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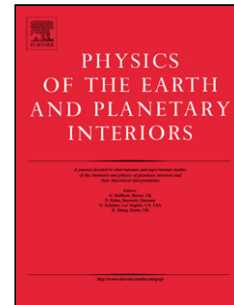
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1 **Crustal structure beneath the Iberian Peninsula and surrounding**
2 **waters: a new compilation of deep seismic sounding results.**

3

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9

10

11 **Abstract**

12

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

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

27

28 **Keywords**

29 Iberia, Crustal model, Moho depth

30

31

32 **Introduction**

33

34 Since the early 70s, the crustal structure beneath the Iberian Peninsula and its
35 continental margins has been explored by a high amount of controlled-source seismic
36 experiments, which provided information about the seismic wave velocities and the
37 geometry and depth of the main crustal interfaces. The purpose of this contribution is to
38 revisit those results, with a special emphasis in compiling the crustal depths, to provide
39 a regional Moho-depth model of the whole area. Even if information about physical
40 properties of the crust can be achieved after a number of geophysical techniques
41 (tomography, receiver functions, potential fields analysis, etc.), the wide-angle
42 reflection/refraction seismic profiles appear to be the most reliable technique to
43 constrain the velocity-depth distribution and Moho depth, as the position of the main
44 interfaces and the seismic velocity values are readily inferred from the data through
45 modelling with determinable uncertainties. First compilations of seismic crustal
46 parameters in the Iberian Peninsula were attempted by Banda et al. (1983) and Banda
47 (1988), but since then a lot of subsequent experiments have been carried out, mainly in
48 the northern part of the Peninsula, the Valencia Trough, the Betics, the Gulf of Cadiz
49 and the Iberian Massif. Compilations available at global or continental-european scales

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

57

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

71

72

73 **Outline of Iberian seismic exploration experiments**

74

75 In order to compile the crustal parameters, we have first revisited more than 50 research
76 projects developed during the last 30 years in terrestrial and marine domains around
77 Iberia. We selected those experiments focused in the whole crustal structure, carried out
78 in most cases by academic institutions, and did not consider the high resolution profiles
79 performed by oil prospecting companies, mainly focused in the sedimentary features.
80 Figure 1 summarizes the location of the compiled refraction/wide-angle reflection and
81 the multichannel reflection profiles. An enormous amount of publications have resulted
82 from these experiments, and only significant, key references are listed here on the
83 bibliography, but which may allow the interested reader to found most of the published
84 works. A more exhaustive compilation of publications is presented in Gallart et al.
85 (2006).

86
87 The pioneer seismic experiments around Iberia were marine refraction investigations,
88 using a small number of OBS or sonobuoys, carried out in the Valencia Trough-
89 Balearic domains (Fahlquist, 1963, Hinz, 1973) and in the Atlantic Margin (Purdy,
90 1975). The first seismic experiments on land were performed during the early 70's in
91 the Algarve region (S Portugal) by an international team leaded by the Zurich
92 University (Mueller et al., 1973, Sousa Moreira et al., 1978), extending soon afterwards
93 to Southern Spain (Udías 1975). In particular, a 500 km long terrestrial profile through
94 the Betics (Banda and Ansorge, 1980) and 3 lines crossing the Alboran Sea where
95 recorded using a limited number of analogical stations, shifted between repeated shots
96 at a same point to densify the profile (Working Group for Deep Seismic Sounding in
97 Alboran 1974, 1978). During the late 70's, new profiles were acquired in Southern
98 Spain, sampling the Gulf of Cadiz, the Gibraltar area, the Iberian System and the
99 Balearic Islands (Udías, 1980, Medialdea et al., 1986, Barranco et al., 1990, Zeyen et

100 al., 1985, Banda et al., 1980). The central part of the Iberian Massif was also sampled in
101 the late 70's, using quarry blasts as energy sources (Banda et al., 1981).

102

103 The Pyrenees were exhaustively explored by deep seismic profiles during the late 70's.
104 Two E-W profiles throughout the northern and southern domains of the chain were
105 recorded (Daignières et al., 1981, Gallart et al., 1981), as well as a N-S transect and
106 multiple complementary profiles in the eastern Pyrenees (Gallart et al., 1980). Up to 64
107 analogical instruments and near to 20 explosions were used, reaching station spacing
108 between 3 and 5 km. In 1984, the French "Étude Croûte continentale et Océanique par
109 Réflexion et réfraction Sismique" (ECORS) programme acquired a 300 km long, N-S
110 oriented multichannel marine profile in the Bay of Biscay (Marillier et al., 1988, Bois
111 and Gariel, 1997). In the following years, the ECORS-Pyrenees Team carried out the
112 first academic deep multichannel seismic profile on land implemented partially in
113 Iberia, that crossed the Pyrenees in a NNE-SSW direction and provided high-quality
114 data to constrain the Pyrenean orogenesis (ECORS Pyrenees Team, 1988, Choukroune
115 1989). Complementary wide-angle profiles were also acquired along the same line
116 (Surinach et al., 1993, Daignières et al., 1998). Still in the ECORS framework, another
117 transect was recorded later on in the Western Pyrenees (ECORS-Arzacq, Daignières et
118 al., 1994, Damotte, 1998).

119

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

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

137

138 In 1988 the Valencia Trough was largely explored within the VALSIS experiment. Up
139 to 200 km of multichannel seismics were acquired, including common deep point,
140 common offset point and expanding spread profiles (Watts et al., 1990, Torné et al.,
141 1992, Pascal et al., 1992). The shots from some of these profiles where recorded
142 onshore by portable seismic stations, providing the first ‘onshore-offshore’ transects in
143 Iberia (Gallart et al., 1990). The same geographical area, between the Balearic islands
144 and NE Iberia, was explored in 1989 in a wide-angle experiment, using explosive
145 sources recorded by 110 land stations and 10 OBS (Dañobeitia et al., 1992) to constrain
146 the velocity-depth structure.

147

148 In the late 80s, the large scale “Iberian Lithospheric Heterogeneity and Anisotropy”
149 (ILIHA) experiment provided relevant information about the crustal and upper mantle

150 structure beneath Iberia, including evidences of the presence of seismic anisotropy in
151 the uppermost mantle. Up to 6800 km of profiles crossing the Peninsula along different
152 azimuths where recorded with station spacing of about 4 km (Díaz et al., 1993a, 1993b).
153 In the same period, a number of new profiles crossing the Eastern Betics where acquired
154 with higher station density (Banda et al., 1993).

155

156 In the early nineties, the focus of activity shifted to multichannel reflection profiles, in
157 the framework of the Spanish “Estructura Sísmica de la Corteza Ibérica” (ESCI)
158 Program that allowed to record up to 450 km of terrestrial and 1325 km of offshore
159 seismic profiles in southern, eastern and northern Iberia. On land, an NW-SE oriented
160 profile was acquired in the Betics (Garcia-Dueñas et al., 1994), a short profile
161 connecting the ECORS line to the Mediterranean coast was implemented across the
162 Catalan Coastal Range (Gallart et al., 1994a), and two N-S and E-W profiles were shot
163 in the in Cantabrian Mountains (Pérez-Estaún, 1994, Pulgar et al. 1996, Gallastegui et
164 al., 1997). Offshore, two seismic profiles were acquired in southern Spain, one sampling
165 the northern part of the Alboran Sea in a NNE-SSW direction and the second one,
166 oriented approximately E-W, connecting to the SudBalearic basin (Booth-Rea et al.,
167 2007). The first profile was also recorded on land by a few seismic stations (Gallart et
168 al., 1995). The Alboran Sea was explored again in 1992 by a set of short (50 km)
169 refraction profiles in its NW part recorded on land by up to 24 stations (Gallart et al.,
170 1994b) and by the larger scale CONRAD experiment that recorded five multichannel
171 seismic profiles oriented approximately N-S crossing the whole basin (Watts et al.,
172 1993).

173

174 The marine component of the ESCI Programme included also the acquisition of another
175 multichannel profile in the Valencia Trough, oriented NW-SE, between Tarragona coast
176 and S of Mallorca island, recorded also onshore (Gallart et al., 1995), and allowing in
177 this way to complete a 700 km-long seismic transect from the Pyrenees to the South
178 Balearic Basin (Vidal et al., 1998). The ESCI Programme was completed in 1993 with
179 the acquisition of two profiles in the North-Iberian Margin, one oriented E-W sampling
180 the Hercynian structures and the other oriented N-S, extending northwards the
181 previously acquired land profile to obtain a transect orthogonal to the main structures
182 (Alvarez-Marrón et al., 1996, Ayarza et al., 1998). In both cases the profiles were
183 recorded by land stations to obtain wide-angle data that control the velocity structure
184 (Fernández-Viejo et al., 1998; Gallastegui et al., 2002). Extensive exploration on land of
185 the northern part of Iberia was also performed in the 90s within two research projects
186 that recorded a large E-W refraction/wide-angle reflection profile covering a total of
187 960 km from Galicia to the Pyrenees Chain, as well as a set of transverse profiles
188 sampling the transition between the Duero Basin and the Cantabrian Mountains (Pulgar
189 et al. 1996; Fernández-Viejo et al., 2000, Pedreira et al., 2003).

190

191 In the mid-nineties, the French project LISA sampled different areas of the western
192 Mediterranean from seismic multichannel profiling (Mauffret et al., 2001, Nercessian et
193 al., 2001). Five of the acquired profiles were shot in the vicinity of the eastern
194 termination of the Pyrenees and were recorded by land stations to investigate the
195 transition between the areas affected by the Alpine compression and the Neogene
196 extension (Gallart et al., 2001). However, most of acquisition activity was focused on
197 the marine seismic exploration of the Atlantic margins of Iberia, in the framework of the
198 large scale “Iberian Atlantic Margins” (IAM) European project. Up to 3500 km of

199 multichannel profiles were acquired in the North-Iberian and Atlantic margins, the
200 Gorringe bank and the Gulf of Cadiz (Banda et al., 1995). Profiles IAM12, oriented N-S
201 along the La Coruña longitude, IAM11 oriented E-W in front the central coast of
202 Portugal and IAM3, oriented NE-SW in front of Cabo San Vicente were recorded on
203 land, providing images of the continent-oceanic transition (Fernández-Viejo et al., 1998,
204 González et al., 1996; González et al., 1999). After the IAM project, additional
205 experiments were implemented in Atlantic Margins, to better constrain the seismic
206 velocity structure. A wide-angle profile, including the deployment of up to 16 OBS, was
207 shot in the same position of the previously acquired IAM9 line (Chian et al., 1999, Dean
208 et al., 2000), exploring the structure of the ocean-continent transition. The northern part
209 of the Atlantic margin was investigated in the ISE97 experiment that acquired more
210 than 4000 km of multichannel seismics, recorded also by a network of OBS and land
211 stations (Pérez-Gussinye et al., 2003, Henning and Sawyer, 2004). In 1998, the
212 BIGSETS project sampled the epicentral area of the 1755 Lisbon earthquake by up to
213 2700 km of multichannel seismic profiles.

214

215 The seismic exploration activity in the 21th century started with the investigation of the
216 tectonic evolution of the Gulf of Cadiz, where two main E-W oriented multichannel
217 seismic profiles were acquired in the framework of the TASYO project (Medialdea et
218 al., 2004). The same area was investigated in 2002 by the VOLTAIRE project, which
219 allowed the acquisition of more than 1000 km of multichannel seismic profiles (Zitellini
220 et al., 2004). The TECALB experiment, carried out in 2004, provided a set of
221 multichannel seismic profiles sampling the Eastern Alboran Sea (Comas et al., 2004). In
222 2006, the West-Med experiment, allowed the acquisition of wide-angle data in the
223 Alboran Sea and the transition to the South Balearic basin, using a network of OBS and

224 land stations (Galvé et al., 2007). The same area has been investigated in 2006 by the
225 MARSIBAL cruise, using in this case multichannel seismic profiling (Comas et al.,
226 2007).

227

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

239

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

248

249

250 **Seismic structure beneath the Iberian Peninsula and surrounding waters**

251

252 *Iberian Massif*

253

254 A large part of central and western Iberia is covered by the Iberian Massif, affected by
255 the Variscan orogeny and mostly undeformed since then. The crust is seismically
256 differentiated in three layers and shows a structure similar to other Variscan domains in
257 Europe. The basement has a thickness of 8-12 km and velocities ranging from 5.9 to 6.1
258 km/s (Banda et al., 1980). Some authors have introduced a low velocity at the bottom of
259 this layer, even if recent high resolution experiments can not confirm such a structure
260 (Palomeras et al., 2008). The intermediate crustal layer, with velocities of 6.2-6.4 km/s
261 reaches depths of 23-25 km. A lower crust, with velocities of 6.7-6.8 km/s is defined
262 above the Moho discontinuity, located at 30-33 km. A crustal root seems to be present
263 beneath the Central System, where the crustal depth reaches 34 km as a consequence of
264 a thickening of the middle crust layer (Suriñach and Vegas, 1982). Beneath the Atlantic
265 coast of Iberia, the crust displays thicknesses of 27-29 km and starts thinning toward the
266 oceanic domain (Díaz et al., 1993a). In SW Portugal, the crust has been modelled with a
267 strong gradient in the upper crust and a pronounced LVZ (Mueller et al., 1973, Sousa
268 Moreira et al., 1978). However, an alternative interpretation assuming a model closer to
269 the one obtained for central Iberia can also explain the data (González et al., 1998).
270 Multichannel seismic profiling across the Variscan belt in SW Iberia revealed the
271 existence of a mid-crustal reflective body, 140 km long and of variable thickness (up to
272 5 km), that has been interpreted as an Early Carboniferous mantle derived intrusion
273 (Carbonell et al., 2004). Wide-angle modelling along the same profile shows a 31-34

274 km thick crust, with the lower crust thickening to the center of Iberia (Palomeras et al.,
275 2008).

276

277 *Alpine Chains*

278

279 The presence of a more or less pronounced root underneath the areas that underwent
280 significant deformation during the Alpine orogeny has become apparent since the first
281 seismic investigations in Iberia. In the early 80s the crust beneath the Pyrenean chain
282 was modelled with a sedimentary layer on top of a basement with seismic velocities of
283 6.1-6.2 km/s that overlays an undifferentiated mid-lower crust below 11-14 km depth
284 where the velocities reach 6.3-6.4 km/s. The crustal thickness beneath the Pyrenean
285 axial zone reaches 45-50 km, while the northern European crust does not exceed 30 km
286 depth (Daignières et al., 1981, Gallart et al., 1981). This image was confirmed by the
287 ECORS multichannel seismic profile, which shows well-defined reflectors in the entire
288 crust with an overall fan-shape geometry, and a marked crustal thickening from the
289 southern Pyrenean domain towards the Axial zone, depicting an imbrication of the
290 Iberian crust beneath the European one (Choukroune et al., 1990). No evidences for the
291 persistence of a crustal root eastwards, toward the Mediterranean Sea have been inferred
292 either from the land refraction profiles (Gallart et al., 1980) or from the onshore-
293 offshore experiments in the eastern termination of the Pyrenees (Gallart et al., 2001).
294 The important differences in Moho depths between the Iberian and the European
295 domains observed in the central and western Pyrenees are not present in this area, which
296 is marked by a continued thinning seaward, the Moho reaching 25 km depth in front of
297 Cap de Creus.

298

299 A remarkable result derived from the extensive seismic exploration in the northern part
300 of Iberia is that all the profiles sampling areas affected by the Alpine orogeny show a
301 crustal structure similar to that inferred for the Pyrenean Chain (Fernández-Viejo et al.,
302 1998; Pedreira et al., 2003). A quasi-continuous crustal root is hence depicted along the
303 strike of the Pyrenean-Cantabrian range where Moho depths reach 46-48 km, with a
304 local, relative thinning to 40 km depth beneath the Mesozoic sediments of the Basque-
305 Cantabrian Basin. Seismic and gravity modelling in the whole area shows consistent
306 images of a crustal indentation and wedging between the Iberian and the European-
307 Cantabrian Margin crusts (Fernández-Viejo et al., 1998; Gallastegui et al., 2000;
308 Pedreira et al., 2003; 2007). A 10 km-thick lower crustal layer of 6.6-6.8 km/s is
309 modelled on top of the Moho. The presence of high velocity bodies embedded at mid-
310 crustal levels has also been inferred from the seismic data, and they have been
311 interpreted as intrusions from the European-Cantabrian Margin lower crust indenting
312 southward the Iberian crust (Pedreira et al., 2003, 2007). A significant thinning of the
313 crust to the westernmost part of the Cantabrian Mountains, where Moho depths are
314 about 30 km, depicts the transition to the zones of the Iberian Massif which had not
315 been significantly reworked by the Alpine orogeny.

316

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

324 East, the crust is only of 23 km thick, and has a high velocity body (6.9 km/s) in the
325 lower levels. West of this fault system, the presence of a LVZ 5.4 km/s at depths of 7 to
326 12 km has been inferred from the data. The crustal thicknesses vary strongly, between
327 the 38 km reached beneath Granada and the 24 km beneath Adra, close to the Alboran
328 sea (Banda and Ansorge, 1980). SW of Málaga seismic data evidences an anomalous
329 structure that could be explained by a thin crust, a massive presence of peridotites or a
330 combination of both features (Banda et al., 1993). In the Westernmost Betics Chain, the
331 upper, middle and lower crusts are evidenced, with velocities of 6.1, 6.4 and 7.0 km/s
332 underlying a sedimentary cover that has important thickness variations. The crustal
333 depth varies from 25 km under the inner arc of the Betics to 31 km in the coast west of
334 Gibraltar (Medialdea et al., 1986). Towards the Alboran Sea, the velocity-depth
335 distribution is poorly constrained from the published datasets. The crust seems to
336 quickly get thinner, reaching depths of about 15 km but without showing features of
337 oceanic crust. It overlies an uppermost mantle with apparently low velocities (Hatzfeld
338 and Bensari, 1977; Working Group for DSS in the Alboran Sea 1974, 1978).

339

340 The results available for the Iberian Chain, an area of Mesozoic cover deformed during
341 the Alpine compression, show an average crustal thickness of 30-32 km for most of the
342 chain, similar to the values in the Central Iberian Massif. However, a local thickening of
343 a few kilometers has been detected in the central northern part of the chain (Zeyen et al.,
344 1985). A similar crustal root has also been observed farther south, along a refraction
345 profile oriented NE-SW where the Moho reaches 40 km depth (Gallart et al., 2004).

346

347 *Valencia Trough*

348

349 The transition between the NE Iberian Peninsula and the Valencia Trough, a basin
350 developed during the Neogene as part of the general Cenozoic rift system of western
351 Europe, is marked by a strong thinning of the crust, changing from 35 km inland to 15-
352 18 km in the center of the basin. The crust thickens again to the SE beneath the Balearic
353 promontory, reaching 30 km beneath Mallorca island. The basement shows seismic
354 velocities of 6.0 - 6.1 km/s, while in the lower crust, where most of the crustal thinning
355 is accommodated, the velocities are of 6.4-6.5 km/s. The uppermost mantle beneath the
356 axial zone is characterized by a low velocity of about 7.8 km/s, interpreted as
357 consequence of the rifting process that affected this area. To the SE, in the South
358 Balearic basin, the crust becomes very thin (6 km) and has probably an oceanic origin
359 (Banda et al., 1980, Dañobeitia et al., 1992, Collier et al., 1994, Vidal et al., 1998).

360

361 *Atlantic and Cantabrian Margins*

362

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

371

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

374 Chian et al., 1999) and imaged with MCS profiling (Pickup et al., 1996). East of
375 $10^{\circ}45'W$, the crust is of continental type, with a smooth uprising of the Moho from 31
376 km beneath Iberia to 12 km. West of this longitude, the crust is described as transitional,
377 with an upper layer 2-4 km thick modelled with a strong velocity gradient (4.5 – 7.0
378 km/s) and a second crustal layer 4 km thick and a small velocity gradient around 7.6
379 km/s. West of $12^{\circ}40' W$ the crust is clearly oceanic, with a 2 km thick upper layer with
380 velocities 4.5-6.5 km/s over a lower layer of 3.5-4.5 km and seismic velocities of 6.7 to
381 7.2 km/s.

382

383 In front of NW Iberia, the morphology of the margin is complex with, from East to
384 West, a small continental platform, a large basin about 100 km wide (Galicia Interior
385 Basin) where the Moho depth thins to 15 km, a structural high (Galicia Bank) where the
386 Moho deepens to 22 km to thin again smoothly towards west to a minimum of 10 km
387 eastwards of the peridotitic ridge (located at around $12.5^{\circ}W$). West of this ridge, the
388 crustal structure is typical of oceanic domains (Whitmarsh et al., 1990, Murillas et al.,
389 1990, Pérez-Gussinyé et al., 2003).

390

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

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

406

407 **Summary of results: crustal transects and Moho-depth model**

408

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

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

434

435 In order to obtain a Moho-depth model for the overall area, we have first compiled the
436 geographical location of the published wide-angle and multichannel seismic profiles
437 that provide information about the whole crustal structure beneath Iberia and its
438 surrounding waters. In some cases, especially for the oldest experiments, the
439 coordinates of the profiles have been recovered directly from the published maps and
440 therefore may involve some degree of inaccuracy (Figure 1). The next step has been to
441 retrieve the Moho depths along the published profiles; if the profile was interpreted
442 assuming a 1D velocity-depth distribution, the reported Moho-depth is adopted along
443 the profile. If 2D models were available, the Moho depth was extracted for enough
444 points to take care of its topographic variations. About 320 points have been compiled
445 in this way, stretching E-W from the Atlantic oceanic crust to the Balearic Promontory
446 and N-S from the thinned crust of the Bay of Biscay to the African coast of Morocco,
447 with a mean density of about one measurement every $0.5^{\circ} \times 0.5^{\circ}$. The final compilation is

448 presented in Figure 3 and is also presented as an electronic table as complementary
449 material.

450

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

471

472

473 **Discussion and Conclusions**

474

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

486

487 One of the most significant features established since long ago is the crustal thickening,
488 reaching 50 km depth, beneath the Pyrenean range. However, the experiments
489 performed in North Iberia in the last 10 years have revealed that this thickened crust is
490 not limited to the Pyrenees, but extends westwards along the Cantabrian Mountains, up
491 to the contact with the Iberian Massif units at about 6°W, a feature that is not stated in
492 previous regional or global crustal depth compilations (Meissner, 1986, Dezes and
493 Ziegler, 2000). In the Betics, a thickening reaching 38 km is also observed, but seems to
494 be limited to a small area beneath the Internal Betics. The Iberian Chain, oriented NE-
495 SW south of the Ebro Basin, has also a crustal root reaching 40 km at its SE part. The
496 extension to the NW of this root needs still to be investigated. The northern part of the
497 Iberian Massif shows Moho depths between 32 and 40 km, illustrating the transition to

498 the thickened Alpine areas. Thicknesses of about 31-32 km have been reported at the
499 central and southern areas of the Variscan domains, even if recent high density
500 experiments suggest that the crust is slightly thicker in the southwestern zone, reaching
501 probably 33-34 km.

502

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

521

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

527

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

547 presented in our compilation and the RF estimations do not exceed 2 km, hence
548 documenting the consistency of the results inferred from two independent seismic
549 methodologies.

550

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

558

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981

982 **Figure Captions**

983

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

989

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

998

999 **Figure 3:** Compilation of crustal depth thicknesses along published deep seismic
1000 sounding profiles overlying a smoothed topographic map.

1001

1002 **Figure 4:** Interpolated crustal depth model for the whole investigated area. Colour scale
1003 depicts the crustal thickness variations. Crustal thickness isolines are represented every
1004 2 km.

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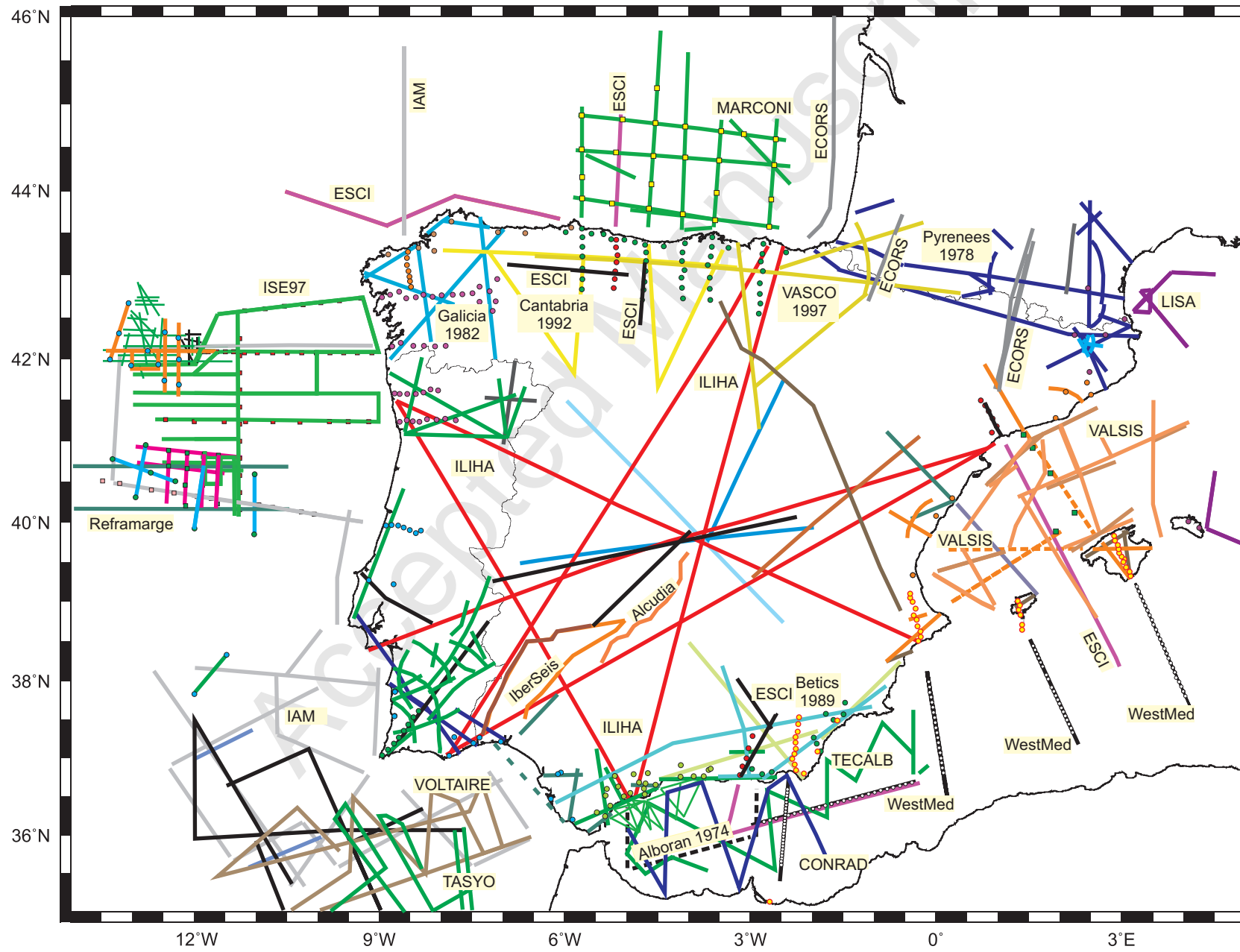


Figure 1

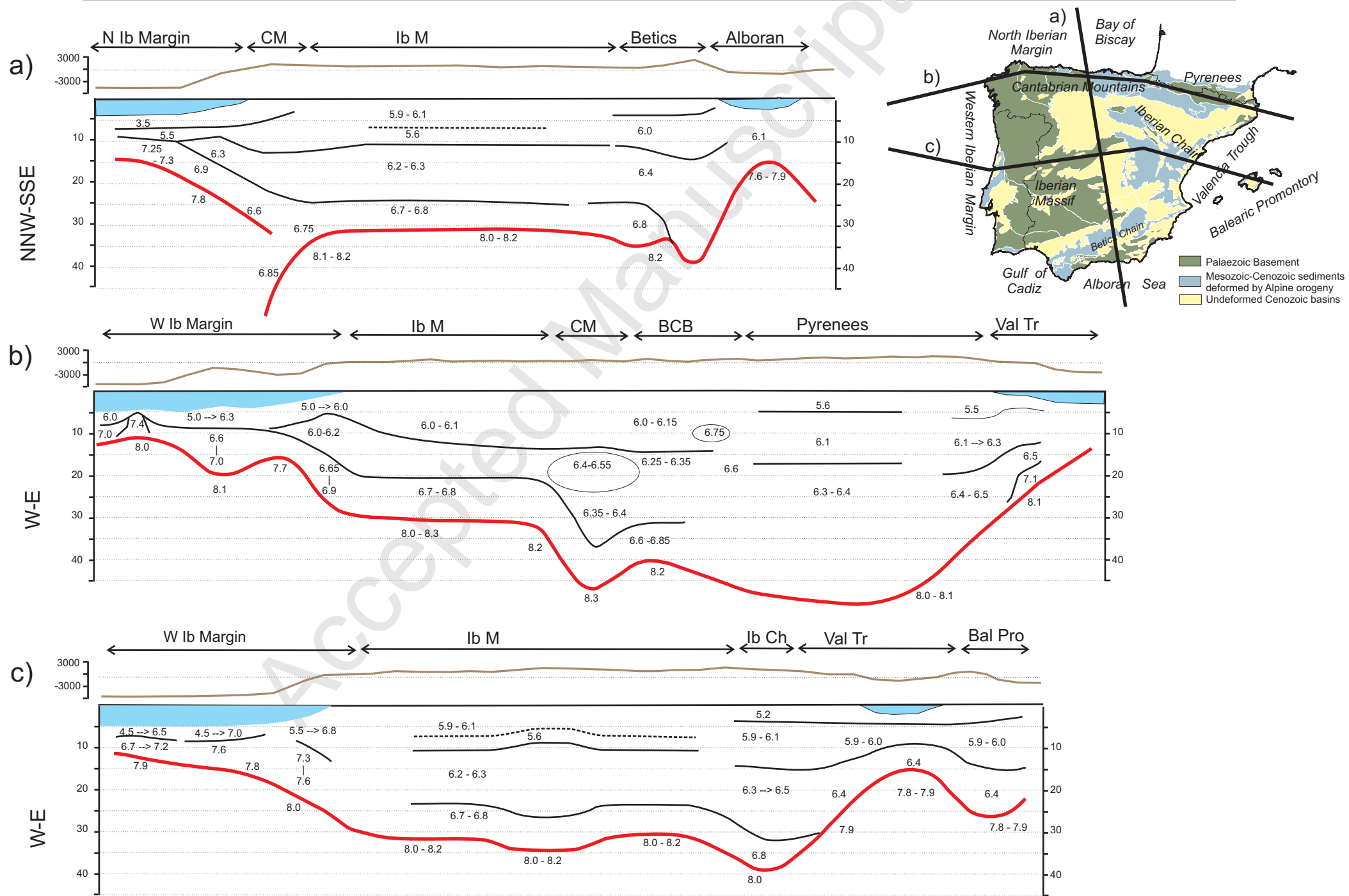


Figure 2

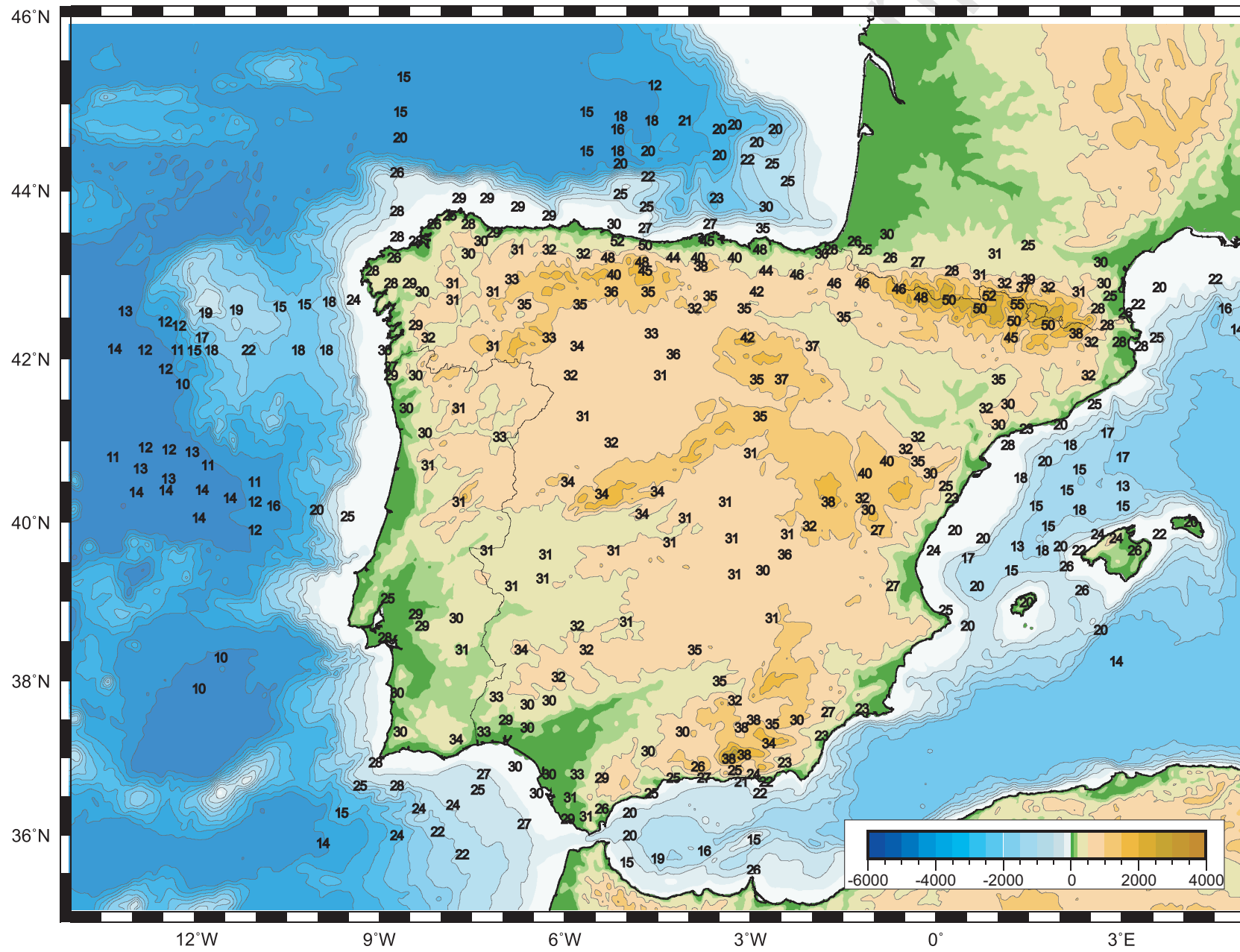


Figure 3

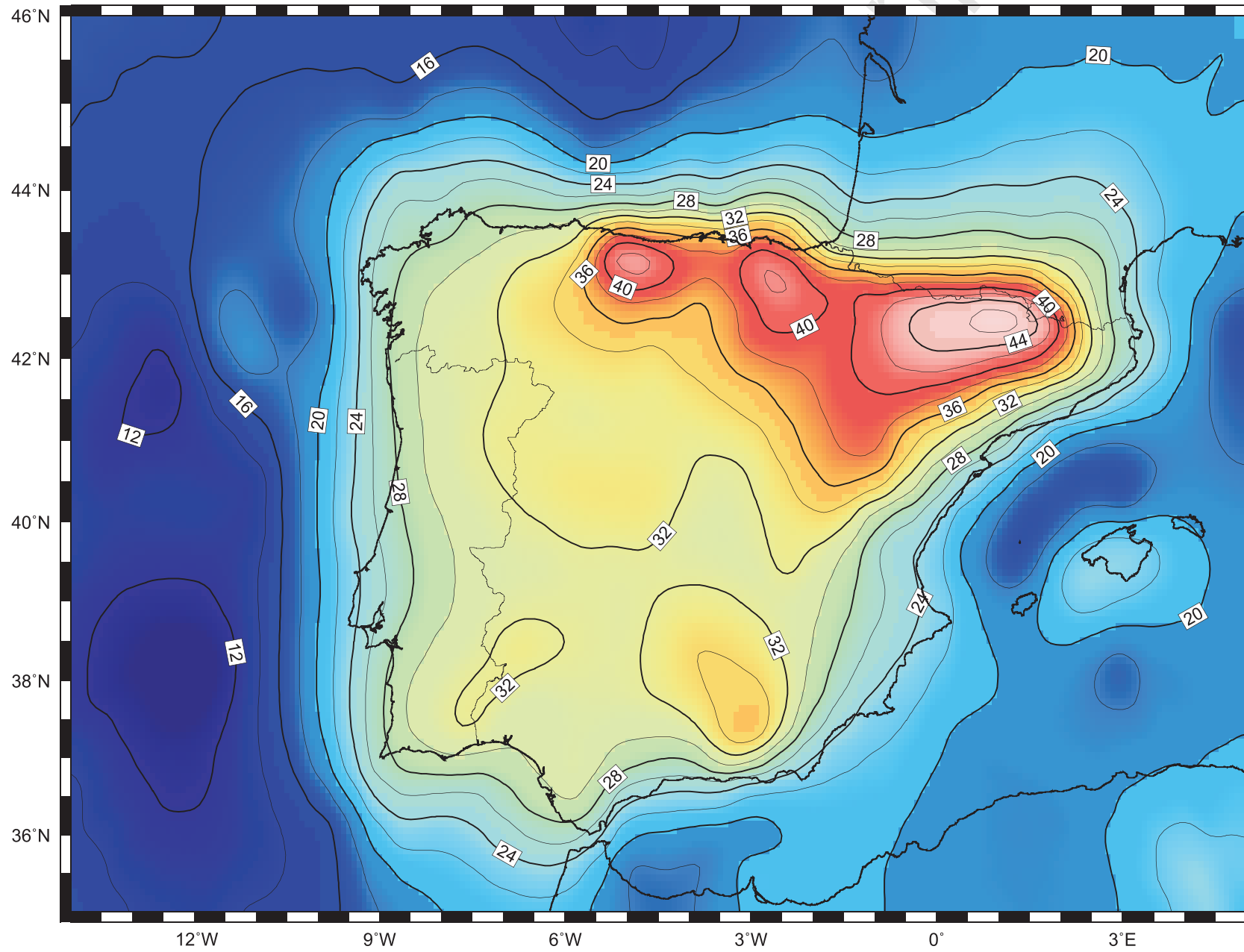


Figure 4

