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J. Diaz, J. Gallart

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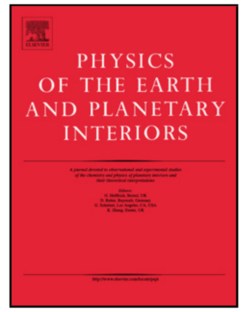

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Authors: J. Díaz, J. Gallart

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Crustal structure beneath the Iberian Peninsula and surrounding waters: a new compilation of deep seismic sounding results.

J. Díaz* and J. Gallart

Institut of Earth Sciences "J. Almera", CSIC. c/ Sole Sabaris s/n, 08028 Barcelona, Spain.

* Corresponding author. Tel: +34 93 409 54 10, Fax: +34 934110012 E-mail: jdiaz@ija.csic.es

Abstract

We present here an updated compilation of crustal parameters beneath the Iberian Peninsula and surrounding waters, inferred from extensive deep seismic exploration performed in the last three decades. Firstly, the more relevant experiments developed in both terrestrial and marine domains are revisited, together with the corresponding seismic velocity-depth models published that reveal the characteristics of the different tectonic domains sampled, including oceanic zones, continental margins, orogenic and rift belts. The results are summarized in three crustal transects sketched along representative directions. Secondly, we compiled the Moho depths along all the available seismic profiles to produce a geo-referred database. This database has then been interpolated using kriging algorithms to obtain a continuous Moho depth model, in the form of a regular grid file. This integrative Moho map for a key area in the Western Mediterranean documenting the interaction between European and African plates can

contribute to constrain further regional studies, either at crustal, lithospheric or mantle scales.

Keywords

Iberia, Crustal model, Moho depth

Introduction

Since the early 70s, the crustal structure beneath the Iberian Peninsula and its continental margins has been explored by a high amount of controlled-source seismic experiments, which provided information about the seismic wave velocities and the geometry and depth of the main crustal interfaces. The purpose of this contribution is to revisit those results, with a special emphasis in compiling the crustal depths, to provide a regional Moho-depth model of the whole area. Even if information about physical properties of the crust can be achieved after a number of geophysical techniques (tomography, receiver functions, potential fields analysis, etc.), the wide-angle reflection/refraction seismic profiles appear to be the most reliable technique to constrain the velocity-depth distribution and Moho depth, as the position of the main interfaces and the seismic velocity values are readily inferred from the data through modelling with determinable uncertainties. First compilations of seismic crustal parameters in the Iberian Peninsula were attempted by Banda et al. (1983) and Banda (1988), but since then a lot of subsequent experiments have been carried out, mainly in the northern part of the Peninsula, the Valencia Trough, the Betics, the Gulf of Cadiz and the Iberian Massif. Compilations available at global or continental-european scales

(Meissner, 1986, Dezès and Ziegler, 2001, Laske et al. 2001) do not resolve significant regional features of this key area of the Western Mediterranean, which deserves particular attention in present-day integrated research initiatives in European geosciences. These researches would certainly benefit from the existence of large, upgraded geo-referred databases, and the continuous Moho depth model we infer here can contribute to constrain the lithospheric features on the interaction domains between European and African plates.

The main tectonic domains in the Iberian Peninsula and its surrounding waters that will be considered in revisiting the seismic datasets are: a) The Iberian Massif, extending at the central and western part of Iberia, where the Hercynian basement outcrops or is covered by almost undeformed Tertiary sediments; b) the areas strongly affected by the Alpine orogenesis: i) the Pyrenees, extending from the Mediterranean sea to the Cantabrian Mountains, ii) the Iberian Chain, an area of Mesozoic cover deformed during the Alpine compression, iii) The Betics Chain, related to the complex tectonics of the Gibraltar Arc System; c) the Valencia Trough, a basin developed during the Neogene as part of the general Cenozoic rift system of western Europe, d) the Atlantic Margins, that can be subdivided into three broad zones: the Gulf of Cadiz, an active area with strong sedimentary cover and significant seismicity, the Western Atlantic, a classical example of passive margin, and the Cantabrian Margin, characterised by a very abrupt topography.

Outline of Iberian seismic exploration experiments

In order to compile the crustal parameters, we have first revisited more than 50 research projects developed during the last 30 years in terrestrial and marine domains around Iberia. We selected those experiments focused in the whole crustal structure, carried out in most cases by academic institutions, and did not consider the high resolution profiles performed by oil prospecting companies, mainly focused in the sedimentary features. Figure 1 summarizes the location of the compiled refraction/wide-angle reflection and the multichannel reflection profiles. An enormous amount of publications have resulted from these experiments, and only significant, key references are listed here on the bibliography, but which may allow the interested reader to found most of the published works. A more exhaustive compilation of publications is presented in Gallart et al. (2006).

The pioneer seismic experiments around Iberia were marine refraction investigations, using a small number of OBS or sonobuoys, carried out in the Valencia Trough-Balearic domains (Fahlquist, 1963, Hinz, 1973) and in the Atlantic Margin (Purdy, 1975). The first seismic experiments on land where performed during the early 70's in the Algarve region (S Portugal) by an international team leaded by the Zurich University (Mueller et al., 1973, Sousa Moreira et al., 1978), extending soon afterwards to Southern Spain (Udías 1975). In particular, a 500 km long terrestrial profile through the Betics (Banda and Ansorge, 1980) and 3 lines crossing the Alboran Sea where recorded using a limited number of analogical stations, shifted between repeated shots at a same point to densify the profile (Working Group for Deep Seismic Sounding in Alboran 1974, 1978). During the late 70's, new profiles where acquired in Southern Spain, sampling the Gulf of Cadiz, the Gibraltar area, the Iberian System and the Balearic Islands (Udías, 1980, Medialdea et al., 1986, Barranco et al., 1990, Zeyen et al., 1985, Banda et al., 1980). The central part of the Iberian Massif was also sampled in the late 70's, using quarry blasts as energy sources (Banda et al., 1981).

The Pyrenees were exhaustively explored by deep seismic profiles during the late 70's. Two E-W profiles throughout the northern and southern domains of the chain were recorded (Daignières et al., 1981, Gallart et al., 1981), as well as a N-S transect and multiple complementary profiles in the eastern Pyrenees (Gallart et al., 1980). Up to 64 analogical instruments and near to 20 explosions were used, reaching station spacing between 3 and 5 km. In 1984, the French "Étude Croûte continentale et Oceéanique par Réflexion et réfraction Sismique" (ECORS) programme acquired a 300 km long, N-S oriented multichannel marine profile in the Bay of Biscay (Marillier et al., 1988, Bois and Gariel, 1997). In the following years, the ECORS-Pyrenees Team carried out the first academic deep multichannel seismic profile on land implemented partially in Iberia, that crossed the Pyrenees in a NNE-SSW direction and provided high-quality data to constrain the Pyrenean orogenesis (ECORS Pyrenees Team, 1988, Choukroune 1989). Complementary wide-angle profiles were also acquired along the same line (Surinach et al., 1993, Daignières et al., 1998). Still in the ECORS framework, another transect was recorded later on in the Western Pyrenees (ECORS-Arzacq, Daignières et al., 1994, Damotte, 1998).

In the early 80s the seismic exploration activity on land was focused in the Iberian Massif. The NW corner of Iberia was studied in a widespread survey, involving inter-station distances of 1 to 2.5 km. (Córdoba et al., 1987, 1988). Those profiles provide one of the few examples of direct modelization of S wave velocities (Téllez et al., 1993, Téllez and Córdoba, 1998). Some complementary profiles where fired in N Portugal

(Mendes-Victor et al., 1988) and additional ones where recorded in central Spain (Suriñach and Vegas, 1988). During the same time period, the DSDP consortium decided to establish drill holes near the limit between the Galicia Bank and the Atlantic abyssal plain, and a preliminary multichannel seismic survey was performed over this zone, acquiring a number of deep penetration profiles mainly oriented E-W (Groupe Galice, 1979, Mauffret and Montardert, 1988). The profiling activity in the Atlantic Margin continued in 1986-87 by a British wide-angle-/refraction survey in the Tagus Abyssal Plain (Whitmarsh et al., 1990, Pinheiro et al., 1992) and by the Reframarge experiment, using the same technique to explore the limit between the Galicia Bank and the Iberian abyssal plain (Whitmarsh et al., 1996). Later on, in 1990, the Lusigal experiment sampled again the Tagus Plain using in this case multichannel seismic profiles (Beslier et al., 1993).

In 1988 the Valencia Trough was largely explored within the VALSIS experiment. Up to 200 km of multichannel seismics were acquired, including common deep point, common offset point and expanding spread profiles (Watts et al., 1990, Torné et al., 1992, Pascal et al., 1992). The shots from some of these profiles where recorded onshore by portable seismic stations, providing the first 'onshore-offshore' transects in Iberia (Gallart et al., 1990). The same geographical area, between the Balearic islands and NE Iberia, was explored in 1989 in a wide-angle experiment, using explosive sources recorded by 110 land stations and 10 OBS (Dañobeitia et al., 1992) to constrain the velocity-depth structure.

In the late 80s, the large scale "Iberian Lithospheric Heterogeneity and Anisotropy" (ILIHA) experiment provided relevant information about the crustal and upper mantle structure beneath Iberia, including evidences of the presence of seismic anisotropy in the uppermost mantle. Up to 6800 km of profiles crossing the Peninsula along different azimuths where recorded with station spacing of about 4 km (Díaz et al., 1993a, 1993b). In the same period, a number of new profiles crossing the Eastern Betics where acquired with higher station density (Banda et al., 1993).

In the early nineties, the focus of activity shifted to multichannel reflection profiles, in the framework of the Spanish “Estructura Sísmica de la Corteza Ibérica” (ESCI) Program that allowed to record up to 450 km of terrestrial and 1325 km of offshore seismic profiles in southern, eastern and northern Iberia. On land, an NW-SE oriented profile was acquired in the Betics (Garcia-Dueñas et al., 1994), a short profile connecting the ECORS line to the Mediterranean coast was implemented across the Catalan Coastal Range (Gallart et al., 1994a), and two N-S and E-W profiles were shot in the in Cantabrian Mountains (Pérez-Estaún, 1994, Pulgar et al. 1996, Gallastegui et al., 1997). Offshore, two seismic profiles were acquired in southern Spain, one sampling the northern part of the Alboran Sea in a NNE-SSW direction and the second one, oriented approximately E-W, connecting to the SudBalearic basin (Booth-Rea et al., 2007). The first profile was also recorded on land by a few seismic stations (Gallart et al., 1995). The Alboran Sea was explored again in 1992 by a set of short (50 km) refraction profiles in its NW part recorded on land by up to 24 stations (Gallart et al., 1994b) and by the larger scale CONRAD experiment that recorded five multichannel seismic profiles oriented approximately N-S crossing the whole basin (Watts et al., 1993).

The marine component of the ESCI Programme included also the acquisition of another multichannel profile in the Valencia Trough, oriented NW-SE, between Tarragona coast and S of Mallorca island, recorded also onshore (Gallart et al., 1995), and allowing in this way to complete a 700 km-long seismic transect from the Pyrenees to the South Balearic Basin (Vidal et al., 1998). The ESCI Programme was completed in 1993 with the acquisition of two profiles in the North-Iberian Margin, one oriented E-W sampling the Hercynian structures and the other oriented N-S, extending northwards the previously acquired land profile to obtain a transect orthogonal to the main structures (Alvarez-Marrón et al., 1996, Ayarza et al., 1998). In both cases the profiles were recorded by land stations to obtain wide-angle data that control the velocity structure (Fernández-Viejo et al., 1998; Gallastegui et al., 2002). Extensive exploration on land of the northern part of Iberia was also performed in the 90s within two research projects that recorded a large E-W refraction/wide-angle reflection profile covering a total of 960 km from Galicia to the Pyrenees Chain, as well as a set of transverse profiles sampling the transition between the Duero Basin and the Cantabrian Mountains (Pulgar et al. 1996; Fernández-Viejo et al., 2000, Pedreira et al., 2003).

In the mid-nineties, the French project LISA sampled different areas of the western Mediterranean from seismic multichannel profiling (Mauffret et al., 2001, Nercessian et al., 2001). Five of the acquired profiles were shot in the vicinity of the eastern termination of the Pyrenees and were recorded by land stations to investigate the transition between the areas affected by the Alpine compression and the Neogene extension (Gallart et al., 2001). However, most of acquisition activity was focused on the marine seismic exploration of the Atlantic margins of Iberia, in the framework of the large scale “Iberian Atlantic Margins” (IAM) European project. Up to 3500 km of multichannel profiles were acquired in the North-Iberian and Atlantic margins, the Gorringe bank and the Gulf of Cadiz (Banda et al., 1995). Profiles IAM12, oriented N-S along the La Coruña longitude, IAM11 oriented E-W in front the central coast of Portugal and IAM3, oriented NE-SW in front of Cabo San Vicente were recorded on land, providing images of the continent-oceanic transition (Fernández-Viejo et al., 1998, González et al., 1996; González et al., 1999). After the IAM project, additional experiments were implemented in Atlantic Margins, to better constrain the seismic velocity structure. A wide-angle profile, including the deployment of up to 16 OBS, was shot in the same position of the previously acquired IAM9 line (Chian et al., 1999, Dean et al., 2000), exploring the structure of the ocean-continent transition. The northern part of the Atlantic margin was investigated in the ISE97 experiment that acquired more than 4000 km of multichannel seismics, recorded also by a network of OBS and land stations (Pérez-Gussinye et al., 2003, Henning and Sawyer, 2004). In 1998, the BIGSETS project sampled the epicentral area of the 1755 Lisbon earthquake by up to 2700 km of multichannel seismic profiles.

The seismic exploration activity in the 21th century started with the investigation of the tectonic evolution of the Gulf of Cadiz, where two main E-W oriented multichannel seismic profiles were acquired in the framework of the TASYO project (Medialdea et al., 2004). The same area was investigated in 2002 by the VOLTAIRE project, which allowed the acquisition of more than 1000 km of multichannel seismic profiles (Zitellini et al., 2004). The TECALB experiment, carried out in 2004, provided a set of multichannel seismic profiles sampling the Eastern Alboran Sea (Comas et al., 2004). In 2006, the West-Med experiment, allowed the acquisition of wide-angle data in the Alboran Sea and the transition to the South Balearic basin, using a network of OBS and land stations (Galvé et al., 2007). The same area has been investigated in 2006 by the MARSIBAL cruise, using in this case multichannel seismic profiling (Comas et al., 2007).

After the sinking, in late 2002, of the "Prestige" oil-tanker at about 250 km NW of the Galician coasts, an emergency multidisciplinary investigation was launched over the sinking area, located in the limit between the Galicia Bank and the Iberian Abyssal Plain. In this framework, a seismic experiment including multichannel seismic profiles and OBS was carried out on in 2003 (Díaz et al., 2008). At the same year, the MARCONI large scale project investigated the deep structure of the eastern half of the Bay of Biscay. Up to 1800 km of multichannel seismic profiles were acquired and the signals were recorded by 24 OBS and by a network of 36 land stations to constrain the velocity structure of the area (Ruiz, 2007). Still in 2003, a seismic transect on land was acquired beneath the central part of the Iberian Chain to investigate the presence of a crustal root (Gallart et al., 2004).

On land, the IBERSEIS experiment, carried out in 2001, provided a high resolution image of the SW Iberian Massif, using both multichannel and wide-angle methods. In the wide-angle profile up to 690 seismic stations where deployed, providing a resolution of 150 to 400 m, that is clearly an order of magnitude higher than all previous experiments (Simancas et al, 2003, Carbonell et al., 2004). In 2007, the ALCUDIA project has allowed to extend 300 km towards the Northeast the previously acquired IBERSEIS line, providing a complete transect from the Gulf of Cadiz to the Hercynian domain of the Spanish Meseta (Carbonell et al., 2007).

Seismic structure beneath the Iberian Peninsula and surrounding waters

Iberian Massif

A large part of central and western Iberia is covered by the Iberian Massif, affected by the Variscan orogeny and mostly undeformed since then. The crust is seismically differentiated in three layers and shows a structure similar to other Variscan domains in Europe. The basement has a thickness of 8-12 km and velocities ranging from 5.9 to 6.1 km/s (Banda et al., 1980). Some authors have introduced a low velocity at the bottom of this layer, even if recent high resolution experiments can not confirm such a structure (Palomeras et al., 2008). The intermediate crustal layer, with velocities of 6.2-6.4 km/s reaches depths of 23-25 km. A lower crust, with velocities of 6.7-6.8 km/s is defined above the Moho discontinuity, located at 30-33 km. A crustal root seems to be present beneath the Central System, where the crustal depth reaches 34 km as a consequence of a thickening of the middle crust layer (Suriñach and Vegas, 1982). Beneath the Atlantic coast of Iberia, the crust displays thicknesses of 27-29 km and starts thinning toward the oceanic domain (Díaz et al., 1993a). In SW Portugal, the crust has been modelled with a strong gradient in the upper crust and a pronounced LVZ (Mueller et al., 1973, Sousa Moreira et al., 1978). However, an alternative interpretation assuming a model closer to the one obtained for central Iberia can also explain the data (González et al., 1998). Multichannel seismic profiling across the Variscan belt in SW Iberia revealed the existence of a mid-crustal reflective body, 140 km long and of variable thickness (up to 5 km), that has been interpreted as an Early Carboniferous mantle derived intrusion (Carbonell et al., 2004). Wide-angle modelling along the same profile shows a 31-34 km thick crust, with the lower crust thickening to the center of Iberia (Palomeras et al., 2008).

Alpine Chains

The presence of a more or less pronounced root underneath the areas that underwent significant deformation during the Alpine orogeny has become apparent since the first seismic investigations in Iberia. In the early 80s the crust beneath the Pyrenean chain was modelled with a sedimentary layer on top of a basement with seismic velocities of 6.1-6.2 km/s that overlays an undifferentiated mid-lower crust below 11-14 km depth where the velocities reach 6.3-6.4 km/s. The crustal thickness beneath the Pyrenean axial zone reaches 45-50 km, while the northern European crust does not exceed 30 km depth (Daignières et al., 1981, Gallart et al., 1981). This image was confirmed by the ECORS multichannel seismic profile, which shows well-defined reflectors in the entire crust with an overall fan-shape geometry, and a marked crustal thickening from the southern Pyrenean domain towards the Axial zone, depicting an imbrication of the Iberian crust beneath the European one (Choukroune et al., 1990). No evidences for the persistence of a crustal root eastwards, toward the Mediterranean Sea have been inferred either from the land refraction profiles (Gallart et al., 1980) or from the onshore-offshore experiments in the eastern termination of the Pyrenees (Gallart et al., 2001). The important differences in Moho depths between the Iberian and the European domains observed in the central and western Pyrenees are not present in this area, which is marked by a continued thinning seaward, the Moho reaching 25 km depth in front of Cap de Creus.

A remarkable result derived from the extensive seismic exploration in the northern part of Iberia is that all the profiles sampling areas affected by the Alpine orogeny show a crustal structure similar to that inferred for the Pyrenean Chain (Fernández-Viejo et al., 1998; Pedreira et al., 2003). A quasi-continuous crustal root is hence depicted along the strike of the Pyrenean-Cantabrian range where Moho depths reach 46-48 km, with a local, relative thinning to 40 km depth beneath the Mesozoic sediments of the Basque-Cantabrian Basin. Seismic and gravity modelling in the whole area shows consistent images of a crustal indentation and wedging between the Iberian and the European-Cantabrian Margin crusts (Fernández-Viejo et al., 1998; Gallastegui et al., 2000; Pedreira et al., 2003; 2007). A 10 km-thick lower crustal layer of 6.6-6.8 km/s is modelled on top of the Moho. The presence of high velocity bodies embedded at mid-crustal levels has also been inferred from the seismic data, and they have been interpreted as intrusions from the European-Cantabrian Margin lower crust indenting southward the Iberian crust (Pedreira et al., 2003, 2007). A significant thinning of the crust to the westernmost part of the Cantabrian Mountains, where Moho depths are about 30 km, depicts the transition to the zones of the Iberian Massif which had not been significantly reworked by the Alpine orogeny.

The seismic profiles exploring the other major Alpine domain in Iberia, the Betics Chain, have evidenced the differences between the Iberian Massif and the external and internal Betic domains. In the transition zone to the internal Betics, the crust thins first to 32 km and then thickens to 37-38 km. The absence of differentiated lower crust beneath the external Betics has been related with the Mesozoic rifting episode of the South-Iberian passive margin (Banda et al., 1993). In an East-West direction, the Palomares-Alhama de Murcia fault system seems to limit two crustal blocks; to the

East, the crust is only of 23 km thick, and has a high velocity body (6.9 km/s) in the lower levels. West of this fault system, the presence of a LVZ 5.4 km/s at depths of 7 to 12 km has been inferred from the data. The crustal thicknesses vary strongly, between the 38 km reached beneath Granada and the 24 km beneath Adra, close to the Alboran sea (Banda and Ansorge, 1980). SW of Málaga seismic data evidences an anomalous structure that could be explained by a thin crust, a massive presence of peridotites or a combination of both features (Banda et al., 1993). In the Westernmost Betics Chain, the upper, middle and lower crusts are evidenced, with velocities of 6.1, 6.4 and 7.0 km/s underlying a sedimentary cover that has important thickness variations. The crustal depth varies from 25 km under the inner arc of the Betics to 31 km in the coast west of Gibraltar (Medialdea et al., 1986). Towards the Alboran Sea, the velocity-depth distribution is poorly constrained from the published datasets. The crust seems to quickly get thinner, reaching depths of about 15 km but without showing features of oceanic crust. It overlies an uppermost mantle with apparently low velocities (Hatzfeld and Bensari, 1977; Working Group for DSS in the Alboran Sea 1974, 1978).

The results available for the Iberian Chain, an area of Mesozoic cover deformed during the Alpine compression, show an average crustal thickness of 30-32 km for most of the chain, similar to the values in the Central Iberian Massif. However, a local thickening of a few kilometers has been detected in the central northern part of the chain (Zeyen et al., 1985). A similar crustal root has also been observed farther south, along a refraction profile oriented NE-SW where the Moho reaches 40 km depth (Gallart et al., 2004).

Valencia Trough

The transition between the NE Iberian Peninsula and the Valencia Trough, a basin developed during the Neogene as part of the general Cenozoic rift system of western Europe, is marked by a strong thinning of the crust, changing from 35 km inland to 15-18 km in the center of the basin. The crust thickens again to the SE beneath the Balearic promontory, reaching 30 km beneath Mallorca island. The basement shows seismic velocities of 6.0 - 6.1 km/s, while in the lower crust, where must of the crustal thinning is accommodated, the velocities are of 6.4-6.5 km/s. The uppermost mantle beneath the axial zone is characterized by a low velocity of about 7.8 km/s, interpreted as consequence of the rifting process that affected this area. To the SE, in the South Balearic basin, the crust becomes very thin (6 km) and has probably an oceanic origin (Banda et al., 1980, Dañobeitia et al., 1992, Collier et al., 1994, Vidal et al., 1998).

Atlantic and Cantabrian Margins

In the Atlantic Margins of Iberia the transition from continental to oceanic crust is mapped with significant variations between the different zones. The seismic models obtained beneath the Gulf of Cadiz indicate that the whole area has a continental-type crust, with a progressive thinning from 27 km in the east to 20 km in the westernmost area (González et al., 2001). The onshore recordings of an SW-NE oriented MCS profile in front of Cape San Vicente have revealed that the crust undergoes a strong but continuous thinning from 31 km onshore Iberia to less than 15 km in the Horseshoe Abyssal Plain, over horizontal distances of 120 km (González et al., 1996).

In front of the coast of central Portugal, the transition between the continental and the oceanic domains has been modelled using wide-angle seismic data (Dean et al., 2000;

Chian et al., 1999) and imaged with MCS profiling (Pickup et al., 1996). East of 10º45'W, the crust is of continental type, with a smooth uprising of the Moho from 31 km beneath Iberia to 12 km. West of this longitude, the crust is described as transitional, with an upper layer 2-4 km thick modelled with a strong velocity gradient (4.5 – 7.0 km/s) and a second crustal layer 4 km thick and a small velocity gradient around 7.6 km/s. West of 12º40' W the crust is clearly oceanic, with a 2 km thick upper layer with velocities 4.5-6.5 km/s over a lower layer of 3.5-4.5 km and seismic velocities of 6.7 to 7.2 km/s.

In front of NW Iberia, the morphology of the margin is complex with, from East to West, a small continental platform, a large basin about 100 km wide (Galicia Interior Basin) where the Moho depth thins to 15 km, a structural high (Galicia Bank) where the Moho deepens to 22 km to thin again smoothly towards west to a minimum of 10 km eastwards of the peridotitic ridge (located at around 12.5ºW). West of this ridge, the crustal structure is typical of oceanic domains (Whitmarsh et al., 1990, Murillas et al., 1990, Pérez-Gussinyé et al., 2003).

The structure beneath the North Iberian or Cantabrian margin has important lateral variations. In the western sector the transition is marked by a rapid and smooth thinning of the crust, from 30 km on land to 15 km in the abyssal plain the Bay of Biscay. MCS profiling has suggested the presence there of oceanic crust, interpreted as an arrested subduction (Álvarez-Marrón et al., 1996, Ayarza et al., 2004). In the central part of the margin the inferred models show the indentation of the Cantabrian margin crust between the middle and lower Iberian crust. The Moho depth shifts abruptly from more than 45 km to 30 km beneath the shoreline and then thins smoothly till 18-20 km

(Fernández-Viejo et al., 1998). The N-S and E-W profiles acquired during the MARCONI experiment in the eastern half of the margin show an important crustal thinning to the NW part of the study area, where the Moho is located at depths of 10-14 km and the velocities in the upper and lower crust are, respectively, lower and higher than expected, depicting an elongated and thinned transitional crust. Towards the eastern termination of the North Iberian margin, the crust is clearly of continental type (Ruiz, 2007).

Summary of results: crustal transects and Moho-depth model

The velocity-depth distribution along three illustrative transects crossing the Iberian Peninsula and its margins is sketched in Figure 2. The location of these transects has been chosen to follow, as much as possible, the profiles where direct crustal modelling is available. We use them to compile and discuss the main crustal parameters beneath Iberia. Figure 2a shows a transect oriented NNW-SSE from the Bay of Biscay to the African coast, sampling the thinned continental crust of the abyssal plain, the crustal imbrication related to the Alpine compression beneath the Cantabrian Mountains, the typical Iberian Massif crust and the significant crustal thickening beneath the Internal Betics, followed by the crustal thinning beneath the Alboran Sea. The second transect (Figure 2b) is oriented grossly E-W along the northern part of Iberia. It samples the eastern termination of the Iberian Abyssal Plain, with a typical oceanic crustal structure, and goes through the Galicia Margin, crossing the peridotitic ridge, the Galicia Bank, the Galicia Interior Basin and the continental platform. On land, the transects samples the Iberian Massif units and depicts clearly the transition to the areas affected by the Alpine orogeny, with crustal thicknesses reaching almost 50 km along the Cantabrian-

Pyrenean range. Locally, intrusions of the European-Cantabrian lower crust and thinning beneath the Basque-Cantabrian basin are observed. At the eastern end of the Pyrenees, the crust thins once the extended domains of the Western Mediterranean are reached. The third transect presented here (Figure 2c) is also oriented E-W but sampling the central part of Iberia. Its western termination shows the Atlantic oceanic crust. It crosses afterwards the typical non-volcanic passive margin of Iberia, and reaches the Iberian Massif units. Eastwards, the transect evidences the local crustal thickenings beneath the Central System and the Iberian Chain, and it illustrates the transition to the Valencia Trough, an area of clearly extended, thinned continental crust and it ends by documenting the thicker crust beneath the Balearic Promontory.

In order to obtain a Moho-depth model for the overall area, we have first compiled the geographical location of the published wide-angle and multichannel seismic profiles that provide information about the whole crustal structure beneath Iberia and its surrounding waters. In some cases, especially for the oldest experiments, the coordinates of the profiles have been recovered directly from the published maps and therefore may involve some degree of inaccuracy (Figure 1). The next step has been to retrieve the Moho depths along the published profiles; if the profile was interpreted assuming a 1D velocity-depth distribution, the reported Moho-depth is adopted along the profile. If 2D models where available, the Moho depth was extracted for enough points to take care of its topographic variations. About 320 points have been compiled in this way, stretching E-W from the Atlantic oceanic crust to the Balearic Promontory and N-S from the thinned crust of the Bay of Biscay to the African coast of Morocco, with a mean density of about one measurement every 0.5ºx0.5º. The final compilation is presented in Figure 3 and is also presented as an electronic table as complementary material.

As a final step, we undertake the construction of a Moho-depth model using ordinary kriging as the interpolation method. This method has the advantage to take into account the knowledge of the spatial continuity of the variable to estimate. Each data point is weighted in the kriging procedure with a coefficient which takes care of the distance to the neighbour points. To obtain these coefficients, the spatial autocorrelation in the form of semi-variograms of the available data is computed and modelled. This procedure tries to ensure a correct weighting function for not-uniform data distributions. We have used the KT3D code, a part of the GSLIB package (Deutsch and Journal, 1998). The semi-variogram for the Moho-depth distribution has been modelled using a spherical model with a sill located at 70 km^2 beyond a range of 3º (325 km). The variograms along different directions show some evidences of spatial anisotropy, but we decided not to retain this contribution into the final model to avoid overmodelling, as the data are not conclusive in this respect. The final grid, spatially filtered and plotted using the GMT software package (Wessel and Smith, 1998), is presented in Figure 4 and can be downloaded in netCDF format at http://www.ija.csic.es/gt/jd/Moho_Iberia. It must be pointed out that for some regions, in particular at the transition from the Pyrenees chain to the Iberian Ranges through the Ebro Basin, or at the limit between the Guadalquivir basin and the Betics and in the SW Mediterranean Sea, the interpolated Moho-depths may not reflect correctly the real crustal thicknesses, because experimental data is very scarce in these areas.

Discussion and Conclusions

The lithosphere of the Iberian Peninsula and its surrounding waters has been sampled from a huge number of active seismic experiments during the last three decades. However, a specific compilation of its seismic crustal features has not been attempted since about 20 years, and a great amount of results and constraints is available since then. We have revisited here all these seismic reflection and refraction experiments to summarize main crustal parameters and to build up a comprehensive map of crustal thicknesses by compiling Moho depths. We came up with a geo-referred database that has then been interpolated using kriging algorithms to obtain a continuous Moho depth model, in the form of a regular grid file. We took care that in this map the geographical areas readily sampled by the profiles and those where the final model comes from interpolation are well recognized.

One of the most significant features established since long ago is the crustal thickening, reaching 50 km depth, beneath the Pyrenean range. However, the experiments performed in North Iberia in the last 10 years have revealed that this thickened crust is not limited to the Pyrenees, but extends westwards along the Cantabrian Mountains, up to the contact with the Iberian Massif units at about 6ºW, a feature that is not stated in previous regional or global crustal depth compilations (Meissner, 1986, Dezes and Ziegler, 2000). In the Betics, a thickening reaching 38 km is also observed, but seems to be limited to a small area beneath the Internal Betics. The Iberian Chain, oriented NE-SW south of the Ebro Basin, has also a crustal root reaching 40 km at its SE part. The extension to the NW of this root needs still to be investigated. The northern part of the Iberian Massif shows Moho depths between 32 and 40 km, illustrating the transition to the thickened Alpine areas. Thicknesses of about 31-32 km have been reported at the central and southern areas of the Variscan domains, even if recent high density experiments suggest that the crust is slightly thicker in the southwestern zone, reaching probably 33-34 km.

The Valencia Trough and the Alboran Sea show a clear thinning related to the large scale extensional tectonics that affected those areas. The connection between both domains has still to be established, and it is an objective of some ongoing projects. The Atlantic margins illustrate the transition between the oceanic crust, where the Moho is located at 10-14 km, to the continental domain, with depths exceeding 31 km. In southern and central Iberia this transition appears quite smooth, depicting the characteristics of a typical non-volcanic passive margin. In front of Galicia (NW Iberia) the morphology of the margin is more complex, due to the presence of the extended Galicia Interior Basin and the peridotitic ridge, a fact that is also missing in previous compilations. Finally, the North Iberian margin shows a great east-west variation. In its Western part, the image is similar to the West Atlantic margin, with a rather smooth transition from the continental crust on land to the oceanic crust in the abyssal plain of the Bay of Biscay. In the central part of the margin the image is similar to that of the Pyrenean range, with crustal imbrication and thickening beneath the shoreline. In the eastern half of the basin, the seismic properties suggest an elongated and thinned transitional crust towards the centre of the abyssal plain, without evidences for oceanic crust. At the eastern termination of the margin, in the Aquitanian platform, the crust is also thinned but preserves the usual continental properties.

At an overall scale, a clear anticorrelation is observed between the topographic and Moho depth profiles (see Figure 2), reflecting what would be expected if the crust was compensated following the Airy hypothesis. However, differences between the Moho depths from DSS profiles and the isostatic Moho depths can locally reach up to 10 km beneath some thickened (Pyrenees) or thinned (Valencia Trough) regions.

The consistency of the crustal depth results compiled here from active seismic profiles can be checked with respect to results from other independent seismic methods, such as surface waves or receiver functions. Published works related to dispersion of surface waves (ex. Badal et al. 1993, Corchete et al., 1995) focus in obtaining large scale mantle tomographic images and do not properly constrain the base of the crust. The same happens with continental-scale studies (ex. Peter et al., 2008). More recent works use surface wave analysis to infer models of the uppermost part of the crust, either from earthquakes (p.e. Chourak et al., 2003) or from seismic noise (Villaseñor et al., 2007), but the corresponding models do not extend to Moho depths. On the other hand, estimations of the crustal thickness beneath some areas in Spain have been inferred from teleseismic Receiver Functions (RF) analyses. Using pseudo-migration of RFs, Díaz et al., (2003) imaged the base of the crust in a couple of lithospheric transects located beneath the western termination of the Pyrenees and the Cantabrian Mountains. Later on, the same authors extended the work to NW Iberia (Díaz et al, 2008). In all cases, the depth of the base of the crust is remarkably coincident with the results from DSS profiles. Julià and Mejia (2004) presented local estimates of crustal thicknesses, obtained using the H-K stacking method, for 10 stations in Iberia. More recently, Mancilla et al. (2008) presented first results of a similar study in Southern Iberia using a dense network of stations. In most cases, the differences between the crustal thicknesses presented in our compilation and the RF estimations do not exceed 2 km, hence documenting the consistency of the results inferred from two independent seismic methodologies.

The integrative Moho map we have derived for this key area in the Western Mediterranean can contribute to constrain further regional studies documenting the interaction between European and African plates, either at crustal, lithospheric or mantle scales. The bibliographic effort needed to compile all the information used here will serve in establishing a database of active seismic experiments beneath Iberia, to be integrated in large-scale geosciences projects such as the ongoing Spanish Topo-Iberia or the coming ESF-TopoEurope ones.

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Figure Captions

Figure 1: Location of the compiled refraction/wide-angle reflection and deep multichannel reflection profiles beneath the Iberian Peninsula and surrounding waters. Different colours account for each main experiment. Offshore circles depict the position of OBS instruments. Inland circles represent stations having recorded onshore-offshore profiles.

Figure 2: Velocity-depth distributions along representative transects. The directions have been chosen to follow the zones with available models. (a) NNW-SSE (b) E-W (North Iberia) (c) E-W (Central Iberia). The main tectonic units are indicated on top of each transect. CM: Cantabrian Mountains, Ib M: Iberian Massif, “W Ib Margin”: West Iberian Margin, BCB: Basque Cantabrian Basin, “Val Tr”: Valencia Trough, “Ib Ch” Iberian Chain, “Bal Pro”: Balearic Promontory. Each transect includes its topographic profile. The inset presents a simplified geological map of Iberia showing the geometry of the transects.

Figure 3: Compilation of crustal depth thicknesses along published deep seismic sounding profiles overlying a smoothed topograpic map.

Figure 4: Interpolated crustal depth model for the whole investigated area. Colour scale depicts the crustal thickness variations. Crustal thickness isolines are represented every 2 km.

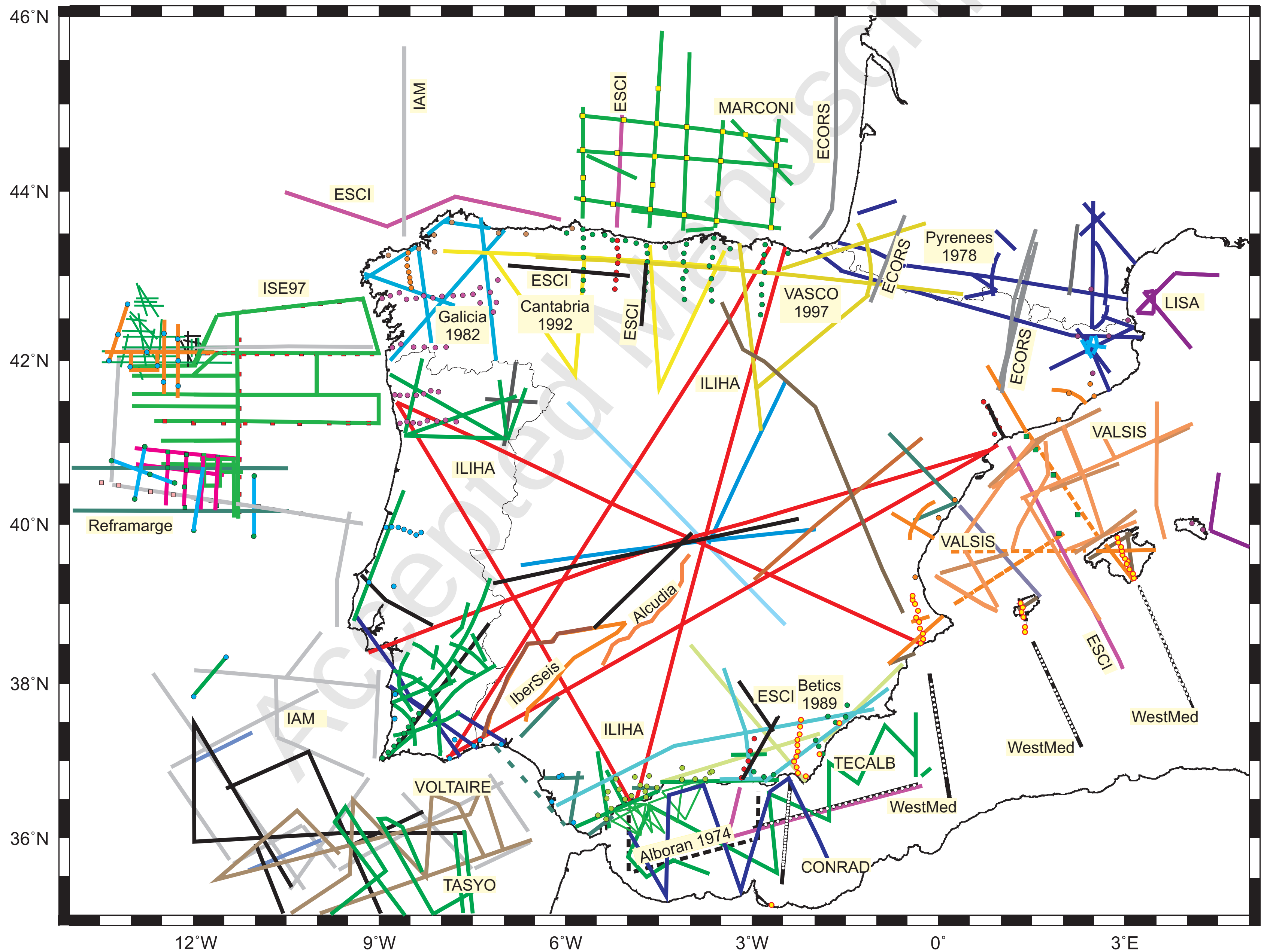
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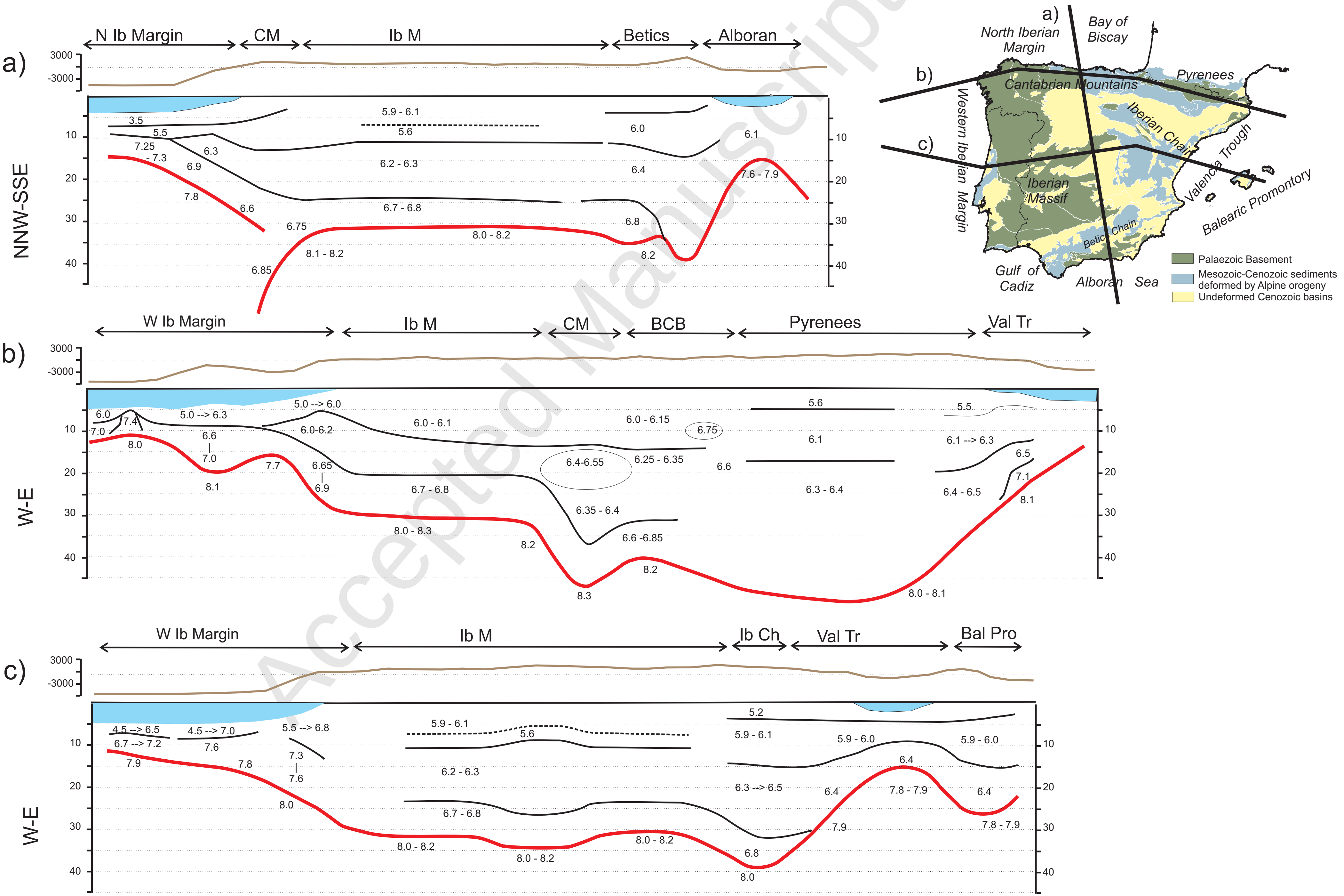
Figure 1



a)
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CM
Ib M
Betics
Alboran
NNW-SSE
North Iberian Margin
Bay of Biscay
Cantabrian Mountains
Pyrenees
Iberian Chain
Valencia Trough
Western Iberian Margin
Iberian Massif
Betic Chain
Balearic Promontory
Gulf of Cadiz
Alboran Sea
Palaezoic Basement
Mesozoic-Cenozoic sediments deformed by Alpine orogeny
Undeformed Cenozoic basins
b)
W Ib Margin
Ib M
CM
BCB
Pyrenees
Val Tr
W-E
c)
W Ib Margin
Ib M
Ib Ch
Val Tr
Bal Pro
W-E

Figure 2

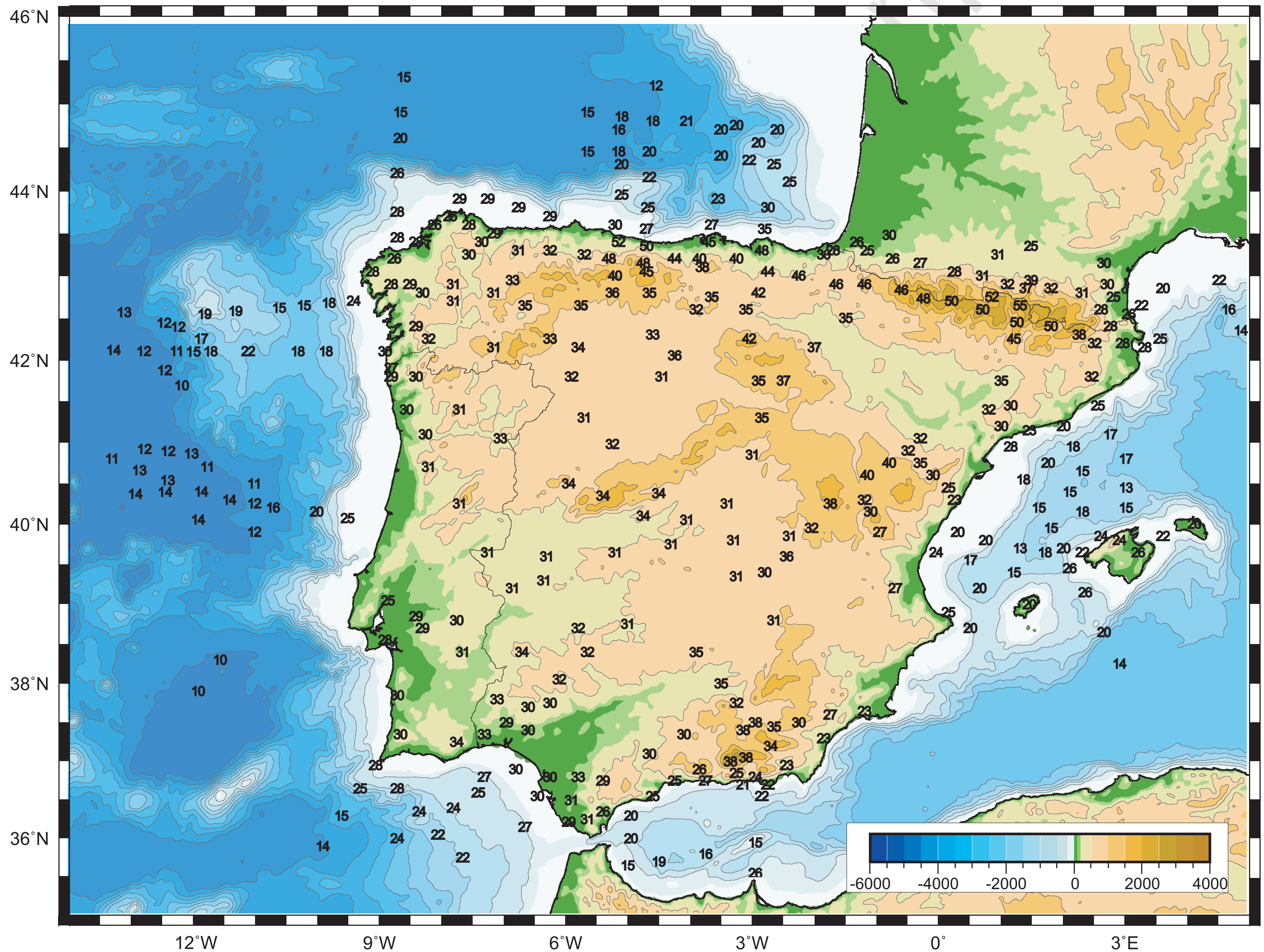
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Figure 3

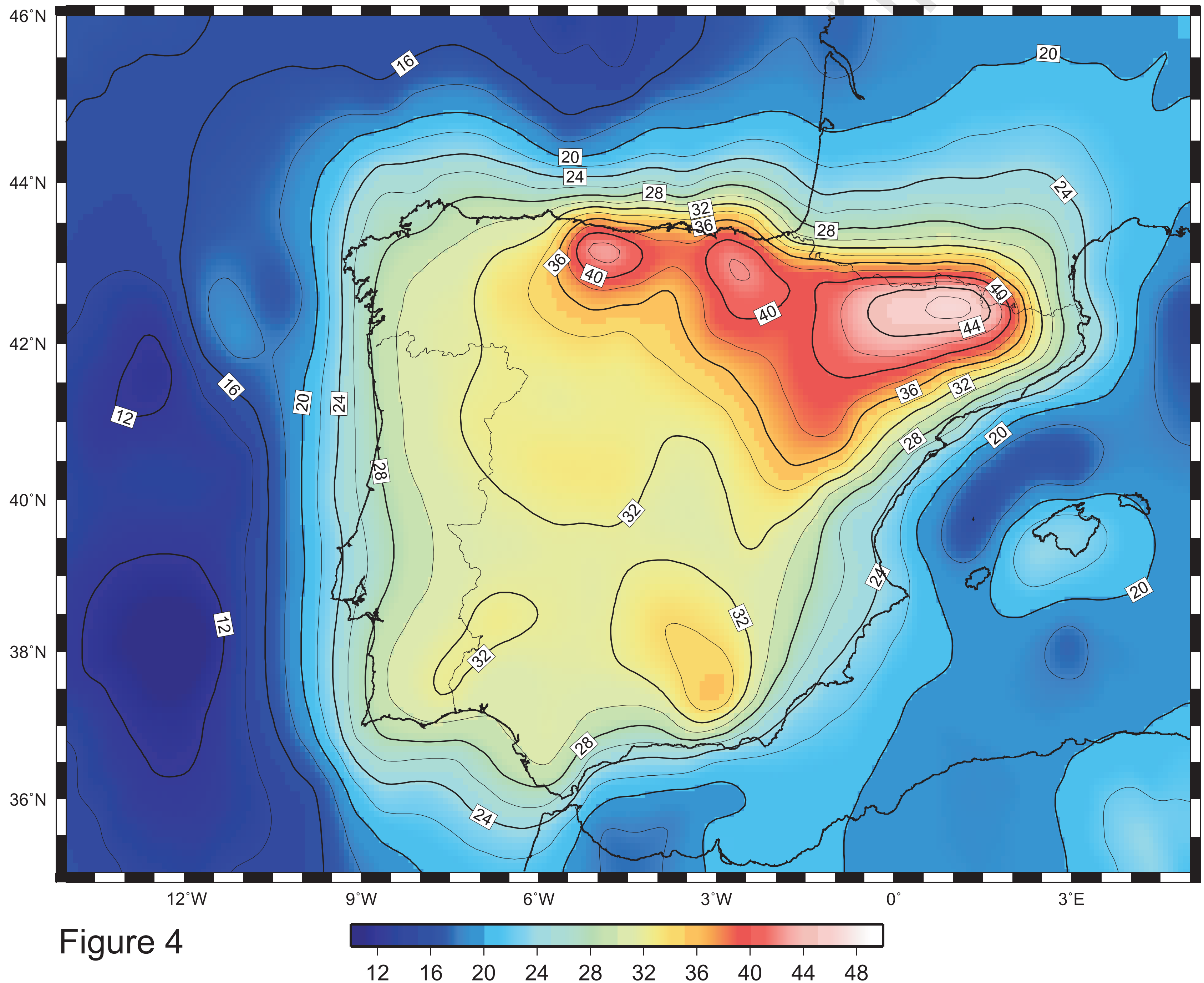

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Figure 4