Zahn, R., Comas, M.C., and Klaus, A. (Eds.), 1999
Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 161

5. THE SEDIMENTARY RECORD OF THE ALBORAN BASIN: AN ATTEMPT AT SEDIMENTARY SEQUENCE CORRELATION AND SUBSIDENCE ANALYSIS[1]

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ABSTRACT

Neogene marine sediments in the Betic Neogene Basins of the Alboran Domain (Betic Cordillera) have their counterparts in the Alboran Sea basin. Lower Miocene to Pliocene deposits in the Alboran Sea basin (studied from seismic data, commercial wells, and Ocean Drilling Program Leg 161) and coeval sedimentary sequences in the Betic Neogene Basins cropping out on land were correlated on the basis of biostratigraphic criteria. Major unconformities representing common events in basin evolution were distinguished offshore and onshore. Two important hiatuses, in the lower Tortonian (calcareous nannofossil zone NN9) and in the lower Pliocene (zone NN13 and parts of zones NN12 and NN14), recognized throughout the domain, correspond with basin-wide events. Calcareous nannofossils from cuttings from the commercial well Andalucía-A1 were used to derive a new age estimate for sediments in the Alboran Basin. Backstripping analysis, performed at Site 976 (Western Alboran Basin) and at two commercial wells, Andalucía-A1 (Eastern Alboran Basin) and Granada-D1 (onshore), reveals two periods of subsidence, one in the middle Miocene (15.5–14.5, 13–10.7 Ma) and the other in the late Pliocene–Pleistocene (2.5–0 Ma), which can be correlated with rifting episodes in the tectonic evolution of the basin. This analysis also shows a rapid uplift at the Tortonian/Messinian boundary that can be correlated with partial emergences of the Alboran Domain.

INTRODUCTION

The Alboran Basin, in the westernmost Mediterranean, is bounded to the north by the Betic Cordillera (southern Spain) and to the south by the Rif and Tell Mountains, which are connected through the Gibraltar Arc (Fig. 1). The Internal Zones of the Betic Cordillera contain numerous intramontane depressions and corridors filled with Miocene–Pleistocene sedimentary sequences (Fig. 2). These depressions, commonly known as Betic Neogene Basins, were analyzed from several viewpoints, including sedimentary, tectonics, magmatism, and geophysics, although their origin and evolution remain a subject of much debate (e.g., Montenat et al., 1992; Sanz de Galdeano and Vera, 1992; Rodríguez-Fernández and Sanz de Galdeano, 1992). The Betic Neogene Basins include marine to continental sedimentary sequences from early Miocene to Holocene age, accompanied by local alkali to calc-alkali magmatism from the middle Miocene to Pliocene (Hernandez et al., 1987). The sedimentary sequences of the Betic Neogene Basins vary in character, with highly variable facies distribution and thickness largely controlled by tectonic processes.

Pleistocene to middle Miocene sediments from the Alboran Sea basin (Fig. 2) were drilled at Site 976 during Ocean Drilling Program Leg 161 (Comas, Zahn, Klaus, et al., 1996). In addition, the entire sedimentary sequence beneath the northern shelf of the Alboran Sea basin is also known from commercial borehole data. Results from both commercial and scientific drilling indicate that sedimentary sequences from the Alboran Sea basin have counterparts in marine deposits cropping out in the Betic Neogene Basins. The existence of these outcrops proves that during the Miocene the marine Alboran Basin occupied a broader area, extending beyond the present limits of the Alboran Sea basin (Comas et al., 1992; Jurado and Comas, 1992).

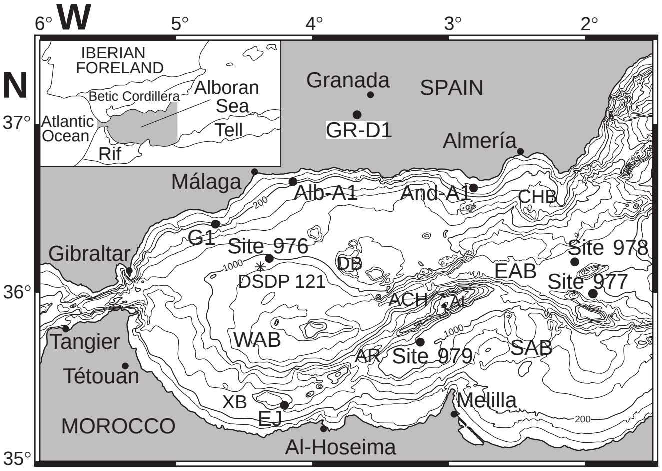

Figure 1. Bathymetric map of the Alboran Sea showing Leg 161 sites, Deep Sea Drilling Project (DSDP) Site 121, and commercial boreholes offshore (G1, Alb-A1, And-A1, EJ, and GR-D1). The insert map shows the location of the Alboran Sea between the Betic and Rif Cordilleras. ACH = Alboran Channel, Al = Alboran Island, AR = Alboran Ridge, CHB = Chella Bank, DB = Djibouti Bank, EAB = Eastern Alboran Basin, SAB = Southern Alboran Basin, and WAB = Western Alboran Basin, and XB = Xauen Bank. Contour lines every 200 m.

The aim of this paper is to correlate the sedimentary sequences of the Alboran Sea basin with coeval sediments cropping out in the Betic Neogene Basins. Previous age estimates from commercial borehole data were calibrated and occasionally modified on the basis of examination of calcareous nannofossils in cutting samples from well Andalucía-A1. The nannofossil scales of Martini (1971) and Okada and Bukry (1980) were used for age determinations in both onshore sediments and rocks recovered from well Andalucía-A1. At Hole 976B, the calcareous nannofossil biozonation employed by Leg 161 is implemented (Comas, Zahn, Klaus, et al., 1996).

Backstripping was performed for Hole 976B and two commercial wells, Andalucía-A1 (Northeastern Alboran Basin) and Granada-D1

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[1] Zahn, R., Comas, M.C., and Klaus, A. (Eds.), 1999. *Proc. ODP, Sci. Results,* 161: College Station, TX (Ocean Drilling Program).

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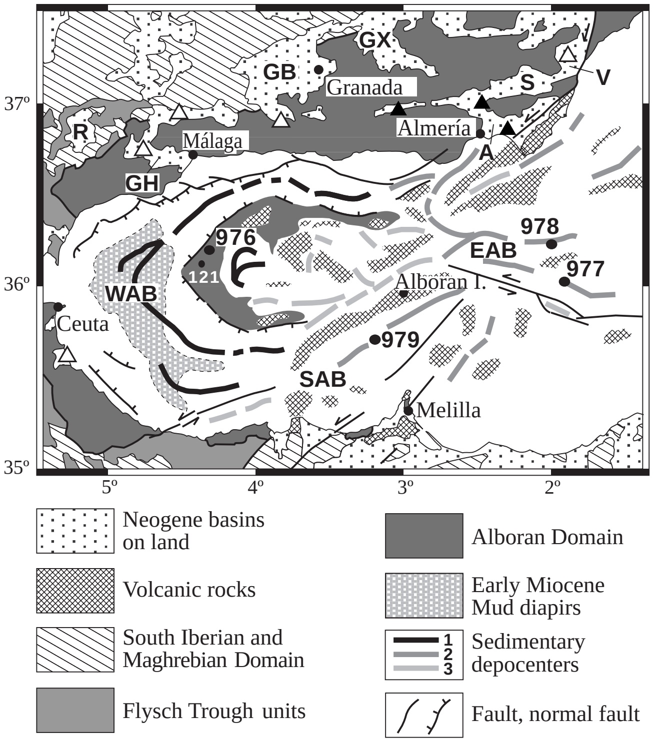


Figure 2. Geologic sketch of the Alboran Sea basin showing the location of main sedimentary depocenters, DSDP Site 121, and Leg 161 sites. Betic Neogene Basins outcrops (mainly Miocene to Pliocene marine sediments) onshore are indicated for Spain. Sedimentary depocenters in the Alboran Sea: 1 = depocenters consisting of lower Miocene to Pleistocene deposits; 2 = depocenters consisting of middle Miocene to Pleistocene deposits; 3 = depocenters consisting of Messinian/Pliocene to Pleistocene deposits. Black triangles = outcrops of lower Miocene marine sediments; white triangles = outcrops of Middle Miocene marine sediments. A = Almeria basin, EAB = Eastern Alboran Basin, GB = Granada Basin, GX = Guadix basin, GH = Guadalhorce basin, R = Ronda basin, S = Sorbas basin, SAB = Southern Alboran Basin, V = Vera basin, and WAB = Western Alboran Basin.

(onshore), to document the subsidence-uplift history of the basin (Fig. 1).

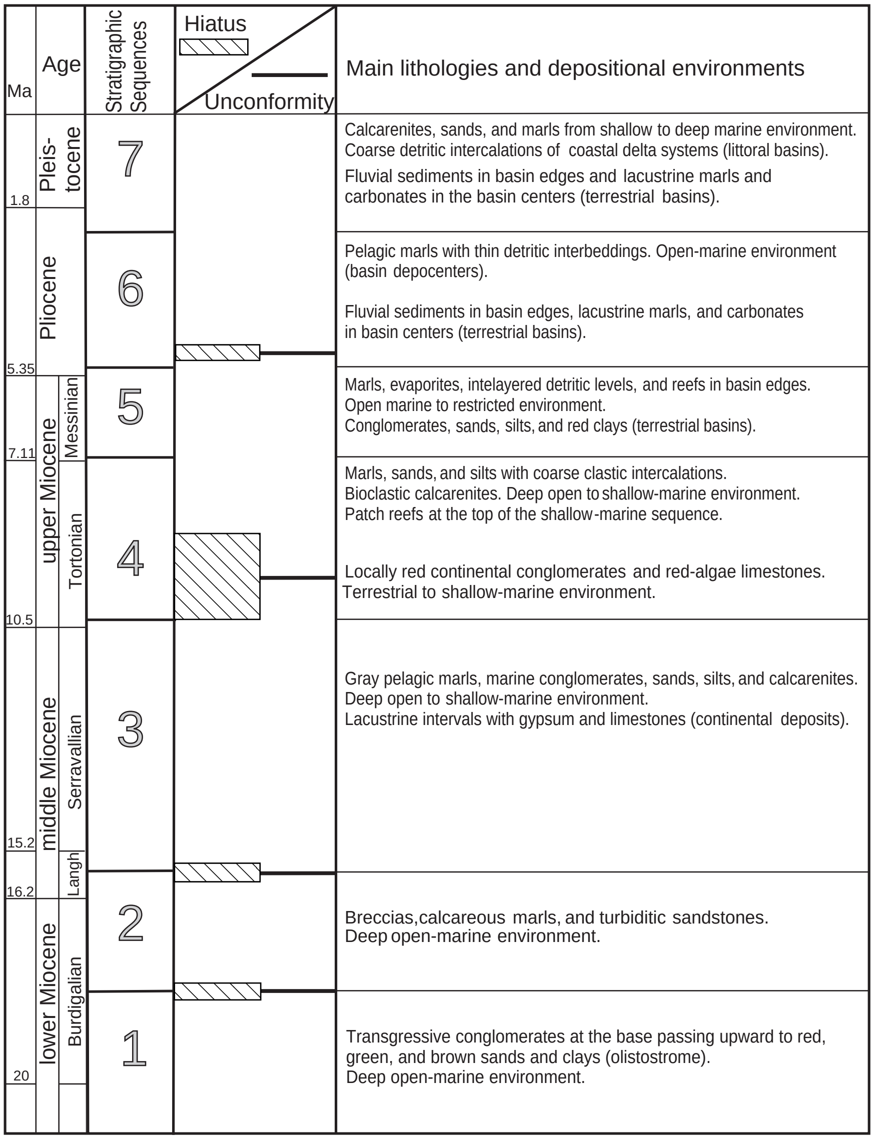
SUMMARY OF ONSHORE SEDIMENTS

Outcropping sediments of the Betic Neogene Basins are located over Alboran Domain rocks (Alpujárride, Nevado-Filábride, and Maláguide complexes). The Neogene stratigraphic sequences of these basins are incomplete and intensely deformed as a result of significant crustal-scale tectonics during the Miocene (García-Dueñas et al., 1992).

Analysis of the sedimentary record cropping out in the different Betic Neogene Basins allowed the reconstruction of a stratigraphic composite section of these basins to correlate this sedimentary cover with the Neogene sequence laid down in the Alboran Sea basin. This reconstruction is also based on available stratigraphic data presented by several authors (e.g., Montenat et al., 1992; Rodríguez-Fernandez and Sanz de Galdeano, 1992; Sanz de Galdeano and Vera, 1992).

The outcropping sedimentary sequences of the Betic Neogene Basins include several regional-scale discontinuities, from which the Neogene deposits can be divided into seven main stratigraphic units (depositional sequences in the sense of Mitchum et al., 1977). In normal stratigraphic order (from bottom to top; Fig. 3), these sequences are as follows:

1. Lower Burdigalian sequence. This sequence is up to 80 m thick and lies unconformably upon the Alpujárride and Maláguide metamorphic units. The main lithology corresponds to a basal transgressive conglomerate that changes upward to marly sands and clays with intercalated coarse breccias and turbiditic layers. In the western part of the Betic Cordillera, olistostromes rest on this sequence, which suggests a deep marine basin environment.
2. Upper Burdigalian–lower Langhian sequence. This sequence comprises gray calcareous marls, conglomerates, and turbiditic sands. The sequence is poorly known because of the scarcity of well-preserved outcrops. In some places in the central Betics, the sequence is covered by olistostromes or by sediments from the overlying sequence, which implies a deep marine environment for this sequence as well. Thickness ranges from 10 to 50 m.
3. Upper Langhian–Serravallian sequence. This sequence comprises the main portion of the middle Miocene deposits and is characterized by a complete transgressive to regressive sedimentary cycle. The lower part of the sequence is composed of continental red conglomerates, calcareous marls, bioclastic calcarenites, and marls with interbedded turbidite layers. Depositional environments range from continental to shallow and deep marine. Coarse clastic formations occur at the upper part of the sequence, which was deposited in continental or marine environments, depending on the location. Occasional lacustrine sediments with gypsum and lignite are also present (La Peza and Umbria Formations; Rodríguez-Fernández, 1982; Völk and Rondeel, 1964).
4. Tortonian sequence. The sedimentary record of this age consists of two parts, of lower and upper Tortonian age. The lower Tortonian sediments lie unconformably on the Alpujárride units and in some places over Nevado-Filábride units. In the eastern Alboran Domain (Eastern Betic Cordillera), continental red conglomerates (Tortonian-1 of Montenat, 1977) contain the first occurrence of clasts from the Nevado-Filábride Complex. Lower Tortonian sediments are missing from most of the marine sedimentary sequences recognized on land, which suggests a significant hiatus at this time (Fig. 3). The upper Tortonian sediments correspond to transgressive conglomerates and sands that are ubiquitous in all the basins. Up sequence, the sediments change to calcarenites in the shallow edges and calcareous marls in the deeper parts of the basins. The upper portion of the sequence contains thick clastic wedges (fan deltas) of breccias and conglomerates interbedded with silts and marls, or channel-fill breccias along the basin axis. Some patch reefs crown the topsets of fan deltas, which indicates shallow marine conditions during sedimentation (Dabrio and Polo, 1988; Santisteban and Taberner, 1988; Dabrio, 1990). Thickness ranges from hundreds to thousands of meters.
5. Messinian sequence. This sequence comprises either marine or continental deposits. In places with a good sedimentary record, several episodes of open to restricted marine sedimentation, separated by minor unconformities, can be distinguished. Each episode contains shallow turbiditic sands, bioclastic calcarenites grading upward to marls, fringing reefs in the basin edges (Martín and Braga, 1994), and gypsum with thin detritic intercalations. In the continental realms, fine detrital sediments in the central parts are bordered by conglomerates, sands, and clays deposited by fluvial systems. Thickness ranges from zero to >100 m.
6. Pliocene sequence. Pliocene sediments were deposited in continental and littoral environments. In continental sedimentary basins, fluvial and lacustrine depositional environments are indicated by the presence of conglomerates, sands, and clays found at the edges, changing to marls and freshwater limestones with lignite in the central parts. Thickness ranges from tens to hundreds of meters. Littoral basins contain coarse detrital wedges, conglomerates, and sands from coastal deltas (Postma, 1984); calcareous marls with intercalated sandy layers are common in the deeper parts of the basins.



Stratigraphic Sequences	Main lithologies and depositional environments
7	Calcarenites, sands, and marls from shallow to deep marine environment. Coarse detritic intercalations of coastal delta systems (littoral basins). Fluvial sediments in basin edges and lacustrine marls and carbonates in the basin centers (terrestrial basins).
6	Pelagic marls with thin detritic interbeddings. Open-marine environment (basin depocenters). Fluvial sediments in basin edges, lacustrine marls, and carbonates in basin centers (terrestrial basins).
5	Marls, evaporites, intelayered detritic levels, and reefs in basin edges. Open marine to restricted environment. Conglomerates, sands, silts, and red clays (terrestrial basins).
4	Marls, sands, and silts with coarse clastic intercalations. Bioclastic calcarenites. Deep open to shallow-marine environment. Patch reefs at the top of the shallow-marine sequence. Locally red continental conglomerates and red-algae limestones. Terrestrial to shallow-marine environment.
3	Gray pelagic marls, marine conglomerates, sands, silts, and calcarenites. Deep open to shallow-marine environment. Lacustrine intervals with gypsum and limestones (continental deposits).
2	Breccias, calcareous marls, and turbiditic sandstones. Deep open-marine environment.
1	Transgressive conglomerates at the base passing upward to red, green, and brown sands and clays (olistostrome). Deep open-marine environment.

Figure 3. Main sedimentary sequences and unconformities or hiatuses differentiated in the Betic Neogene Basins. Short descriptions of lithologies and sedimentary environments of sequences are also given.

7. Pliocene–Pleistocene sequence. This sequence comprises sediments also deposited in both continental and marine environments. Lithologies and sedimentary environments are the same in all the Betic Neogene Basins. Littoral basins contain bioclastic calcarenites, sands, and marls in both the edges and the central parts. Coarse detrital wedges, conglomerates, and sands from coastal deltas (Bardaji et al., 1995) are also present at some basin edges. Thickness ranges from tens to several hundreds of meters.

SUMMARY OF OFFSHORE SEDIMENTS

The Alboran Sea basin contains a Neogene sequence, up to 7 km thick, formed by marine facies sediments that fill basement grabens or half grabens (Fig. 2). The architecture of the sedimentary cover beneath the Alboran Sea basin is well documented from seismic profile data (Maldonado et al., 1992; Comas et al., 1992; Watts et al., 1993; and references therein).

Commercial exploration wells provide information about lithologies and ages of the sedimentary sequences, up to 3 km thick, that occur in the basin beneath the Spanish continental shelf (Comas et al., 1992; Jurado and Comas, 1992). Analysis and correlation through a dense grid of multichannel seismic reflection lines and wireline log interpretations allowed Jurado and Comas (1992) to identify six lithoseismic units within the sedimentary cover of the Alboran Sea basin (Fig. 4).

The lithology and ages of sediments forming these units are known from cutting samples from the commercial wells (Jurado and Comas, 1992). The upper Aquitanian–Burdigalian (seismic Unit VI) deposits lie directly over the basement and contain olistostromes and overpressured shales. The middle to upper Miocene (Langhian to lower Tortonian) deposits (Units V and IV) consist of overpressured shales at the base (Subunit Vb; Fig. 4), and change upward into graded sand-silt-clay turbidites (Unit IV). Unit III (late Tortonian and earliest Messinian in age) is formed of thick sandstone intervals that alternate with claystone and silty clay beds, which correspond to turbidite layers. The Messinian deposits (Unit II) consist of distal marine or shallow carbonate facies, as well as and gypsum and anhydride intervals, although thick evaporite sequences are missing.

Seismic profile images show Burdiglian–Holocene (seismic Units VI to I) sequences filling the main depocenters of the Western Alboran Basin. In the central Alboran and Eastern Alboran Basin, however, most of the sedimentary depocenters seem to be filled mainly by deposits that are probably younger than late Tortonian (seismic

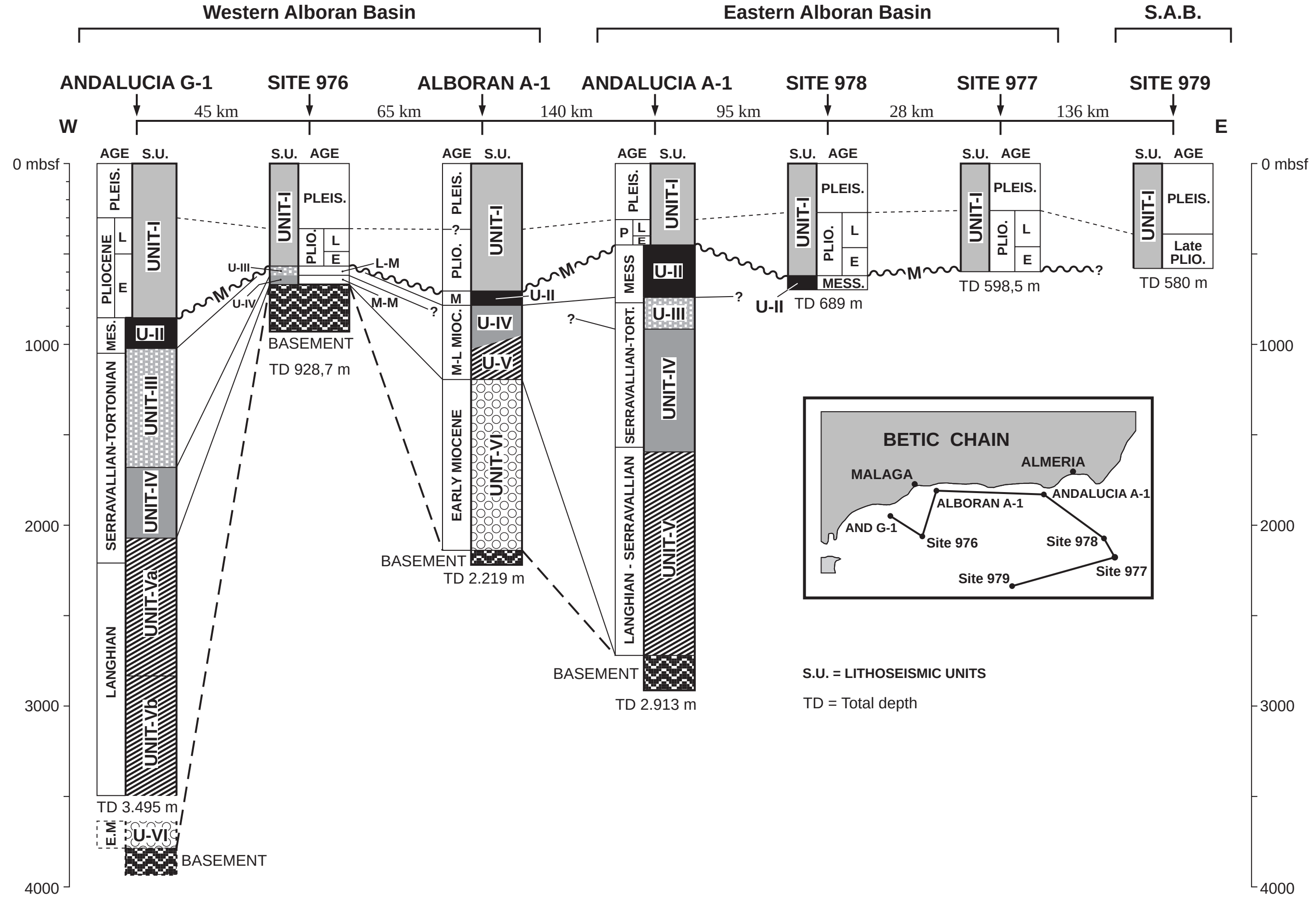


Figure 4. Correlation between sedimentary sequences drilled at Sites 976, 977, 978, and 979, and those encountered in commercial boreholes on the South Spanish shelf (from Comas et al., Chap. 44, this volume). S.A.B. = Southern Alboran Basin.

Units III to I), although the easternmost major depocenters probably contain lower or middle Miocene deposits (Fig. 2).

In seismic images, all the lithoseismic units appear to be bounded by unconformities of probable tectonic significance, although major regional unconformities occur at the top of the Burdigalian deposits (Unit VI), within upper Tortonian sediments (base of seismic Unit III), and at the base of Pliocene–Pleistocene seismic Unit I. The reflector marking the base of Pliocene–Pleistocene Unit I (Fig. 4) reveals a highly erosional and locally angular unconformity, which can be correlated with the M-reflector (Ryan, Hsü, et al., 1973) and corresponds to the top of the Messinian evaporites recognized elsewhere in the Mediterranean (Comas, Zahn, Klaus, et al., 1996).

Volcanic and volcanoclastic levels, intercalated throughout the middle and upper Miocene sequences, and large mud diapirs in the Western Alboran Basin, formed of undercompacted shales that are rooted in seismic Units VI and V, are particularly characteristic of the entire Alboran Sea basin (Comas et al., 1992).

Sample and stratigraphic data for the deep-sea deposits in the basin are provided solely from drilling at Deep Sea Drilling Project (DSDP) Site 121 (Ryan, Hsü, et al., 1973) and Leg 161 Sites 976–979 (Comas, Zahn, Klaus, et al., 1996). Sediments recovered at these sites consist mainly of a variety of fine-grained sediments, ranging from nannofossil clay to clay and silty clay, with minor sand levels. Sedimentary facies are dominated by calcareous to terrigenous hemipelagites and terrigenous muddy turbidites (Comas, Zahn, Klaus, et al., 1996).

Hole 976B, in the Western Alboran Basin, a region from which the Messinian deposits were eroded, cored the entire 650-m-thick sedimentary cover and penetrated 267 m into metamorphic basement rocks. The stratigraphic sequence, ranging from uppermost middle Miocene to the Pleistocene–Holocene (Fig. 4), records three major hiatuses located between the upper and lower Pliocene (Zanclean and Piacenzian), the lower Pliocene and uppermost Miocene (Zanclean and Messinian), and within the upper Miocene (Tortonian; Shipboard Scientific Party, 1996b).

Sites 977 and 978 in the Eastern Alboran Basin sampled 598.5 m and 485 m (from 213 to 698.0 mbsf), respectively, of upper Miocene (from Hole 978A only) and Pliocene–Holocene sediments (Fig. 4). A hiatus was recognized in the lower Pliocene between 490.59 and 490.63 mbsf at Site 977. A conglomerate interval containing volcanic rock pebbles, recovered at the base of the Pliocene sequence, has been correlated with the M-reflector and interpreted as corresponding to the M-unconformity (Shipboard Scientific Party, 1996a).

The stratigraphic section recovered at Site 979, which penetrates into the South Alboran Basin, ranges from upper Pliocene to uppermost Pleistocene/Holocene (Fig. 4).

An attempt to correlate the seismic units and isochrons from the sediments drilled by commercial wells on the Iberia shelf with those from Leg 161 sites in the deeper Alboran Sea basin is shown in Figure 4.

SUBSIDENCE ANALYSIS

The stratigraphic sequences recovered from the Granada-D1 and Andalucía-A1 commercial wells and from Hole 976B were used to determine subsidence and uplift episodes in the basement of the Alboran Sea basin. We used the backstripping computer program of Allen and Allen (1990), which calculates total subsidence and basement subsidence by decompaction of the sedimentary sequences. The program assumes an “Airy-type” isostatic model, and tectonic subsidence is calculated by removal of the sediment load effect. Although backstripping analysis for the Alboran Basin was also performed by Docherty and Banda (1992), Cloetingh et al. (1992), and Watts et al. (1993), our analysis employs new biostratigraphic data that allow us to better determine the main hiatuses detected in the stratigraphic record. This improved determination of periods with sedimentation has enabled us to distinguish, in the Andalucía-A1 well, two episodes of subsidence during the middle Miocene, and two during the upper Miocene (Fig. 5C).

For the Granada-D1 and Andalucía-A1 wells, we adopted the standard porosity and density values from Sclater and Christie (1980). We introduced paleobathymetric corrections on the basis of the new sedimentary and micropaleontological data from our study. For Hole 976B, we used porosity, density, sedimentary, and biostratigraphic data from Leg 161 (Shipboard Scientific Party, 1996b). These data were processed using the decompaction-porosity computer program of Stam et al. (1987). Eustatic sea-level changes were not incorporated in this backstripping analysis because their effect on the final results is negligible.

Described below are the main subsidence and uplift episodes common to all the studied wells that were determined by backstripping analysis. Subsidence diagrams (Fig. 5) show the total and tectonic subsidence uplift at the three holes. In Andalucía-A1 well (Fig. 5C), two periods of heavy subsidence (from ~15.5 to 14.5 Ma and from 13 to 10.7 Ma) can be distinguished. These episodes could be related to coeval rifting events during the middle Miocene, which are depicted in onshore basement units (e.g., García-Dueñas et al., 1992). Subsidence analysis at Andalucía-A1 well revealed a third subsidence episode located in the middle Tortonian (9.2–8.5 Ma). This episode was also detected in the Granada-D1 well, although it seems to have had a minor importance in the subsidence history of the sector in which this well is located (<200 m of tectonic subsidence). The significance of this subsidence episode in the tectonic evolution of the Betic Cordillera should be analyzed in future studies.

Sediments from Hole 976B record a significant sudden period of subsidence that occurred in a short period of time (11–10.7 Ma; Fig. 5B) and may well be correlated with the youngest rifting event recognized in the Andalucía-A1 well. Another period of subsidence (2.5–0 Ma) is recorded in this same hole in the upper Pliocene–Pleistocene, which can be correlated with the Pliocene–Pleistocene subsidence episode described by Comas et al. (1992) in the Alboran Basin.

The Granada-D1 well (Fig. 5A) shows a sudden period of uplift at the Tortonian/Messinian boundary. This event could be correlated with the continentalization of the Granada Basin, coincident with a late Tortonian compressional event that affected the entire Betic Cordillera and Rif (e.g., García-Dueñas et al., 1992; Cloetingh et al., 1992; Rodríguez-Fernández and Martín-Penela, 1993; Crespo-Blanc et al., 1994; and Martínez-Martínez et al., 1997).

The subsidence history during the Pliocene is different in all of the wells studied, which probably indicates different evolutions controlled by local tectonic processes that determined local and coeval uplift and subsidence in the Betic Cordillera and Alboran Sea. The significance of this observation must be integrated in the tectonic evolution of the region in future studies.

MAIN EVENTS IN BASIN EVOLUTION

During the Miocene, the Alboran basin spread out north–south beyond the present limits of the Mediterranean Sea. A comparison of onshore (Betic Neogene Basins) and offshore (Alboran Sea basin) deposits, both from the ancestral Alboran Basin, reveals similarities in ages, but some lithological differences in the Neogene sedimentary sequence. Major lithological differences probably resulted from the development of different types of depositional environments on the northern margin of the Miocene Alboran Basin throughout its paleogeographic evolution.

Several extensional episodes could be responsible for the main unconformities present in the onshore and offshore Neogene sedimentary record. The extensional episodes described onshore have been dated as early Burdigalian, middle Langhian, and late Serravallian–early Tortonian (García-Dueñas el al., 1992; Crespo-Blanc et al., 1994). The base of the lower Burdigalian sequence (Sequence 1 in Fig. 3 and seismic Unit VI in Fig. 4) corresponds to the transgression after the Burdigalian extensional episode. This transgression signals the beginning of sedimentation in the entire Alboran Basin (Comas et al., 1992; Rodríguez-Fernández and Sanz de Galdeano, 1992).

In the Betic Neogene Basins, the lower middle Miocene transition is characterized by a scarcity of sediment, probably as a consequence of significant coeval extensional tectonics (the Langhian extension of García-Dueñas et al., 1992, and Crespo et al., 1993). In the Western Alboran basin, large olistostromes (seismic Unit VI) were probably deposited as a result of backthrusting in the Gibraltar Arc (Balanyá and García-Dueñas, 1987, 1988; García-Dueñas et al., 1992). Two important periods of rifting and subsidence occurred in the basin during the Langhian and Serravallian (Figs. 5B, 5C), followed by significant shallowing in the environments at the end of the middle Miocene. The marine or continental character of the Serravallian sediments probably depended upon the location of the sedimentary realm in relation to the extensional detachment on which the basin depocenters were seated. Offshore seismic data indicate that the extensional evolution of the Alboran Basin was complete by the late Tortonian (Comas et al., 1992), which agrees with dates reported for the Betic Neogene Basins.

The red continental conglomerates forming the lower Tortonian deposits in the continental environments of the Betic Neogene Basins can be correlated with an important hiatus in marine sediments, recognized in both the Betic Neogene Basins and the Alboran Sea basin. The hiatus comprises the NN9 calcareous nannofossil zone (Martini, 1971) and the *Neogloboquadrina acostaensis* planktonic foraminifer zone (Cande and Kent, 1995).

A significant upper Tortonian transgressive episode is marked by the existence of upper Tortonian deposits lying unconformably over metamorphic basement or ancient Neogene sediments throughout the entire Alboran Basin. In the Alboran Sea basin, this transgression corresponds to Reflector III (Fig. 4), at the base of Unit III (Comas et al., 1992). In the Betic Neogene Basins the transgressive episode is marked by the top of red continental conglomerates from stratigraphic sequence 4 (Fig. 3).

At the end of the Tortonian, a contractive reorganization of the Alboran Sea basin produced folding and strike-slip faulting with tectonic inversion of many previous structures (Comas et al., 1992; Rodríguez-Fernández and Martín-Penela, 1993; Comas, Zahn, Klaus, et al., 1996, and references therein). In the western and central part of

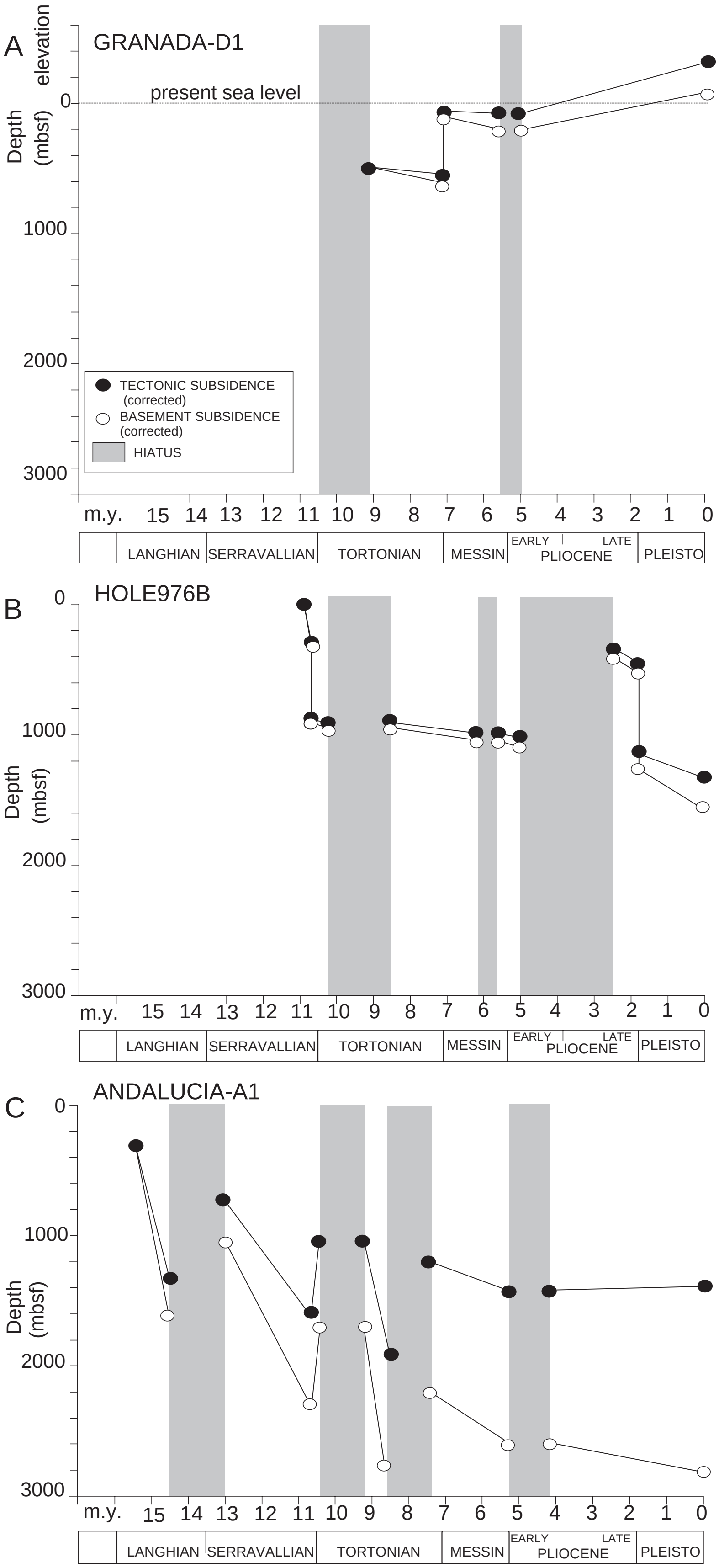


Figure 5. Subsidence curves constructed from a backstripping analysis of commercial borehole Granada-D1 **(A),** Hole 976B **(B),** and commercial borehole Andalucía-A1 **(C).**

the Betic Cordillera, the Alboran Domain emerged during the early Messinian (Rodríguez-Fernández and Sanz de Galdeano, 1992; Sanz de Galdeano and Vera, 1992).

A fall in sea level and tectonic reorganization during the late Messinian resulted in a general desiccation of the Betic Neogene Basins. The flooding in the early Pliocene affected the Betic Neogene Basins close to the Alboran Sea basin (Rodríguez-Fernández and Sanz de Galdeano, 1992; Sanz de Galdeano and Vera, 1992). During the Pliocene, a hiatus is recorded in the NN13 and parts of the NN12 and NN14 nannofossil zones (Martini, 1971) in the Betic Neogene Basins and in the Alboran Sea basin**.**

The latest tectonic reorganization, during the late Pliocene and Pleistocene, resulted in substantial paleogeographic changes in the marine realm and the present seafloor morphology of the Alboran Sea basin (Comas et al., 1992; Watts et al., 1993).

CONCLUSIONS

Major unconformities of the Neogene sedimentary record in the Alboran Basin, representing common events in basin evolution, were evidenced offshore and onshore.

Results from commercial and scientific drilling indicate that sedimentary sequences from the Alboran Sea basin have their counterparts in marine deposits cropping out in the Betic Neogene Basins.

Several hiatuses were detected in the upper Neogene sedimentary record. The upper Miocene section began with an important hiatus in the marine basinal deposition, coincident with the NN9 calcareous nannoplankton zone in the lower Tortonian. Another lower Pliocene hiatus coincides with NN13 and parts of the NN12 and NN14 nannoplankton zones.

Backstripping analysis shows several periods of subsidence that could be correlated with two rifting events in the middle Miocene (15.5–14.5 and 13–10.7 Ma) and with Pliocene–Pleistocene subsidence (2.5–0 Ma) in the Alboran Basin. A sudden period of uplift at the Tortonian/Messinian boundary is related to north–south compression during the late Tortonian, and is also correlated with the continentalization of the Granada Basin. Subsidence during the Pliocene differs in all of the wells studied, which indicates local and coeval uplift probably because of local tectonic processes.

ACKNOWLEDGMENTS

We wish to thank Cristino Dabrio (University of Madrid) and Peter F. Friend (University of Cambridge) for their critical revision of the manuscript and their useful suggestions. This study was undertaken by CICYT project AMB-95-1557 and by Research Group RNM 0163 of the Junta de Andalucía.

REFERENCES

Allen, P.A., and Allen, J.R., 1990. *Basin Analysis: Principles and Applications:* Oxford (Blackwell Sci. Publ.).

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.

Bardaji, T., Goy, J.L., Morner, N.A., Zazo, C., Silva, P., Somoza, L., Dabrio, C.J., and Baena, J., 1985. Towards a Pliopleistocene Chronostratigraphy in the Eastern Betic Basins (SE. Spain). *Geodin. Acta,* 8:112–126.

Cande, S.C., and Kent, D.V., 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *J. Geophys. Res.,* 100:6093–6095.

Cloetingh, S., van der Beek, P.A., van Rees, D., Roep, Th.B., Biermann, C., and Stephenson, R.A., 1992. Flexural interaction and the dynamics of Neogene extensional basin formation in the Alboran-Betic region. *Geo-Mar. Lett.,* 12:66–67.

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

Crespo, A., García-Dueñas, V., and Orozco, M., 1993. Systèmes en extension dans le Chaîne Bètique centrale: que reste-t-il de la structure en nappes du Complexe Alpujarride. *C. R. Acad. Sci. Ser. 2,* 317:971–977.

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,* 13:78–88.

Dabrio, C., and Polo, M.D., 1988. Late Neogene fan deltas and associated coral reefs in the Almanzora Basin, Almería Province, southeastern Spain. *In* Nemec, W., and Steel, R. (Eds.), *Fan Deltas and Related System: Sedimentology and Tectonic Settings:* London (Blackie and Sons), 354–367.

Dabrio, C.J., 1990. Fan-delta facies asssociations in Late Neogene and Quaternary basins of southeastern Spain. *In* Colella, A., and Prior, D.B. (Eds), *Coarse-Grained Deltas.* Int. Assoc. Sedimentol., 91–111.

Docherty, J.I.C., and Banda, E., 1992. A note on the subsidence history of the northern margin of the Alboran Sea. *Geo-Mar. Lett.,* 12:82–87.

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.

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.

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.

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.

Martín, J.M., and Braga, J.C., 1994. Messinian events in the Sorbas Basin in sutheastern Spain and their implications in the recent history of the Mediterranean. *Sediment. Geol.,* 90:257–268.

Martínez-Martínez, J.M., Soto, J.I., and Balanyá, J.C., 1997. Large scale structures in the Nevado-Filábride Complex and crustal seismics fabrics of the deep seismic reflection profile ESCI-Béticas 2. *Bol. Soc. Geol. Esp.,* 477–489.

Martini, E., 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. *In* Farinacci, A. (Ed.), *Proc. 2nd Int. Conf. Planktonic Microfossils Roma:* Rome (Ed. Tecnosci.), 2:739–785.

Mitchum, R.M., Vail, P.R., and Thompson, S., 1977. Seismic stratigraphy and global changes of sea level, Part 2: The depositional sequence as a basic unit for stratigraphic analysis. *In* Payton, C.E. (Ed.), *Seismic Stratigraphy: Applications to Hydrocarbon Exploration.* Am. Assoc. Pet. Geol., 26:53–62.

Montenat, C., 1977. Les bassins Néogènes du levant d´Alicante et de Murcia (Cordillères bétiques orientales. Espagne). *Doc. Lab. Geol. Fac. Sci. Lyon,* 69.

Montenat, C., Ott d'Estevou, P., De Larouzier, F.D., and Bedu, P., 1992. Originalite geodynamique des bassins Neogenes du domain Betique orientale. *IGAL, Notes et Memoires,* 21:11–49.

Okada, H., and Bukry, D., 1980. Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation (Bukry, 1973; 1975). *Mar. Micropaleontol.,* 5:321–325.

Postma, G., 1984. Mass flow conglomerates in a submarine canyon: Abrioja fan delta, Pliocene, SE Spain. In *Sedimentology of Gravels and Conglomerates.* Can. Soc. Pet. Geol., 10:237–258.

Rodríguez-Fernández, J., 1982. *El Mioceno del sector central de las cordilleras Béticas* [Ph.D. dissert.]. Univ. Granada.

Rodríguez-Fernández, J., and Martín-Penela, A.J., 1993. Neogene evolution of the Campo de Dalias and the surrounding offshore areas - (Northeastern Alboran Sea). *Geodin. Acta,* 6:255–270.

Rodríguez-Fernández, J., and Sanz de Galdeano, C., 1992. Onshore Neogene Stratigraphy in the North of the Alboran Sea (Betic Internal Zones): paleogeographic implications. *Geo-Mar. Lett.,* 12:123–128.

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

Santisteban, C., and Taberner, C., 1988. Sedimentary model of siliciclastic deposits and coral reefs interrelation. *In* Doyle, L.J., and Roberts, H.H. (Eds.), *Carbonate-clastic Transitions:* Amsterdam (Elsevier), 35–76.

Sanz de Galdeano, C., and Vera, J., 1992. Stratigraphic record and paleogeographical context of the Neogene basins in the Betic Cordillera Spain. *Basin Res.,* 4:21–36.

Sclater, J.G., and Christie, P.A.F., 1980. Continental stretching: an explanation of the post-mid-cretaceous subsidence of the central North Sea basin. *J. Geophys. Res.,* 85:3711–3739.

Shipboard Scientific Party, 1996a. Site 977. *In* Comas, M.C., Zahn, R., Klaus, A., et al., *Proc. ODP, Init. Repts.,* 161: College Station, TX (Ocean Drilling Program), 299–353.

————, 1996b. Site 976. *In* Comas, M.C., Zahn, R., Klaus, A., et al., *Proc. ODP, Init. Repts.,* 161: College Station, TX (Ocean Drilling Program), 355–388.

Stam, B., Gradstein, F.M., Lloyd, P., and Gillis, D., 1987. Algorithms for porosity and subsidence history. *Computers and Geosci.,* 13:317–349.

Völk, H.R., and Rondeel, H.E., 1964. Zur gliederungdes des juntertiars in becken von Vera, Sudspanien. *Geol. Mijnbow,* 43:310–315.

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

Date of initial receipt: 7 May 1997
Date of acceptance: 30 October 1997
Ms 161SR-207