Main features of the deep structure of the central Betic Cordillera (SE Spain) from the ESCI-Béticas deep seismic reflection profiles

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Abstract: The ESCI-Béticas1 profile suggests that the crust of the Iberian Massif continues below the External Zones, which is confirmed by total field magnetic anomalies. The upper mantle is reflective and makes it difficult to locate the Moho; however, it is possible to distinguish an increase in Moho depth from Nort to South. In the ESCI-Béticas2 profile, the kilometric-scale folds of the Internal Zones do not deform the intermediate and deep crust reflectors, probably due to the existence of decollement levels. The Moho is nearly horizontal below the mountain chain, a region of abrupt topography with the highest relief of the Iberian Peninsula in Sierra Nevada. Gravimetric data show that the thickened crust of the Betic Cordillera (35 to 38 km) has a very sharp transition to the thin crust of the Alborán Sea, very near the coast line. The upper and lower crusts are differentiated in both profiles. Total field magnetic anomalies in the Internal Zones are related to shallow bodies of metamorphic rocks and mineralisations. Most of these new data are not in accordance with previous geophysical and geological interpretations, and need to be taken into account in any new models proposed.

Keywords: Betic Cordillera, deep seismic reflection profiles, crustal structure, Moho seismic features.

Resumen: Los perfiles de sísmica de reflexión profunda ESCI-Béticas, realizados a través de la región central de la Cordillera Bética, proporcionan nuevos datos sobre la estructura de la corteza y del manto superior. En ambos perfiles se diferencia bien la existencia de la corteza superior y de la inferior. El perfil ESCI-Béticas1, con dirección NW-SE, desde el Macizo Ibérico hasta el límite entre las Zonas Externas y las Zonas Internas, muestra que la corteza del Macizo Ibérico continua bajo las Zonas Externas. No se ha podido determinar con exactitud la posición de la Moho debido a que la corteza inferior y el manto superior muestran numerosos reflectores. Además la calidad del perfil disminuye notablemente hacia su extremo meridional. No obstante, se puede observar un aumento de la profundidad de la Moho desde el Norte hacia el Sur. El perfil ESCI-Béticas2, de dirección NE-SW, está situado a través de las Zonas Internas. Los pliegues de tamaño kilométrico relacionados con los principales rasgos topográficos de las Zonas Internas no deforman los reflectores intermedios y altos de la corteza, probablemente debido a la existencia de niveles de despegue. En este perfil la Moho se identifica por una banda de reflectores de gran amplitud. La Moho es subhorizontal bajo la cadena de montañas hasta cerca de la línea de costa, en una región de topografía abrupta que alcanza en Sierra Nevada las cotas más altas de la Península Ibérica. Los datos gravimétricos muestran que la corteza engrosada de la Cordillera Bética (35 a 38 km) tiene una transición muy rápida hacia la corteza delgada del Mar de Alborán (15 km en la zona central) cerca de la línea de costa. Las anomalías magnéticas muestran que el Macizo Ibérico continúa bajo las Zonas Externas de las Cordilleras Béticas. Las anomalías magnéticas en las Zonas Internas están relacionadas con cuerpos someros de rocas metamórficas y con mineralizaciones. La mayor parte de los nuevos datos obtenidos de los perfiles de sísmica de reflexión profunda ESCI-Béticas permiten discutir los modelos geofísicos y geológicos que han sido propuestos previamente para la Cordillera y deben de ser tenidos en cuenta en los futuros modelos que se propongan.

Palabras clave: Cordillera Bética, perfiles de sísmica de reflexión profunda, estructura de la corteza, características sísmicas de la Moho.

Seismic, gravimetric and magnetometric studies have contributed in the last twenty years to a better knowledge of the deep structure of the Betic Cordillera, although there are a lot of differences in detail between the models proposed. The first deep seismic reflection profiles were obtained recently (García-Dueñas *et al.*, 1994) and provide new data for discussion on the deep structure of the Betic Cordillera and its boundary with the Alborán Sea.

Seismic refraction profiles made in the area (Working Group for deep seismic sounding in Spain 1974-1975, 1977; Ansorge *et al.*, 1978; Working Group for deep seismic sounding in the Alborán Sea 1974-1975, 1978; Banda & Ansorge, 1980; Banda *et al.*, 1993; Suriñach & Vegas, 1993) indicate that while the Betic Cordillera crust is somewhat thick (35 to 38 km), the crust thins progressively towards the Iberian Massif (near 30
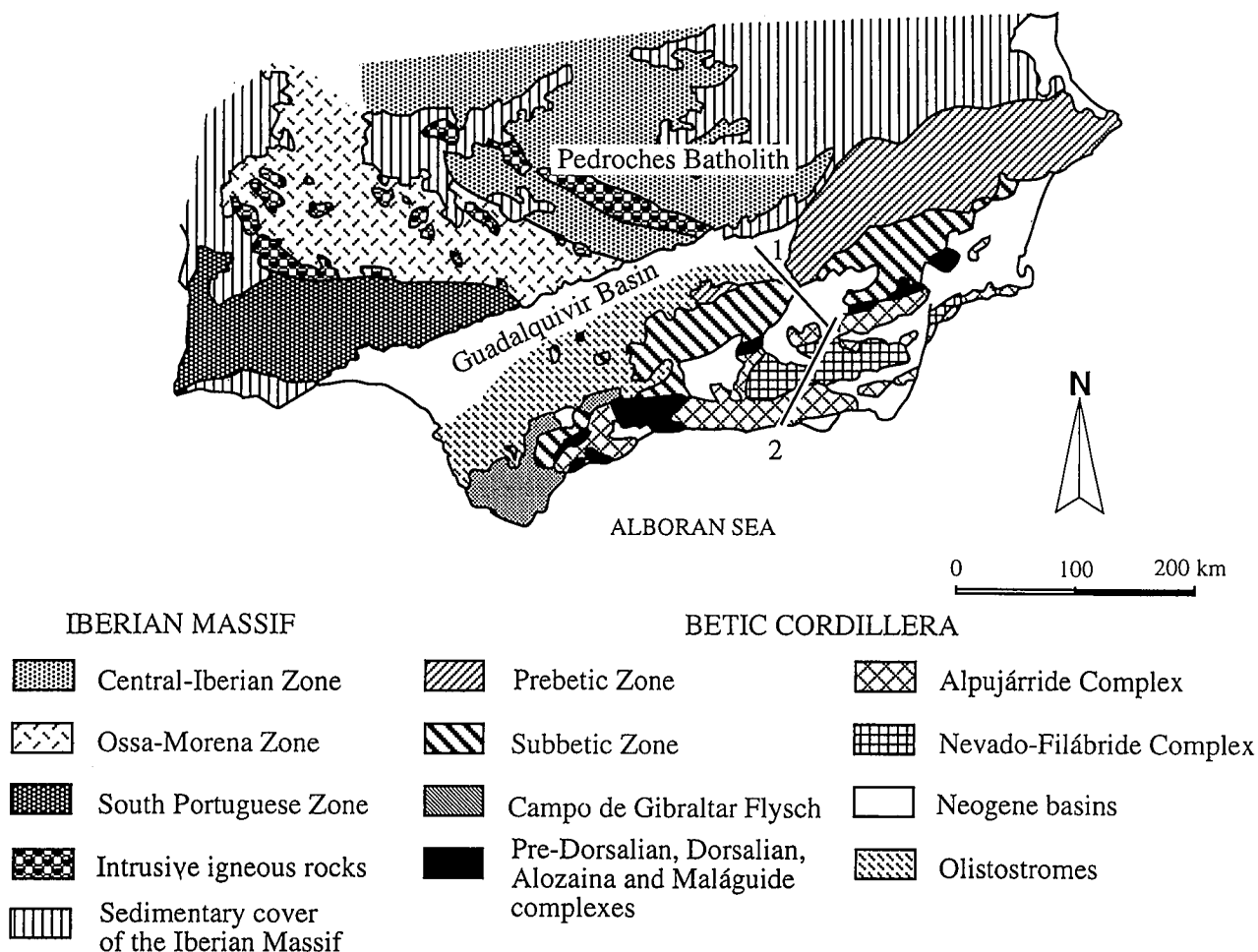
Figure 1.- Main geological characteristics of Betic Cordillera and southern zone of Iberian Massif. 1 and 2, ESCI-Béticas deep seismic reflection profiles.

km). Banda et al. (1993) propose that this transition occurs in a region with crustal thinning. They suggest, in addition, that there is no lower crust below the Internal Zones of the Cordillera. In this region the upper crust contains a subhorizontal major contact at 10 km in depth.

Gravimetric studies (Bonini et al., 1973; Suriñach & Udías, 1978; Casas & Carbó, 1990; Cloething et al., 1992; Torné & Banda, 1992; van der Beek & Cloething, 1992; Watts et al., 1993) agree with seismic research on general crustal geometry. Gravimetry also indicates that the crust of the Betic Cordillera has a sharp transition to a thin continental crust towards the Alborán Sea (15 km below the centre of the sea) (Cloething et al., 1992; Torné & Banda, 1992; van der Beek & Cloething, 1992; Watts et al., 1993).

Seismic studies have determined P- and S-wave velocities in the crust and mantle, as well as their principal structural features (Marillier & Mueller, 1985, Krishna et al., 1992; Blanco & Spakman, 1993; Paulssen & Visser, 1993; Plomerova et al., 1993). These studies show the presence of an anomalous mantle below the Alborán Sea, also confirmed by gravimetry (Hatzfeld, 1976; Torné & Banda, 1992).
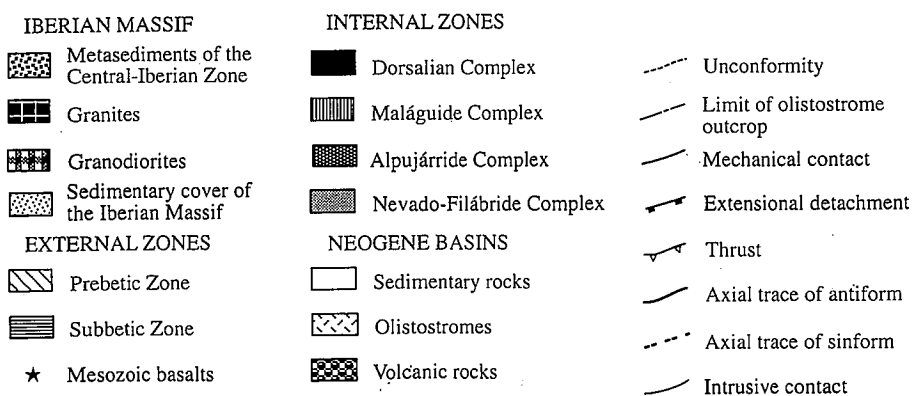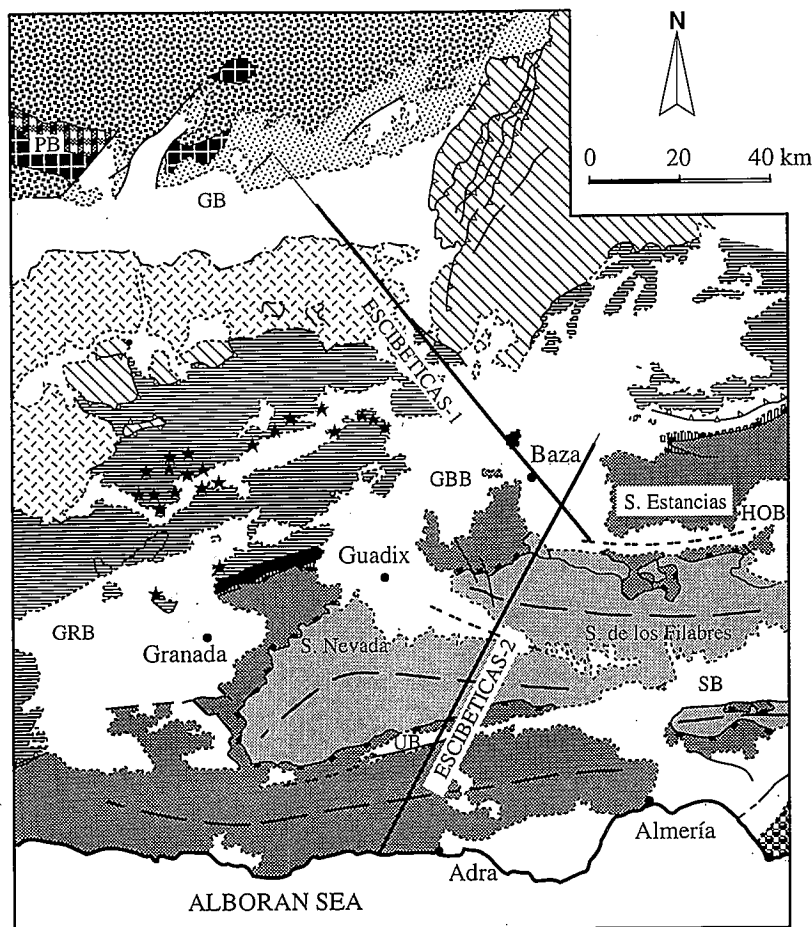
The stable crustal area of the Iberian Massif that bounds the Betic Cordillera to the North has been studied by seismic refraction profiles (Banda et al., 1981; Suriñach & Vegas, 1988; ILIHA DSS Group, 1993).

This stable crust has a nearly constant thickness of 30 km, as in the rest of the Iberian Massif (Payo & Ruiz de la Parte, 1977; Córdoba et al., 1988; Suriñach & Vegas, 1988).

The aim of this paper is to study the deep seismic reflection profiles made across the central sector of the Betic Cordillera and to outline the minimum features required for any crustal model proposed for this area. Bouguer and total-field magnetic anomalies have also been discussed and modeled along two profiles coinciding with the ESCI-Béticas deep seismic reflection profiles.

Geological setting

The basement of the External Zones crops out in the Iberian Massif (Figs. 1, 2 and 3) and comprises the Central-Iberian, Ossa-Morena, and South Portuguese zones (Julivert et al., 1974) (Fig. 1). These zones are composed essentially of sequences of Precambrian to Lower Carboniferous siliciclastic rocks that show Variscan metamorphism and are affected by penetrative fabrics (Julivert et al., 1984). Main folds trend NW-SE and have kilometric sizes, with axial planes that are subvertical or with high dips towards the NE. Boundaries between these zones are left-lateral subvertical shear zones with NW-SE strikes. In the Ossa-Morena and South Portuguese zones, there are alignments of basic and acid igneous rock bo-

IBERIAN MASSIF

▨ Metasediments of the Central-Iberian Zone

▦ Granites

▨ Granodiorites

▨ Sedimentary cover of the Iberian Massif

EXTERNAL ZONES

▧ Prebetic Zone

▤ Subbetic Zone

★ Mesozoic basalts

INTERNAL ZONES

■ Dorsalian Complex

▦ Maláguide Complex

▨ Alpujárride Complex

▨ Nevado-Filábride Complex

NEOGENE BASINS

▢ Sedimentary rocks

▨ Olistostromes

▨ Volcanic rocks

⸺ Unconformity

⸺ Limit of olistostrome outcrop

⸺ Mechanical contact

⸺ Extensional detachment

⸺ Thrust

⸺ Axial trace of antiform

⸺ Axial trace of sinform

⸺ Intrusive contact

Figure 2.- Geological map of the central sector of Betic Cordillera. Thick lines indicate seismic profiles. Geological cross-sections extend along length of thin lines. Neogene basins: GRB, Granada Basin; GBB, Guadix-Baza Basin; GB, Guadalquivir Basin; HOB, Huercal-Overa Basin; SB, Sorbas Basin; UB, Ugíjar Basin; P.B., Pedroches Batholith.

dies trending NW-SE, that intruded during the Devonian-Carboniferous (Simancas, 1984). In the Central-Iberian Zone, there is an elongated batholith trending NW-SE composed of granitic and granodioritic rocks (Pedroches Batholith, Figs. 1 and 2) containing more basic differentiates, that intruded during the Carboniferous-Permian (García-Casco et al., 1989). A thin unconformable sedimentary cover composed of Permo-Triassic red sandstones and clays, and Jurassic dolostones lies on the southern edge of the Iberian Massif.

Analysis of seismic refraction profiles in these areas (Banda et al., 1981; Suriñach & Vegas, 1988; ILIHA DSS Group, 1993) show that the crust, as in the rest of the Iberian Massif, has a thickness of nearly 30 km, with very small variations. Crustal thickness increases towards the South (Banda et al., 1993).

The boundary between the Iberian Massif and the External Zones is occupied by the Guadalquivir Basin, which is filled with Neogene siliciclastic and carbonatic sediments (Santos-García et al., 1991). On the southern edge, there are also olistostromes emplaced from the External Zones (Perconig & Martínez-Díaz, 1977). These olistostromes overlie the northern part of the External Zones and gradually give way to the Neogene sediments in the basin (Perconig & Martínez-Díaz, 1977; Blankenship, 1992).

The External Zones (Prebetic and Subbetic) are formed mainly by Mesozoic and Cenozoic sedimentary rocks. The Prebetic Zone is composed predominantly of Mesozoic and Cenozoic carbonatic and terrigenous rocks with shallow-water and transitional facies. The sequences are thin and become incomplete near the Iberian

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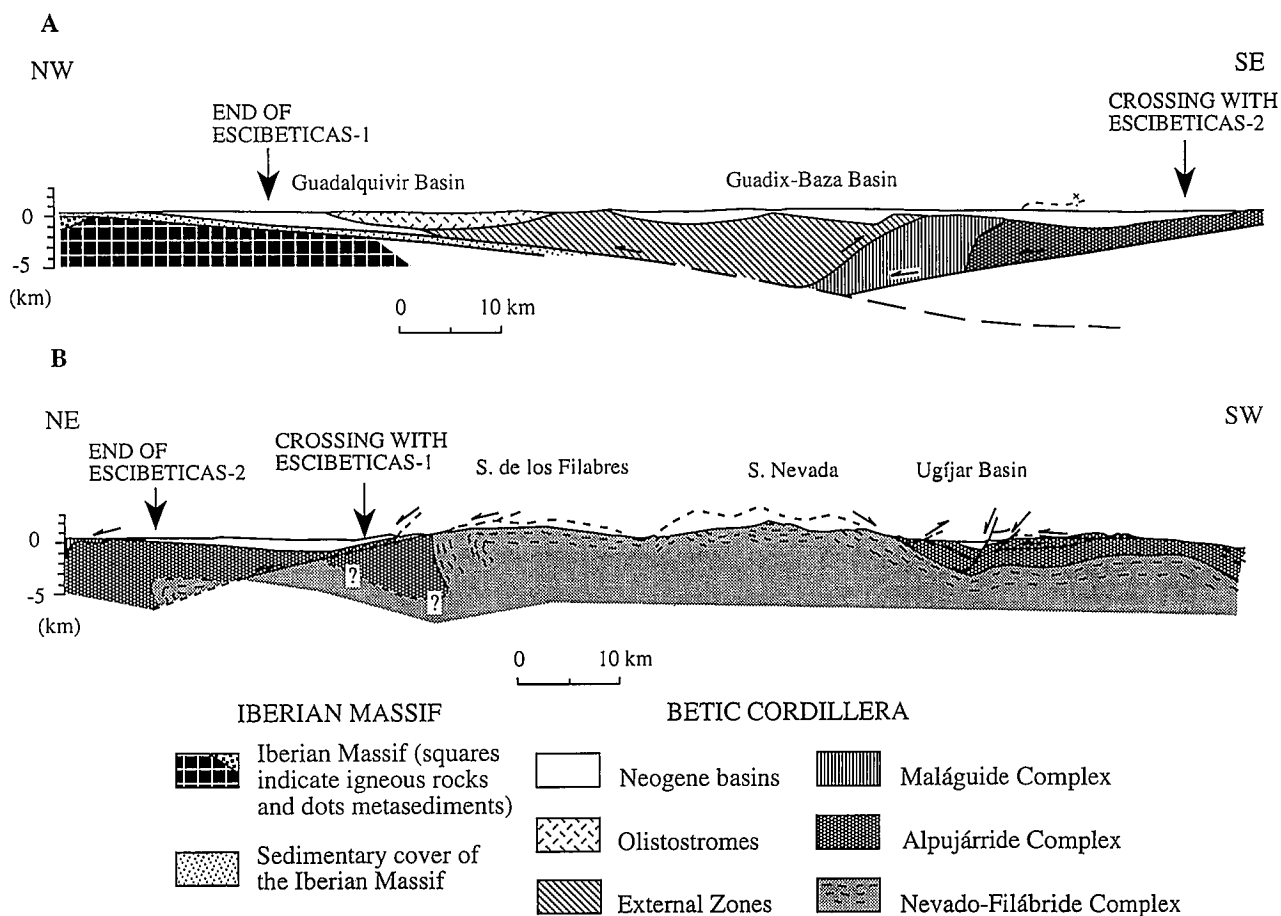
Figure 3.- Geological cross-sections: A, along ESCI-Béticas1 seismic profile; B, along ESCI-Béticas2 seismic profile. Location indicated in Fig. 2.

Massif (García-Hernández *et al.*, 1980). The Subbetic Zone contains Triassic rocks that are mainly terrigenous with evaporites (Keuper facies) and ophite bodies. The Jurassic of the Subbetic is characterised by large lateral variations in the facies and in the thickness of the sequences and by the predominance of pelagic facies (García-Hernández *et al.*, 1980). In the central part of the Subbetic Zone, the Jurassic and Cretaceous sequences contain basaltic bodies aligned ENE-WSW (Puga & Ruiz Cruz, 1980). The External Zones are structured in thrusts and folds, with Triassic rocks forming the decollement level (Sanz de Galdeano, 1973). Several right-lateral strike-slip faults, with ENE-WSW strikes, cut obliquely across the above-mentioned structures (Hermes, 1978; de Smet, 1984).

Seismic and magnetometric studies, in addition to boreholes (Perconig & Martínez-Díaz, 1977; Lanaja, 1987; Socias *et al.*, 1991; Blankenship, 1992), indicate that the Iberian Massif crust continues below the Guadalquivir Basin and part of the External Zones. The isobaths of the cover/basement contact show that the strike of the basement top is N70°E and the dip is around 3°-4° towards the SSE (Perconig & Martínez-Díaz, 1977; Lanaja, 1987; Blankenship, 1992).

The Internal Zones comprise several complexes of tectonic units. The Campo de Gibraltar Flysch (overlying the External Zones), and the Predorsalian, Dorsalian and Alozaina complexes, which crop out near the External/Internal Zones boundary, consist of Mesozoic

and Cenozoic sedimentary rocks (Balanyá & García-Dueñas, 1987). The stratigraphic series of the Nevado-Filábride, Alpujárride, and Maláguide complexes include pre-Mesozoic and younger rocks. The first two underwent alpine metamorphism and are made up of metapelites, metapsammites and marbles with bodies of gneiss, metabasites, and metamorphosed ultrabasic rocks (e.g. Fontboté, 1983). The Maláguide is formed by Palaeozoic rocks affected by Variscan and alpine metamorphism, overlaid by a cover of mainly carbonatic Mesozoic and Cenozoic sedimentary rocks (e.g. Martín-Algarra, 1987).

Rocks from the Internal Zones underwent an alpine deformation with crustal thickening before the Upper Oligocene (Monié *et al.*, 1991). This stage may explain the alpine high pressure/low temperature metamorphism in the Alpujárride (Goffé *et al.*, 1989) and upper Nevado-Filábride rocks (Puga & Díaz de Federico, 1978; Bakker *et al.*, 1989). After this stage, stacking of tectonic units probably occurred, which could explain the superposition of different complexes and the stratigraphic repetitions within the complexes (Monié *et al.*, 1991). Later penetrative extensional deformations caused thinning of this stacking and reactivated previous structures, making it difficult to establish their geometry and kinematics. In fact, the contacts between the tectonic units of the Internal Zones are generally Upper Oligocene to Lower Tortonian low-angle normal faults (Galindo-Zaldívar *et al.*, 1989; Aldaya *et al.*, 1991).

Kilometric size open-to-close folds have developed since the Upper Miocene. They trend E-W and have vergence towards the N in the eastern sector of the chain (Weijermars et al., 1985). Faults also developed during the same period, including high- and low-angle normal faults, and left-lateral strike-slip faults in the eastern part of the Cordillera (Coppier et al., 1990).

The External/Internal Zones boundary in this traverse is located below the sediments of the Guadix-Baza Basin, making direct observation impossible (Figs. 2 and 3). However, this contact crops out towards the East, in the region to the North of the Sierra de las Estancias (Fig. 3), where the External Zones overlie the Internal Zones by means of a thrust fault dipping North and with a top-to-the-SE sense of movement (Paquet, 1969; Baena-Pérez et al., 1977, 1979; Banks & Warburton, 1991; Lonergan, 1993; Allerton et al., 1993, 1994).

The basins on top of the Internal Zones are filled by Miocene to Quaternary sediments that can reach thicknesses of more than 2 km (e.g. the Granada Basin, Morales et al., 1990). In the eastern part of the Cordillera there are also volcanic rocks. Marine sediments up to the Upper Tortonian (Granada and Guadix-Baza basins) or the Pliocene (Sorbas Basin) are found (Sanz de Galdeano and Vera, 1992). More recent sediments are continental. The Alborán Basin is also a Neogene basin that continues below sea level and its basement is similar to that of the Internal Zones (Jurado & Comas, 1992). This basin is filled by Neogene sediments and volcanic rocks.

ESCI-Béticas deep seismic profiles

The main technical features of the ESCI-Béticas seismic profiles were described by García-Dueñas et al. (1994). The profiles were obtained by the Compagnie Générale de Géophysique across the central area of the Betic Cordillera and have a total length of 196 km (Figs. 1 and 2). The northern profile (ESCI-Béticas1) is located across the External Zones, from the Iberian Massif and the Guadalquivir Basin up to the boundary between the External and Internal Zones in the Guadix-Baza Basin. Its trend (N140°E) is orthogonal to the trend of the geological structures of the External Zones in this area and is 90 km long. The southern profile (ESCI-Béticas2) runs from the Guadix-Baza Basin to the sea and cuts across the Internal Zones. This profile has a length of 106 km and a trend of N30°E, oblique to the Neogene E-W folds.

We considered the final stack profiles when sketching the positions of the reflectors (Fig. 4). In order to establish an approximate equivalence between the record times in the seismic reflection profiles and the depth, we compiled the propagation velocities of P-waves obtained for the Adra, Guadix, and Iberian Massif areas in previous seismic refraction profiles (Banda & Ansorge, 1980; Working Group for deep seismic sounding in Spain 19741975, 1977; Ansorge et al., 1978; Medialdea et al., 1986; Barranco et al., 1990; Banda et al., 1993) (Fig. 5). The different velocity models proposed by each author for the same area cause differences in the determination of the actual depth of the reflectors. However, the depth can generally be established with an accuracy greater than 1 - 2 km.

In the whole ESCI-Béticas1 profile and between 0 and 2 s, we identified subhorizontal discontinuous reflections of low amplitude. These reflectors may correspond to lithological contacts in the Iberian Massif basement rocks, and to contacts in the sedimentary rocks of the External Zones in the profile. The NW side of the ESCI-Béticas1 profile shows a cross-section of the Iberian crust, where the main seismic features can be recognised. However, towards the SE side of the profile, the quality progressively worsens and the number of identified reflectors is lower. In the NW part of the profile, from the top downwards, it is possible to distinguish several zones:

- Between 0 and 7 s, a transparent zone is identified, mostly corresponding to the upper crust.

- A zone between 7 and 10 s with low-dipping (towards the NW) or subhorizontal discontinuous reflections of high amplitude, which corresponds to the lower crust.

- A deep zone below 10 s. In the upper part of this zone and between 10 and 14 s, bands of low-amplitude reflectors nearly 1 s thick alternate with bands of high-amplitude reflectors between 0.2 - 0.4 s thick. As discussed below, this zone of alternating bands may represent the lithospheric mantle with the Moho as its upper boundary. The reflectors have a SE dipping component and are slightly oblique to the Moho.

Towards the SE, the only observable fact is that the boundaries of these zones become diffuse and, like the reflectors, have a SE low-dipping component. The above-mentioned zones can not be recognised in the area of intersection with the ESCI-Béticas2 profile.

In the ESCI-Béticas2 profile, three subhorizontal zones are also identified along nearly the entire profile and could correspond to those differentiated in the ESCI-Béticas1 profile. They are, from the top downwards:

- A transparent zone between 0 and 6 s corresponding to the upper crust. As in the ESCI-Béticas1 profile, between 0 and 1.5 s there are discontinuous subhorizontal (or slightly dipping with NE or SW components) low-amplitude reflections that may be related to lithological contacts or shear zones in the rocks of the Alpujárride or Nevado-Filábride complexes. The most important structure is a band of high-amplitude reflections, the Upper Crustal Reflector (U.C.R. in García-Dueñas et al., 1994) located in the NE sector of the profile. This band comprises reflectors with a NE low-dipping component located between 2.5 and 6 s, where it joins the contact with the reflective lower crust.

- A reflective zone located between 6 and 11 s that corresponds to the lower crust. This zone generally shows subhorizontal high-amplitude reflectors, except below Sierra Nevada where they have apparent dips towards the NE and below the Sierra de los Filabres where they have apparent dips towards the SW. The upper boundary contains subhorizontal high-amplitude reflec-
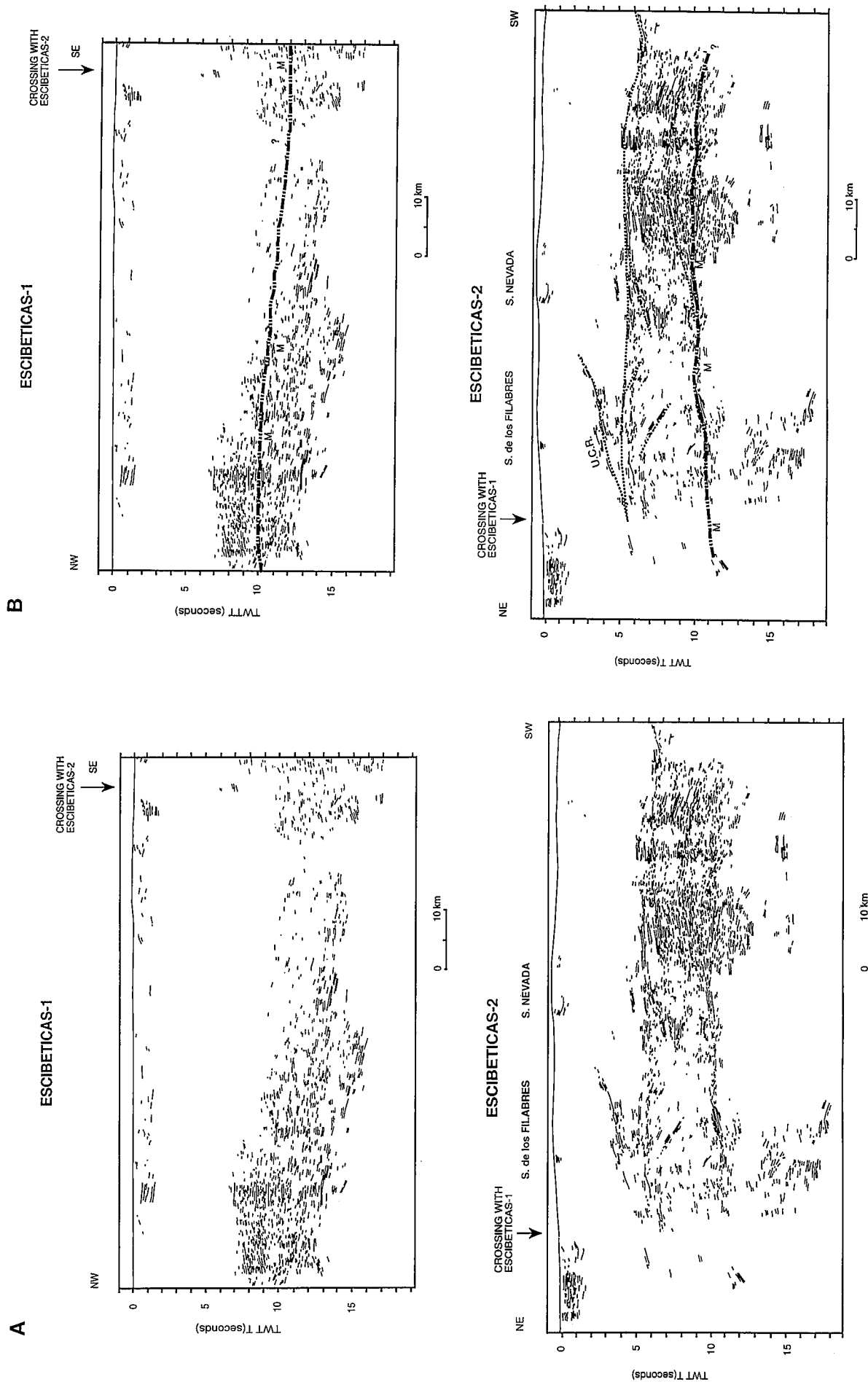
Figure 4.- ESCI-Béticas1 and 2 deep seismic reflection profiles. A. Reflector diagrams of the seismic reflection profiles. B. Interpretation of profiles (M, Moho; U.C.R., Upper Crustal Reflector).
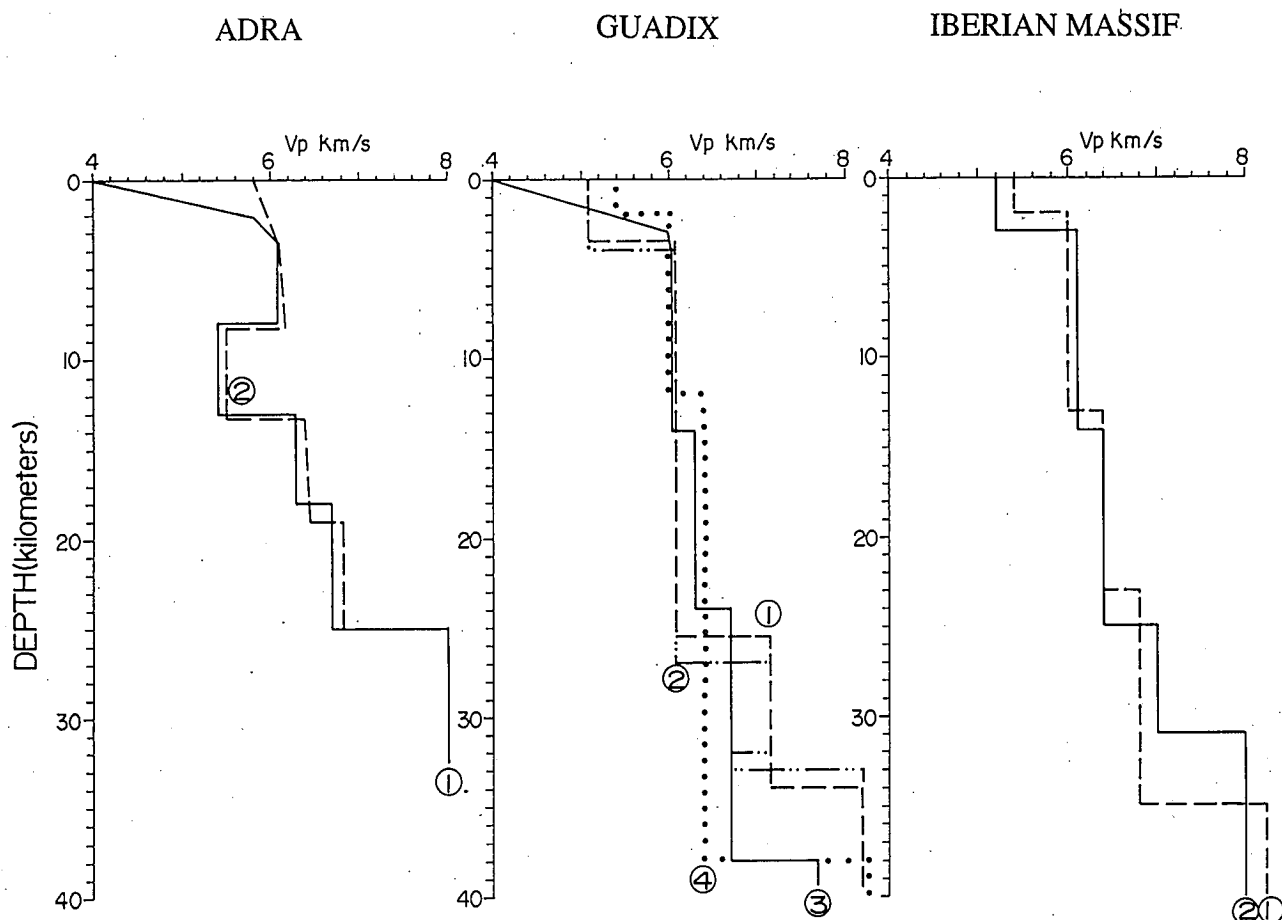
ADRA GUADIX IBERIAN MASSIF

Figure 5.- Variation of P-wave velocities according to depth in three zones. Adra zone. (1, Banda & Ansorge, 1980; 2, Barranco *et al.*, 1990). Guadix zone (1 and 2, Ansorge *et al.*, 1978; 3, Banda & Ansorge, 1980; 4, Banda *et al.*, 1993). Iberian Massif (1, Banda *et al.*, 1993; 2, Medialdea *et al.*, 1986).

tions with great continuity. The lower boundary is a band of high-amplitude reflections that suggest that the Moho is located near 11 s. The Moho is continuous and nearly horizontal, at least up to the vicinity of the profile end near the coast line. Both upper and lower boundaries are slightly undulating in the stack profile, although their undulations do not coincide either with topographic highs or with the large folds of the surface rocks.

- A deep band below 11 s corresponds to the lithospheric mantle and has transparent regions that merge laterally with regions of high-amplitude subhorizontal or SW dipping reflections.

Although in both profiles three main zones have been identified (they could be correlated, since their main features are similar), the position of their boundaries in the intersection zone of the two profiles cannot be accurately located. Two main problems arise in the correlation of these two profiles: one is the low quality in the southeastern part of the ESCI-Béticas1 profile, and the other is the apparent difference in depth between the two profiles for the band of reflections interpreted as the Moho.

Analysis of gravimetric data

A Bouguer anomaly map of the area (Fig. 6) has been assembled after Instituto Geográfico Nacional (1975)

and Bonini *et al.* (1973). In the Betic Cordillera, there is a large negative Bouguer anomaly that surpasses -150 mGals. As pointed out by Casas & Carbó (1990), this minimum is caused by two effects: local minima are produced by the sedimentary basins, and the regional minimum is produced by variations in crustal thickness. The anomaly is elongated E-W to ENE-WSW, parallel to the structural and topographic alignments. The anomaly is asymmetrical in the N-S profiles: the northern slope is irregular and with a low gradient, while the southern slope is sharp and rectilinear, E-W oriented, and subparallel to the coast line for more than 150 km with very high gradients. Near the coast line, though still on land, the gradient decreases notably and on the coast the Bouguer anomaly values are near 0 and generally positive, increasing gently towards the sea (Fig. 6).

2-D gravimetric models have been constructed along two Bouguer anomaly profiles, following the ESCI-Béticas2 and 2 deep seismic reflection profiles and their prolongations (Figs. 6 and 7). The models were developed taking into account the main features established by the deep seismic reflection profiles and the data from the field geology. There are several models that fulfil these conditions and are in accordance with the Bouguer anomaly but here we propose those with the simplest geometry. In the ESCI-Béticas1 profile, infinite bodies orien-
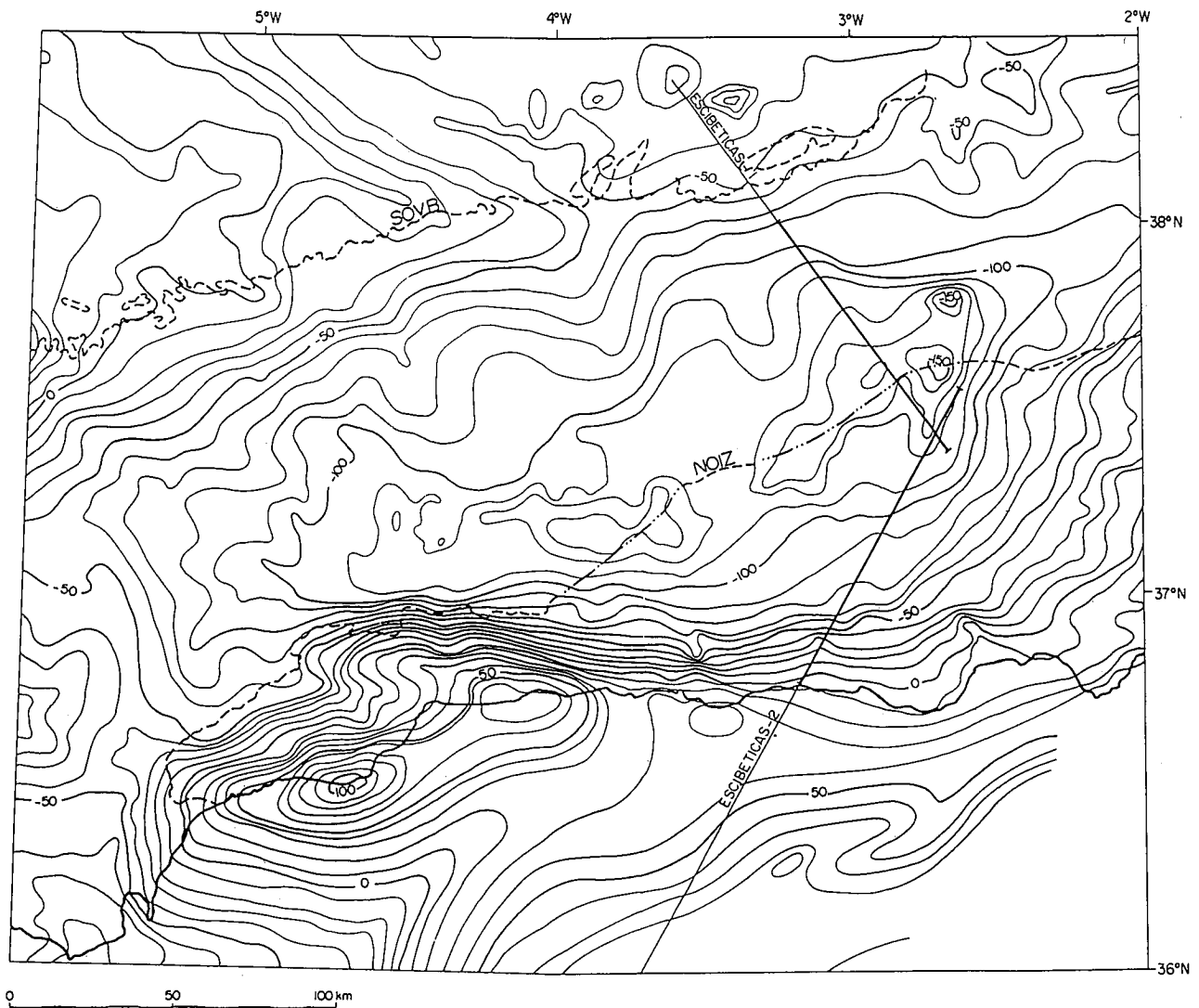
Figure 6.- Bouguer anomaly map (mGal). Land data from Bouguer anomaly map, scale 1:500,000 (Instituto Geográfico Nacional, 1975). Alborán Sea data from Bonini *et al.* (1973). An upper crust mean density of 2.67 g/cm³ was considered for both. Thick lines indicate position of seismic profiles. Gravimetric models have been extended along length of thin lines. SOVB, Southern limit of Variscan belt outcrops. NOIZ, Northern limit of Internal Zones outcrop. Dashed lines correspond to outcrops of this boundary. Dot-dash lines represent supposed position of the boundary below Neogene basins.

ted N80°E have been considered according to the variation in crustal thicknesses in the northern part of the chain (Fig. 7, Table I). In the ESCI-Béticas2, infinite bodies oriented N90°E have been modeled taking into account the strike of the gravimetric anomaly (Fig. 7, Table I).

Analysis of magnetic data

Study of the magnetic anomalies was based on the Aeromagnetic Map of Peninsular Spain (Scale 1:1,000,000) by Ardizone *et al.* (1989). The magnetic anomalies of the southern Iberian Massif consist in NW-SE elongated dipoles or sets of dipoles oriented NW-SE (Fig. 8), parallel to the strikes of the geological structures (Fig. 1). These anomalies, and therefore the Iberian Massif crust, continue below the Guadalquivir Basin and the External Zones to a region near the External/Internal Zones boundary (Socias *et al.*, 1991). Towards the SE, the magnetic anomalies are E-W oriented, subparallel to

the trends of the Internal Zones folds. The Neogene volcanic rock bodies produce N30°E oriented anomalies, which are very intense in the region E of Almería (Figs. 2 and 8).

We considered a model containing bodies with very simple geometry, making approximate adjustments of only the high-amplitude magnetic anomalies and taking only induced magnetism into account. Although this constitutes a source of error it does, however, allow us to determine roughly the rocks responsible for the magnetic anomalies and their position. We made this assumption because it is impossible to establish the trend of the remnant magnetism in large rock volumes in this area, as shown by palaeomagnetic research in the External Zones (e.g. Osete *et al.*, 1988; Platzman, 1992, 1994; Allerton *et al.*, 1993), which indicates significant rotations of rocks varying between 0° and more than 180° during the Neogene. That is why we considered equivalent magnetic susceptibilities for the anomalous bodies.
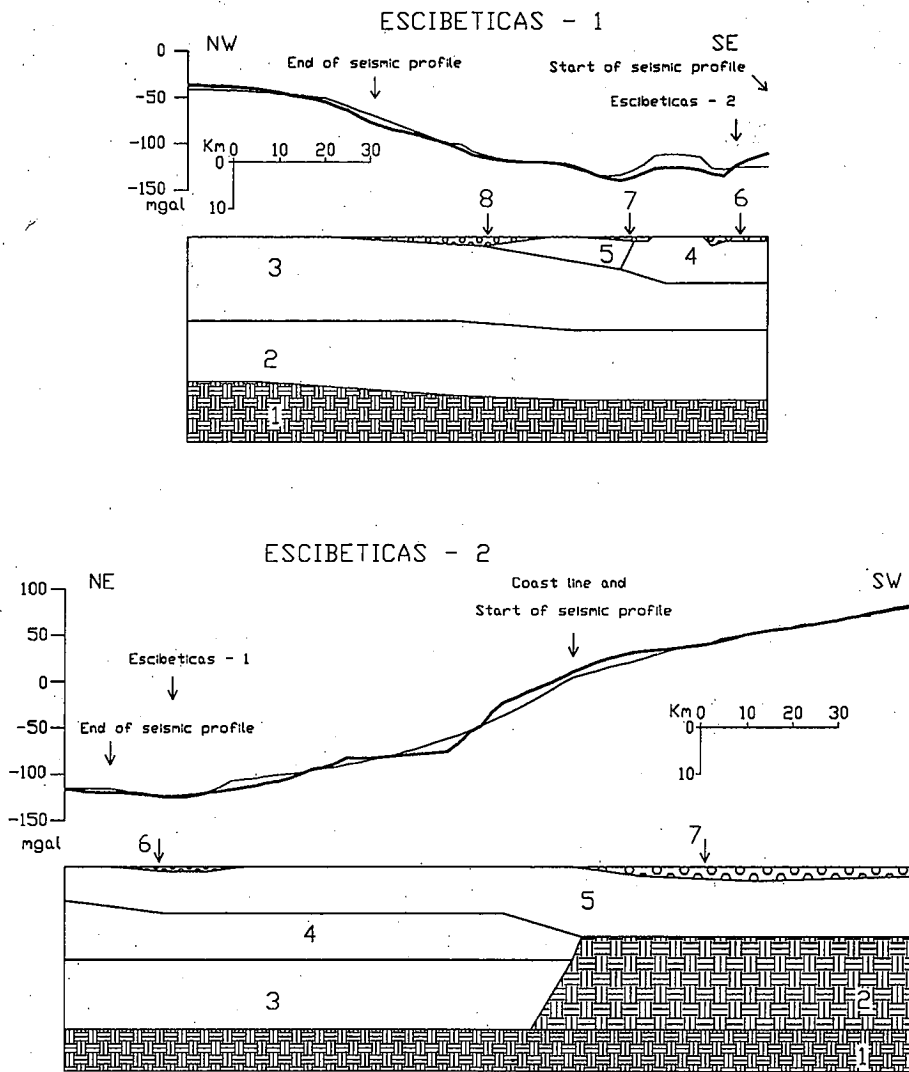
ESCIBETICAS - 1

ESCIBETICAS - 2

Figure 7.- Profiles of Bouguer anomaly and gravimetric models (A and B). Thick line profile, measured Bouguer anomaly. Thin line profile, calculated Bouguer anomaly. Infinite bodies elongated in a N80°E strike are considered in ESCI-Béticas1 profile (N142°E) and infinite bodies elongated in a N90°E strike are assumed in ESCI-BéticasS2 profile (N30°E).

A) ESCIBETICAS-1 GRAVIMETRIC PROFILE

| ANOMALOUS BODY	MEAN DENSITY	INTERPRETATION
1	3.33 g/cm³	Upper Mantle
2	2.89 g/cm³	Lower Crust
3	2.80 g/cm³	Intermediate Crust
4	2.72 g/cm³	Upper Crust of the Internal Zones
5	2.54 g/cm³	External Zones
6	2.45 g/cm³	Southern Baza Basin
7	2.45 g/cm³	Northern Baza Basin
8	2.25 g/cm³	Guadalquivir Basin and Olistostromes

Table I.- Parameters used in the models of Bouguer anomalies and geological attribution of the anomalous bodies.

B) ESCIBETICAS-2 GRAVIMETRIC PROFILE

ANOMALOUS BODY	ANOMALOUS BODY	INTERPRETATION
1	-	Upper Mantle
2	3.20 g/cm³	Anomalous Mantle
3	2.89 g/cm³	Lower Crust
4	2.80 g/cm³	Intermediate Crust
5	2.72 g/cm³	Upper Crust of the Internal Zones
6	2.45 g/cm³	Guadix-Baza Basin
7	2.40 g/cm³	Sediments of Alborán Sea
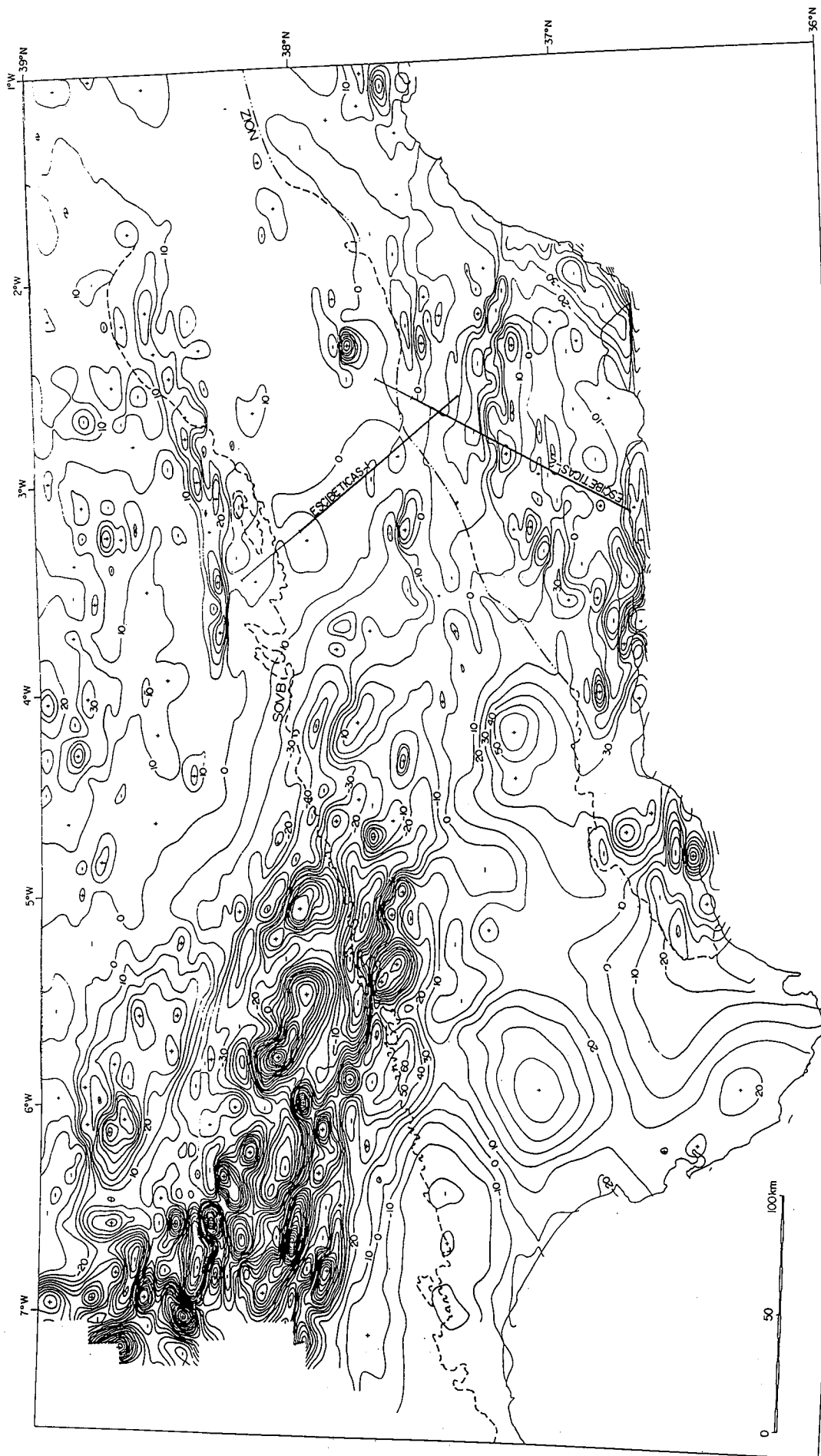
Figure 8.- Map of total field aeromagnetic anomalies (nT) simplified from Aeromagnetic Map of Peninsular Spain (Ardizone *et al.*, 1989). Thick lines indicate position of seismic profiles. Magnetic models have been extended along length of thin lines. SOVB, Southern limit of Variscan belt outcrops. NOIZ, Northern limit of Internal Zones outcrops. Dashed lines correspond to outcrops of this boundary. Dot-dash lines represent supposed position of the boundary below Neogene basins.
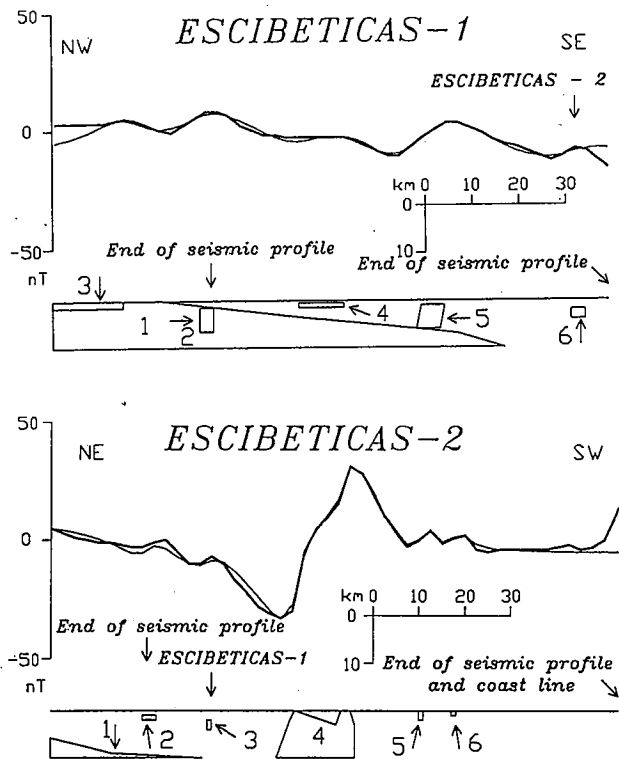
Figure 9.- Magnetic anomaly profiles and magnetic models. Thick line profile, measured magnetic anomaly. Thin line profile, calculated magnetic anomaly. It is assumed in all models that the magnetism produced by anomalous bodies is induced. In ESCI-Béticas1 (N142°E) infinite bodies elongated in a N120°E strike are considered and in profile ESCI-Béticas2 (N30°E) infinite bodies elongated in a N90°E strike are assumed.

We modeled two magnetic anomaly profiles located in the same position as the gravimetric and deep seismic reflection profiles. The 2-D models consider infinite N120°E-oriented bodies in the northern profile (ESCI-Béticas1, Fig. 9), and N90°E-oriented bodies in the southern profile (ESCI-Béticas2, Fig. 9), as corresponds to the elongation of the anomalies in the profile regions. While in the ESCI-Béticas1 profile the magnetic anomalies trend N 120°E, because they are produced by anomalous bodies located in the upper crust, the gravimetric Bouguer anomalies are oriented E-W because they are mainly related to the variation in crustal thickness. Characteristics of the anomalous bodies can be seen in Fig. 9 and in Table II.

Discussion

The upper crust of the Betic Cordillera is generally transparent in the deep seismic reflection profiles, which do not provide new data on its structure. In the ESCI-Béticas2 profile, scarce low-amplitude reflectors have been identified near the surface. Where the basement crops out, these reflectors may be associated to lithological contacts or to shear zones from units of the Internal Zones. In the Guadix-Baza basin, reflectors related to the sediments were also identified, although the basal unconformity cannot be well observed. In the upper crust of the ESCI-Béticas2 profile, the most important reflector

band recognised is the Upper Crustal Reflector (U.C.R.), which may correspond to a band of mylonites associated with a shear zone that does not crop out on the surface. In the northern part of the ESCI-Béticas1 profile, reflectors corresponding to the sediments of the Guadalquivir Basin and to the upper part of the Iberian Massif are also visible. In this profile, the contact between the sedimentary rocks of the External Zones and the Guadalquivir Basin over the Iberian Massif is not seen, although commercial seismic reflection profiles and boreholes made in this area confirm the presence of the Iberian basement, at least in the northern sector (Lanaja, 1987).

The upper/lower crust boundary is detected at the NW end of the ESCI-Béticas1 profile around 7 s (23 to 25 km in depth), which agrees with seismic refraction studies of the Iberian Massif (Banda *et al.*, 1981; Banda *et al.*, 1993). Their prolongation towards the SE area of the profile seems to have a SE low-dipping component, although the boundary became very diffuse due to a decrease in the number of identified reflectors.

The position of the Moho in this seismic reflection profile is somewhat controversial. Generally, the Moho separates a lower crust with high reflectivity from an upper mantle with low reflectivity (e.g.. Barnès, 1994). Therefore, in the ESCI-Béticas1 profile, the Moho seems to be located around 12.5 s in the NW of the profile, around 14 s or even more in the centre of the profile, and deeper at the SE end. These times, taking into account the velocity models of P waves for this area (Fig. 5), correspond to depths of around 40-41 Km at the NW end. These depths are much lower than those obtained by seismic refraction surveys in the NW end of the profile (35 km, Banda *et al.*, 1993) and in the southern Iberian Massif, where they reach around 30 to 32 km in depth (Suriñach & Vegas, 1988; ILIHA DSS Group, 1993). We agree with the explanation proposed by García-Dueñas *et al.* (1994) that the Moho must be located inside the reflective zone. In fact, there are bands of high reflectivity in the lower part of this zone, around 10, 11, 12, and 12.5 s, indicating a laminated structure. Seismic refraction data from the ILIHA DSS Group (1993), although on a different scale, also suggest a laminate character for the lithospheric mantle below the southern Iberian Massif. The main difference is the band of reflections where the Moho is supposed to be located. García-Dueñas *et al.* (1994) associated the Moho to the band at 12 s (TWT) at the NW end of the profile. We suggest that it may be higher and associated with the reflections around 10 s (TWT), in the upper part of this laminate structure). This position better explains the previous seismic data. Gravimetric data also disagree with low depths for the Moho in this region, since a crust with a thickness of around 40 km below the Guadalquivir Basin would have to give rise to a gravimetric minimum that is not seen.

García-Dueñas *et al.* (1994) explain the differences in depth between the reflection and refraction seismic data on the basis of the thick sedimentary sequences (5 km or more) of the Guadalquivir Basin and of the External Zones with low seismic velocities that produce delays throughout the profile. However, at the NW end of

A) ESCIBETICAS-1 MAGNETIC PROFILE

ANOMALOUS BODY	EQUIVALENT MAGNETIC SUSCEPTIBILITY	INTERPRETATION
1	0.0032 SI	Pedroches Batholith
2	0.0152 SI	Basic or intermediate differentiate in the Pedroches Batholith
3	0.0082 SI	Detritic cover of the Iberian Massif
4	0.0040 SI	Probably ophite bodies
5	0.0080 SI	Probably basalt bodies
6	0.0140 SI	Probably metamorphosed igneous rocks of the Internal zones

Table II.- Parameters used in the models of total field magnetic anomalies and geological attribution of the anomalous bodies.

B) ESCIBETICAS-2 MAGNETIC PROFILE

ANOMALOUS BODY	EQUIVALENT MAGNETIC SUSCEPTIBILITY	INTERPRETATION
1	0.0032 SI	Prolongation of Pedroches Batholith
2	0.0050 SI	Probably metamorphosed igneous rocks of the Internal Zones
3	0.0140 SI	Probably metamorphosed igneous rocks of the Internal Zones
4	0.0050 SI	Fe-mineralizations in joints of the Nevado-Filabride
5	0.0100 SI	Outcropping peridotites of the Cerro del Almirez
6	0.0100 SI	Probably Hematites mineralizations

the profile, boreholes made in the Guadalquivir Basin close to the profile (Lanaja, 1987) indicate that the cover of the Iberian Massif (with thicknesses lower than 270 m, Azcarate Martín et al., 1977; Ortiz Castro et al., 1976) is located at a depth of 500-600 m. There are also parts of the profile with a thin sedimentary cover that cannot explain long delays. In addition, in the ESCI-Béticas2 profile the band of reflections that we associate with the Moho could continue near the intersection with the ESCI-Béticas1 profile at a depth of around 11 s (TWT), indicating that the Moho is not as deep in the southern part of the ESCI-Béticas1 profile.

However, although reflectors in the upper mantle are generally scarce, they have been described below Scotland (Brewer et al., 1983; Reston, 1993), Hungary (Pogsay et al., 1990), northern Europe (Ansorge et al., 1992), the Appalachian mountain chain (Hall et al., 1990) and the NW of the USA (Best, 1991). Although infrequent, some reflectors are also located in the mantle in the ESCI-Béticas2 profile, suggesting that the mantle may be reflective below this region.

Although recent seismic refraction experiments have questioned the existence of a lower crust below the Internal Zones (Banda et al., 1993), both deep seismic reflection profiles and previous seismic refraction profiles identified such a lower crust below the Internal Zones. The reflectors in this zone could correspond to shear zones as well as to lithological contacts between gneisses and metabasites, such as those observed in the Ivrea-Verbano Zone (Rutter & Brodie, 1992) and in the kinzi-

gites around the Ronda and Beni-Boussera ultrabasic massifs (Loomis, 1972), where a lower crust crops out.

In the NW of the ESCI-Béticas1 profile, the lower crust has approximate seismic widths of 3.5 to 4 s (10 to 12 km thick according to Banda et al., 1993), while below the Internal Zones the values are near 5 s (approximately 18 km). This fact contrasts with the almost constant thickness of the upper crust. The thickening of the lower crust towards the South may have been produced through SW and NE-dipping shear zones, corresponding to the anastomosing reflections that join the upper boundary of the lower crust. This boundary could represent a decollement marked by subhorizontal reflections. The strength profiles calculated by van der Beek & Cloething (1992) for the western sector of the mountain chain also agree with the location of a decollement on this boundary.

The Moho in the ESCI-Béticas2 profile is defined by a band of subhorizontal reflectors around 11 s up to near the coast line. Although it is not possible to locate accurately the southern end of this subhorizontal band of reflections, due to proximity to the profile end, seismic refraction data for the Alborán Sea show that the Moho rises abruptly towards the South: from 20 km under the coast line (Barranco et al., 1990) to 15 km in the central zone of the sea (Hatzfeld, 1976; Working Group for deep seismic sounding in the Alborán Sea 1974-1975, 1978; Hatzfeld & Frogneux, 1980; Suriñach & Vegas, 1993), with a slope greater than 40°N. Gravimetric models made on the boundary of the Alborán Sea (Torné & Banda,

1992) show that the minimum dip of the Moho must be greater than 60°N near the coast line.

The location of the reflectors observed in the lower zone of the ESCI-Béticas2 profile may give rise to controversial interpretations. There are zones with reflectors that dip gently with a southwestwards component, cutting the subhorizontal reflectors of the Moho but not displacing them, which can be interpreted as lateral crustal structure reflections. However, there are also reflectors in the mantle between 11 and 16 s subparallel to the Moho, which do not cross-cut it.

P-wave velocities indicate that the lithospheric mantle below the Betic Cordillera corresponds to a "standard" mantle (Banda et al., 1993; ILIHA DSS Group, 1993), which is also confirmed by gravimetric models (van der Beek & Cloething, 1992; Torné & Banda, 1992; Watts et al., 1993). However, below the sea, the mantle is anomalous with a slightly lower density, as suggested by the anomalous spread velocities of the seismic waves (Suriñach & Vegas, 1993). This fact coincides with the presence below the Alborán Sea of a thin continental crust with high thermal flow (Albert-Bertrand, 1979; Basov et al., 1994).

The geometry of the upper part of the gravimetric models was developed taking into account field geology data. The Internal Zones rocks also form the basement of the Alborán Sea. They are found in the shallowest zone and are overlaid by the sedimentary rocks and sediments of the Neogene Alborán, Guadix-Baza, and Ugíjar basins. Towards the North, the External Zones and Guadalquivir Basin rocks (grouped with the olistostromes), overlie the upper crust of the Iberian Massif. We consider a dip towards the N for the External/Internal Zones boundary, as discussed in the Geological setting.

According to the deep seismic reflection profiles, there is a lower crust below the Internal Zones. The upper/lower crust boundary was located almost 20 km below the Internal Zones, taking into account the deep seismic reflection profiles and the crustal velocity models proposed for this region.

The deep seismic reflection profiles suggest that the Moho below the Internal Zones is practically flat and slightly deeper than it is below the Iberian Massif. We assumed progressive crustal thickening between the Iberian Massif and the Betic Chain according to the low gravimetric gradient. The transition between the thin crust of the Alborán Sea and the thick crust of the Internal Zones can only be modeled by considering that it occurs in a very narrow band where the Moho dips more than 60°N in a zone located between 10 and 20 km to the North of the coast line. These models agree with previous research by Cloething et al. (1992), Torné & Banda (1992), van der Beek & Cloething (1992), and Watts et al. (1993), who all found a very similar geometry for the Moho near the coast line West of this traverse. It also agrees with the seismic refraction data studied by Gallart et al. (this vol.) for this area. These facts indicate that the Moho has an E-W oriented staircase shape between Málaga and Almería, which bounds the anomalous mantle located below the sea.

In the Alborán Sea there is an anomalous mantle revealed both by the velocity of P and S waves (Working Group for deep seismic sounding in the Alborán Sea 1974-1975, 1978; Marillier & Mueller, 1985; Suriñach & Vegas, 1993) and by other gravimetric studies (Hatzfeld, 1976; Torné & Banda, 1992; Watts et al., 1993), while in the rest of the traverse the mantle is normal.

The prolongation of the magnetic anomalies from the Iberian Massif to the External Zones indicates that the Variscan structures are not displaced by any strike-slip fault with kilometric-scale displacement, as proposed by Araña & Vegas (1974) but rather that the Iberian Massif upper crust extends below the External Zones and is flexured as proposed by van der Beek & Cloething (1992). In line with this interpretation, the magnetic profiles show the presence of a wedge-shaped anomalous body in the ESCI-Béticas1 and 2 magnetic profiles (body 1, profile 1; body 1, profile 2, Fig. 9). This body roughly coincides with the top of the Iberian Massif basement and crops out as the granitic and granodioritic Pedroches batholith. A small anomalous body (body 2, profile 1, Fig. 9) located below the Guadalquivir Basin is probably associated with a more basic differentiate within the batholith.

A thin sheet-like body in the northern part of the ESCI-Béticas1 magnetic profile (body 3, profile 1, Fig. 9) may correspond to the Permo-Triassic red lutites, sandstones, and conglomerates from the cover of the Iberian Massif.

The magnetic anomalous body in the Sierra de los Filabres (body 4, profile 2; Fig. 9) corresponds to schists and metapsammites with mineralisations of siderite, hematite, and goethite within a recent tensional joint system (Molina-Molina & Ruiz-Montes, 1993). The mineralisations are more abundant in the Sierra de los Filabres than in the eastern Sierra Nevada (Molina-Molina and Ruiz-Montes, 1993), which explains why the same rocks do not produce magnetic anomalies in the eastern Sierra Nevada. Near this region, body 5 from magnetic profile 2 (Fig. 9) crops out as a body of metamorphosed peridotites in the Cerro del Almirez (Puga & Díaz de Federico, 1978).

The other magnetic anomalous bodies do not crop out. However, in the adjacent regions there are abundant outcrops of Mesozoic basalts and ophites (bodies 4 and 5, profile 1; Fig. 9), metamorphosed igneous rocks of the Internal Zones (body 6; profile 1; bodies 2 and 3, profile 2, Fig. 9), or Fe-mineralisations (body 6, profile 2, Fig. 9). We suggest that these rocks may correspond to the anomalous bodies (Table II).

The magnetic models indicate that the bodies causing the magnetic anomalies are always located in the upper part of the crust, with a good fit between theoretical and real anomalies if one considers their base in the Internal Zones to be located above a depth of 10 km.

A geological model of the traverse that includes all these data and is based on the geometry of the gravimetric and magnetic models (Figs. 7 and 9) is shown in Fig. 10. In the Internal Zones, the uppermost crust continues below the Alborán Sea, but the intermediate and lower

N   S
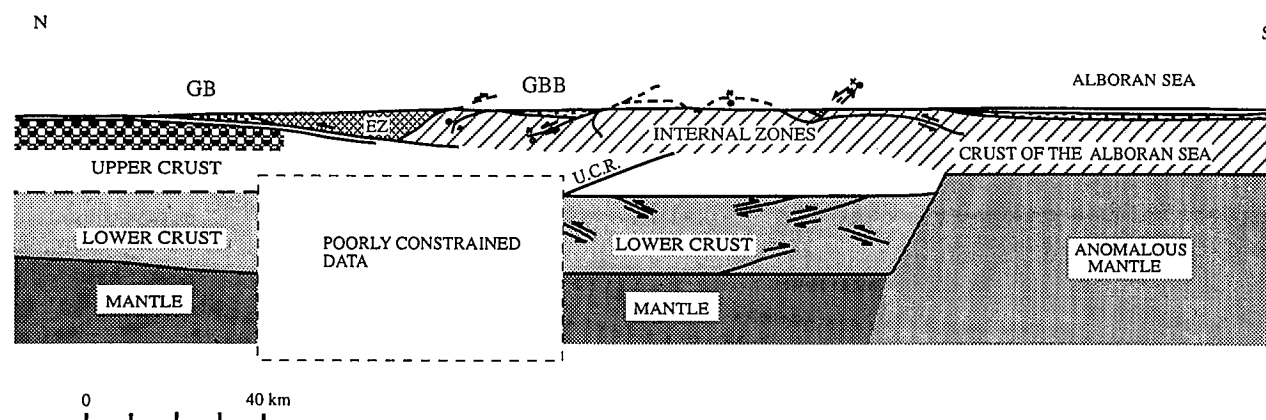
Figure 10.- Possible geological model. GB, Guadalquivir Basin. GBB, Guadix-Baza Basin. EZ, External Zones. IZ, Internal Zones. Kinematics of main contacts are indicated. Discussion in text.

crust located beneath are of unknown affinity. The lower and upper crusts of the Iberian Massif continue below the External Zones and are flexured, according to the data of van der Beek & Cloething (1992). The lack of data in the area of intersection of the profiles does not allow the relationships between the Iberian Massif and the Internal Zones to be established. There are two main possibilities: one is that the lower crust of the Internal Zones corresponds to the lower crust of the Iberian Massif. The other hypothesis is that the lower crust of the Internal Zones represents the root of the Internal Zones and could include reworked basement from the Iberian Massif. The first hypothesis implies that the Internal Zones, which are in continuity with the Alborán Sea crust, thrust onto the Iberian Massif crust, which extends up to the vicinity of the coast line. This motion agrees with the crustal structure proposed by van der Beek & Cloething (1992) and Watts et al. (1993) for the Betic Cordillera. A major problem is that no basal decollement can be seen in the seismic reflection profiles.

wer crust of unknown affinity below the Internal Zones with reflectors undeformed by the superficial folds, indicating the existence of at least one detachment level in the upper/lower crust boundary or in the upper crust. However, there are not enough data to locate accurately this detachment. The lithospheric mantle has internal reflectors below the Internal Zones. Below the Guadalquivir Basin, seismic refraction and gravimetry data suggest that the crust is around 30-35 km thick and that the lithospheric mantle is reflective with a laminate structure.

Nevertheless, the absence of quality seismic data in the region where the profiles intersect prevents more detailed structural analysis of this sector of the mountain chain.

Conclusions

Data provided by the deep seismic reflection profiles ESCI-Béticas1 and ESCI-Béticas2 do not allow the whole crustal structure of the central area of the Betic Cordillera to be precisely established. However, these profiles do provide new data that question some previous models of the crustal structure of the Cordillera and establish some constraints that models should fulfil.

Below the Internal Zones the Moho is subhorizontal or slightly undulating and its shape does not have a direct relationship with the regional topography. The transition from the Betic Cordillera crust to the thin crust of the Alborán Sea occurs in a narrow area where the Moho dips sharply towards the North.

Comparing the ESCI-Béticas1 and 2 profiles, the upper crust presents no thickening. There is probably a shear zone with a NW dipping component located North of Sierra Nevada at intermediate depths (between 2.5 and 6 s TWT in seismic profiles) that does not, however, continue up to the surface. There is a well-differentiated lo-

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