Pageoph, Vol. 116 (1978), Birkhäuser Verlag, Basel

Crustal Seismic Profiles in the Alboran Sea – Preliminary Results

By The Working Group for Deep Seismic Sounding in the Alboran Sea 1974[1])

Abstract – In September 1974, deep seismic sounding experiments were performed in the Alboran Sea. The crustal seismic profiles were carried out with shotpoints at sea along approximately the 36°N parallel and along the 3°W and 5°W meridians with stations on land in Morocco and Spain following these three directions. The first interpretation of the data indicates a thinned continental crust with a Moho depth of 16 km on top of a slightly anomalous upper mantle ($7.5 < V_p < 7.9$ km/s) beneath the center of the Alboran Sea. Towards Spain the transition to the continental margin is characterized by a very rapid thickening of the crust. Towards Morocco a rather abrupt thickening is observed only for the Rif region, while in the eastern part (north–south profile along 3°W) the dip of the Moho is very slight.

Key words: Seismic profiles in the Alboran Sea; Crustal structure of the Alboran Sea; Alboran Sea, Crustal structure.

1. Introduction

From the geodynamic point of view the Alpine–Mediterranean area is a controversial region. In spite of many studies of its geological history the relation between the Alpine orogenic belts and the adjoining sea and land areas is not yet fully understood. In its programme development the Inter-Union Commission on Geodynamics (1972) had proposed a study of the Alpine–Mediterranean region. Beyond the studies of neotectonics and paleotectonics the ICG Working Group 3 had encouraged regional crustal investigations. The straits of Gibraltar and the Sea of Alboran are considered as key areas.

Many authors (Le Pichon, 1968; Minster *et al.*, 1974) assume that the Eurasian and African lithospheric plates converge since 53 My. Seismological evidence for the present dynamics of the Euro-African plate margin has been presented by Udias *et al.* (1976). Several hypotheses on the origin of the straits of Gibraltar and the Alboran Sea have been advanced recently (Andrieux *et al.*, 1971; Auzende *et al.*, 1973; Loomis, 1975). As all these models depend heavily on the knowledge of deep structure as deduced by seismology, the realization of deep seismic soundings

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became necessary in the Alboran Sea. In these experiments an alignment of shotpoints at sea and recording stations on land was chosen following the experiences in the study of the oceanic lithospheric structure during the 1973 experiment between the Madeira and Canary Islands (STEINMETZ and HIRN, 1973). A programme with several profiles in the Alboran Sea was organized by France in collaboration with Morocco and Spain during September, 1974.

2. *The experiments*

The experiments were organized by the Institut de Physique du Globe, Paris, with the financial support of the Institut National d'Astronomie et de Géophysique (INAG) from 6–15 September 1974, with the collaboration of the Service de Physique du Globe, Rabat (Morocco), and of the Spanish Navy and the Working Group for Deep Seismic Sounding of the Spanish National Committee for the International Geodynamics Project with the support of the Consejo Superior de Investigaciones Científicas, the Instituto Geográfico y Catastral, Madrid, and the University of Barcelona.

For the study of the crust in the Alboran Sea and in the transition zone between the sea and the adjacent Spanish and Moroccan continental areas, several shotpoints were fired in the Alboran Sea along three profiles with recording stations occupying the landward sections of the profiles in Spain and Morocco (Fig. 1). This distribution resulted in various single-ended and reversed profiles.

Profile 1: Along the 5°W meridian 12 shotpoints (No. 501 to 512) were placed at 10 km intervals between the Spanish and Moroccan coasts and recorded in the same north–south direction at a total of 18 stations: in Spain, 12 (No. 100 to 112) with a mean separation of 9 km between Ronda (105) and Osuna (111), in Morocco, 6 (NKM, BB, TF1 to TF4) with a mean separation of 30 km between Beni Bouchra and Fès (TF4) in the Rif.

Profile 2: Along a ENE–WSW line from Beni Bouchra (BB) to Alboran Island (ALB), 14 shotpoints (No. 513, 601 to 613) at 10 km intervals were recorded at the stations ALB, BB, MOT and NKM (see Fig. 1).

Profile 3: Along the 3°W meridian 8 shotpoints (No. 701 to 708) were placed at 10 km intervals and recorded at fourteen stations: 9 in Spain (401 to 409) with a mean separation of 9 km between Adra (401) and Guadix (409) in the Cordillera Betica; 5 in Morocco (MKL and MD1 to MD4) with a mean separation of 30 km between Cabo Tres Forcas (MD1) and Debdou (MD4).

Five stations, namely 101, 111, BB, 402 and ALB were not removed during the whole experiment and recorded all the shots. Likewise, in the permanent seismological

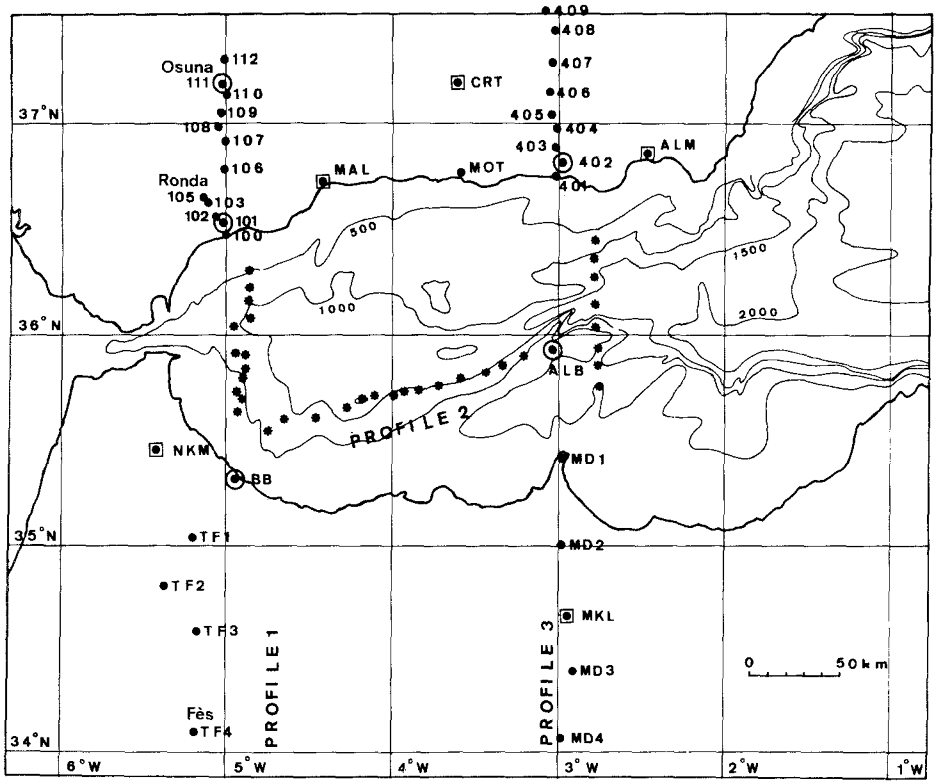

Figure 1

∗ Shots, • Temporary stations, ⊙ Temporary fixed stations in the experiments, ▣ Permanent seismological stations participating in the experiments.

stations at Malaga (MAL), Cartuja (CRT), Almeria (ALM), Nakhla (NKM) and Mechra-Klila (MKL) field equipment was installed during the experiments.

This system of single-ended and reversed profiles yielded information about the gross structure of the upper lithosphere, covering the following ranges:

Profile 1: Spanish stations $20 < \Delta < 180$ km
Moroccan stations $50 < \Delta < 240$ km

Profile 2: Alboran station $10 < \Delta < 160$ km
Beni Bouchra station $40 < \Delta < 110$ km

Profile 3: Spanish stations $40 < \Delta < 180$ km
Moroccan stations $80 < \Delta < 260$ km

All the shots were fired in the Alboran Sea by the French vessel *Cap Fagnet* during a large-scale experiment from the Açores Islands to Corsica (Operation Grands Profils Sismiques of the Institut de Physique du Globe, Paris). Table 1

Table 1

Shot (No.)	Date	Time (GMT)	Longitude (°W)	Latitude (°N)	Water depth below sea level (m)	Charge size (kg)
Profile 1						
501	09/11/74	13:13:05.84	4.9317	35.6362	440	300
502		14:11:39.28	4.9300	35.7318	460	300
503		19:54:03.56	4.9412	35.9163	714	300
504		21:49:18.69	4.9480	36.0343	871	300
505	09/12/74	08:54:39.32	4.8462	36.2997	650	300
506		09:44:42.57	4.8547	36.2237	780	50
507		10:23:34.87	4.8533	36.1583	865	300
508		10:59:23.12	4.8467	36.0800	970	50
509		13:13:15.73	4.8850	35.8943	740	300
510		13:39:08.16	4.8850	35.8340	575	50
511		14:10:15.68	4.9000	35.8022	536	50
512		15:02:20.53	4.9000	35.6958	452	50
513		16:33:53.92	4.7413	35.5462	490	300
Profile 2						
601		20:38:04.14	4.6483	35.5938	760	300
602		21:48:45.07	4.4488	35.6085	1225	300
603		23:28:26.28	4.2678	35.6597	1410	300
604		23:52:18.92	4.1905	35.6992	1480	300
605	09/13/74	00:22:28.20	4.1000	35.7030	1450	300
606			3.9908	35.7187	1450	300
607		01:11:52.86	3.9304	35.7192	1370	300
608		01:43:55.22	3.8367	35.7362	1370	300
609		02:28:01.59	3.7218	35.7597	1330	300
610		02:56:17.92	3.5898	35.7843	1220	300
611		03:43:16.17	3.4387	35.8153	870	300
612		04:21:05.25	3.3333	35.8417	580	300
613		05:09:18.52	3.2060	35.9080	613	300
Profile 3						
701		07:55:59.61	2.7717	35.7637	560	300
702		11:29:13.58	2.7645	35.8583	970	300
703		11:55:58.89	2.7683	35.9370	1100	300
704		12:28:58.48	2.7733	36.0348	470	300
705		13:37:10.64	2.7693	36.1380	1725	300
706		15:48:06.75	2.7888	36.4508	780	300
707		17:31:10.96	2.7803	36.3637	1130	300
708		18:08:44.29	2.7708	36.2625	1640	300

The charge depth for 300 kg and 50 kg is 100 m and 70 m respectively.

gives the data for all shots (date, origin times, coordinates, charge sizes). Twenty-nine charges of 300 kg were fired at a depth of approximately 100 m and five charges of 50 kg were detonated at about 70 m depths. The charge depths were determined roughly according to the conditions for optimum efficiency (MUELLER *et al.*, 1973; GROUPE GRANDS PROFILS SISMIQUES AND GERMAN RESEARCH GROUP FOR EXPLOSION SEISMOLOGY, 1972). The position of the shotpoints was located by satellite navigation.

The shots were recorded by 26 similar portable seismic refraction stations: 19 of the Institut National d'Astronomie et de Géophysique, France, 4 of the Instituto Geográfico y Catastral, Madrid, and 3 of the University of Barcelona. Each station consists of three-component (2 Hz) seismometers, a frequency modulation multiplex system and magnetic tape recording. The time signal used was transmitted by station

Table 2
Stations coordinates

Station (°N)	Longitude (°W)	Latitude (°N)	Elevation (m)
(1) *Morocco*			
BB	4.9355	35.3208	220
NKM	5.4100	35.4481	200
TF1	5.2002	35.0485	950
TF2	5.3655	34.8152	630
TF3	5.1667	34.5802	180
TF4	5.1763	34.1035	220
MD1	2.9680	35.4022	100
MD2	2.9793	35.0133	160
MKL	2.9383	34.6647	220
MD3	2.8980	34.3927	455
MD4	2.9888	34.0788	740
(2) *Spain*			
ALB	3.0333	35.9412	20
MOT	3.5803	36.7825	
100	5.0082	36.4903	60
101	5.0112	36.5284	340
102	5.0546	36.5531	480
103	5.1094	36.6316	1060
104	5.1222	36.6694	1020
106	5.0021	36.7926	980
107	4.9972	36.9006	520
108	5.0374	36.9912	560
109	4.9996	37.0439	600
110	4.9871	37.1354	340
111	5.0210	37.1782	400
112	4.9980	37.3025	220
MAL	4.4111	36.7275	60
ALM	2.4598	36.8528	65
CRT	3.5979	37.1900	774
401	3.0068	36.7600	20
402	2.9888	36.8387	260
403	3.0263	36.8886	340
404	3.0101	36.9783	500
405	3.0323	37.0428	1400
406	3.0429	37.1389	1760
407	3.0342	37.2877	1180
408	3.0196	37.4387	1220
409	3.1049	37.5333	1250

HBG (75 kHz) near Geneva, Switzerland, by the time service of the Observatorio de Marina, San Fernando, Spain, and by electronic clocks calibrated against HBG signals in Rabat and Almeria before and after the experiments. Table 2 gives the co-ordinates of recording stations.

All analog data were played back, and then subsequently were digitized at the Institut de Physique du Globe, Paris, at a rate of 200 samples per second. The digital data obtained were filtered, normalized and plotted. Several of the record sections are shown in the text.

The water depth below the sea level at the shotpoints is given in the last column of Table 1. Because of the great variations of the thickness of water and sediments along all profiles, for all record sections we correct the travel time of each phases Pg, PMP and Pn by replacing the water layer ($V_P = 1.52$ km/s), plio-quaternary sediments ($V_P = 2.2$ km/s) and consolidated sediments ($V_P = 4.0$ km/s) beneath the shot-points by the same thickness of a crustal material ($V_P = 6.1$ km/s). The thickness and the mean P-velocities of sediments were given by the Institut Français du Pétrole in Rueil (France) (personal communication). To correct travel time from sediments below the stations, we use the intercept line of the Pg phase.

3. *Preliminary results*

Profile 1: (Figs. 2 and 3)

The recording of the shots 501 to 512 at the stations BB and 101 represents a reversed profile between 45 and 75 km from Beni Bouchra.

The equations of the travel time curves for the refracted waves are

101: Pg: $t = 1.53 \pm 0.15 + \Delta/(6.08 \pm 0.20)$ sec
Pn: $t = 6.03 \pm 0.02 + \Delta/(10.40 \pm 0.12)$ sec
BB: Pg: $t = 2.00 \pm 0.08 + \Delta/(6.10 \pm 0.12)$ sec
Pn: $t = 1.92 \pm 0.07 + \Delta/7.53 \pm 0.22)$ sec.

The true velocity for the Pg wave is 6.1 km/s, and the depth to basement must be placed several kilometers below a superficial layer which may consist of Cenozoïc sediments and altered basement rocks. This superficial layer seems to thicken towards the Moroccan coast.

The true velocity for the Pn wave appears to be anomalously high ($V_p = 8.6$ km/s). The Moho depth may be placed between 15 and 20 km at a distance of 45 and 85 km, respectively, from Beni Bouchra. To the north, under the spanish coast a horizontal Mohorovicic discontinuity at 20 km depth can explain the observed travel times. The high Pn velocity may be related to the existence of the peridotites observed in surface near Beni Bouchra (BB) in Morocco and near Ronda in Spain (station 105).

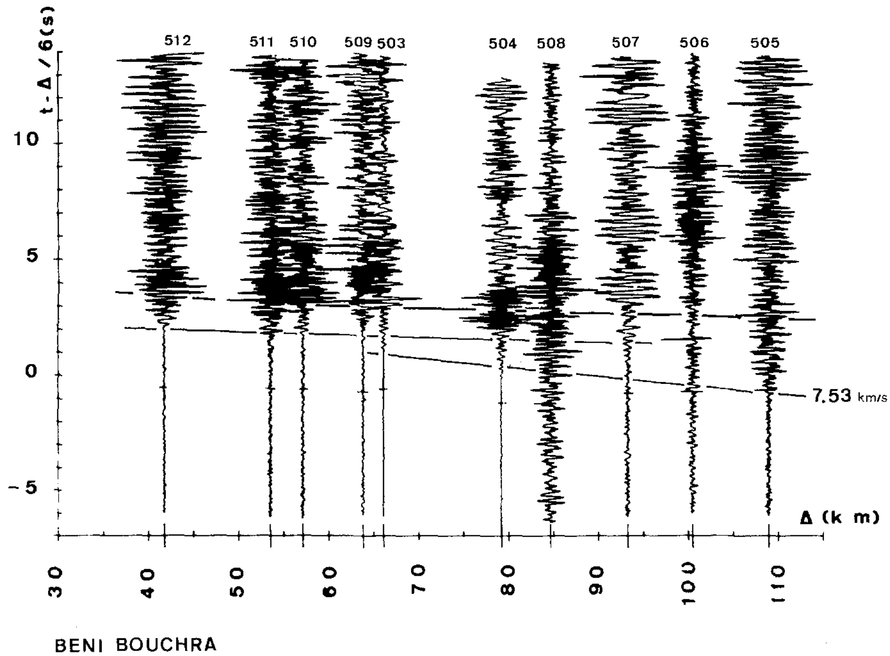

Figure 2
Record section of the profile 1 for the Beni Bouchra station (shots No. 503 to 512). Filter band-pass is 2 to 8 Hz.

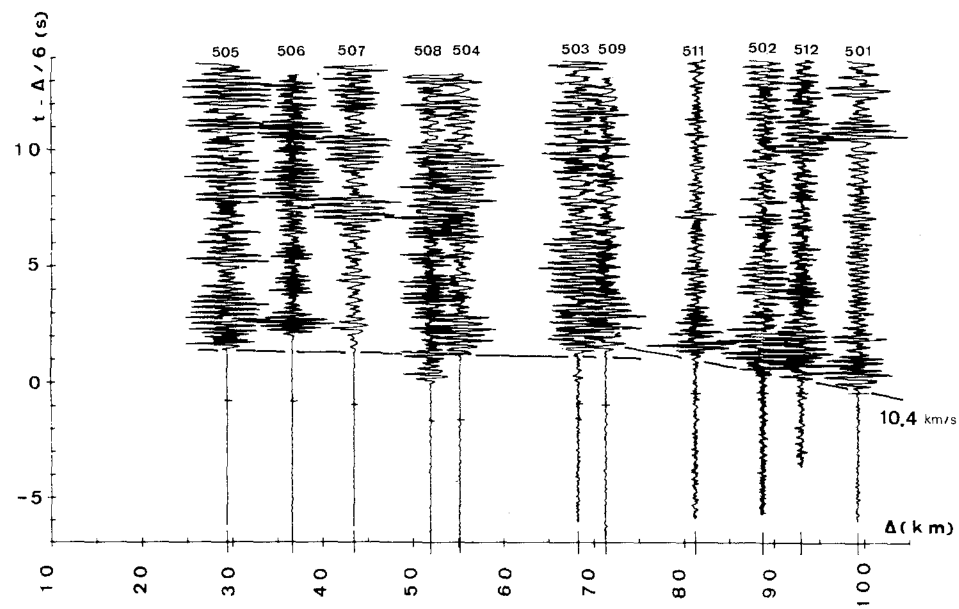

Figure 3
Record section of the profile 1 for the station No. 101 (shots No. 501 to 509, 511 and 512). Filter band-pass is 2 to 8 Hz.

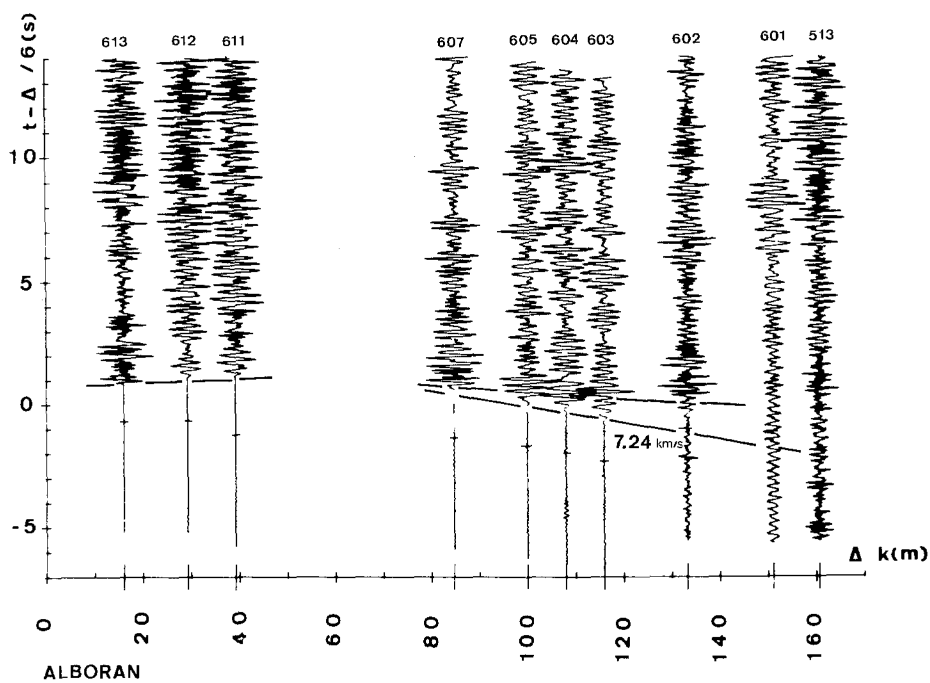

Figure 4
Record section of the profile 2 for the Alboran station (shots No. 513, 601 to 605, 607, 611 to 613). Filter band-pass is 2 to 8 Hz.

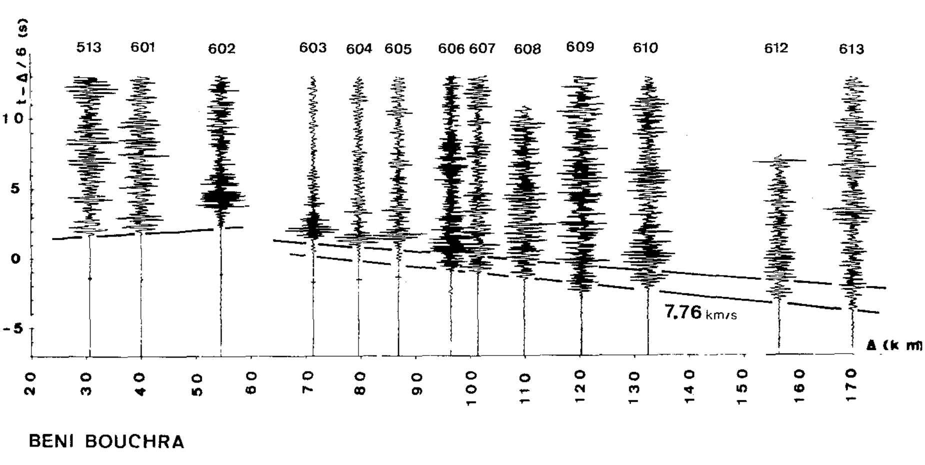

Figure 5
Record section of the profile 2 for the Beni Bouchra station (shots No. 513, 601 to 610, 612 and 613). Filter band-pass is 2 to 8 Hz.

Profile 2: (Figs. 4 and 5)

For this profile, the shot line was located near the axis of the Alboran Sea in an area where the thickness of the Plioquaternary and Cenozoïc sediments is known. After corrections mentioned above, the equations of the travel time curves for the refracted waves are:

ALB: Pg: $t = 0.77 \pm 0.01 + \Delta/(5.77 \pm 0.04)$ sec
Pn: $t = 2.69 \pm 0.09 + \Delta/(7.24 \pm 0.13)$ sec
BB: Pg: $t \sim 2.1 + \Delta/6.0$ sec
Pn: $t = 2.64 \pm 0.12 + \Delta/(7.76 \pm 0.09)$ sec.

The true velocity for the Pg wave from this reversed profile is about 5.9 km/s. After corrections, the intercepts of the Pg travel time curves are still significant. This fact shows the existence of a low-velocity sedimentary layer which thickens toward the Moroccan coast.

The true velocity for the Pn wave is 7.5 ± 0.1 km/s, and the Moho dips down from east to west with a slope of 5 percent.

Along this profile the PMP waves are observed in both directions. The t^2, Δ^2 method applied to the wide-angle reflection times gives a mean velocity (V_m) within the crust and a mean depth for the Moho (H_m), as follows:

ALB: $V_m = 6.16 \pm 0.03$ km/s; $H_m = 16.3 \pm 1.0$ km
BB: $V_m = 6.56 \pm 0.08$ km/s; $H_m = 22.5 \pm 2.3$ km.

These values confirm the existence of a Moho dipping down from east to west (mean Moho depth 17 km). The mean velocity within the crust is about 6.3 ± 0.1 km/s.

On the other hand the travel time curve for the Pn wave recorded in Nakhla (NKM) in the northern part of the Moroccan Rif is

$$t = 4.1 \pm 0.4 + \Delta/(7.4 \pm 0.3) \text{ sec.}$$

Although the value of the apparent Pn velocity is poorly defined, the greater value of the intercept time compared to that of the BB station indicates a rapid thickening of the crust from the Alboran Sea to the Rif.

Profile 3: (Figs. 6 and 7)

On this profile, the Pn waves show generally good first arrivals. The travel time curves for the stations MD2 and 402 are:

MD2: $85 < \Delta < 140$ km; $t = 4.13 \pm 0.14 + \Delta/(7.69 \pm 0.15)$ sec
402: $45 < \Delta < 120$ km; $t = 4.16 \pm 0.03 + \Delta/(8.10 \pm 0.08)$ sec.

From this reversed profile the true P velocity in the upper mantle appears to be 7.86 ± 0.05 km/s with a small downward slope (3 percent) from south to north in the center of the Alboran Sea. The observations along the land profiles indicate that the Moho goes down very gently under eastern Morocco and very rapidly under southern Spain (HATZFELD and BEN SARI, 1976; WORKING GROUP FOR DEEP SEISMIC SOUNDING IN SPAIN 1974–75, 1977).

The PMP waves recorded at stations MD2 and 402 give the following values of V_m and H_m:

MD2: $V_m = 6.0 \pm 0.1$ km/s; $H_m = 17 \pm 1$ km
402: $V_m = 6.1 \pm 0.1$ km/s; $H_m = 18 \pm 1$ km.

These values of crustal thickness are in agreement with those obtained from the Pn waves. The PMP waves recorded at the station in Alboran Island yield 15 km depth for the Moho in the center of the Alboran Sea.

4. Conclusions

The first results obtained from deep seismic soundings in the Alboran Sea are summarized in Fig. 8 which illustrates the following points:

(1) The Pn velocity observed below the Moho ($V_p = 7.5$ km/s) is low, indicating the existence of an anomalous upper mantle beneath the center of the Alboran Sea.

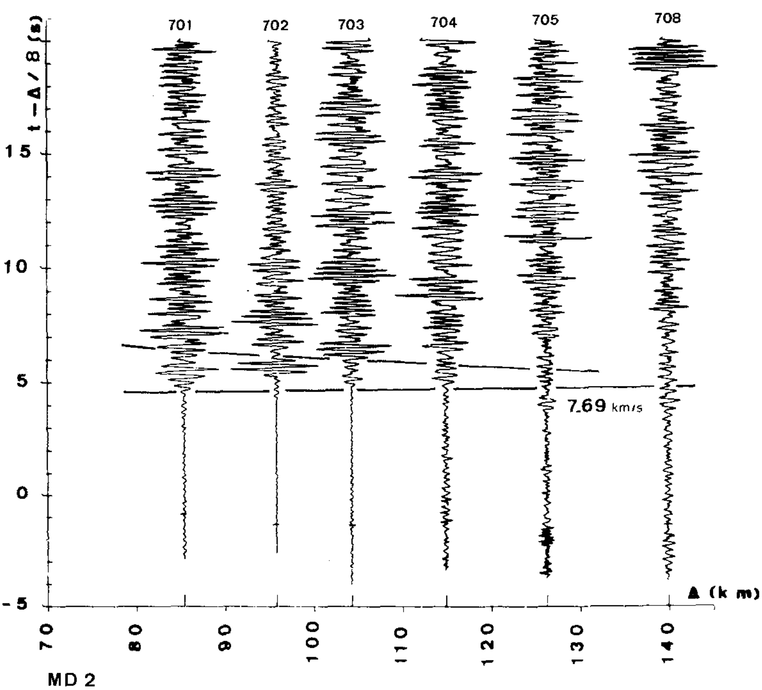

Figure 6
Record section of the profile 3 for the station No. MD2 (shots No. 708, 701 to 705). Filter band-pass is 2 to 8 Hz.

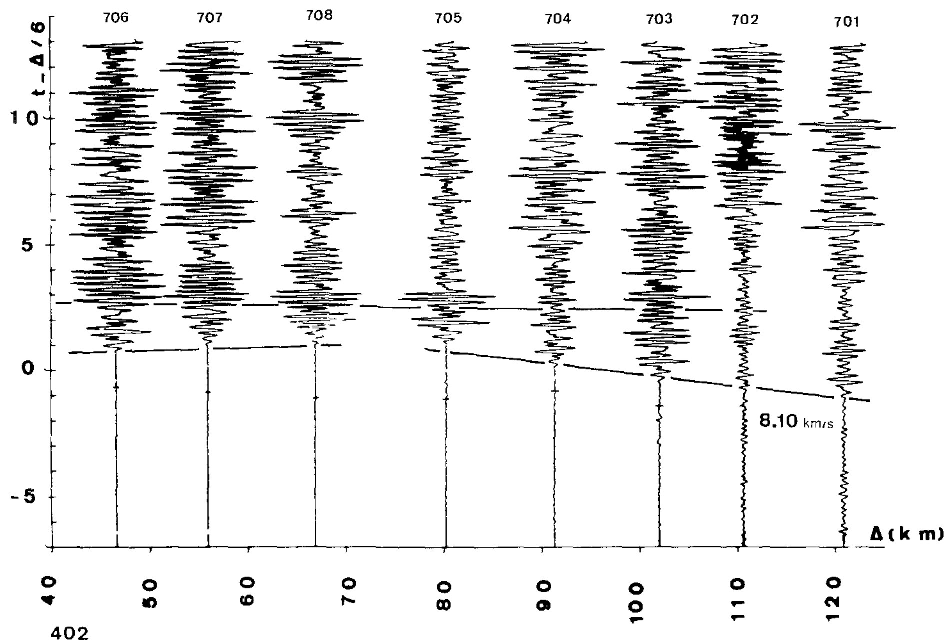

Figure 7
Record section of the profile 3 for the station No. 402 (shots No. 701 to 708). Filter band-pass is 2 to 8 Hz.

The greatest velocity (V_P = 7.9 km/s) observed at the east of Alboran Island seems to indicate a progressive transition towards a normal deep oceanic basin upper mantle in the western part of the Mediterranean Sea.

(2) Under the Alboran Sea the mean Moho depth is about 16 km. The mean crustal velocity lies between 6.0 and 6.3 km/s. No layer of higher velocity could be found in the lower crust.

(3) Towards Spain the transition to the continental margin is characterized by a very rapid thickening of the crust. Towards Morocco a rather abrupt thickening is, observed only for the Rif region. To the east (Cabo Très Forcas), the dip of the Moho towards the south is very slight.

(4) At the west, the high Pn velocity (V_P = 8.4 km/s) observed between Ronda and Beni Bouchra cannot be explained by peridotites under the observing stations but by a possible extension into the sea area. KORNPROBST (1976) has proposed a model in which peridotites are considered as mechanically emplaced during the Alpine orogeny, from the shallowest part of the mantle.

If we exclude the western part of the Alboran Sea where strong lateral heterogeneities are supposed, the crustal structure in the center of the Alboran Sea seems quite different from a typical oceanic crust as discussed by SHOR and RAITT (1969) and LE PICHON (1969). The velocities and the thicknesses observed are characteristic of a thinned continental crust overlaying an anomalous upper mantle as found in rift systems.

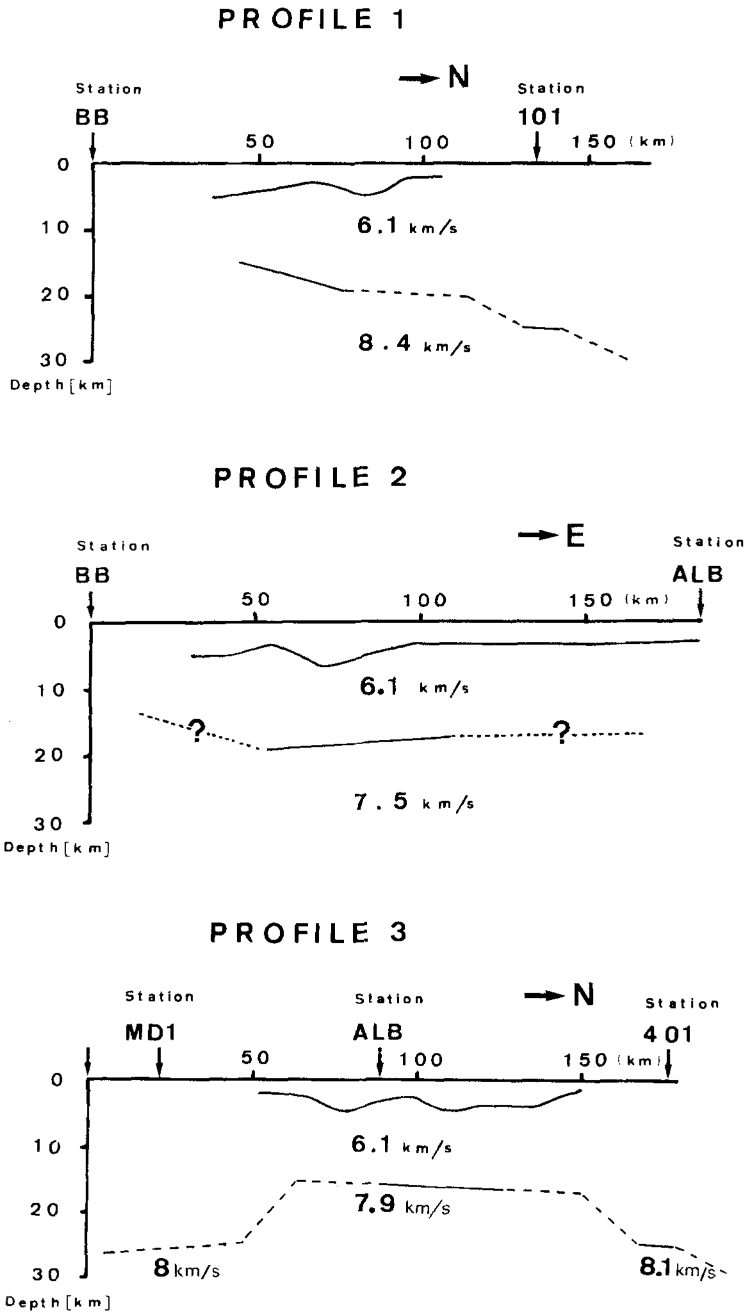

Figure 8

Crustal structure in Alboran Sea. The mean crustal velocity is 6.1 km/sec for all profiles. Full lines and dashed lines are depths given by reversed and non reversed profiles respectively. For the profile 2, the dashed lines are extrapolated depths.

Acknowledgements

The organizers and authors cordially thank all participants who contributed so much to the success of these experiments. They are particularly indebted to the Spanish sailors on Alboran Island, the Service Géologique and the Service de la Carte in Morocco, the Communication Center of the Spanish Navy (San Fernando) and the Observatorio Sismológico de Málaga.

The financial support was provided by the Institut National d'Astronomie et de Géophysique (INAG) (Projets 32-32, 32-01 and 32-23 of the Programme Géodynamique de la Méditerranée occidentale et de ses abords) and the Consejo Superior de Investigaciones Científicas (Proyecto Geodinámico, 1973-75). We appreciate the help of J. Ansorge, J. Mezcua, St. Mueller and A. Udías in reading of manuscript.

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This report was prepared by G. Perrier, D. Hatzfeld and M. Boloix.

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(Received 20th January 1977)