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Seismic analysis of the southern margin of the Alboran Sea

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Abstract—This study is based on a structural and sedimentary analysis of high resolution seismic profiles carried out on the southern margin of the Alboran sea.

In the eastern area, recent tectonic movements have strongly affected the deposits. The Alboran Ridge was structured in a complex antiform at the end of the Pliocene; its present disposition, in horst and subsiding trough structures with a thick infilling, is the result of Quaternary to Recent recurrent faulting. In the western area, near Gibraltar Strait, alternate stages of erosion and construction are apparent in the sequences of the marginal plateau, particularly in the northern part, which progrades towards the Strait. Hydrodynamic patterns and glacio-eustatic variations of sea level have played a prominent role in the genesis of sedimentary bodies.

Neither sedimentation nor tectonics seem to indicate a general Miocene–Pliocene boundary but the Pliocene–Quaternary transition is marked, on the ridge and marginal areas, by a major discontinuity; it can be correlated with onshore neotectonic data.

Résumé—Cette étude s'appuie sur l'analyse structuro-sédimentaire de profils sismiques haute résolution effectués sur la marge méridionale de la mer d'Alboran.

Dans le secteur oriental, les manifestations tectoniques récentes ont influencé la répartition des aires de sédimentation: la Ride d'Alboran a été structurée en antiforme complexe à la fin du Pliocène; sa position actuelle en horst, bordé au sud par un sillon subsident à épais remplissage, résulte de rejeux verticaux quaternaires se poursuivant actuellement. Dans le secteur occidental, à proximité du Détroit de Gibraltar, l'étude des séquences de dépôt du plateau marginal indique des phases successives d'erosion et de construction particulièrement visibles dans la partie Nord de ce plateau, progradant dans son ensemble en direction du Détroit. Le régime hydrodynamique et les variations glacio-eustatiques du niveau marin ont joué un rôle prépondérant dans la mise en place des dépots. Le passage Miocène–Pliocène ne semble se marquer ni sur le plan tectonique ni sur le plan sédimentaire. Par contre la transition Pliocène–Quaternaire se marque dans les zones marginales et sur la Ride d'Alboran par une discontinuité majeure. Elle peut être corrélée avec les évènements néotectoniques connus à terre.

INTRODUCTION

Enclosed in the Betico–Rifean Arc, at the contact between two major plates (Africa and Iberia), the Alboran Sea represents the liaison between the Atlantic Ocean and Mediterranean Sea.

Since 1967, geophysical studies (deep seismic sounding, gravimetric and aeromagnetic surveys) with a low density coverage, have mainly concerned the basin; they have been aimed primarily at dating the formation of Alboran Basin and obtaining information about Atlantic–Mediterranean relations after the opening of the Strait of Gibraltar at the end of the Messinian salinity crisis. Plio-Quaternary structural and sedimentary events remain relatively poorly studied.

This work deals with original data on the southern margin of the Alboran Sea; a closely spaced grid of 35 high resolution seismic reflection profiles (sparker 500–3000 J) was obtained in 1981–1985 on board the N/O Winnaretta- Singer (Fig. 1).

GEOLOGICAL SETTING

The Rifean orogen, located in the southern part of the Alboran Sea, forms an arc with a convexity facing southwest. It is structurally divided into three concentric zones overthrusted southward (Fig. 2): (1) internal zones (Paleozoic massifs and Mesozoic carbonate slices); (2) flysch units (Cretaceous–Cenozoic thrust sheets); and (3) external zones (complex allochthonous bodies of marls and shales) (Durand-Delga *et al.* 1962, Faure-Muret et Choubert 1971, Suter 1981). It is limited by two virgations (Andrieux *et al.* 1971); the first, at the Gibraltar Strait, links the Rifean and Betic orogens, and the second represents, on the eastern side, a sinistral strike–slip fault related to an African basement promontory (Melilla peninsula).

The Rifean orogen evolution has occurred, from the Upper Lutetian to the Tortonian, during several tectonic episodes leading to the overthrusting, towards the west (Western Rif) and the south (Eastern Rif), of the different zones. Tangential stresses ended at the Tortonian with the external zones structuration; the post-tectonic period is characterized by the formation of the Alboran Sea essentially by recurrent vertical movements (Bousquet et Philip 1976, Armijo *et al.* 1977, Rampnoux *et al.* 1977).

Scientific data on the Alboran Sea are very fragmentary and of unequal quality. The DSDP 121 drill hole, located in the western basin, on the slope of a basement rise, reached a metamorphic basement similar to the Betico–Rifean rocks; the sedimentary suite consists of 140 m of Messinian marls unconformably overlain by 700 m of hemipelagic and turbiditic Plio–Quaternary deposits (Ryan *et al.* 1973). The occurrence of Messinian evaporitic deposits associated with diapir-like features observed on seismic lines (Olivet *et al.* 1973, Auzende *et*

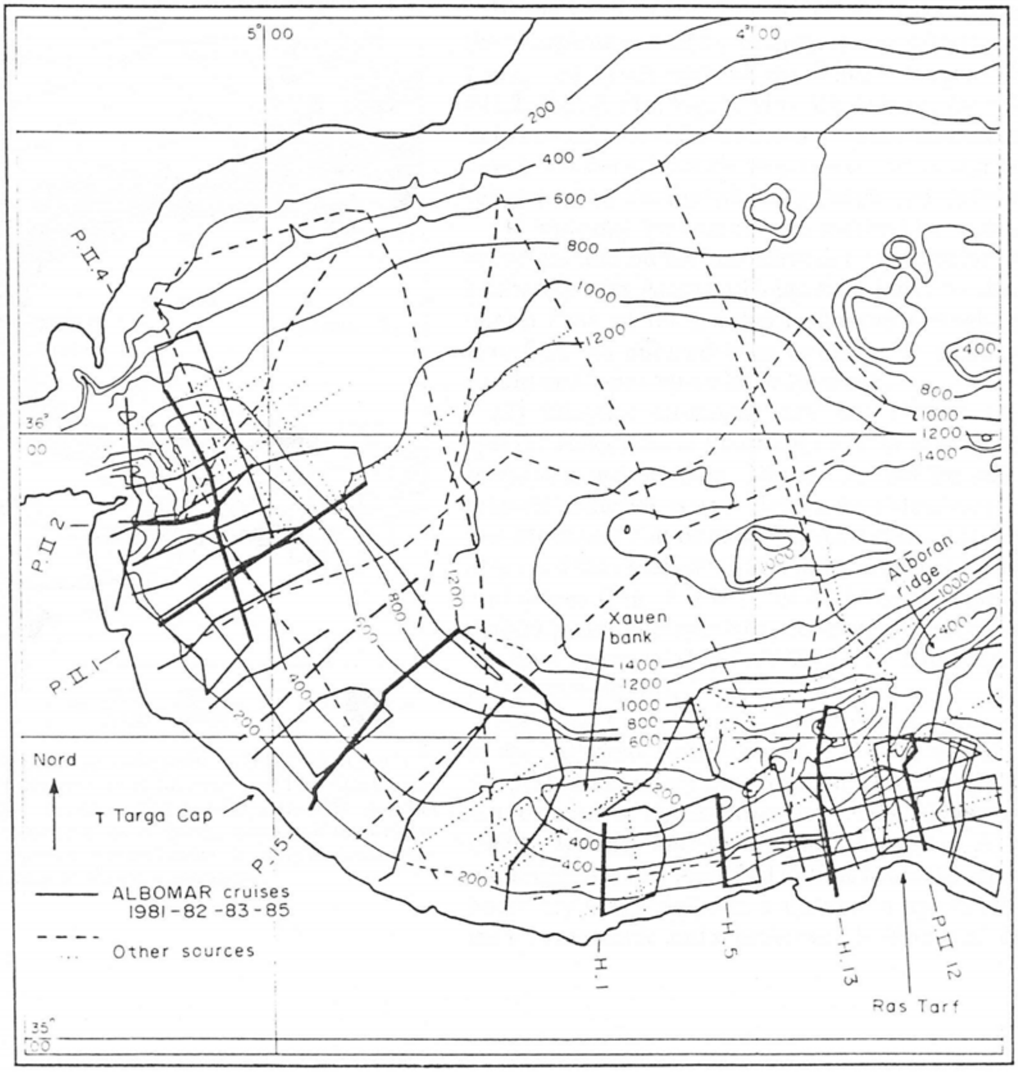


Fig. 1. Bathymetric map of the Alboran sea modified on the southern side from Albomar cruises' data. Geophysical tracklines are shown and presented sections are indicated by heavy lines.

al. 1975) is still controversial (Mulder and Parry 1976). According to seismic data and estimated rates of sedimentation, the beginning of sedimentary fill dates back to the Middle Miocene (Olivet *et al.* 1973); nevertheless, onshore studies show a progressive extension (east to west) of the marine domain, from the Tortonian to the Pliocene.

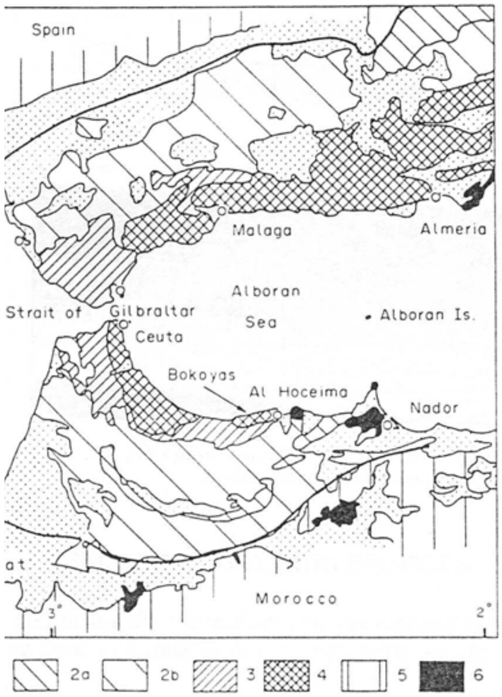
The models of the geodynamic evolution of the Alboran Sea depend upon the interpretation of structural and sedimentary data. Some studies of pre-Messinian or Messinian structures suggest that the history of the Alboran Sea, prior to the Plio–Quaternary, is similar to that of other Mediterranean areas: the downwarping of substratum at the southern border of the Alboran Sea is interpreted, as in the Algerian margin, as an incipient southward subduction (Auzende *et al.* 1971).

Other studies are based on onshore structural trends and marine morphological features: NE–SW strikes in the prolongation of transcurrent faults of the Betico–Rifean orogen (Leblanc 1980, Malod 1982, Olivier 1982), and a fault zone in a N–NE direction crossing the central part of the Alboran Sea (Dillon *et al.* 1980).

All these data assume a Lower Miocene (Mulder and Parry 1976) or Upper Miocene (Auzende 1975) structuration of the Alboran Sea. The occurrence of evaporitic Messinian deposits favours the opening and deepening of basins prior to or during Messinian. Plio–Quaternary tectonic activity is sometimes referred to but never plays a prominent role in the structural interpretations.

LITHOSTRATIGRAPHY AND ACOUSTIC STRATIGRAPHY

The only publications concerning stratigraphic determinations are those of Giermann *et al.* (1968), data from corehole DSDP-121 (Ryan *et al.* 1973) and from sampling result of petroleum companies on Xauen Bank (Courtesy of Mr Winnock) in addition to a sampling cruise off the Eastern Rif (cruise Albosed 1, N/O Georges Petit). Moreover, we have correlated the near-shore parts of our seismic profiles with sections on the Neogene onshore basins of Boudinar and Melilla (Houzay 1975, Guillemin 1976, Gensous *et al.* 1986).



plified geological map. Adapted from IFP-CNEXO 1974. 1: ry basins of post-structural Miocene and Plio–Quaternary external zone, pre-Betic and pre-Rif areas; 2B: external o- and intra-Betic areas in Spain, meso- and intra-Rif in 3: flysch nappes; 4: internal zones; 5: autochthonous substratum; 6: Neogene volcanism.

In the western area in front of the Bokkoyas massif, the nearshore acoustic basement is correlated to internal zones and flysch units of the Rifean orogen, (Fig. 3, PII.2, Fig. 7, H1; Fig. 8, H5). Elsewhere, the relations between seismic reflectors and acoustic basement show that it has been recently structured. Aeromagnetic and seismic data allow the following distinctions to be made.

(1) Volcanic basement rises marked by high energy reflectors and numerous refraction hyperbolae, mainly located on the Alboran Ridge banks and on the continental flank of the southern Alboran Trough, east of Ras-Tarf. As inferred from onshore volcanism, its age would be Upper Miocene or Pliocene.

(2) Diapiric structures are not characterized by specific reflectors and correlation with nearby onshore sections is not possible. The nature and the age of the diapiric material is still debatable (Messinian salt or pre-Messinian salt or clay). Nevertheless, it is distinctly observed that diapiric movements occurred during several stages (Fig. 4, PII.1, 40–47 km); in some places, diapirs pierce the overlying sedimentary series causing sea floor upheaval (Fig 1; 35°25′, 4°35′), indicating very recent movements.

Sequence C, clearly observable on the southern flank of the Alboran Ridge (Fig. 7, H1; Fig. 8, H5) is the deepest sedimentary unit reached; it is interpreted as a non-evaporitic Upper Miocene facies (Gensous *et al.* 1986). In the Plio–Quaternary deposits, A and B sequences are distinguished but the accurate age of their boundary is not definite; a Calabrian age is estimated from neotectonic and seismic data (Dillon *et al.* 1980).

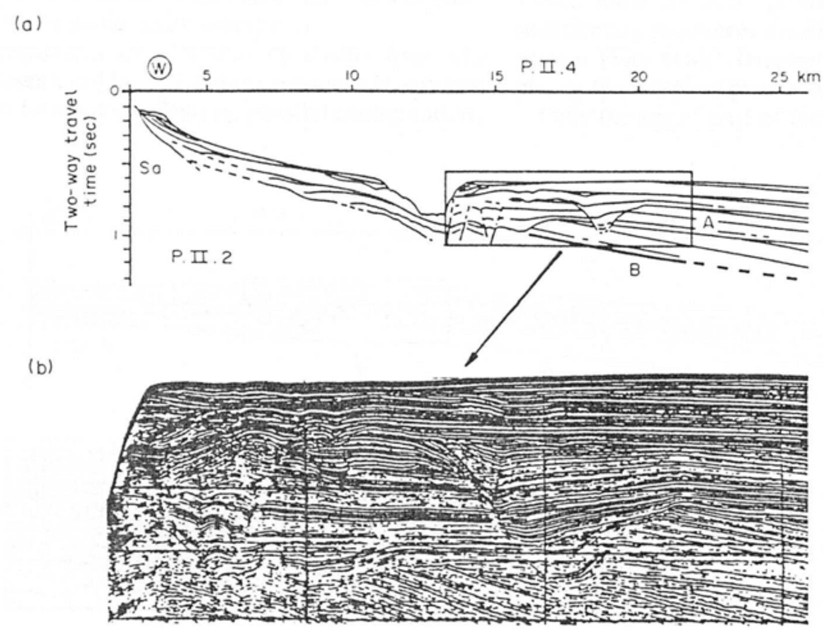


Fig. 3. PII.2 seismic profile across the borderland of a marginal plateau east of Ceuta (see Fig. 1 for location). (a) Interpreted seismic line. (b) Real section of the contoured part showing: actual and quaternary Ceuta canyon; superposition of sedimentary sub-sequences in 'A' sequence.

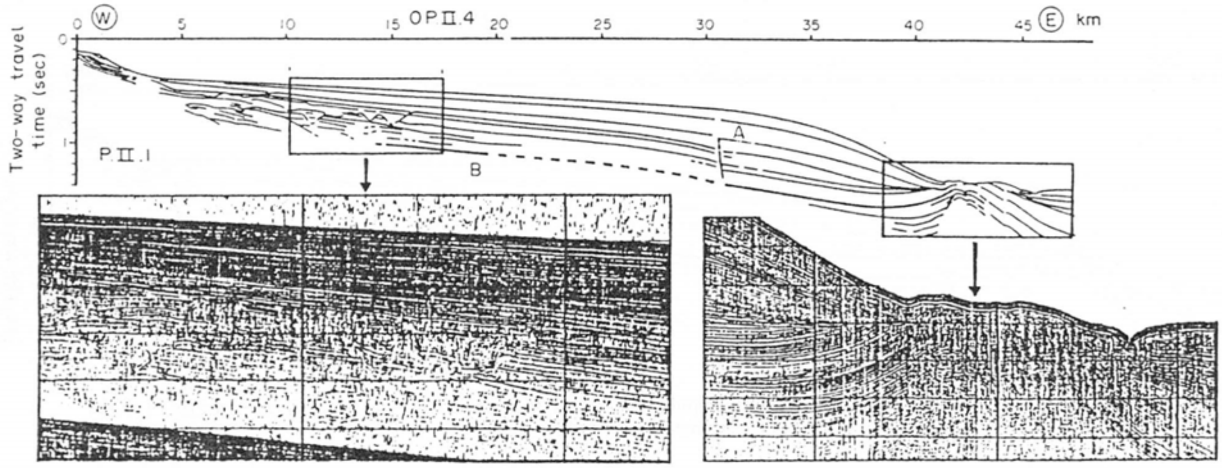


Fig. 4. PII.1 seismic profile across the marginal plateau south-east of Ceuta (see Fig. 1 for location). Note the sedimentary erosional features between coast and 17 km, and the dome-like structure at the foot-slope.

SEISMIC REFLECTION PROFILES

Profiles facing the internal zones to the east and southeast of the Strait of Gibraltar (lat. 35°30′–36°05′ north)

Seventeen profiles were obtained in this area, four of which are shown in Figs. 3–6 (profiles PII.2, PII.1, PII.4, P15).

The bathymetric map (Fig. 1) reveals a narrow continental shelf (edge at 100–120 m) followed, at between 300 and 600 m depth, by an elongated marginal plateau. It is connected with the western Alboran Basin by a slope varying between 600 and 900 m. Continental shelf and marginal plateau are intersected by the Gibraltar Strait channel (oriented N.60°). A well developed canyon, which runs perpendicular to the coast and veers northwest into the Strait of Gibraltar, cuts the marginal plateau and the upper continental shelf.

Three sequences are identified on seismic lines: (1) acoustic basement (Sa); (2) a lower sequence B with low to medium frequency reflectors, parallel configuration, gently dipping seaward; and (3) an upper sequence A with high frequency reflectors, highly stratified. Reflectors are generally parallel to the bottom but may be slightly divergent, displaying a convex profile near the edge of the plateau.

The type of acoustic basement cannot be easily identified. Nearshore (Fig. 3, PII.2), there is little doubt that it represents a foundered prolongation of Rifean internal zones. The relationship with the sedimentary cover is masked by slumping phenomena which affect the whole section, and by complex alternate erosional and sedimentary features related to the Ceuta Canyon (Fig. 3(b)). To the south of the area, acoustic basement rises occur frequently on the continental shelf. Seaward, dome structures upturning sedimentary layers locally appear at the foot of the marginal plateau (Fig. 4, PII.1, 40–45 km). Seismic profiles show that overlying sedimentary sequences exhibit successive stages of formation (Fig. 4(b)). Diapiric structures piercing completely the marginal plateau are also noted.

Only the upper part of the sequence B is visible. To

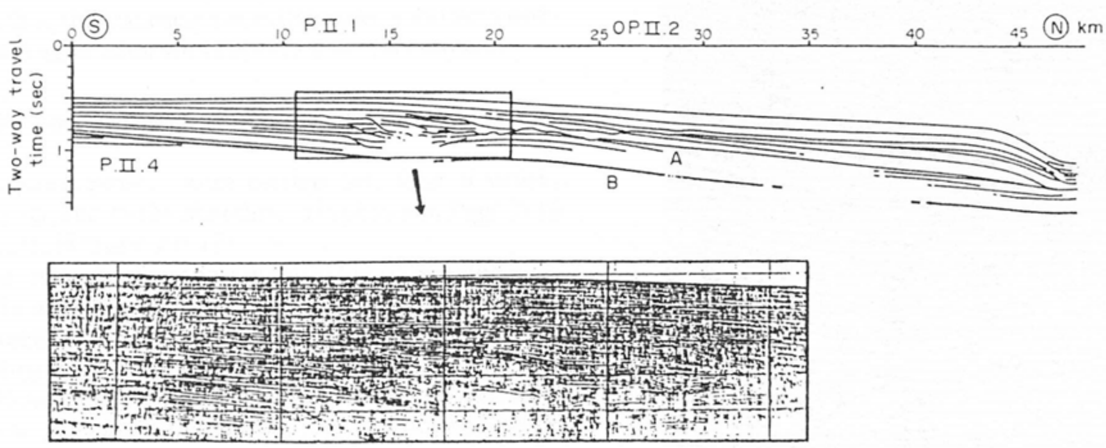


Fig. 5. PII.4 seismic profile at right angle of the two precedent seismic lines (intersections are plotted on interpreted lines). It shows the marginal plateau structure with northward prograding sub-sequences infilling channels (see Fig. 4) and abutting against the Strait of Gibraltar.

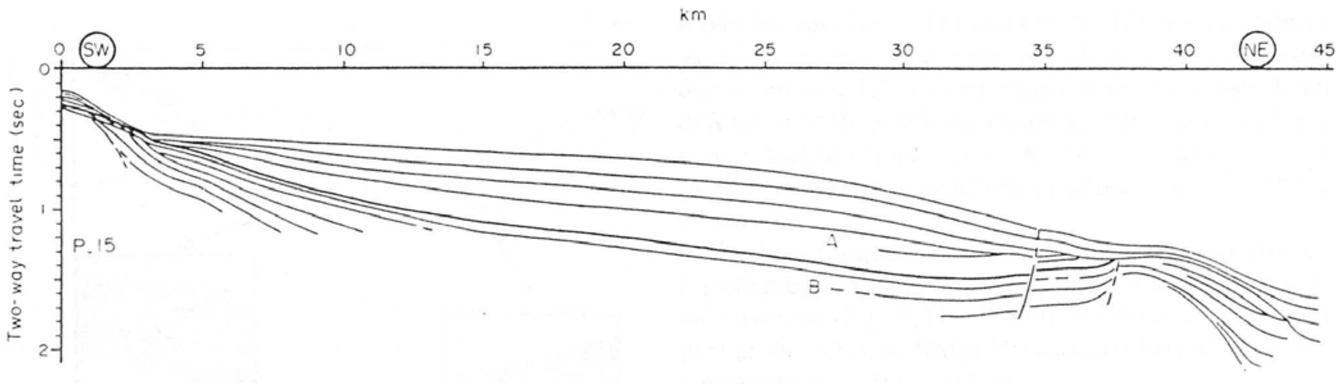


Fig. 6. P15 seismic profile across the southern part of the marginal plateau showing deepening of sequence 'B' reflectors and the beginning of a subsident trough.

the south, continuous subparallel reflectors suggest undisturbed hemipelagic sedimentation. Profile P15 (Fig. 6) clearly displays the shoreward rise of the sequence and lateral passage from hemipelagic to progradational shelf facies. The seaward divergent configuration of reflectors implies irregular subsidence with intervening calm stages as inferred by onlaps in sequence B (Fig. 6, P15, 3–7 km). To the north, it is difficult to identify the top of the sequence B on the marginal plateau and external slope (Fig. 3, PII.2 and Fig. 4, PII.1, oriented perpendicular to the shore).

Sequence A generally rests conformably on sequence B, except shoreward, where sequence A reflectors overlap underlying reflectors (Fig. 6, P15). In the northern part of the area, sequence A shows high complexity and at least four subsequences can be recognized, they appear very conspicuously on profiles PII.2 and PII.1 (Figs. 3 and 4). The occurrence of such figures in the underlying B sequence cannot be observed because of acoustic absorption. The top of the subsequences is marked by an erosional discontinuity, mainly located at the upper part of the marginal plateau. Profile PII.4 (Fig. 5), parallel to the shoreline, indicates that erosional figures on the marginal plateau do not extend to the south of profile PII.1, but spread northward, as far as the Strait of Gibraltar (Fig. 4). Finally, in a north–south direction, these subsequences show a very distinct northward progradation with important vertical growth.

Profiles facing the eastern Rif (3°W–4°20W)

Nineteen profiles were carried out; four of which, perpendicular to the shoreline, are shown in Figs. 7–10 (H1, H5, H13 and PII.12).

The main physiographic feature (Fig. 1) is a configuration in a trough, bounded to the south by the African continent and to the north by a northeast–southwest trending ridge called the Alboran Ridge (Fig. 7, H1; Fig. 8, H5 and Fig. 9, H13). The continental shelf is very narrow (<5 km) with a shelf break at about 100–120 m depth; an abrasion platform, at the same depth, forms the upper surface of the banks of the Alboran Ridge. Another terrace locally appears further down the continental slope

with a tilted surface at 250–300 m, located on the southern flank of the Alboran Ridge (Fig. 9, H13).

Four sequences are recognized on seismic profiles, one corresponding to acoustic basement, the other three to sedimentary sequences with gradual lateral changes (prograding shelf edge, slope, basin). Related sequences appear distinctly on the southern flank of the Alboran Ridge.

The acoustic basement shows two distinct configurations: (1) along the continental shelf bordering the Bok-

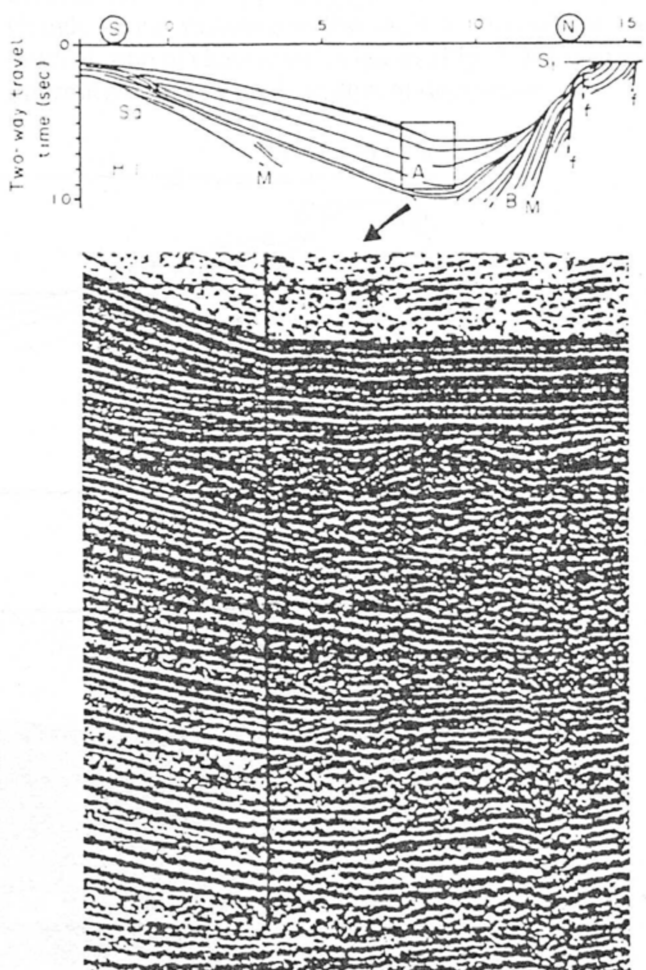


Fig. 7. pH1 seismic profile in the eastern area across the trough and the

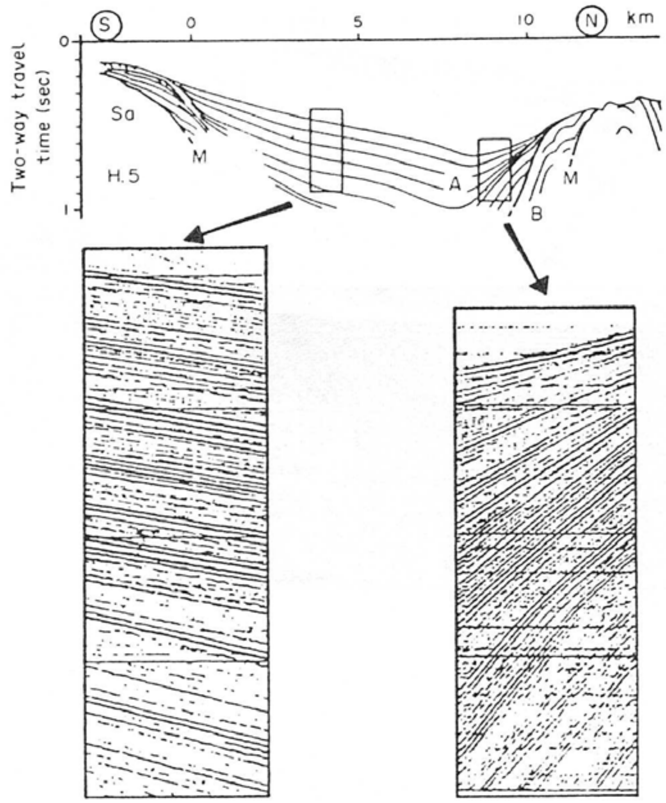


Fig. 8. H5 seismic profile across the trough and the Alboran Ridge. The southward flank of the ridge shows good example of the relations tectonics/sedimentation. Note also the stratified nature of the ridge (dredge samples assumed of Upper Miocene age). Shoreward, onlaps of reflectors (sequence A) and continuous parallel reflections are indicative of relative stability of the continental shelf.

koyas Massif (Fig. 7, H1 and Fig. 8, H5), which appe as a stable structural base on which sediments w deposited; and (2) in other places, it seems to have be deformed with overlying draping sediments, durin recent tectonic phase (Fig. 9, H13, 23 km), or it probably an early established structure (Fig. 10, PII. 17 km).

The lower sequence C consists of parallel continuo high to medium frequency, reflectors folded in an anti nal structure (Fig. 8, H5, 13 km). It constitutes the m part of the Alboran Ridge but acoustic basement loc appears (Fig. 9, H13, 23 km).

Sequence B overlies sequence C. The boundary is a sharp unconformity but is emphasized by a str acoustic reflector (reflector M); on some profiles (Fig H5, 11 km), reflectors of the lower part of sequenc are onlapping reflectors of sequence C. Gener sequence B consists of well stratified, low to medi frequency reflectors with parallel or slightly diverg configuration.

Sequence A rests unconformably on sequence B (gular or erosional unconformity). It is highly strati with high frequency-high amplitude reflectors. On southern flank of the Alboran Ridge, the lower reflect are subparallel and onlap the tilted sequence B: upper and medium reflectors are strongly divergent become laterally subparallel in the central part of trough. Great variation in the angle of distribution intercalation of chaotic facies lenses (Fig. 7, H1) sugg intermittent mass gravity sediment deposition.

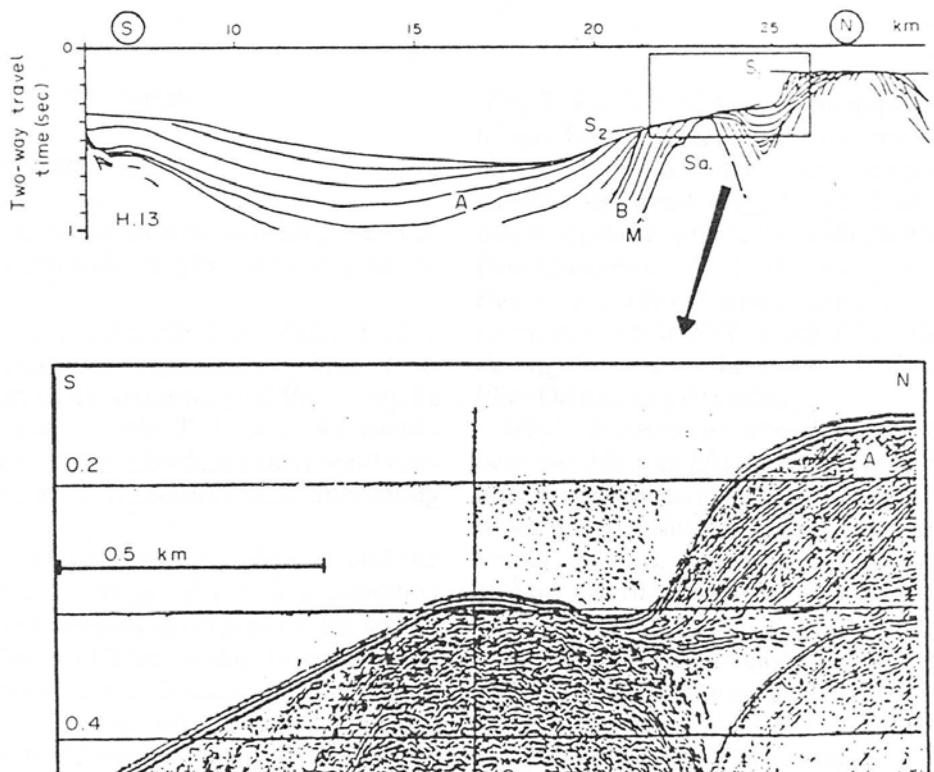


Fig. 9. H13 seismic profile little eastward of the precedent. The two abrasion surfaces (S1 and S2) at the top and on the southward flank of the Alboran Ridge may be related to Holocene sea level variations, but tectonic interference is assumed (S2).

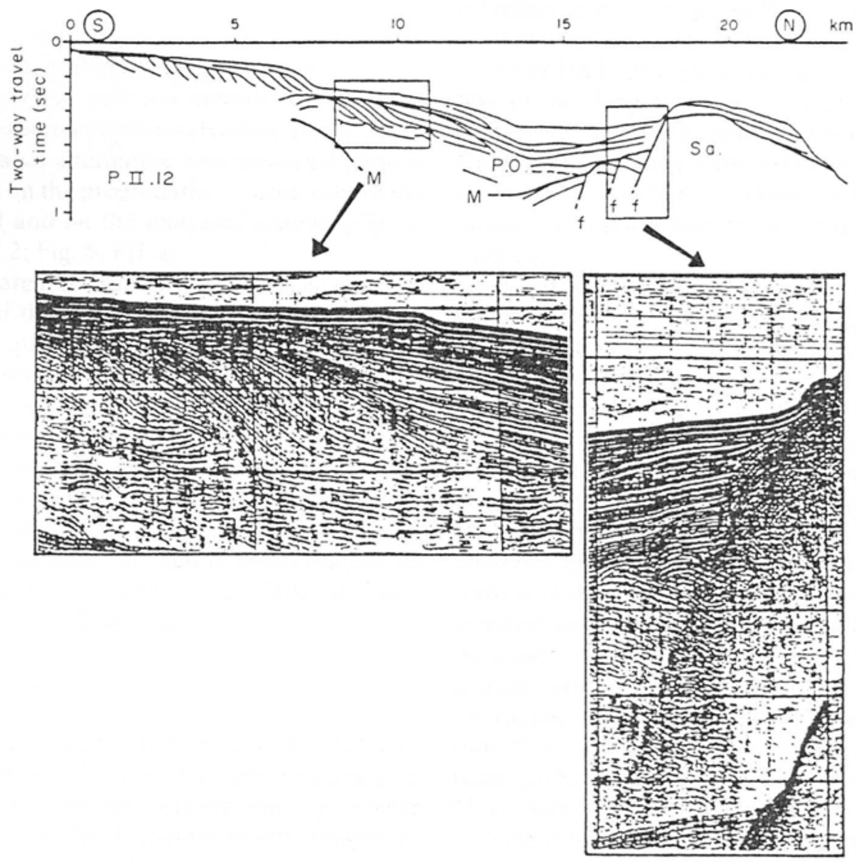


Fig. 10. PII.12 seismic profile. Continental shelf shows quaternary erosional surfaces in a progradational prism (2–8 km). Note the normal faulting and substratum tilting to the north (20 km). The trough and Alboran Ridge are farther seaward.

DISCUSSION

Tectonics and sedimentation

Subsidence was a continuous process during the Plio–Quaternary, with amplitude varying according to the different areas.

In the western area, profiles PII.2 and PII.1 (Figs. 3 and 4) show that seaward deepening of sequence B reflectors occurs during the deposition of the overlying sedimentary sequence. Profile P15 (Fig. 6) clearly demonstrates the role of the subsidence (divergent configuration of sequence A reflectors) with alternating quiescent stages.

In the eastern area, between the continent and the Alboran Ridge, sedimentation occurs in a subsiding trough. Reflectors are strongly divergent on the southern flank of the Alboran Ridge, while the continental border has been more stable because of the Rifean basement proximity; another manifestation of subsidence is testified by tilted erosional surfaces related to Quaternary glaciations (Fig. 9, H13, 20–25 km, surface S2) (Gensous *et al.* 1986).

Distensive faulting is frequent. In the western area, some fault flexures are present on the edge of the marginal plateau (Fig. 4, PII.1, 30 km) as well as some slumping on the outer shelf facing the Ceuta promontory (Fig. 3, PII.2, 0–12 km): these faults seem to be Recent in age. In the eastern area, faulting occurs on the southern flank of the ridge where sedimentary strata are strongly upturned (Fig. 7, H1, 3 km) but the precise dating of these structures is difficult (beginning of the Plio–Quaternary ?). In the Ras Tarf and Al Hoceima Bay areas, recent tectonic activity is demonstrated by numerous NNW–SSE faults (Fig. 10, PII.12, 17 km) cutting the acoustic basement, the Upper Miocene and Plio–Quaternary deposits.

Uplift movements appear difficult to demonstrate near the Alboran Island, where volcanic basement rises upturn conformable Mio–Pliocene sequences; the resulting anticlinal structure, established during the Upper Pliocene, and the age of the volcanism (15–18 Ma) (Hernandez 1983), both suggest a polyphased evolution.

The uplifted blocks east of Ras Tarf (Fig. 10, PII.12, 20 km) were structured before the Upper Miocene but were subsequently affected by tectonic distension leading to their present tilted configuration (Gensous *et al.* 1986).

The present position of Upper Miocene deposits on the top of the Xauen Bank (Fig. 7, H1, 15 km; Fig. 8, H5, 13 km) and on the continental shelf front of the Boudinar Basin suggest a recent uplift stage and important subsidence of the adjacent trough.

Sedimentary processes

Processes controlling the formation of sedimentary bodies are dependent on the structural setting.

In the western area, with low subsidence rates, the Plio–Quaternary sedimentation is characterized by regular deposition stages alternating with erosional periods clearly displayed on the progradational sequences of the continental shelf and on the marginal plateau (Fig. 3, PII.1; Fig. 4, PII.2; Fig. 5, PII.4).

In the eastern area, the sedimentation is controlled by the subsidence of the trough. Basin deposits show successive phases of quiescence (continuous parallel reflectors) and of instability with enhanced gravitational movements (chaotic sliding masses or lensoid infilling) (Fig. 7, H1). Sedimentological data from coring across the western Alboran Basin show that sub-Recent deposits consist of sediment gravity flows alternating with hemipelagic mud series (Huang and Stanley 1972). The very narrow continental shelf is marked along its entire length by a small progradational slope, also present on all the Alboran Ridge banks.

Sea level variations

Seismic facies and dredge sampling on the Alboran Ridge show that the Upper Miocene sequence is hemipelagic; it is overlain conformably by Lower Pliocene deposits. In the Boudinar Basin, sequences dating from the Tortonian–Messinian (Boudinar Basin) are also in conformity with Pliocene deposits. There is no evidence of evaporitic facies, even if the Upper Messinian deposits show a regressive tendency (Houzay 1975). These data are not in agreement with the opinion which links the Messinian salinity crisis to a lowering of sea level of several thousand metres. In this area in the western zone, seismic sections show very marked erosional phases separating the subsequences of the marginal plateau; in the eastern zone, various fossilised abrasion platforms are present on the continental shelf and on the Alboran Ridge. These features likely correspond to Quaternary eustatic variations.

During the Plio–Quaternary, drastic changes of the sedimentary environment were registered in the deposits. The oldest one is marked by a discontinuity, apparent near the topographic rises (continental shelf, banks of the Alboran Ridge), which disappears seaward in the basins. It is correlated to the compressive phase of Upper Quaternary, reported onshore (Rampnoux *et al.* 1977) and inducing upheaval of the margin areas. In addition, several recent discontinuities have been identified.

CONCLUSION

Based on the available seismic coverage, the main features of the post-Miocene evolution of Moroccan margin can be described as follows.

The whole margin has undergone important post-Miocene tectonic activity particularly east of 4°30′W meridian. It is characterized by: (1) a general tendency to the subsidence of marine areas and the uplift of adjacent land (distensive tectonic?); (2) the structuration of an elongated horst running obliquely into the continental margin (Xauen and Tofino Banks, Alboran Ridge); seismic data show that this complex anticlinal structure of sedimentary rather than volcanic nature locally rests on acoustic basement rises (Lower–Middle Miocene).

The main tectonic phase is dated at the Pliocene–Quaternary limit. All these data suggest that the structural evolution of the Alboran Sea continued after the Messinian salinity crisis.

A very marked differentiation is observed between the eastern (east of 4°30′) and western areas (west of a NE–SW axis crossing the Targa cap). In the eastern zone, the Plio–Quaternary sedimentation is mainly controlled by tectonics (topographic features reflect this influence except for more recent ones, related to eustatism, at the shelf edge and the top of the banks). In the western area, sedimentation is mainly influenced by dynamic processes. Sequence analysis on the marginal plateau, which was perhaps shallower than today, shows alternating stages of northward progradation and erosion. They are related to the modifications of the hydraulic pattern in the Alboran Sea during the Quaternary. More detailed study would be necessary for a better understanding of this complex problem in connection with the Atlantic–Mediterranean relations.

The region between the eastern and western parts is interpreted as a key zone. It separates major structural trends and outlines the volcanic area of the eastern Rif; a more detailed study of this area will be carried out later.

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