. Geophys. Res.,* 78:1372–1382.

Bourgois, J., Mauffret, A., Ammar, A., and Demnati, N.A., 1992. Multichannel seismic data imaging of inversion tectonics of the Alboran Ridge (Western Mediterranean Sea). *Geo-Mar. Lett.,* 12:117–122.

Bryden, H.L., and Kinder, T.H., 1991. Recent progress in strait dynamics. *Rev. Geophys., Suppl., (U.S. Nat. Rep. Int. Union Geodesy Geophys. 1987–1990),* 617–631.

Bryden, H.L., and Stommel, H.M., 1984. Limiting processes that determine basic features of the circulation in the Mediterranean Sea. *Oceanol. Acta,* 7:289–296.

Calvert, S.E., 1990. Geochemistry and origin of the Holocene sapropel in the Black Sea. *In* Ittekkot, V., Kempe, S., Michaelis, W., and Spitzy, A. (Eds.), *Facets of Modern Biogeochemistry:* Berlin (Springer-Verlag), 326–352.

Calvert, S.E., Nielsen, B., and Fontugne, M.R., 1992. Evidence from nitrogen isotope ratios for enhanced productivity during the formation of eastern Mediterranean sapropels. *Nature,* 359: 223–225.

Cande, S.C., and Kent, D.V., 1992. A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. *J. Geophys. Res.,* 97:13917–13951.

Castradori, D., 1993. Calcareous nannofossils and the origin of eastern Mediterranean sapropels. *Paleoceanography,* 8:459–471.

Chalouan, A., and Michard, A., 1990. The Ghomarides nappes, Rif coastal range, Morocco: a variscan ship in the Alpine beds. *Tectonics,* 9:1565–1583.

Channell, J.E.T., and Mareschal, J.C., 1989. Delamination and asymmetric lithospheric thickening in the development of the Tyrrhenian Rift. *In* Coward, M.P., Dietrich, D., and Park, R.G. (Eds.), *Conference on Alpine Tectonics:* Geol. Soc. Spec. Publ., London, 45:285–302.

Cita, M.B., Kastens, K.A., McCoy, F.W., Aghib, F., Cambi, A., Camerlenghi, A., Corselli, C., Erba, E., Giambastiani, M., Herbert, T., Leoni, C., Malinverno, P., Nosetto, A., and Parisi, E., 1985. Gypsum precipitation from cold brines in an anoxic basin in the eastern Mediterranean. *Nature,* 314:152–154.

Cita, M.B., and McKenzie, J.A., 1986. The terminal Miocene event. *In* Hsü, K.J. (Ed.), *Mesozoic and Cenozoic Oceans.* AGU Geodyn. Ser., 15:123–140.

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

Comas, M.C., García-Dueñas, V., Soto, J.I., and Campos, J., 1993. An extensional basin developed on a collisional orogen: the Alborán Sea. *In* Seranne, M., and Malavielle, J. (Eds.), *Late Orogenic Extension in Mountain Belts.* Doc. B.R.G.M. Fr., 219:44–46.

Comas, M.C., Soto, J.I., and de la Linde, J., in press. Structure and evidences for extension in the Alboran Sea basin: implications for tectonic evolution. *Tectonics.*

Crespo-Blanc, A., Orozco, M., and García-Dueñas, V., 1994. Extension versus compression during the Miocene tectonic evolution of the Betic Chain: late folding of normal fault systems. *Tectonics,* 13.1:78–88.

Davies, G.R., Nixon, P.H., Pearson, D.G., and Obata, M., 1993. Tectonic implications of graphitized diamonds from the Ronda peridotite massif, southern Spain. *Geology,* 21:471–474.

De Jong, K., 1991. Tectono-metamorphic studies and radiometric dating in the Betic Cordilleras (SE Spain) [thesis]. Vrije Univ., Amsterdam.

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.

Dercourt, J., Zonenshain, L.P., Ricou, L.E., Kazmin, V.G., Le Pichon, X., Knipper, A.L., Grandjacquet, C., Sbortshikov, I.M., Geyssant, J., Lepvrier, C., Pechersky, D.H., Boulin, J., Sibuet, J.-C., Savostin, L.A., Sorokhtin, O., Westphal, M., Bazhenov, M.L., Lauer, J.P., and Biju-Duval, B., 1986. Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. *Tectonophysics,* 123:241–315.

Dewey, J.F., Helman, M.L., Turco, E., Hutton, D.H.W., and Knott, S.D., 1989. Kinematics of the western Mediterranean. *In* Coward, M.P., Dietrich, D., and Park, R.G., et al. (Eds.), *Conference on Alpine Tectonics:* Geol. Soc. Spec. Publ., London, 45:265–283.

Dickey, J.S., Jr., Lundeen, M.T., and Obata, M., 1979. Geologic map of the Ronda ultramafic complex. *Geol. Soc. Am.,* Chart Ser., 29:1–4.

Diester-Haass, L., 1973. No current reversal at 10,000 yrs B.P. in the Strait of Gibraltar. *Mar. Geol.,* 15:M1–M19.

Dillon, W.P., Robb, J.M., Greene, H.G., and Lucena, J.C., 1980. Evolution of the continental margin of Southern Spain and the Alboran Sea. *Mar. Geol.,* 36:205–226.

Doblas, M., and Oyarzun, L., 1989. "Mantle core complexes" and Neogene extensional detachment tectonics in the western Betic Cordilleras, Spain: an alternative model for the emplacement of the Ronda Peridotite. *Earth Planet. Sci. Lett.,* 93:76–84.

Emeis, K.-C., Camerlenghi, A., McKenzie, J.A., Rio, D., and Sprovieri, R., 1991. The occurrence and significance of Pleistocene and Upper Pliocene sapropels in the Tyrrhenian Sea. *Mar. Geol.,* 100:155–182.

Emeis, K.-C., Robertson, A.H.F., Richter, C., et al., 1996. *Proc. ODP, Init. Repts.,* 160: College Station, TX (Ocean Drilling Program).

Faugères, J.C., Gonthier, E., and Stow, D.A.V., 1984. Contourites drift molded by deep Mediterranean outflow. *Geology,* 12:296–300.

Frizon de Lamotte, D., 1987. Un exemple de collage synmétamorphe: la déformation miocène des Temsamane (Rif externe, Maroc). *Bull. Soc. Geol. Fr.,* 3:337–344.

Galdeano, A., Courtillot, V., Le Borgne, E., Le Mouel, J.-L., and Rossignol, J.-C., 1974. An aeromagnetic survey of the southwest of the western Mediterranean: description and tectonic implications. *Earth Planet. Sci. Lett.,* 23:323–336.

Galindo, J., González Lodeiro, F., and Jabaloy, A., 1989. Progressive extensional shear structures in a detachment contact in the Western Sierra Nevada (Betic Cordilleras, Spain). *Geodin. Acta,* 3:73–85.

García-Dueñas, V., and Balanyá, J.C., 1991. Fallas normales de bajo ángulo a gran escala en las Béticas occidentales. *Geogaceta,* 9:29–33.

García-Dueñas, V., Balanyá, J.C., and Martínez-Martínez, J.M., 1992. Miocene extensional detachments in the outcropping basement of the northern Alboran basin (Betics) and their tectonic implications. *Geo-Mar. Lett.,* 12:88–95.

García-Dueñas, V., and Martínez-Martínez, J.M., 1988. Sobre el adelgazamiento mioceno del Dominio de Alborán, el despegue extensional de Filabres (Béticas orientales). *Geogaceta,* 5:53–55.

Gasse, F., Téhet, R., Durant, A., Gilbert, E., and Fontes, J.-C., 1990. The arid-humid transition in the Sahara and the Sahel during the last deglaciation. *Nature,* 346:141–146.

Gasse, F., and van Campo, E., 1994. Abrupt post-glacial climate events in West Asia and North Africa monsoon domains. *Earth Planet. Sci. Lett.,* 126:435–456.

Gensous, B., Tesson, M., and Winnock, E., 1986. La marge meridionale de la Mer d'Alboran: caracteres structuro-sedimentaires et évolution recente. *Mar. Geol.,* 72:341–370.

Giermann, G., Pfannenstiel, M., and Wimmenauer, W., 1968. Relation entre morphologie, tectonique et volcanisme en mer d'Alboran (Mediterranée occidentale): resultats preliminaires de la campagne Jean-Charcot (1967). *C. R. Somm. Seances Soc. Geol. Fr.,* 4:116–118.

Goffé, B., Michard, A., García-Dueñas, V., González Lodeiro, F., Monié, P., Campos, J., Galindo-Zaldivar, J., Jabaloy, A., Martínez-Martínez, J.M., and Simancas, F., 1989. First evidence of high-pressure, low-temperature metamorphism in the Alpujarride nappes, Betic Cordilleras (S.E. Spain). *Eur. J. Mineral.,* 1:139–142.

Grimson, N.L., and Chen, W.P., 1986. The Azores-Gibraltar plate boundary: focal mechanisms, depths of earthquakes, and their tectonic implications. *J. Geophys. Res.,* 91:2029–2047.

Grousset, F.E., Joron, J.L., Biscaye, P.E., Latouche, C., Treuil, M., Maillet, N., Faugeres, J.C., and Gonthier, E., 1988. Mediterranean outflow through the Strait of Gibraltar since 18,000 years B.P.: mineralogical and geochemical arguments. *Geo-Mar. Lett.,* 8:25–34.

Hatzfeld, D., 1978. Etude sismolopique et graviuietique de le structure profonde de la user d'Alboran. Mise en evidence d'un manteau anomal. *C. R. Acad. Sci. Paris, Ser. D,* 283:1021–1024.

Hernandez, J., de Larouzière, F.D., Bolze, J., and Bordet, P., 1987. Le magmatisme néogène bético-rifain et le couloir de décrochement trans-Alboran. *Bull. Soc. Geol. Fr.,* 3:257–267.

Hilgen, F.J., 1991. Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the geomagnetic polarity time scale. *Earth Planet. Sci. Lett.,* 104:226–244.

Horvath, F., and Berckhemer, H., 1982. Mediterranean back arc basins. *In* Berckhemer, H., and Hsü, K.J. (Eds.), *Alpine-Mediterranean Geodynamics.* Ber. Inst. Meteorol. Geophys. Univ. Frankfurt/Main, Geodyn. Ser., 7:141–173.

Houseman, G.A., MacKenzie, D.P., and Molnar, P., 1981. Convective instability of a thickened boundary layer and its relevance for the thermal evolution of continental convergence belts. *J. Geophys. Res.,* 86:6115–6132.

Hsü, K.J., Montadert, L., et al., 1978. *Init. Repts. DSDP,* 42 (Pt. 1): Washington (U.S. Govt. Printing Office).

Huang, T., and Stanley, D., 1972. Western Alboran Sea: sediment dispersal, ponding and reversal of currents. *In* Stanley, D. (Ed.), *The Mediterranean Sea: A Natural Sedimentation Laboratory:* Stroudsburg, PA (Dowden, Hutchinson and Ross), 521–560.

Jurado, M.J., and Comas, M.C., 1992. Well log interpretation and seismic character of the Cenozoic sequence in the Northern Alboran Sea. *Geo-Mar. Lett.,* 12:129–136.

Kastens, K.A., Mascle, J., Auroux, C., et al., 1987. *Proc. ODP, Init. Repts.,* 107: College Station, TX (Ocean Drilling Program).

Kazakov, O.V., Mitulov, S.N., and Shlezinger, A.Y., 1982. Struktura osadochnogo chekhla al'boranskogo basseyna Sredizemnogo morya po dannym seysmoakusticheskogo profilirovaniya. *Izv. Akad. Nauk SSSR, Ser. Geol.,* 5:98–110.

Keigwin, L.D., Aubry, M.-P., and Kent, D.V., 1987. North Atlantic late Miocene stable-isotope stratigraphy, biostratigraphy, and magnetostratigraphy. *In* Ruddiman, W.F., Kidd, R.B., Thomas, E., et al., *Init. Repts. DSDP,* 94 (Pt. 2): Washington (U.S. Govt. Printing Office), 935–963.

Kinder, T., and Parrilla, G., in press. The summer 1982 Alboran Sea gyre. *J. Geophys. Res.*

Kornprobst, J., 1973. Petrographical studies of "acoustic basement" and associated breccia at Site 121—western Alboran Basin: a comparison with the Betico-Rifean basement. *In* Ryan, W.B.F., Hsü, K.J., et al., *Init. Repts. DSDP,* 13 (Pt. 2): Washington (U.S. Govt. Printing Office), 759–761.

Kullenberg, B., 1952. On the salinity of the water contained in marine sediments. *Goeteborgs K. Vetensk. Vitterhets-Samh. Handl., Ser. B,* 6:3–37.

La Violette, P.E. (Ed.), 1994. *Seasonal and Interannual Variability of the Western Mediterranean Sea:* Washington (Am. Geophys. Union), Coastal and Estuarine Studies, 46.

Leaman, K.D., 1994. The formation of Western Mediterranean deep water. *In* La Violette, P.E. (Ed.), *Seasonal and Interannual Variability of the Western Mediterranean Sea:* Washington (Am. Geophys. Union), Coastal and Estuarine Studies, 46:227–248.

Lehman, S.J., and Keigwin, L.D., 1992. Sudden changes in North Atlantic circulation during the last deglaciation. *Nature,* 356:757–762.

Lourens, L.J., 1994. Astronomical forcing of mediterranean climate during the last 5.3 million years [Ph.D. thesis]. Univ. Utrecht.

Lourens, L.J., Hilgen, F.J., Gudjonsson, L., and Zachariasse, W.J., 1992. Late Pliocene to early Pleistocene astronomically forced sea surface productivity and temperature variations in the Mediterranean. *Mar. Micropaleontol.,* 19:49–78.

Lundeen, M., 1978. Emplacement of the Ronda peridotite, Sierra Bermeja, Spain. *Geol. Soc. Am. Bull.,* 89:172–180.

Lyle, M., Zahn, R., Prahl, F., Dymond, J., Collier, R., Pisias, N., and Suess, E., 1992. Paleoproductivity and carbon burial across the California Current: the MULTITRACERS transect, 42°N. *Paleoceanography,* 7:251–272.

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

Malinverno, A., and Ryan, B., 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as a result of arc migration driven by sinking of the lithosphere. *Tectonics,* 5:227–245.

Mauffret, A., El-Robrini, M., and Gennesseaux, M., 1987. Indice de la compression récente en mer Méditerranée: un bassin losangique sur la margenor-algérienne. *Bull. Soc. Geol. Fr.*, 8:1195–1206.

McCoy, F.W., and Cornell, W., 1990. Volcaniclastic sediments in the Tyrrhenian Basin. *In* Kastens, K.A., Mascle, J., et al., *Proc. ODP, Sci. Results*, 107: College Station, TX (Ocean Drilling Program), 291–305.

McKenzie, J.A., Sprovieri, R., and Channell, J.E.T., 1990. The terminal Messinian flood and earliest Pliocene paleoceanography in the Mediterranean: results from ODP Leg 107, Site 652, Tyrrhenian Sea. *Mem. Soc. Geol. Ital.*, 44:81–91.

MEDOC Group, 1970. Observation of formation of deep water in the Mediterranean Sea. *Nature*, 227:1037–1040.

Monié, P., Galindo-Zaldivar, J., González Lodeiro, F., Goffé, B., and Jabaloy, A., 1991. ^{40}Ar/^{39}Ar geochronology of Alpine tectonism in the Betic Cordilleras (southern Spain). *J. Geol. Soc. London*, 148:289–297.

Monié, P., Torres-Roldán, R.L., and García-Casco, A., 1994. Cooling and exhumation of the western Betic Cordilleras, ^{40}Ar/^{40}Ar thermochronological constraints on a collapsed terrane. *Tectonophysics*, 238:353–379.

Montenat, C., Ott d'Estevou, P., De Larouzière, F.D., and Bedu, P., 1992. Originalite geodynamique des bassins Neogenes du domain Betique orientale. *Institut Géologique Albert de Lapparent, Notes et Memoires*, 1-21: 11–49.

Montenat, C., Ott d'Estavou, P., and Masse, P., 1987. Tectonic sedimentary character of the Betic Neogene basins evolving in a crustal transcurrent shear zone (SE Spain). *Bull. Cent. Rech. Explor.-Prod. Elf-Aquitaine*, 11:1–22.

Morel, J.L., 1989. Etats de contrainte et cinematique de la chaine rifaine (Maroc) du Tortonien a l'actuel. *Geodin. Acta*, 3:238–294.

Morley, C.K., 1992. Notes on Neogene basin history of the western Alboran Sea and its implication for the tectonic evolution of the Rif-Betics orogenic belts. *J. African Earth Sci.*, 14:57–65.

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.), *Structural History of the Mediterranean Basins:* Paris (Ed. Technip), 401–410.

Murdoch, W.W., and Onuf, C.P., 1974. The Mediterranean as a system, part I: large ecosystems. *Int. J. Environ. Stud.*, 5:275–284.

Olausson, E., 1961. Studies of deep-sea cores. *Rep. Swed. Deep-Sea Exped., 1947–1948*, 8:335–391.

Olivet, J.L., Bonnin, J., Beuzart, P., and Auzende, J.M., 1984. Cinématique de l'Atlantique nord et central. *Publ. Cent. Natl Exploit. Oceans, Rapp. Sci. Tech.*, 54:108–112.

Ott d'Estevou, P., and Montenat, C., 1992. Le bassin de Sorbas-Tabernas. *Doc. Travaux de l'IGAL*, 12-13:101–128.

Pastouret, L., Olivet, J.L., Auzende, J.M., and Rehault, J.P., 1975. Remarques complementaires sur le Neogene de la Mer d'Alboran. *Bull. Soc. Geol. Fr.*, 17:1168–1171.

Platt, J.P., 1986. Dynamics of orogenic wedges and the uplift of high pressure metamorphic rocks. *Geol. Soc. Am. Bull.*, 97:1037–10057.

Platt, J.P., and England, P.C., 1994. Convective removal of lithosphere beneath mountain belts: thermal and mechanical consequences. *Am. J. Sci.*, 294:307–336.

Platt, J.P., and Vissers, R.L.M., 1989. Extensional collapse of thickened continental lithosphere: a working hypothesis for the Alboran Sea and Gibraltar Arc. *Geology*, 17:540–543.

Polyak, B.G., Fernàndez, M., Khutosky, M.D., Soto, J.I., Basov, I.A., Comas, M.C., Khain, V.Ye., Alonso, B., Apagova, G.V., Mazurova, I.S., Negredo, A., Tochitsky, V.O., de la Linde, J., Bogdanov, N.A., and Banda, E., in press. Heat flow in the Alboran Sea (the Western Mediterranean). *Tectonophysics.*

Prahl, F.G., and Wakeham, S.G., 1987. Calibration of unsaturation patterns in long-chain ketone compositions for paleotemperature assessment. *Nature*, 330:367–369.

Prell, W.L., and Kutzbach, J.E., 1992. Sensitivity of the Indian monsoon to forcing parameters and implications for its evolution. *Nature*, 360:647–652.

Rahmstorf, S., 1994. Rapid climate transitions in a coupled ocean-atmosphere model. *Nature*, 372:82–85.

Raymo, M.E., Hodell, D., and Jansen, E., 1992. Response of deep ocean circulation to initiation of Northern Hemisphere glaciation (3–2 Ma). *Paleoceanography*, 7:645–672.

Raymo, M.E., Ruddiman, W.F., Backman, J., Clement, B.M., and Martinason, D.G., 1989. Late Pliocene variation in Northern Hemisphere ice sheets and North Atlantic deep water circulation. *Paleoceanography*, 4:413–446.

Rehault, J.P., Mascle, J., and Boillot, G., 1984. Evolution geodinamique de la Mediterranee depuis l'Oligocene. *Mem. Soc. Geol. Ital.*, 27:85–96.

Reid, J.L., 1979. On the contribution of the Mediterranean Sea outflow to the Norwegian-Greenland Sea. *Deep-Sea Res. Part A*, 26:1199–1223.

Rio, D., Raffi, I., and Villa, G., 1990. Pliocene-Pleistocene calcareous nannofossil distribution patterns in the Western Mediterranean. *In* Kastens, K.A., Mascle, J., et al., *Proc. ODP, Sci. Results*, 107: College Station, TX (Ocean Drilling Program), 513–533.

Rohling, E.J., and Gieskes, W.W.C., 1989. Late Quaternary changes in Mediterranean intermediate water density and formation rate. *Paleoceanography*, 4:531–545.

Rohling, E.J., and Hilgen, F.J., 1991. The eastern Mediterranean climate at times of sapropel formation: a review. *Geol. Mijnbouw*, 70:253–264.

Rohling, E.J., Vergnaud-Grazzini, C., and Zaalberg, R., 1993. Temporary repopulation by low-oxygen tolerant benthic foraminifera within an Upper Pliocene sapropel: evidence for the role of oxygen depletion in the formation of sapropels. *Mar. Micropaleontol.*, 21:207–219.

Rossignol-Strick, M., 1985. Mediterranean Quaternary sapropels, an immediate response of the African Monsoon to variation of insolation. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 49:237–263.

Royden, L.H., 1993. The tectonic expression of slab pull at continental convergent boundaries. *Tectonics*, 12:303–325.

Ryan, W.B.F., Hsü, K.J., et al., 1973. *Init. Repts. DSDP*, 13 (Pts. 1 and 2): Washington (U.S. Govt. Printing Office).

Sancetta, C., Lyle, M., Heusser, L., Zahn, R., and Bradbury, J.P., 1992. Late-glacial to Holocene changes in winds, upwelling, and seasonal production of the Northern California current system. *Quat. Res.*, 38:359–370.

Schott, F., and Leaman, K.D., 1991. Observations with moored acoustic Doppler current profilers in the convection regime in the Gulf of Lions. *J. Phys. Oceanogr.*, 21:558–574.

Shackleton, N.J., Backman, J., Zimmerman, H., Kent, D.V., Hall, M.A., Roberts, D.G., Schnitker, D., Baldauf, J.G., Desprairies, A., Homrighausen, R., Huddlestun, P., Keene, J.B., Kaltenback, A.J., Krumsiek, K.A.O., Morton, A.C., Murray, J.W., and Westberg-Smith, J., 1984. Oxygen isotope calibration of the onset of ice-rafting and history of glaciation in the North Atlantic region. *Nature*, 307:620–623.

Sonnenfeld, P., 1974. No current reversal at 10,000 yrs B.P. in the Strait of Gibraltar: a discussion. *Mar. Geol.*, 17:339–340.

Sparnocchia, S., Manzella, G.M.R., and La Paula, P.E., 1994. The interannual and seasonal variability of the MAW and LIW core properties in the Western Mediterranean. *In* La Violette, P.E. (Ed.), *Seasonal and Interannual Variability of the Western Mediterranean Sea:* Washington (Am. Geophys. Union), Coastal and Estuarine Studies, 46:177–194.

Sprovieri, R., 1992. Mediterranean Pliocene biochronology: a high resolution record based on quantitative planktonic foraminifera distribution. *Riv. Ital. Paleontol. Stratigr.*, 98:61–100.

————, 1993. Pliocene-early Pleistocene astronomically forced planktonic foraminifera abundance fluctuations and chronology of Mediterranean calcareous plankton bio-events. *Riv. Ital. Paleontol. Stratigr.*, 99:371–414.

Srivastava, S.P., Roest, W.R., Kovacs, L.C., Oakey, G., Lévesque, S., Verhoef, J., and Macnab, R., 1990. Motion of Iberia since the Late Jurassic: results from detailed aeromagnetic measurements in the Newfoundland Basin. *Tectonophysics*, 184:229–260.

Steiger, R.H., and Frick, U., 1973. Isotopic dating of Alboran "basement." *In* Ryan, W.B.F., Hsü, K.J., et al., *Init. Repts. DSDP*, 13 (Pt. 2): Washington (U.S. Govt. Printing Office), 762.

Stow, D.A.V., Faugeres, J., and Gonthier, E., 1986. Facies distribution and textural variation in Faro Drift contourites: velocity fluctuation and drift growth. *Mar. Geol.*, 72:71–100.

Thiede, J., 1978. A glacial Mediterranean. *Nature*, 276:680–683.

Thierstein, H.R., and Berger, W.H., 1978. Injection events in ocean history. *Nature,* 276:461–466.

Thunell, R.C., 1981. Late Miocene–early Pliocene planktonic foraminiferal biostratigraphy and paleoceanography of low latitude marine sequences. *Mar. Micropaleontol.,* 6:71–90.

Thunell, R.C., and Williams, D.F., 1989. Glacial-Holocene salinity changes in the Mediterranean Sea: hydrographic and depositional effects. *Nature,* 338:493–496.

Thunell, R.C., Williams, D.F., and Howell, M., 1987. Atlantic-Mediterranean water exchange during the late Neogene. *Paleoceanography,* 2:661–678.

Tiedemann, R., Sarnthein, M., and Shackleton, N.J., 1994. Astronomic timescale for the Pliocene Atlantic $\delta^{18}O$ and dust flux records of Ocean Drilling Program Site 659. *Paleoceanography,* 9:619–638.

Tintoré, J., Viúdez, A., Gomis, D., Alonso, S., and Werner, F.E., 1995. Mesoscale variability and Q vector vertical motion in the Alboran Sea. *In* La Violette, P.E. (Ed.), *Seasonal and Interannual Variability of the Western Mediterranean Sea:* Washington (Am. Geophys. Union), Coastal and Estuarine Studies, 46:47–71.

Torné, M., and Banda, E., 1992. Crustal thinning from the Betic Cordillera to the Alboran Sea. *Geo-Mar. Lett.,* 12:76–81.

Torné, M., Banda, E., García-Dueñas, V., and Balanyá, J.C., 1992. Mantle-lithosphere bodies in the Alboran crustal domain (Ronda Peridotites, Betic-Rifean orogenic belt). *Earth Planet. Sci. Lett.,* 110:163–171.

Torres-Roldán, R., 1979. The tectonic subdivision of the Betic Zone (Betic Cordilleras, Southern Spain): its significance and one possible geotectonic scenario for the westernmost Alpine belt. *Am. J. Sci.,* 279:19–51.

Tubía, J.M., and Cuevas, J., 1986. High-temperature emplacement of the Los Reales peridotite nappe (Betic Cordillera, Spain). *J. Struct. Geol.,* 8:473–482.

Tubía, J.M., and Gil-Ibarguchi, J.L., 1991. Eclogites of the Ojen nappe: a record of subduction in the Alpujárride complex (Betic Cordilleras, southern Spain). *J. Geol. Soc. London,* 148:801–804.

Tziperman, E., and Malanotte-Rizzoli, P., 1991. The climatological seasonal circulation of the Mediterranean Sea. *J. Mar. Res.,* 49:411–434.

Van Os, B.J.H., Lourens, L.J., Hilgen, F.J., De Lange, G.J., and Beaufort, L., 1994. The formation of Pliocene sapropels and carbonate cycles in the Mediterranean: diagenesis, dilution, and productivity. *Paleoceanography,* 9:601–617.

Vergnaud-Grazzini, C., Borsetti, A.M., Cati, F., Colantoni, P., d'Onofrio, S., Saliège, J.F., Sartori, R., and Tampieri, R., 1988. Paleoceanographic record of the last deglaciation in the Strait of Sicily. *Mar. Micropaleontol.,* 1:1–21.

Vergnaud-Grazzini, C., Caralp, M., Faugères, J.-C., Gonthier, É., Grousset, F., Pujol, C., and Saliège, J.F., 1989. Mediterranean outflow through the Strait of Gibraltar since 18000 years BP. *Oceanol. Acta,* 12:305–324.

Vergnaud-Grazzini, C., Devaux, M., and Znaidi, J., 1986. Stable isotope "anomalies" in Mediterranean Pleistocene records. *Mar. Micropaleontol.,* 10:35–69.

Vergnaud-Grazzini, C., and Pierre, C., 1991. High fertility in the Alboran Sea since the Last Glacial Maximum. *Paleoceanography,* 6:519–536.

Veum, T., Jansen, E., Arnold, M., Beyer, I., and Duplessy, J.-C., 1992. Water mass exchange between the North Atlantic and the Norwegian Sea during the past 28,000 years. *Nature,* 356:783–785.

Vincent, E., Killingley, J.S., and Berger, W.H., 1980. The magnetic Epoch-6 carbon shift: a change in the ocean's $^{13}C/^{12}C$ ratio 6.2 million years ago. *Mar. Micropaleontol.,* 5:185–203.

Watts, A.B., Platt, J.P., and Bulh, P., 1993. Tectonic evolution of the Alboran Sea Basin. *Basin Res.,* 5:153–177.

Weijermars, R., 1985. Uplift and subsidence history of the Alboran Basin and a profile of the Alboran Diapir (W-Mediterranean). *Geol. Mijnbouw,* 64:349–356.

Wezel, F.C., 1985. Structural features and basin tectonics of the Tyrrhenian Sea. *In* Stanley, D.J., and Wezel, F.C. (Eds.), *Geological Evolution of the Mediterranean Basin:* Berlin (Springer-Verlag), 153–194.

Williams, D.F., Thunell, R.C., and Kennett, J.P., 1978. Periodic freshwater flooding and stagnation of the eastern Mediterranean Sea during the late Quaternary. *Science,* 201:252–254.

Woodside, J.M., and Maldonado, A., 1992. Styles of compressional neotectonics in the Eastern Alboran Sea. *Geo-Mar. Lett.,* 12:111–116.

Zahn, R., 1992. Deep ocean circulation puzzle. *Nature,* 356:744–746.

————, 1994. Fast flickers in the tropics. *Nature,* 372:621–622.

Zahn, R., and Mix, A.C., 1991. Benthic foraminiferal $\delta^{18}O$ in the ocean's temperature-salinity-density field: constraints on ice-age thermohaline circulation. *Paleoceanography,* 6:1–20.

Zahn, R., and Pedersen, T.F., 1991. Late Pleistocene evolution of surface and mid-depth hydrography at the Oman Margin: planktonic and benthic isotope records at Site 724. *In* Prell, W.L., Niitsuma, N., et al., *Proc. ODP, Sci. Results,* 117: College Station, TX (Ocean Drilling Program), 291–308.

Zahn, R., Sarnthein, M., and Erlenkeuser, H., 1987. Benthic isotope evidence for changes of the Mediterranean outflow during the late Quaternary. *Paleoceanography,* 2:543–559.

Zeck, H.P., Albat, F., Hansen, B.T., Torres-Roldan, R.L., García Casco, A., and Martín-Algarra, A., 1989. A 21±2 Ma age for the termination of the ductile Alpine deformation in the internal zone of the Betic Cordilleras, south Spain. *Tectonophysics,* 169:215–220.

Zeck, H.P., Monié, P., Villa, I.M., and Hansen, B.T., 1992. Very high rates of cooling and uplift in the Alpine belt of the Betic Cordilleras, southern Spain. *Geology,* 20:79–82.

Zenk, W., and Armi, L., 1990. The complex spreading pattern of Mediterranean Water off the Portuguese continental slope. *Deep-Sea Res.,* 37:1805–1823.

Ms 161IR-101