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The Seismic Crustal Structure of the Ossa-Morena Zone and its geological interpretation

La estructura sísmica de la corteza de la Zona de Ossa Morena y su interpretación geológica

J. F. Simancas[1]*, R. Carbonell[2], F. González Lodeiro[1], A. Pérez Estaún[2], C. Juhlin[3], P. Ayarza[4], A. Azor[1], D. Martínez Poyatos[1], G. R. Almodóvar[5], E. Pascual[5], R. Sáez[5], A. Kashubin[3], F. Alonso[5], J. Álvarez Marrón[2], F. Bohoyo[1], S. Castillo[2], T. Donaire[5], I. Expósito[6], I. Flecha[2], E. Galadí[1], J. Galindo Zaldívar[1], F. González[5], P. González Cuadra[4], I. Macías, D. Martí[2], A. Martín, L. M. Martín Parra[7], J. M. Nieto[5], H. Palm[3], P. Ruano[1], M. Ruiz[2], M. Toscano[5].

[1] *Departamento de Geodinámica, Facultad de Ciencias, Universidad de Granada, Granada, Spain*
[2] *Instituto de Ciencias de la Tierra "Jaume Almera", C.S.I.C., Barcelona, Spain*
[3] *Department of Earth Sciences, Uppsala University, Uppsala, Sweden*
[4] *Departamento de Geología, Universidad de Salamanca, Salamanca, Spain*
[5] *Departamento de Geología, Facultad de Ciencias Experimentales, Universidad de Huelva, Huelva, Spain*
[6] *Departamento de Ciencias Ambientales, Universidad Pablo de Olavide, Sevilla, Spain*
[7] *Instituto Geológico y Minero de España, Madrid, Spain*

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Abstract

The IBERSEIS deep reflection seismic experiment has provided a crustal image of the Variscan orogen of southwest Iberia. A brief presentation of the entire seismic profile is given, and then the Ossa-Morena Zone (OMZ) and its boundaries are considered. The crust of the OMZ is shown to be divided into an upper crust, characterized by dominantly NE-dipping reflectivity, and a poorly reflective lower crust. The reflectivity of the upper crust has good correlation with the geological cross-section constructed from surface mapping. In the seismic image, the upper crustal geological structures are seen to merge in the middle crust. Nevertheless, the OMZ middle crust is not a mere detachment level, as it shows very unusual features: it appears as a band of strong reflectivity and irregular thickness (the Iberian Reflective Body, IRB) that we interpret as a great sill-like intrusion of basic rocks. The boundaries of the OMZ are considered sutures of the orogen, and their geometrical features, as deduced from geological mapping and the seismic image, are in accordance with the transpressional character of the Variscan collision recorded in SW Iberia. The present Moho is flat, obliterating the root of the orogen.

Keywords: Deep seismic reflection, structure of the crust, Variscan orogen, Ossa-Morena Zone

Resumen

El experimento de sísmica de reflexión profunda IBERSEIS ha proporcionado una imagen de la corteza del Orógeno Varisco en el sudoeste de Iberia. Este artículo se centra en la descripción de la corteza de la Zona de Ossa Morena (OMZ), que está claramente dividida en una corteza superior, con reflectividad de buzamiento al NE, y una corteza inferior de pobre reflectividad. Las estructuras geológicas cartografiadas en superficie se correlacionan bien con la reflectividad de la corteza superior, y en la imagen sísmica se ven enraizar en la corteza media. Ésta está constituida por un cuerpo muy reflectivo, interpretado como una gran intrusión de rocas básicas. La imagen de las suturas que limitan la OMZ muestra el carácter fuertemente transpresivo de la colisión orogénica varisca registrada en el sudoeste de Iberia. La Moho actual es plana y, en consecuencia, no se observa la raíz del orógeno.

Palabras Clave: Sísmica profunda de reflexión, estructura de la corteza, orógeno varíscico, zona Ossa Morena.

1. Introduction and geological setting

A deep seismic reflection profile (IBERSEIS), 303 km long, has been recently acquired in southwest Iberia, in order to investigate the crustal architecture of this region. The seismic profile runs across the amalgamated South Portuguese (SPZ), Ossa Morena (OMZ) and Central Iberian (CIZ) zones, and their tectonic boundaries (Fig. 1). The crustal image of southwest Iberia thus revealed is a major step in the understanding of this transect of the Variscan orogen. Detailed descriptions and discussions of the IBERSEIS seismic profile can be found in Simancas *et al.*, (2003) and Carbonell *et al.*, (in press). The present paper summarizes information given in those papers, focusing on the OMZ and its boundaries.

The Variscan Belt in Iberia has been originated from a continent-continent collision between an Ibero-Armorican indentor of Gondwana and a northern continent, Laurussia (Brun and Burg, 1982; Matte, 1986). Both boundaries of the OMZ (Fig. 1), the southern one (Fonseca and Ribeiro, 1993) and the northern one (Matte, 1986), have been interpreted as sutures of this continental collision, and must have been connected in some way (Brun and Burg, 1982; Ribeiro *et al.*, 1995; Simancas *et al.*, 2002) to the allochthonous tectonic units with high-pressure metamorphism and ophiolites cropping out in northern Iberia (Arenas *et al.*, 1986; Ribeiro *et al.*, 1990a).

Marking the suture between the OMZ and the SPZ (Fig. 1) there is a strip of oceanic amphibolites, the Beja-Acebuches amphibolites (Bard, 1977; Andrade, 1983; Munhá *et al.*, 1986; Quesada *et al.*, 1994), and a tectonic unit, the Pulo do Lobo, made up by phyllites, quartzites and oceanic metabasalts (Silva *et al.*, 1990; Eden and Andrews, 1990). Small klippen including high-pressure continental rocks and ophiolites, which crop out in southwest OMZ, have been considered also as elements of that suture (Fonseca *et al.*, 1999).

The boundary between the OMZ and the CIZ is marked by the Badajoz-Córdoba Shear zone or Central Unit (Burg *et al.,* 1981; Azor *et al.,* 1994; Simancas *et al.,* 2001), a tectonic unit which includes lenses of retroeclogites (Abalos, *et al.*, 1991; Azor, 1994; López Sánchez-Vizcaíno *et al.*, 2003) and amphibolites with oceanic chemical signature (Gómez Pugnaire *et al.*, 2003). All authors agree that this unit marks a major tectonic contact, but there are two different interpretations: (i) the OMZ/CIZ boundary is a Cadomian suture reactivated as an intraplate shear zone during the Variscan orogeny (Ribeiro *et al.*, 1990b; Quesada, 1991; Abalos *et al.*, 1991); (ii) the OMZ/CIZ is a true Variscan suture (Brun and Burg, 1982; Matte, 1986; Azor *et al.*, 1994; Simancas *et al*, 2001). The radiometric ages for the high-grade metamorphism in the rocks outcropping along this boundary are Variscan, thus supporting the second interpretation, but unfortunately fail consistence between them (Schäfer, 1990; Schäfer *et al.,* 1991; Ordóñez Casado, 1998). We favor the interpretation of this boundary as a Variscan suture, suggesting that it was connected through a transform with the hidden root of the allochthonous tectonic units of northwest Iberia (Simancas *et al.*, 2002). In our view, southwest Iberia has built from the amalgamation of three continental blocks: the SPZ, the OMZ, and the ensemble of the CIZ, West-Asturian-Leonese and Cantabrian zones (Fig. 1). The three latter ones would be part of the Gondwana margin while the SPZ seems to have been part of the Avalonian border of the opposite continent. The OMZ is viewed as a Gondwana-related terrane (Matte, 2001; Simancas *et al.*, 2002). The IBERSEIS deep seismic reflection profile runs across this collage of amalgamated terrains.

2. General features of the IBERSEIS seismic image

The IBERSEIS seismic image (Fig. 2a) features numerous reflection events (Fig. 2b), some of which can be traced to the surface. The Moho, marked by a sharp decrease in reflectivity, is placed at approximately 10.5 s along the entire profile. The seismic image reveals several specific domains that can be put in correspondence with the different tectonic zones recognized in this orogen: the SPZ in the south, the OMZ located in the center and the CIZ to the northeast.

The upper crust of the SPZ shows very distinctive packages of continuous high-amplitude reflections dipping 30º-50º towards the North, which merge into a poorly reflective band in the middle of the crust (Fig. 2). In contrast, subhorizontal reflections and a few SW-dipping reflection packages characterize the fabric of the SPZ lower crust.

In the OMZ, there is also a clear difference in the reflectivity of upper and lower crust, both in terms of orientation and intensity: reflectivity is sub horizontal and very poor in the lower crust and dipping and more abundant in the upper crust. The OMZ lower crust lacks localized reflections, in contrast with the SPZ lower crust and with the

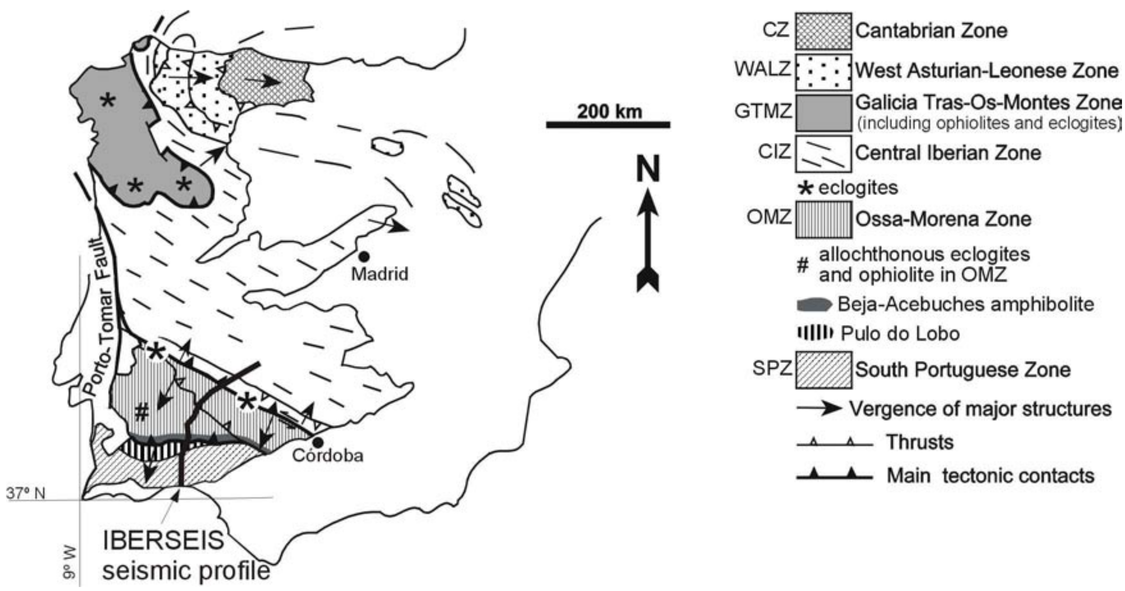

Fig. 1.- The Iberian Massif with the location of the IBERSEIS deep seismic reflection profile.
Fig. 1.- El Macizo Ibérico y localización del perfil de sísmica de reflexión profunda IBERSEIS.

crust under the CIZ (Fig. 2).

An impressive feature of the seismic image is the broad band of high amplitude reflectivity located at mid-crustal level, between 4 and 6 s, in the OMZ and part of the CIZ.

3. The seismic fabric of the OMZ and its boundaries

Straddling the boundary between the SPZ and the OMZ, from CDP 3950 to 5260, the IBERSEIS profile shows a series of steeply-dipping reflections, fan-like in shape and merging at 5 s (Figs. 2 and 3). The southernmost reflection of that fan (PT in Fig. 3) coincides at surface with the thrust bounding the Pulo do Lobo unit; the northernmost reflection of the fan (AF in Figure 3) is the first prominent seismic event of the OMZ upper crust. Farther to the northeast, there exists gently-dipping reflectivity (a in Fig. 3), and infrequent southwest-dipping events are identified between CDPs 6800 and 7200 at 2-3 s (b in Fig. 3). Between CDPs 8000 and 8700, seismic events dipping 40º-45º to the northeast extend from 1 s to 4.5-5 s (c in Fig. 3), nearly in direct connection with the Monesterio thrust mapped at surface by Eguiluz (1987) and Expósito *et al.* (2002). A broad band of high-amplitude reflectivity (CDP interval 10000-11000), dips approximately 30º-35º to the northeast (N1 in Fig. 3). The Central Unit bounding the OMZ and the CIZ is well imaged as a straight band of reflections dipping to the northeast from CDP 10900 (CU in Fig. 3). The upper crust of the adjacent CIZ features less prominent reflections than the OMZ and the SPZ, except for a NE-dipping series of events located between 1 and 4 s (Figs. 2 and 3). Between CDPs 11500 and 12000 a weak fabric is identified dipping 30º to the southwest (e in Fig. 3); the southwest dip contrasts with the one in the adjacent OMZ, and together they delineate a bivergent structure. Farther to the northeast, between CDPs 12000 and 14750, northeast dipping seismic events appear in the upper crust at 2 to 4 s (labeled N2, N3, N4, N5, in Fig. 3).

The lower crust under the OMZ is mostly transparent. However, between CDPs 7400-8500, the reflectivity of the lower crust is marked by reflections dipping to the northeast that extend from the middle crust and reach the Moho (S in Fig. 3). The lower crust under the OMZ between CDPs 9000-13500 is nearly transparent. On the contrary, from CDP 13000 to the end of the profile the reflectivity of the lower crust is very intense (W in Fig. 3). These reflections dip in opposite senses, defining a wedge-like structure.

As mentioned above, a prominent feature in this part of the seismic profile is the 1.5-2 s continuous thick band of high amplitude reflectivity, located at 6 s beneath CDP 6400 and shallowing towards the northeast, where it is located at 3.5 s beneath CDP 15000. We have called it the Iberseis Reflective Body (IRB). This body is irregular in thickness; it tapers away towards the northeast, but to the southwest it is abruptly truncated (W in Fig. 3; see also Fig. 2). The IRB is composed of many lens-shaped reflection packages with a distinct seismic fabric.

4. Geological interpretation

We argue that the IBERSEIS seismic image (Fig. 2) shows essentially the frozen architecture of the orogen

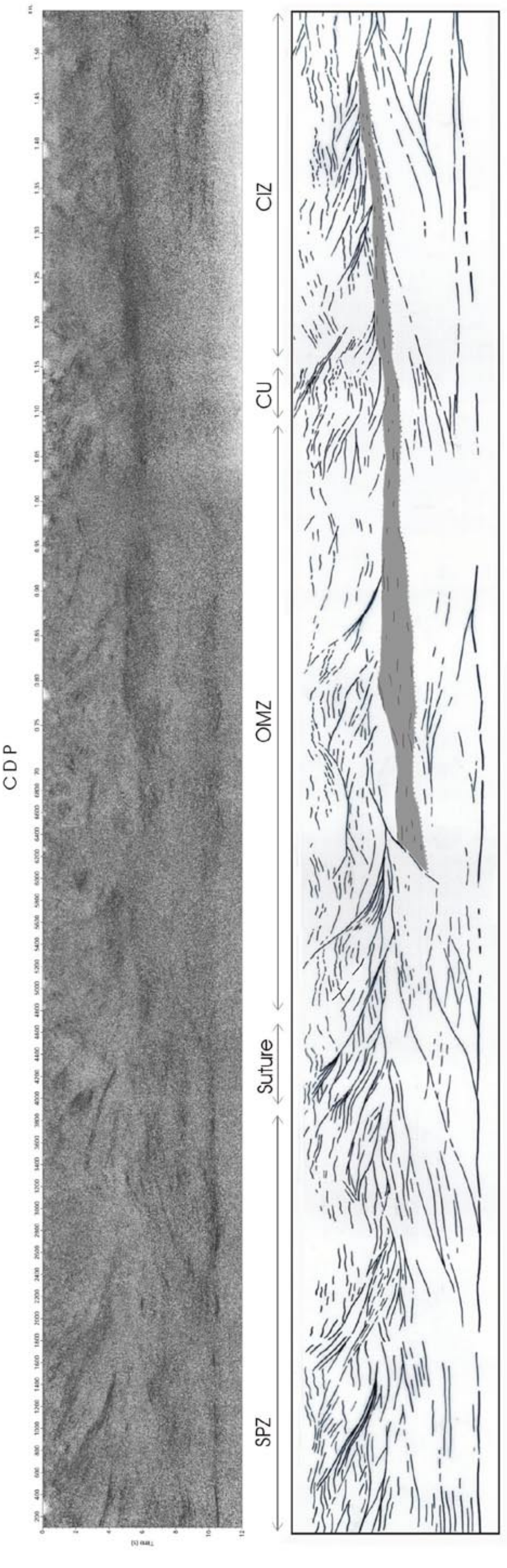

Fig. 2.- a) The IBERSEIS migrated crustal seismic image of SW Iberia; b) hand-drawing of reflectors in the IBERSEIS profile.
Fig. 2.- a) Imagen sísmica migrada IBERSEIS de la corteza del SW de Iberia; b) Dibujo de los reflectores del perfil IBERSEIS.

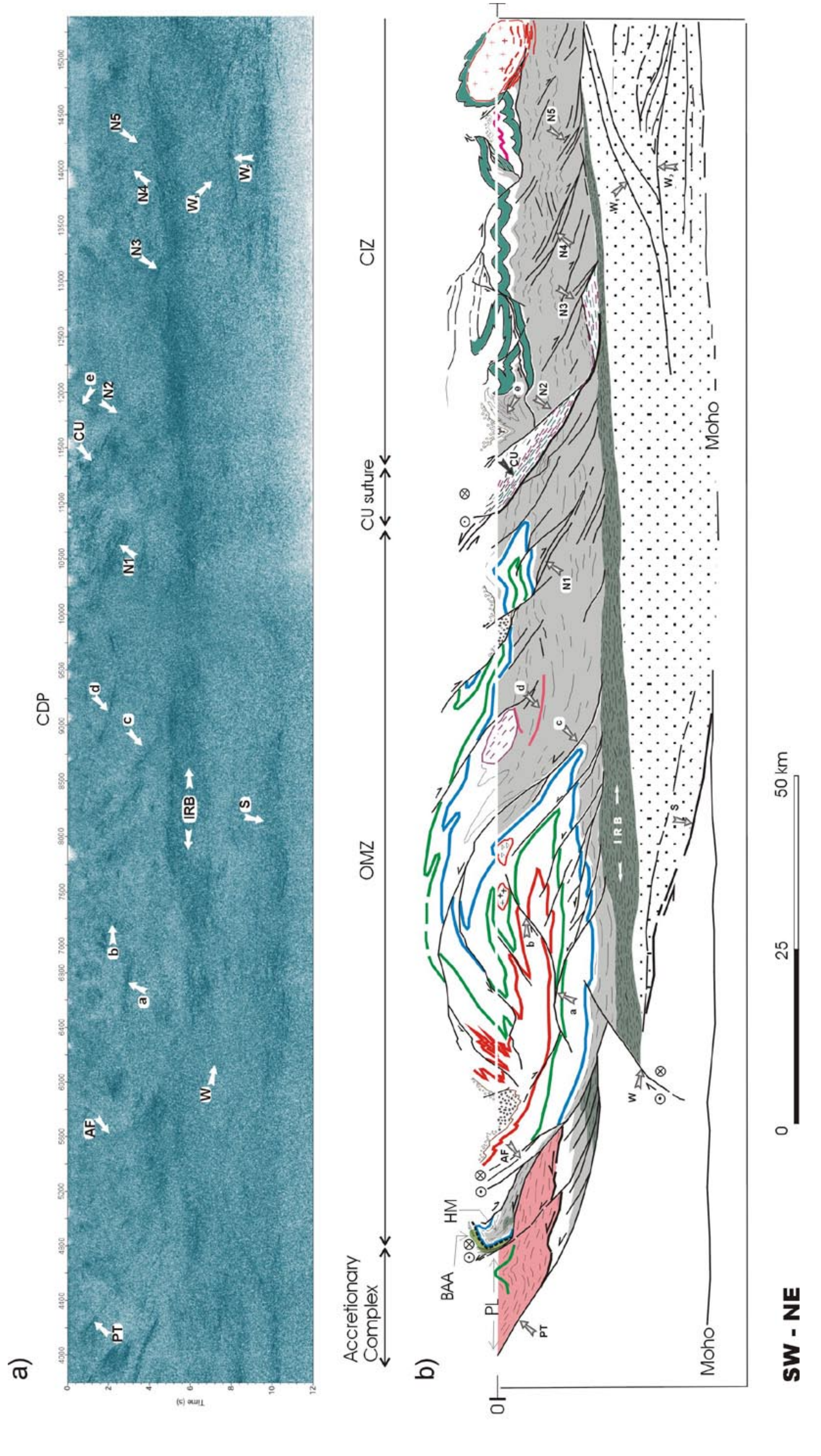

Fig. 3.- a) MIgrated crustal seismic image of the Ossa-Morena Zone and its boundaries; b) geological interpretation.
Fig. 3.- a) Imagen sísmica migrada de la corteza de la zona Ossa Morena y de sus límites: b) Interpretación geológica.

at the end of the Variscan collision. This statement needs, however, a brief discussion about the possible influence of pre-Variscan (Precambrian) and post-Variscan (Alpine) events on the observable crustal architecture.

Upper Precambrian rocks cropping out in southwest Iberia show at some localities Late Precambrian (Cadomian) deformation (Blatrix and Burg, 1981; Dallmeyer and Quesada, 1992), and uppermost Precambrian to lowermost Cambrian calc-alkaline igneous rocks indicate subduction at that time (Sánchez Carretero *et al.,* 1990; Martínez Poyatos, 1997; Pin *et al.*, 1999a). Despite this evidence, detailed structural studies has led us to conclude that Precambrian deformation is poorly penetrative in the OMZ upper crust (Expósito, 2000; Simancas *et al.*, this volume), and can be hardly represented in the seismic fabric. As for the post-Variscan events, the opening of the Atlantic appears not to have affected the crust of the surveyed area, because the crust starts to thin further to the south of the IBERSEIS profile (Matias, 1996; González *et al.*, 1998). On its own, Alpine deformation produced the Betic Orogen in southeastern Iberia, but in southwest Iberia geomorphic and structural studies indicate only minor Alpine reworking of some existing faults, and moderate regional uplift (Stapel, 1999). Accordingly, we argue that the vast majority of structures that have been seismically imaged in the upper crust of southwest Iberia were formed during the Variscan Orogeny.

The case of the lower crust can be different, as it very probably retains the record of Precambrian and/or Early Palaeozoic events. There are, nevertheless, geometric evidences suggesting that in the lower crust under the SPZ and the CIZ a few prominent reflections are also Variscan.

5. Boundary between SPZ and OMZ: the image of a transpressional suture

The Pulo do Lobo Unit (PL in Fig. 3), interpreted as an accretionary prism (Silva *et al.*, 1990; Eden and Andrews, 1990), and the Beja-Acebuches ophiolitic amphibolites (BAA in Fig. 3; Munhá *et al.*, 1986; Quesada *et al.*, 1994; Castro *et al.*, 1996) are the units marking the boundary SPZ/OMZ. We group them here under the name of Accretionary Complex. To the north of the Accretionary Complex, high-grade continental metamorphic rocks form the southern border of the OMZ (HM in Figure 3), geometrically overlying the Beja-Acebuches ophiolite (Bard, 1977; Crespo Blanc, 1989; Castro *et al.*, 1999).

The southern boundary of the Accretionary Complex is the Pulo do Lobo thrust (PT in Fig. 3). The northern boundary is a shear zone between the Beja-Acebuches ophiolite and the continental rocks of the OMZ (Crespo Blanc, 1989), but neither this shear zone nor the thin ophiolite are clearly imaged in the profile. The internal reflectivity of all these units is weak and the base of the Accretionary Complex cannot be considered well defined from the seismic image (Fig. 3).

The Accretionary Complex plus the adjacent continental rocks of the OMZ are intensely sheared by a fan-like ensemble of later faults (between CDPs 3950 and 5200; Figs. 2 and 3). The faults of this fan merge together at 5 s; they have a left-lateral component of displacement, which is very important in the Aroche fault (AF in Fig. 3). The left-lateral displacements indicated by ductile shear zones as the one affecting the Beja-Aracena ophiolite (Crespo Blanc and Orozco, 1988), and by the above referred later faults, are responsible for the missing of some units in the IBERSEIS profile. Small ophiolitic klippen imbricated with high-pressure continental rocks in the southwest of OMZ (Fonseca *et al.*, 1999), west of the IBERSEIS transect, may be a small representation of these missing units. Accordingly, the IBERSEIS section shows a strongly modified image of the suture between the OMZ and the SPZ.

In the middle-to-lower crust under the suture zone, a steep boundary can be traced (W in Fig. 3) marked by the abrupt truncation of the mid-crustal reflectivity of the OMZ. This lateral change in seismic fabric is considered the boundary between the SPZ and the OMZ crusts at this level. Within the lower crust of the OMZ, beneath 8 s, the seismic line images two north-dipping reflections (S in Fig. 3) which we interpret as the deepest seismic expression of the suture.

6. The crust of the Ossa-Morena Zone

The OMZ upper crustal reflectivity shows the existence of large synforms and antiforms, and steeply-dipping reflection bands, the latter ones mostly corresponding to faults. The imaged folds (i. e., the Terena synform, CDPs 5500-7000, and the Monesterio antiform, CDPs 7000-9000) belong to a late folding event. Kilometer-scale recumbent tight folds (Vauchez, 1975; Expósito *et al.,* 2002) are not seismically imaged due to their small interlimb angle. In the southern part of the OMZ, the steeply-dipping reflections correspond mostly to thrusts, the most important and best imaged being the Monesterio thrust (c in Fig. 3; Eguiluz, 1987; Expósito, 2000). Other prominent reflections (labeled a, b) that truncate fine reflectivities are also interpreted as thrusts. In the northern part of the OMZ, most of the steep reflections seem to be normal faults, the most important being the one labeled as N1, which connects with the southern boundary of the Santos de Maimona Lower Carboniferous basin. Thrusts and normal faults merge into the mid-crustal band of strong reflectivity, the IRB.

The lower crust of the OMZ is characterized by poor reflectivity, and we interpret that this is due to geological reasons and not to amplitude losses due to the overlying IRB. If this interpretation is correct, the seismic image would indicate significative differences between the OMZ and the SPZ lower crusts. The intense reflection events in the lower crust under the southern border of the CIZ show cross-cutting relationships, suggesting a lower crustal wedge built up by thrusts (Fig. 3). The resulting stack lifts up the IRB, and it could be related to the generation of the broad antiform known as Extremadura dome, which crops out just northeast of the IBERSEIS profile.

The IRB is the most salient feature of the IBERSEIS seismic profile. It is a conspicuous reflection sequence 150 km long, with an average thickness of 1.5 s, located between 6 s beneath CDP 6000 and 3.5 s beneath CDP 15000 (Figs. 2 and 3). As previously mentioned, the IRB is characterized by lateral changes in thickness, and consists of an amalgamation of lenses with internal seismic fabrics. It features relatively high velocities and densities when compared with the background velocity field. The IRB coincides with a decollement level, but the seismic image of the IRB does not seem to correspond to a decollement structure because of its irregular wavy shape and internal structure. We propose that the IRB is an intrusion of mafic magmatic bodies of mantle origin into a structurally controlled level, probably a main decollement.

Surface geological data support the interpretation given above for the IRB. The OMZ is characterized by the existence of abundant mafic intrusions and volcanism of Lower Carboniferous age (Bard and Fabries, 1970; Capdevila *et al.,* 1973; Aparicio *et al.,* 1977; Sánchez Carretero *et al.,* 1990). On the other hand, Ni-Cu ore deposits have been mentioned in the OMZ in relation to mantle-derived gabbroic intrusions (Tornos *et al.,* 2001; Casquet *et al.*, 2001). Radiometric ages for this magmatism cluster around 340-350 Ma (Dallmeyer *et al.,* 1993, 1995; Casquet *et al.,* 1998; Pin *et al.*, 1999b; Montero *et al.,* 2000), in accordance with geologically inferred ages. On this ground, we propose that the IRB is an Early Carboniferous mafic to ultramafic intrusion within a main mid-crustal detachment.

7. The boundary between OMZ and CIZ

Between CDPs 10900 and 11450, a wedge of northeast-dipping reflectivity cuts across the reflectivity on both sides of it (Figs. 3 and 4). At surface, this wedge corresponds to the fault-bounded outcrop of metamorphic rocks of the Central Unit (the Badajoz-Córdoba Shear Zone of other authors). The seismic contrast of this band has correspondence with its lithologic and metamorphic singularity: it includes amphibolites, orthogneises, paragneises, schists and very rare occurrences of peridotite. The reflectivity in the Central Unit shows a lower part characterized by high-amplitude energy (CU in Fig. 3); it corresponds to gneisses and amphibolites, which are dominant in the lower part of the Central Unit, whereas the less reflective upper part with wavy reflections corresponds to schists. The northern boundary of the Central Unit shows truncation of reflections, thus defining the Matachel fault (N2 in Fig. 3). The Matachel fault cuts the internal reflectivity of the Central Unit, which progressively thins downwards.

The metamorphic evolution of the Central Unit is characterized by an initial high pressure/high temperature event with peak conditions of at least 15 kbar and 700° C (Abalos *et al.*, 1991; Azor, 1994; López Sánchez-Vizcaíno *et al.*, 2003). Acording to the above referred interpretation of this tectonic contact as a Variscan suture (Matte, 1986; Azor *et al.*, 1994; Simancas *et al.*, 2001, 2002), the high-pressure metamorphism is related to the Variscan underthrusting of the Central Unit beneath the southern border of the CIZ, in an early compressional stage whose record has been erased by a later, mainly left-lateral, very penetrative ductile shearing.

As in the boundary between the SPZ and the OMZ, out-of-the-plane (left-lateral) movements have blurred here the image of the suture zone. Nevertheless, some reflections at the northern edge of the OMZ are seen to dip under the Central Unit, indicating that the OMZ is the footwall of the suture between the OMZ and the CIZ.

8. Final comments and conclusions

The high-resolution crustal image given by the IBERSEIS seismic experiment (Fig. 2) shows a thrust pattern within the SPZ, which is characteristic of foreland thrust and fold belts. The thrusts dip to the northeast and merge in the middle crust, indicating a decoupling zone at this level. A different structural pattern (including SW-vergent recumbent folding) characterize the upper crust of the OMZ, but here again the upper crustal structures are seen to accommodate in the middle crust. This is also the case of a set of northeast-dipping reflectors interpreted as normal faults, which dominate the structural grain of the northernmost OMZ and the southern CIZ (Fig. 3).

Surface geological studies in SW Iberia give unambiguous evidence for transpressional (left-lateral) tectonics. The Late Carboniferous fault systems developed at both boundaries of the OMZ (Simancas, 1983; Quesada, 1991; Crespo Blanc, 1992) are perhaps the best expression of left-lateral displacements, but there are also previous oblique-slip synmetamorphic shear zones (Crespo Blanc and Orozco, 1988; Azor *et al.*, 1994) of Early Carboniferous age (Dallmeyer *et al.,* 1993; Ordóñez Casado*,* 1998), preferentially located again in the OMZ boundaries. Furthermore, regional scale mapping reveals tapering and sigmoidal shape of a number of geological units. In the IBERSEIS seismic profile, transpressional evidences are mainly observed at the boundaries between major zones. At the SPZ/OMZ boundary, reflections PT, AF and others (Fig. 3) correspond to faults with variable lateral strike-slip components, and the fan-like image of these faults as seen in the crustal cross-section completes the 3-dimensional geometry of the wedging of some geological units. Features of transpression are observed also in the OMZ-CIZ boundary, where the Central Unit has been imaged as a wedge-shaped structure at depth (Fig. 3). Out-of-the-plane displacements can thus be the main reason why the boundaries SPZ/OMZ and OMZ/CIZ lack or have a poor representation of some units characteristic of sutures in other collision zones.

A general decoupling between upper and lower crust is evident from the asymptotic geometry of all faults towards the middle of the crust (Fig. 2). Accordingly, the seismic image demonstrates that a large amount of the transpressional movements (shortening on-the-plane and lateral displacement out-of-the-plane) is resolved independently in the upper crust. Nevertheless, small amounts of deformation have been accommodated in the lower crust as suggested by the abrupt truncation of the OMZ seismic fabric by reflection W (Fig. 3), and by interpreted back-thrusts within the lower crust of the SPZ (Fig. 2).

The long, thick, irregular, strongly reflective band in the middle of the OMZ crust (the Iberseis Reflective Body, IRB) is a major feature of the IBERSEIS seismic profile and a very unusual seismic structure. Our interpretation for the IRB as a great magmatic mafic reservoir emplaced at a mid-crustal level, following a mechanical discontinuity (i.e., a mid-crustal decollement), gives a frame to explain a number of important petrological and metallogenic data that have been reported in SW Iberia but remained poorly understood. A discussion of this important issue has been developed in Simancas *et al.*, (2003).

The crust is 30-35 km thick all along the IBERSEIS profile, as suggested by the horizontal Moho reflection located at approximately 10.5 s. The Moho reflection beneath the SPZ is sharp and high-amplitude; at surface, the erosion level of most of the SPZ is shallow. According to these observations, it seems that: a) in the SPZ there was no significant crustal thickening; b) the Moho imaged in this part of the IBERSEIS profile is mainly an old pre-Variscan Moho, scarcely modified during the Variscan collision time. Under the OMZ, the Moho is discontinuous and the lower crust is nearly transparent, two facts that are open to a number of explanations. Further to the northeast, under the CIZ (Figs. 2 and 3), arcuate reflections within the lower crust connect asymptotically with a sharp multicyclic reflection, suggesting a Moho of mostly tectonic origin. Considered in its entirety, the Moho is flat and subhorizontal, suggesting that it is mainly a late-orogenic or postorogenic structure that has obliterated the orogenic root of this collisional orogenic region.

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