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Crustal Thinning from the Betic Cordillera to the Alboran Sea

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Abstract. Two profiles have been gravimetrically modelled in the central and eastern parts of the Alboran Sea and Betic Cordillera. The crust in the central part thins from 38 km below the Internal Zones to 18–22 km beneath the Alboran Basin in an area about 30 km wide. The eastern part shows greater thinning, from about 38 to 15 km, distributed over a broader area some 100 km wide. The mode of crustal thinning in the eastern part can be compared with that of a rifted passive margin whereas the central part exhibits a transform style.

Introduction

The Betic Cordillera and the Rif Chain with the Alboran Basin in between form the westernmost segment of the Alpine–Mediterranean mountain belt (Fig. 1). The Alboran Basin appears to have developed since the Early Miocene involving major lithospheric thinning (Durand-Delga 1980; Platt and Vissers 1989; Comas and others 1990).

One of the most outstanding features of the Bouguer gravity anomaly map of the area is the rather uniform strong north-south gradient (4 mGal/km) between longitudes 3° and 4°W, which extends from the coast to about 37°N latitude (Fig. 2). To the east the gravity gradient is oriented northwestern–southeastern and is more gentle (2 mGal/km).

In the last decades several authors have gravimetrically modelled the area along a number of profiles extending from the Betics to the Rif chain. Bonini and others (1973) modelled two profiles along 4° 30′W and 3°W latitude mainly focusing on the coastal highs located in the western part of the study area and the central Alboran Sea gravity high. Haztfeld (1976) used gravity and seismic data to study the crustal structure of the Alboran Basin and particularly the likely presence of an anomalous low P-wave velocity/low-density uppermost mantle. Casas and Carbó (1990) proposed a schematic crustal model along three profiles cutting across the Betics and part of the Alboran Sea.

The crustal structure of the Betic Cordillera is also relatively well known although only along a limited number of seismic refraction/wide angle reflection lines (Fig. 1). The Internal Zones of the Betic Cordillera are characterized by an intracrustal reflector at 10–12 km depth separating v_p velocities of 6.0 km/s and 6.4–6.5 km/s (Banda and others 1992). The lower crust is not well differentiated and the upper mantle has a P-wave velocity of 8.1–8.2 km/s. The total crustal thickness is 38 km in its thickest part and thins toward the Mediterranean. Along the southern coast of Spain a crustal thickness of 24–25 km has been derived (Banda and Ansorge 1980; Barranco and others 1990).

Available seismic data in the Alboran sea are not good enough to give a detailed picture of the crustal configuration, although an estimate of 15 km crustal thickness in the central part of the basin is known from a few published and unpublished studies (Boloix and Hatzfeld 1977; Hatzfeld 1978; Working Group for Deep Seismic Soundings in the Alboran sea 1974, 1978). An important seismic result in this area is the indication for locally fairly low upper mantle P-wave velocity (7.6–7.8 km/s), which could point to the presence of anomalous mantle with densities lower than the standard value of 3,330 kg/m^3 (Hatzfeld 1976) as derived from the empirical relationship between P-wave velocity and density. It remains unclear, however, how the transition from the thickened continental crust of the Betics to the thinned continental crust beneath the Alboran Basin actually occurs.

Gravity analysis using seismic constraints seems an appropriate method to study the deep crustal transition from the Betic Cordillera to the Alboran Sea and thus reach a better understanding of the crustal thinning and in turn of lithospheric extension. This study is mainly focused on the mode of transition from the Betics to the Alboran crust along two profiles located in the central and eastern parts of the Alboran Sea and Betic Cordillera combining gravity and available seismic data.

Gravity Modelling

The gravity map (Fig. 2) has been obtained using available data from the Bureau Gravimétrique International (B.G.I.), from the Spanish "Instituto Geográfico Nacional" and also from available ship tracks including new data collected during a cruise carried out by research vessel R.D. Conrad in the Alboran Sea. Some additional data points at sea have been taken from Morelli and others (1975). The average coverage is one observation per 12 km^2. The different sur-

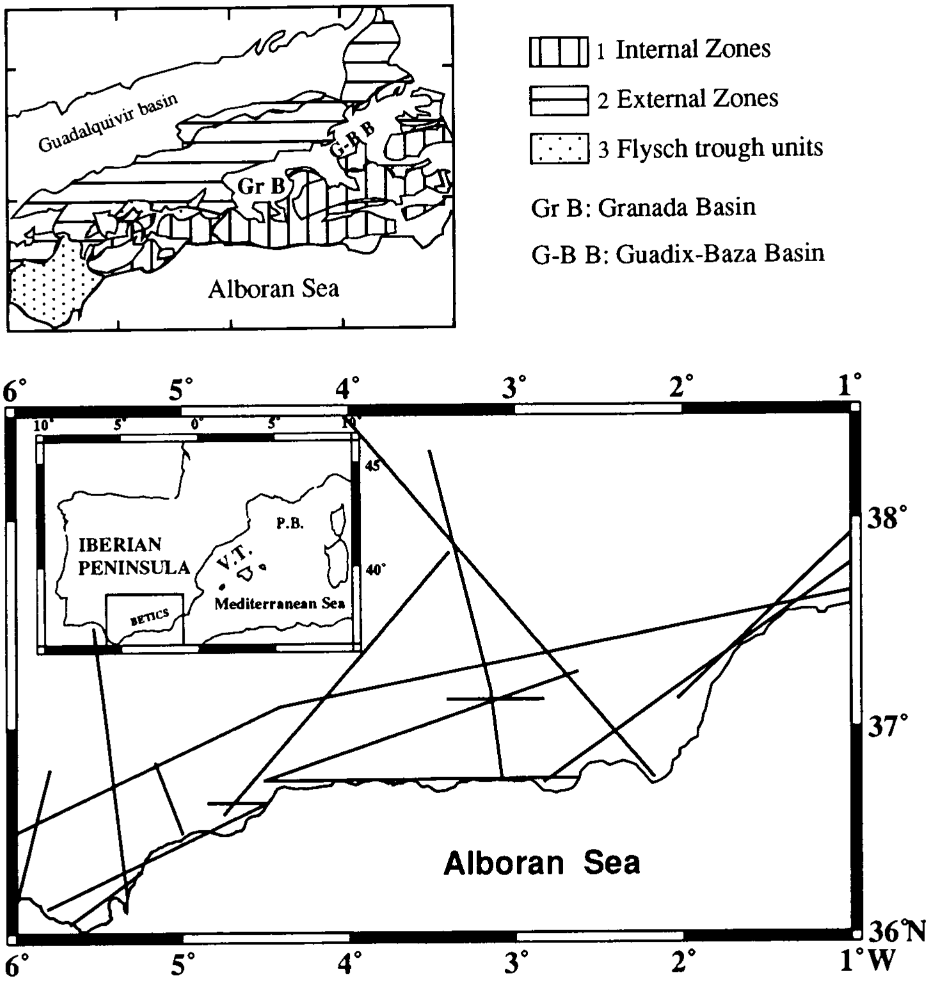

Figure 1. Location map of the Betic area. Solid lines indicate the approximate location of available seismic refraction/wide-angle reflection on land. V.T., Valencia Trough; P.B., Provençal Basin. Upper left panel, simplified geological map of the study area.

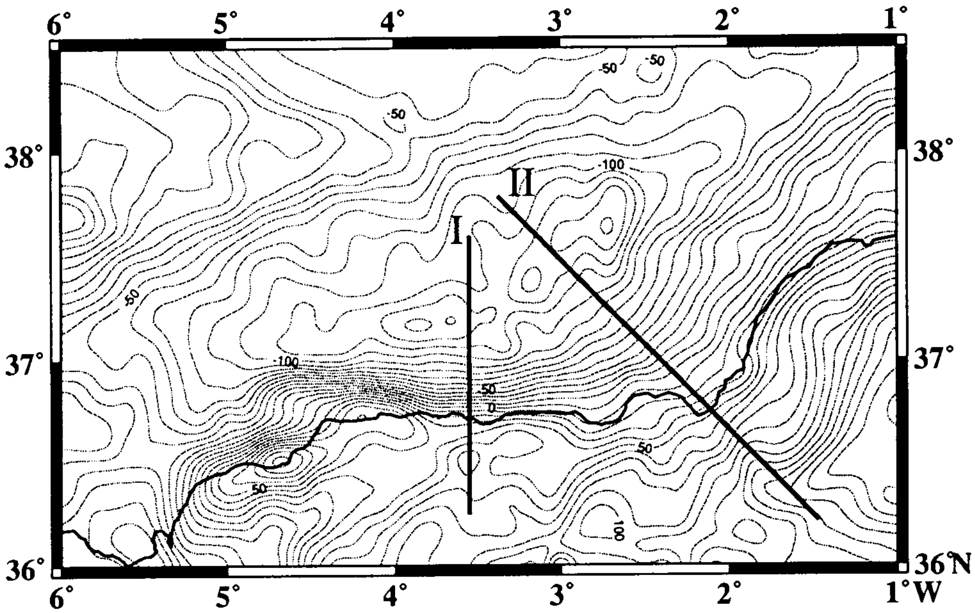

Figure 2. Simple Bouguer gravity anomaly map at 10 mGal interval. Density reduction 2,670 kg/m^3. Solid lines labelled I and II show the location of the gravity profiles.

veys have been tied using the IGSN-71 (International Gravity Standardization Network). A crossover analysis (Wessel and Watts 1988) was applied to remove bias and tilt error in the marine data. A reduction density of 2,670 kg/m^3 and the GRS-67 (Geodetic Reference System) have been adopted as the reference ellipsoid. The sea stations were reduced from free-air gravity values by using the same density to replace the water layer. No terrain correction has been applied.

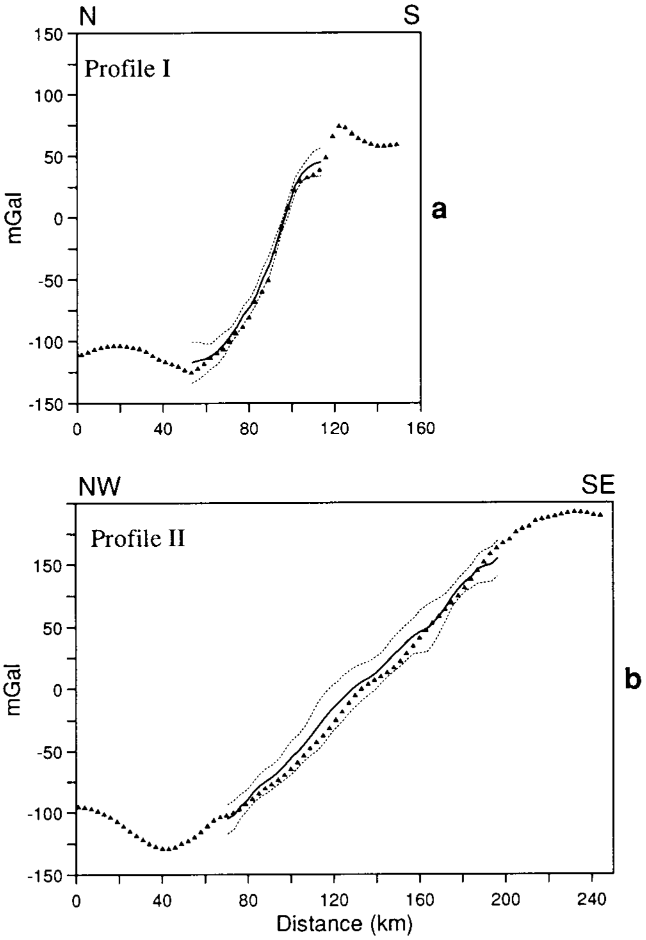

Figure 3. Gravity profiles I (a) and II (b) where the continuous line represents the average value for a window centered on the profile and extending 80 km laterally. Dotted lines indicate the boundaries corresponding to one standard deviation. Triangles indicate observed gravity values along profiles I and II.

Table 1. Parameters used in gravity modelling of Profile I

Body no.	Density (kg/m^3)	Lateral extension −Y (km)	+Y (km)
1	2,350	40	40
2	2,500	80	50
3	2,250	45	20
4	2,400	200	200
5	2,750	70	50
6	2,850	70	50
7	2,900	70	50
8(1)*	3,200	70	50
8(2)†	3,330	70	50

*8 (1) shown in Fig. 4 as solid line.
†8 (2) shown in Fig. 4 as dashed line.

Table 2. Parameters used in gravity modelling of Profile II

Body no.	Density (kg/m^3)	Lateral extension −Y (km)	+Y (km)
1	2,500	80	40
2	2,250	70	80
3	2,400	40	90
4	2,750	80	80
5	2,850	40	200
6	2,900	40	200
7(1)*	3,200	40	200
7(2)†	3,330	40	200

*7 (1) shown in Fig. 4 as solid line.
†7 (2) shown in Fig. 4 as dashed line.

Taking into account the trend in the gravity field in the areas of interest and that our objective is to study the transition of the deep crust from the Alboran Sea to the Betic Cordillera, 2D and 2½ D modelling was considered appropriate. The gravity interpretation presented here has been carried out using 2½ D algorithms (Cady 1980).

Two profiles parallel to the regional gravity gradients have been considered. To obtain the gravity profiles, one data point every 3 km was calculated by projecting gravity values within a 10 km wide strip onto the profile. Values giving topographic noise were rejected before computing the average, which was taken as the final value. In the region of high gravity gradient (Fig. 2) a wider window of 80 km centered on the profiles were used to compute the averaged profile (Figs. 2 and 3). Outside the regions where the gravity data have been stacked we have retained the Bouguer anomaly values corresponding to the line of the profiles as indicated in Figure 2. Models fitting the gravity data within one standard deviation have been considered acceptable.

In profile I (northern–southern orientation) the high gravity gradient area is about 50 km wide (Fig. 3a) and is mainly located in the Internal Zones. Along this profile the Bouguer anomaly varies from minimum values of −125 mGal centered on the Granada Basin to a maximum value of 60 mGal in the Alboran Basin. In profile II (northwestern–southeastern orientation) the transition is about 120 km wide and is characterized by a gentle gravity gradient (Fig. 3b). In this profile minimum values of −125 mGal are reached for the Guadix-Baza Basin, whereas maximum values of 150 mGal are attained in the southeastern part (Alboran Sea).

A variety of sources of information have been used to construct the different models presented in this study. The sedimentary structure of the Alboran Basin and Neogene and Quaternary basins have been taken from commercial seismic data where available and from IGME (1987). Density data were obtained from well log velocity data (Docherty and Banda 1992), and from the empirical relationship between P-wave velocity and density (Nafe and Drake 1961; Woollard 1975). Thus a density of 2,300 kg/m^3 was assigned to the Neogene and Quaternary sediments, but a higher value of 2,500 kg/m^3 seems more appropriate for the subbetic units (External Zones). For the crystalline crust, densities have been chosen as 2,750 kg/m^3 for the upper crust, 2,850 kg/m^3 for the middle crust, and 2,900 kg/m^3 for the lower crust. Different densities of 3,330 kg/m^3 and 3,200 kg/m^3 have been used for the uppermost mantle of the Alboran Basin according to the observed low values of the P-wave velocity as discussed by Hatzfeld (1976).

The 2½ D algorithm used here (Cady 1980) allows a different lateral extension of the bodies on both sides of the chosen profile. The lateral extension of the bodies (Tables 1 and 2) have been adopted according to surface geology

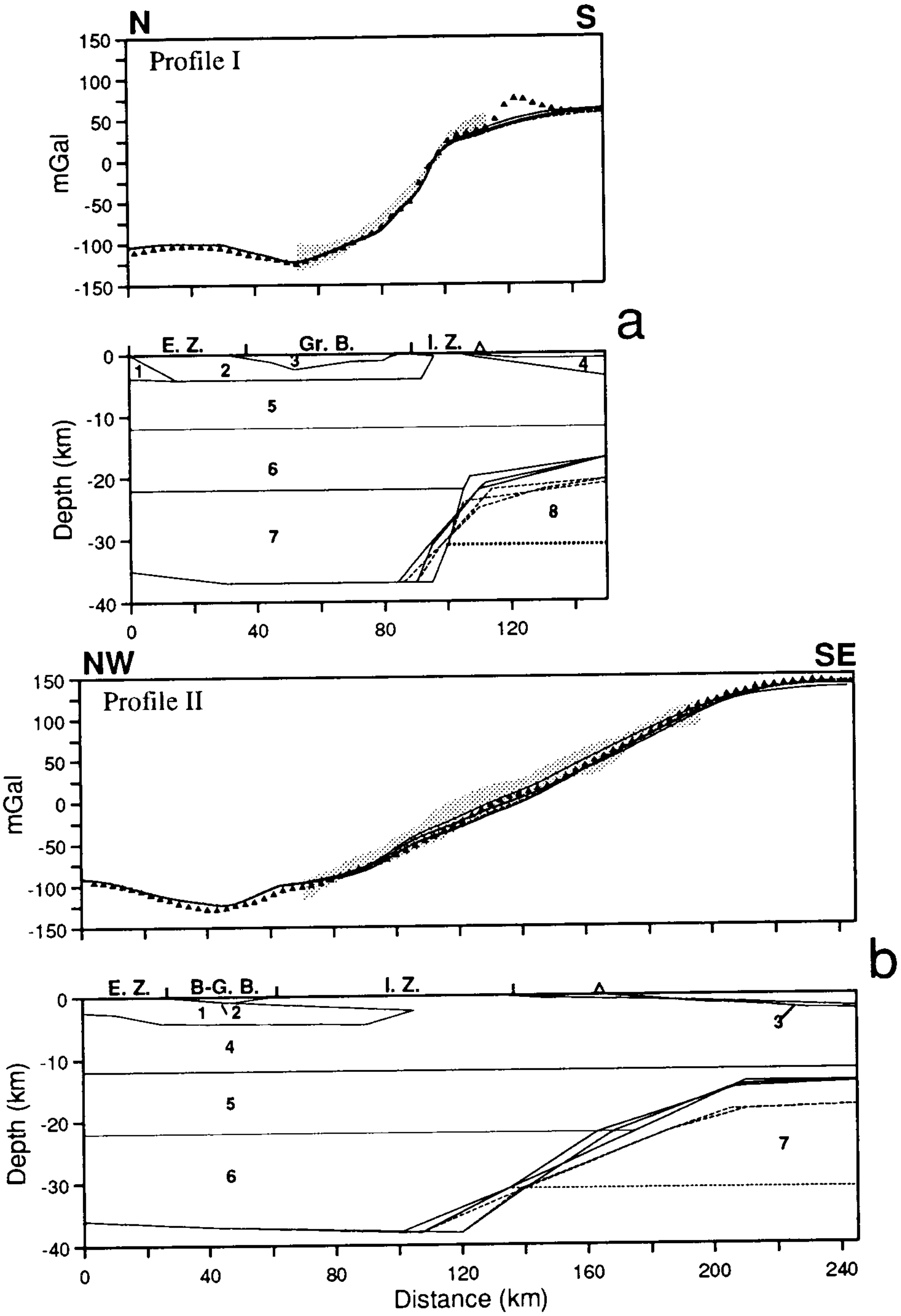

Figure 4. Gravity profiles. Profile I (a). Solid triangles indicate observed Bouguer anomaly values. Solid lines represent computed gravity anomalies for 2½ D models shown in the lower panel (differences of computed gravity values are barely visible on the figure). Shadowed area is the range of gravity values within one standard deviation of the averaged profile (see text). No attempt has been made to model the local anomaly at about km 120. The lower panel shows the geometry and density distribution for different crustal models. E.Z., External Zones; Gr. B., Granada Basin; I.Z., Internal Zones. Empty triangle indicates the location of the shoreline. Parameters used in gravity modelling are shown in Table 1. Profile II (b). Same symbols as in (a) except B-G. B, Baza-Guadix Basin. Parameters used in gravity modelling are shown in Table 2.

(Junta de Andalucía 1985) for the surficial bodies. At depth we have taken a somehow arbitrary criterium based on the regional trend of the Bouguer gravity anomaly.

Figure 4 shows a number of density models and cross-section geometries compatible with the gravity data. It is noteworthy that the southern extension of the subbetic units (density 2,500 kg/m^3) beneath the Betic Internal Zones is needed for the gravity interpretation in both profiles. The transition from the crust in the Alboran Sea to that of the Betic Cordillera, which cannot be resolved with the available seismic data, becomes fairly well defined with the gravity analysis. In profile I (Fig. 4a), the transition area is about 30 km wide with a crustal thinning from 38 to 18–22 km. The different values in the Alboran crust are due to uncertainty in the seismic data and also because we have allowed the mantle density to vary from 3,330 to 3,200 kg/m^3. In profile II (Fig. 4b), the transition zone is spread along a 100 km wide (northwestern–southeastern) area. In this profile the amount of thinning, however, is slightly greater because the crust offshore is thinner than in profile I.

The mode of the transition from the Betic to the Alboran crust is shown in more detail in Figure 5 where the total crustal thickness as deduced from seismic data have also been indicated. In this figure three different computed density models have been included, each of which contains various geometries. Two extreme density models of 3,200

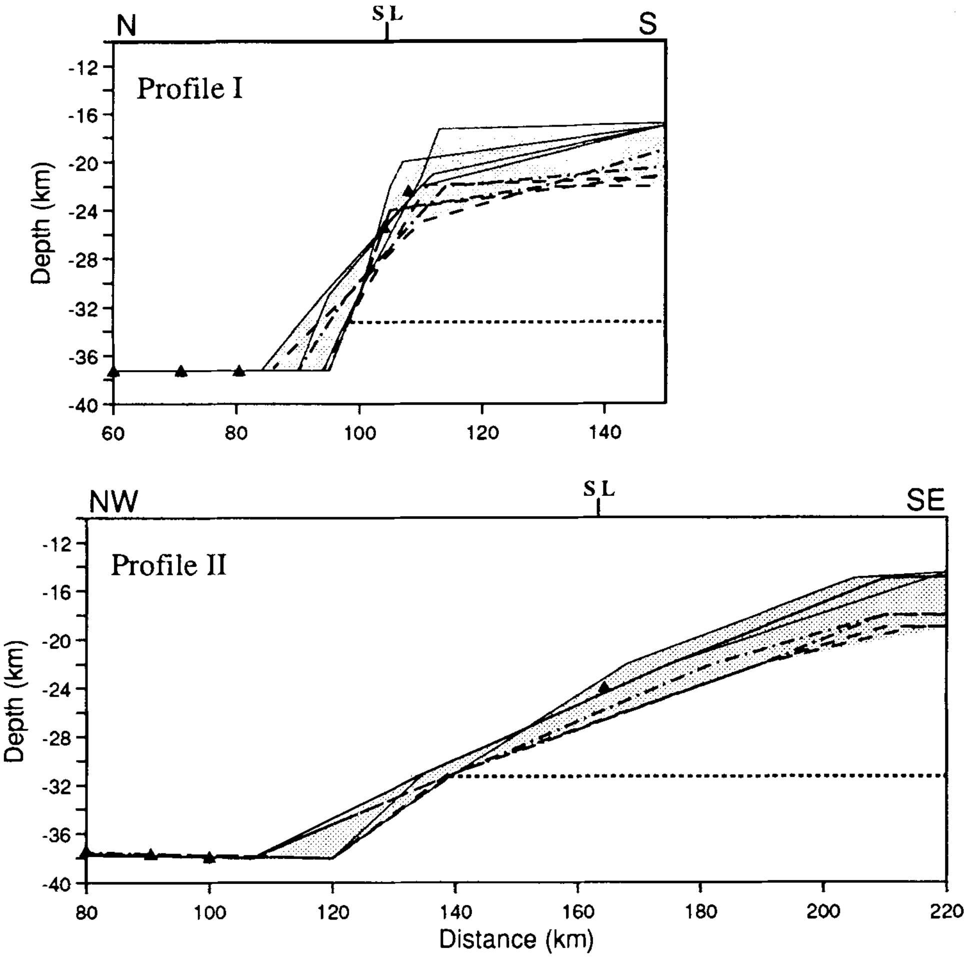

Figure 5. Blown up view of the deep crustal transition from the Alboran sea to the Betic Cordillera for profiles I and II. The shadowed area indicates the range within which models are acceptable according to available gravity and seismic data. Solid, dashed, and dashed-dotted lines indicate depth to the Moho for different density models (see Fig. 4 and text). Dotted-line shows the lower boundary of the anomalous low-density uppermost mantle. SL indicates the location of the shore line. Triangles indicate depth to the Moho as deduced from seismic data.

and 3,330 kg/m^3 for the uppermost mantle in the Alboran Sea have been considered. The first model would imply an anomalous low-density upper mantle, whereas the second one corresponds to a "normal" mantle beneath the Alboran Sea. An intermediate solution can be adopted if only the top of the upper part of the mantle is considered to have a low P-wave velocity and, therefore, density. As can be observed in Figures 4 and 5, any of the solutions mentioned above fits the gravity data. The combination of seismic and gravity interpretation, however, shows that the best solution includes an anomalous low-density uppermost mantle (3,200 kg/m^3) or a crust-mantle transition zone, which would reach maximum depths of about 31 km according to gravity data.

DISCUSSION

A few published gravity studies have already discussed the transition from the Alboran crust to the Betic Cordillera. Bonini and others (1973) investigated the western Betics where large volumes of outcropping and buried peridotites completely distort the regional gravity field. Hatzfeld (1976) and more recently Casas and Carbó (1990) have interpreted gravity data to propose complete crustal sections across the Alboran Sea and the Betic Cordillera. The latter authors infer a crustal thickening from the Alboran to the Betic crust which is fairly uniform with a slight bend at about the position of the shore line. We find that this thickening is more pronounced along our profile I.

Hatzfeld (1976) found that a mantle density of 3,200 kg/m^3 was necessary to fit the gravity data. Our results do not contradict those of Hatzfeld, although we find that an uppermost mantle density of 3,330 kg/m^3 in the Alboran Basin can also be used to fit gravity models. However, when combining the gravity and seismic data sets an uppermost mantle density model of 3,200 kg/m^3 reaching maximum depths of about 31 km seems more appropriate. This is also observed along the Valencia Trough (e.g. Torné and others 1992) therefore suggesting that the westernmost part of the Mediterranean sea is underlain by a low-velocity uppermost mantle or by a crust-mantle transitional zone. Gravity modelling also suggests that thinning is accommodated mainly by the lower crust (Fig. 4). The relative thinning of the upper-middle and lower crust indicates that different beta factors apply to different crustal levels.

The gravity study shows that a different style of crustal thinning from the thickened crust beneath the Betics to the thin crust of the Alboran Basin is observed from east to west. Although in the eastern part of the study area the Moho shallows gently from 38 to 15 km depth, in the central part the Moho rises abruptly from 38 km depth beneath the Betics to 18–22 km under the Alboran Sea. The former resembles the crustal attitude of rifted passive margins such as those of Nova Scotia (Fenwick and others 1968), Bay of

Biscay (Ginzburg and others 1985), or Hatton Bank (White and others 1987), where crustal thinning occurs across horizontal distances of about 100 km. In contrast, the steep rise of the Moho in the western and central part of the study area can be compared with that of Baffin Bay or Central Labrador (Keen and Hyndman 1979). We believe that the different style of thinning is related to different extensional modes between both areas. This is in agreement with the results of tectonic subsidence analysis obtained by Docherty and Banda (1992), who find variations in the mode of tectonic subsidence from east to west.

The geometry of the crustal transition zone of the central part of the study area could correspond to a collapse model as proposed by Platt and Vissers (1989). It can also be compared, however, with margins originated by strike–slip mechanisms (Scrutton 1982). The effects of these mechanisms would be superimposed to crustal thinning due to detachment extensional tectonics (Balanyá and García-Dueñas 1987) and would also be consistent with the S-shaped gravity anomalies observed west of Málaga (Fig. 2), which seem to indicate dextral movements known from surface structural studies.

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