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A review of the current knowledge of the crustal and lithospheric structure of the Valencia Trough Basin

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ABSTRACT

In this paper, we review the current geophysical knowledge of the Valencia Trough Basin, and the surrounding areas. For this purpose, we summarize the most significant regional geophysical datasets acquired since the seventies to investigate the trough (seismic, gravity, geoid and heat flow data). We then focus on the discussion regarding the geometry and physical properties of the present day crustal and lithospheric structure derived from seismic images, as well as combined potential field modelling and their relationships with the Alpine geodynamic evolution of the Valencia Trough. Finally, we discuss the differences in the results regarding the geometry of the lithosphere-asthenosphere boundary obtained by different modelling approaches and the features that, in our view, require further investigation to unravel the true nature of the Valencia Trough, including what could have caused the differences between the crustal structure observed in the SW region compared to the NE region, the asymmetric style of thinning across the trough; the origin of the changes in the lower crustal reflectivity across the basin; the fabric of the uppermost mantle, characterized by anomalously low P-wave velocities; and the physical properties of the lithosphere mantle (density, P-waves velocity, thermal conductivity, temperature distribution, mineralogical composition, etc.).

Key words: 2D and 3D modelling, geophysical data, lithospheric structure, Valencia Trough.

Estructura cortical y litosférica de la Cuenca del Surco de Valencia: Revisión del estado actual del conocimiento

RESUMEN

En este artículo se presenta una recopilación de la estructura cortical y litosférica de la cuenca del Surco de Valencia y sus áreas circundantes. En él se resumen los datos geofísicos más relevantes adquiridos desde los años setenta (sísmica, gravimetría, geoide y flujo de calor). A continuación, el trabajo se centra en la discusión acerca de la geometría y propiedades físicas de la estructura cortical y litosférica actual obtenida a partir de los datos sísmicos y de la modelización de campos potenciales, elevación y flujo de calor, y su relación con la evolución geodinámica alpina del Surco de Valencia. Se discute las diferencias de los resultados de la modelización del límite litosfera-astenosfera, obtenidos utilizando diferentes metodologías así como las características que, bajo nuestro punto de vista, requieren un estudio más detallado con el objeto de conocer el origen y evolución del Surco de Valencia; cuales son las causas de la distinta estructura cortical observada en la región SO respecto a la región NE; de la asimetría que se observa; el origen de las variaciones de reflectividad de la corteza inferior; la fábrica del manto litosférico, caracterizada por unas velocidades de las ondas P anómalamente bajas; y sus propiedades físicas.

Palabras clave: modelización 2D y 3D, datos geofísicos, estructura litosférica, Surco de Valencia.

VERSIÓN ABREVIADA EN CASTELLANO

Introducción

La convergencia entre las placas Africana y Euroasiática dio lugar, en el Mesozoico, a la subducción del Tetis bajo el margen continental de Iberia hasta que dicho océano se cerró por completo (Roest and Srivastava, 1991; Rosenbaum et al., 2002; Cavazza et al., 2004; Stampfli and Borel, 2002, entre otros). El roll-back de la placa oceánica subducida del Tetis dio lugar, durante el Oligoceno-Mioceno, a la formación de la cuenca del Surco de Valencia (v.g. Roca et al., 2004) mediante un mecanismo de back-arc.

En este trabajo, se resumen los conocimientos actuales de la geofísica del Surco de Valencia, y sus alrededores (Fig. 1) prestando especial atención a la discusión acerca de la geometría y las propiedades físicas de la estructura litosférica actual de esta región, obtenida a partir de datos geofísicos, y su relación con la evolución geodinámica alpina del Surco de Valencia.

Contexto geológico

Este trabajo no pretende presentar una descripción detallada de la geología de la zona de estudio. El lector podrá encontrar una información más exhaustiva en Roca et al. (1999), Vergés and Sabat (1999), Roca (2001), y Roca et al. (2004), entre otros.

El Surco de Valencia es una cuenca extensional sumergida de dirección NE situada entre el NE de la Península Ibérica y el Promontorio Balear (Fig. 1). La batimetría alcanza valores máximos a lo largo de su eje, decreciendo desde 2200 m en su borde NE en dirección SO y hacia sus márgenes, donde se encuentran profundidades típicas de plataforma continental. En ambos márgenes la plataforma es muy estrecha, excepto en su mitad NO, donde se acumulan los depósitos siliciclásticos mioceno-cuaternarios derivados del delta del Ebro, lo que da lugar a una plataforma bien desarrollada (Fig. 1)

Toda la cuenca está formada por una corteza de tipo continental adelgazada (v.g. Torne et al., 1992; Roca, 2001) que incluye un basamento formado por rocas metasedimentarias, metamórficas y plutónicas pre-carboníferas, afectadas por la orogenia Varisca, sobre el que descansa de manera discordante una cobertera mesozoica de carbonatos con intercalaciones de evaporitas y rocas siliciclásticas. Los sedimentos cenozoicos son discordantes y están formados por una sucesión terrígena de 2 a 6 km de espesor y edad Oligoceno superior-Cuaternario (Fig. 2).

Tanto el relleno sedimentario como la corteza superior subyacente muestran unas estructuras complejas en las que se superponen los efectos de episodios extensionales y contraccionales, principalmente distribuidas en dos dominios tectónicos claramente diferenciados (Roca and Desegaulx, 1992): el dominio Catalano-Valenciano, donde predominan las estructuras extensionales, y el dominio Bético-Balear, con predominio de las estructuras contractivas (ver recuadro de la Fig. 1).

Datos geofísicos regionales

El Surco de Valencia ha sido objetivo de extensivas campañas geofísicas, sobre todo entre los años 70 y 90. Los datos de sísmica de reflexión y refracción (Fig. 3) han permitido obtener una imagen detallada de la estructura de la corteza, hasta el Moho e investigar las variaciones laterales tanto de velocidad como de reflectividad. Por otro lado, la modelización gravimétrica y de geoide junto elevación y datos de flujo de calor (Fig. 4) se han utilizado para modelizar la estructura del manto litosférico y, en particular, la geometría de la frontera litosfera-astenosfera.

Estructura cortical

La información de la estructura cortical del Surco de Valencia proviene fundamentalmente de la interpretación de datos sísmicos y la modelización de campos potenciales.

La corteza superior y media del Surco de Valencia es de tipo continental, con velocidades de las ondas P entre 5.4-6.4 km s^{-1} *(Pascal et al., 1992; Torne et al., 1992; Dañobeitia et al., 1992). El basamento tiene un carácter no reflectivo que contrasta con una cobertera mesozoica reflectiva. El techo del Mesozoico está caracterizado por un potente reflector que marca una clara discontinuidad que separa los sedimentos mesozoicos del relleno sedimentario cenozoico (Stoeckinger, 1976; Maillard et al., 1992; Roca and Desegaulx, 1992).*

Por lo que se refiere al espesor cortical, se observa cómo disminuye desde 18 km bajo la costa de Iberia hasta 6-12 km en la parte axial de la cuenca para aumentar de nuevo hacia el Promontorio Balear, donde alcanza de nuevo valores cercanos a los 18 km (Banda et al., 1980; Pascal et al., 1993; Torne et al., 1996). A lo largo del eje de la cuenca, el espesor decrece gradualmente hacia el noreste: desde 12 km entre la Península Ibérica y la isla de Ibiza a sólo 5-6 km en la frontera del Surco de Valencia con la Cuenca Liguro-Provenzal.

La corteza inferior está caracterizada por unas velocidades de las ondas P de c. 6.6 km s^{-1} y un espesor que varía desde 9-10 km bajo la plataforma continental a 1-2 km en el centro de la cuenca, donde en algunos lugares llega incluso a desaparecer (Torne et al., 1992). Bajo la plataforma continental es muy reflectiva (COP Line 819, Fig. 5b) mientras que hacia el centro de la cuenca pierde su carácter reflectivo (v.g. Fig. 5c) debido probablemente al efecto de la extensión Cenozoica (Watts et al., 1990; Collier et al., 1994).

Perpendicularmente, en dirección NO-SE, la Moho pasa de una profundidad de 27-32 km bajo la costa de Iberia a 20-22 km bajo la plataforma continental alcanzando valores mínimos de 14 km en el centro del Surco de Valencia. A lo largo de su eje, la Moho pasa de una profundidad de 18-19 km en el extremo SO a 8-10 km en el NE, en la zona de transición hacia la Cuenca Liguro-Provenzal (Fig. 6).

Estructura del manto litosférico

La información sobre el manto litosférico, y la geometría del límite litosfera-astenosfera (LAB) provienen básicamente de la modelización de campos potenciales, elevación y flujo de calor, con la restricción de los datos sísmicos (Zeyen and Fernández, 1994; Ayala et al., 1996, 2003; Roca et al., 2004). Recientemente, Carballo et al. (2014) han incorporado a la modelización datos sísmicos y geoquímicos, lo que ha permitido estudiar posibles cambios en la composición del manto litosférico.

Una de las características distintivas del Surco de Valencia es que la zona superior del manto litosférico está caracterizada por velocidades de las ondas P anómalamente bajas, 7.6-7.8 km s^{-1} cuyo origen es aún objeto de debate.

A pesar de las diferencias debidas a las distintas metodologías utilizadas en los modelos propuestos por distintos autores, los resultados indican que la asimetría que se observa a nivel cortical afecta a toda la litosfera. Las Figs. 8 y 9 muestran un importante adelgazamiento de la litosfera hacia el centro del surco desde 80-90 km bajo la Cuenca del Ebro a 66-75 km bajo la línea de costa, alcanzando c. 60 km en el centro del surco; en el Promontorio Balear, la LAB se encuentra a 65-70 km. A lo largo del eje del Surco de Valencia, la base de la litosfera se mantiene prácticamente constante a 60-65 km, adelgazándose ligeramente hacia la zona de transición con la Cuenca Liguro-Provenzal. Cabe destacar las conclusiones de Carballo et al. (2014), que indican que la composición del manto litosférico corresponde a la de un Manto Superior Primitivo (PUM, Pm_2), según la definición de Jagoutz et al. (1979).

Discusión y observaciones finales

- *No existe consenso sobre el origen de las diferencias que se observan en la configuración cortical en la zona SO con respecto a la zona NE. En el SO se observan potentes series mesozoicas y una corteza mucho más delgada que hacia el NE, lo que sugiere que la zona sur del Surco de Valencia estuvo afectada por la extensión mesozoica que afectó amplias zonas del NE y S de Iberia. Este hecho permite explicar la presencia de una corteza muy adelgazada con potentes acumulaciones de sedimentos que alcanzan espesores de entre 6 y 8 km en la cuenca de Columbretes. Por otra parte, no se observan evidencias claras de estructuras extensionales en la cobertera cenozoica. Las estructuras extensionales son casi imperceptibles hacia el centro y el sur del surco, lo que es difícil de reconciliar con factores de adelgazamiento que pueden alcanzar hasta 3.15 +/- 0.25 en la zona central (Collier et al., 1994).*
- *Las pequeñas discrepancias en la geometría de la Moho obtenidas por distintos autores, sobre todo en áreas donde la información de la sísmica tiene mayor incertidumbre, están relacionadas con pequeñas diferencias en la distribución de densidad utilizadas en la modelización.*
- *Las discrepancias en la geometría de la LAB se atribuyen a las distintas metodologías empleadas, la reducción de los datos de geoide así como a la distinta distribución de densidades en el manto litosférico, aunque en todos los modelos se observa asimetría entre los dos flancos de la cuenca.*
- *La explicación más plausible, de acuerdo con Carballo et al. (2014) es una combinación de una pequeña cantidad de serpentinización junto con anisotropía sísmica, aunque los autores no descartan la influencia de efectos térmicos transitorios.*

Introduction

Combined studies of plate motions, together with geological observations, suggest that the overall N-S convergence between the African and Eurasian plates triggered the subduction of the Mesozoic Maghrebian Tethyan Ocean below the southern continental margin of the Iberian plate up to the complete closure of the Tethys (Roest and Srivastava, 1991; Rosenbaum *et al.,* 2002; Cavazza *et al.,* 2004; Stampfli and Borel, 2002, among others). As pointed out by Roca *et al.* (2004) the inferred “southward” but also “westward” and “eastward” retreat of the subducting Tethyan oceanic slab promoted the formation of the Valencia

Trough Basin (Valencia Trough thereafter) and the Algerian Basin by back-arc extension in the upper Iberian plate. This subduction zone was also responsible for the development of the complex system of Alpine orogens present along the southern Iberian and northern African continental margins (Betic-Rif-Magrebides orogenic system).

Although the internal structure and precise origin of the Valencia Trough was a matter of a significant debate in the 1980s and 1990s, it is now widely accepted that this late Oligocene-Miocene basin and the rest of Neogene Western Mediterranean basins have been shaped by the slab roll-back of the subducting Tethyan oceanic slab (e.g. Vergés and Fernandez, 2012).

Subduction of the Tethyan slab started in the middle Oligocene (aprox. 35 Ma ago) at the eastern margin of the Iberian plate, where large extensional basins developed during the Mesozoic opening of the Maghrebian Tethyan Ocean. The Tethyan subduction first generated the opening of the Valencia Trough and Liguro-Provençal basins, and then, by its displacement outward to the southwest, south and southeast, the Alboran-Algerian and Tyrrhenian basins (see Cavazza *et al.,* 2004 and references therein). The back-arc extension caused a thinning of the crust and lithosphere that in some places, (Liguro-Provençal and Alboran-Algerian basins), resulted in mantle exhumation and the formation of oceanic or quasi-oceanic crust. At the same time, the associated compression triggered the development of a series of thrust systems close to the subduction zone (e.g. Roca *et al.,* 2004).

In this paper, we summarize the current geophysical knowledge of the Valencia Trough and surrounding areas: the southernmost part of the Liguro-Provençal Basin (Gulf of Lions), the NE border of the Iberian Peninsula, and the NW part of the Algerian Basin (see Fig. 1 for location). We especially focus on discussing the geometry and the physical properties of the present day lithospheric structure of this area, derived from geophysical data, and its relationships with the Alpine geodynamic evolution of the Trough.

Geological setting

This contribution does not intend to present a thorough description of the geology of the study area, thus for a more detailed information the reader is referred to the works of Roca *et al.* (1999), Vergés and Sàbat (1999), Roca (2001) and Roca *et al.* (2004), amongst others.

The Valencia Trough belongs to the southwestern prolongation of the Liguro-Provençal Basin. The trough is a NE-trending extensional basin located between the NE Iberian Peninsula and the Balearic Promontory (Fig. 1). Mainly located offshore, the water depths achieve maximum values along its axis, decreasing from 2 200 m at its NE border to the SW, and also towards the trough margins where water depths of a typical continental platform (up to 250 m) are found. Both platforms are rather narrow, except in the southern half of its NW margin which displays a well-developed platform, the Iberian Continental Platform, made up of middle Miocene to Quaternary siliciclastic deposits derived from the Ebro river delta (Figs. 1 and 3).

All the Valencia Trough is floored by a thin continental crust (e.g. Torne *et al.,* 1992; Roca 2001) formed by: a) Pre-Carboniferous meta-sedimentary, metamorphic and plutonic rocks that were affected by the Variscan orogeny; and b) a Mesozoic cover that rests unconformably over these basement rocks. This Mesozoic cover mainly consists of carbonates with some evaporite and siliciclastic interlayers that filled a series of extensional basins developed in the eastern margin of Iberia during the opening of the Tethys (e.g. Stampfli and Borel, 2002). These basins outline the Catalan and Columbrets basins that developed along the present-day Valencia Trough axis. Both basins are characterized by a thick sedimentary infill of more than 4 km and 8 km, respectively. Between these thick basins and the nowadays subducted Tethyan oceanic realm, the Jurassic and Cretaceous of the Balearic Islands is much thinner and mainly formed by a slope and base of the slope facies (Fornós *et al.,* 2004). This reflects the existence of a paleohigh along the present-day Balearic Promontory which developed at the outer part of the Iberian passive margin of the Tethys (Banda and Santanach, 1992).

During the latest Cretaceous-Oligocene, the onset convergence between Iberia and Eurasia (Fernandez *et al.,* 1995; Roca, 1996; Gaspar-Escribano *et al.,* 2003) gave rise to the partial inversion and uplift of these pre-existent extensional basins. This uplift resulted in the erosion and the development of a major unconformity on a regional scale (Stoeckinger, 1976; Martínez del Olmo, 1996) except in minor, piggy-back syncontractional basins that were filled by Eocene to upper Oligocene terrigenous sediments (i.e., Barcelona Basin; Roca *et al.,* 1999).

Overlying these syncontractional sediments and unconformity, the Cenozoic Valencia Trough appears to be filled by a 2 to 6 km thick succession of terrigenous sediments of late Oligocene to recent in age (Fig. 2). Five major packages have been distinguished

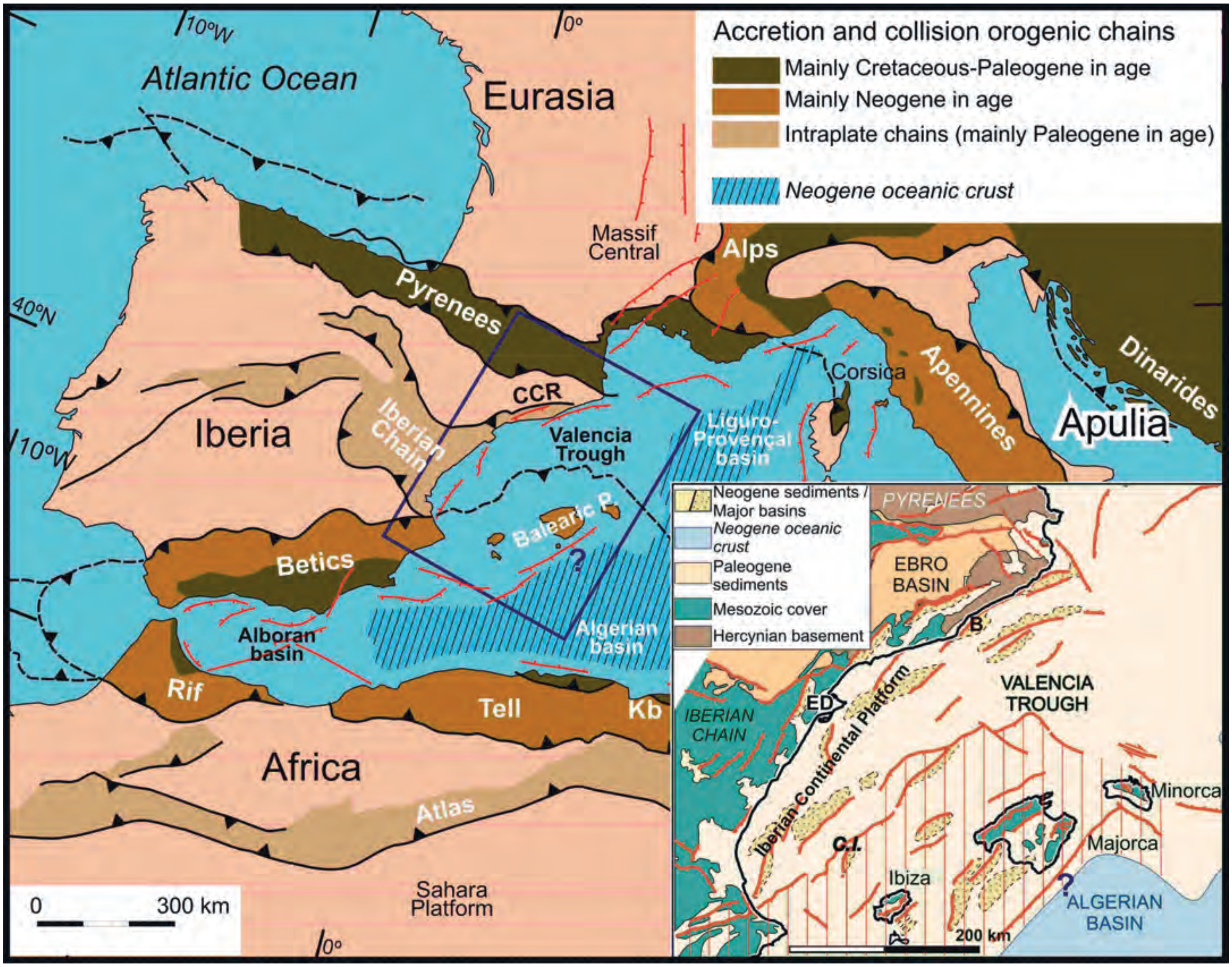

Figure 1. Geological sketch of the western Mediterranean. CCR: Catalan Coastal Ranges; Balearic P.: Balearic Promontory; Kb: Kabylies. Inset bottom right: Tectonic summary map of the Valencia Trough, outlined by the dark blue rectangle on the geological sketch; the hatched area indicates the Betic-Balearic domain (see text for further explanation). B: Barcelona Basin; C. I: Columbretes Islands; ED: Ebro river delta; Modified from Roca (1999, 2004).

Figura 1. *Esquema geológico del Mediterráneo Occidental. CCR: Cordillera Costero Catalana; Balearic P.: Promontorio Balear; Kb: Kabilias. Recuadro inferior derecho: Esquema tectónico del Surco de Valencia, enmarcado por el rectángulo azul oscuro del esquema tectónico general; el área sombreada indica el dominio Bético-Balear (ver texto). B: Cuenca de Barcelona; C. I.: Islas Columbretes; ED: Delta del Ebro; Modificado de Roca (1999, 2004).*

in this succession (Clavell and Berástegui, 1991; Maillard *et al.,* 1992; Martínez del Olmo, 1996; Roca *et al.,* 1999) which from bottom to top are: (1) a basal uppermost Oligocene-lower Burdigalian (early Miocene) package consisting of continental and terrigenous to carbonate outer-shelf marine sediments accumulated in shallow basins limited by extensional faults; (2) an upper Burdigalian-Langhian package formed by trangresive marine shales and carbonates that grades eastwards to calcareous turbidites; (3) a Serravallian (middle Miocene)-lower Messinian (late Miocene) package integrated by basinward prograding clastic sequences and, in the Balearic Promontory, by platform carbonates; (4) the late Messinian evaporite succession deposited in the deepest parts of the trough coevally with the development of a major down-cutting unconformity in the shallower part of the basin; and (5) a Pliocene-Holocene package formed again by basinward prograding clastic sequences and, in the deepest basin parts by deep-sea fans.

Besides these sedimentary rocks, the Valencia

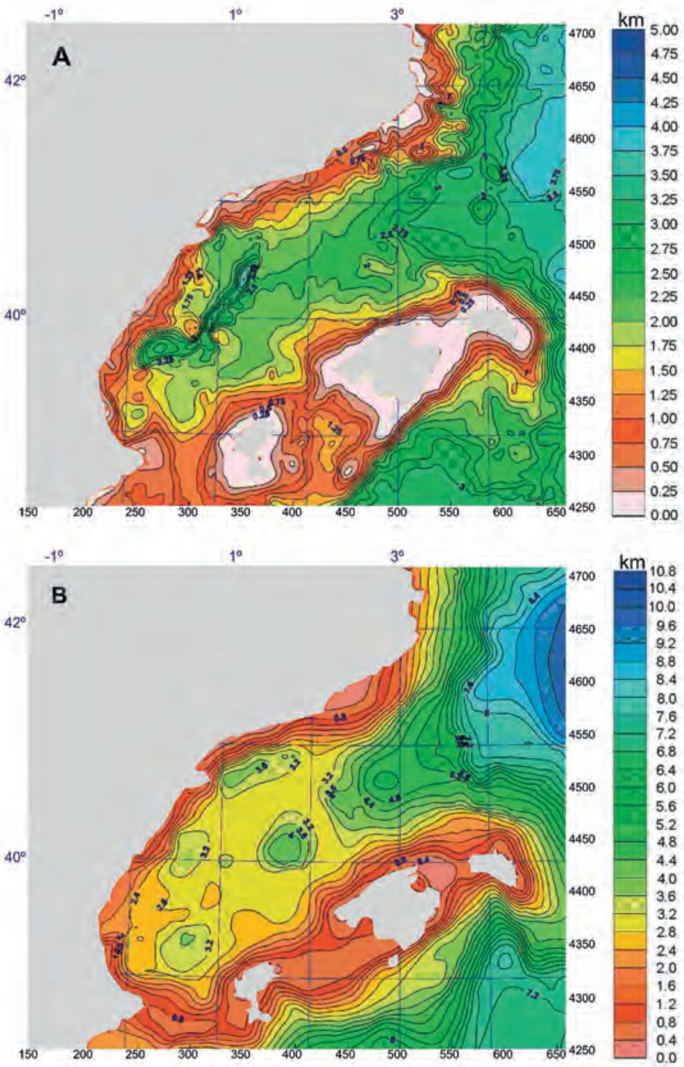

Figure 2. A: Depth to Plio-Quaternary sediments (in km); B: Depth to Miocene sediments (in km). Compiled by Ayala (2001) and Ayala *et al.* (2003).

Figura 2. *A: Profundidad de los sedimentos Plio-Cuaternarios (en km); B: Profundidad de los sedimentos Miocenos (en km). Compilado por Ayala (2001) y Ayala et al. (2003).*

Trough is also filled by Aquitanian (lowermost Miocene) to Recent volcanic rocks that record two main volcanic cycles involving a progression from subduction and collision-related episodes, to intraplate magmatic activity (e.g. Martí *et al.,* 1992). The first cycle, early to middle Miocene in age (32-12 Ma), is mainly calc-alkaline and affects the central and eastern parts of the Valencia Trough and the Balearic islands. It records the subduction of the Maghrebian Tethys beneath the trough and the collision-related episodes developed at this time at the Iberian-Africa boundary (Martí *et al.,* 1992). The second one, mid-Miocene to recent (10-0.01 Ma), affects the entire basin and is characterized by alkaline rocks whose geochemical signature indicates an intraplate nature with partial melting of mantle rocks (Savelli, 1988; Martí *et al.,* 1992).

The Valencia Trough infill and the underlying upper crust show a complex late Oligocene-Miocene structure with both extensional and contractional structures. The different areal distribution of these two kinds of structures has resulted in the definition of two domains with a different tectonic style (Roca and Desegaulx, 1992): the Catalan-Valencian domain and the Betic-Balearic domain (see inset of Fig. 1).

The Catalan-Valencian domain extends from the Iberian mainland coastal areas (including the Neogene basins of the Catalan Coastal Ranges) to the axis of the Valencia Trough. It is characterized by a widespread system of ENE- to NE-trending horsts and grabens, limited by a system of extensional faults that were activated during the late Oligocene-Aquitanian, and have been active throughout the entire Neogene (Roca and Guimerà, 1992; Roca *et al.,* 1999). This extensional structure is well developed in the northeastern parts of the Iberian margin where, along the coast, there are large faults that dip to the southeast and have extensional displacements of about 4-8 km. In contrast, to the southwest fault displacements diminish to becoming imperceptible in front of the Valencia coast where the top of the upper crust is only cut by some local diapirs and minor extensional faults with a displacement lesser than 300 m.

The Betic-Balearic domain corresponds to the SE margin and encompasses the SE part of the Valencia Trough, the Balearic Promontory and the oriental part of the Betic Range. This domain shows the effect of a compressive episode that took place mainly during the lower-middle Miocene, coevally with the extension at the Catalan-Valencian domain. This domain shows a more complex structure consisting of an intricate system of ENE-trending thrusts that involves the Variscan basement as well as the overlying Mesozoic to middle Miocene sedimentary cover (e.g. Sàbat *et al.,* 1988; Gelabert *et al.,* 1992). This orogenic system, which is thought to be part of the Betic Cordillera, has been active from late Oligocene (Sàbat *et al.,* 1988) to middle Miocene (Gelabert *et al.,* 1992), and locally is cut by some younger extensional faults detached at pre-existent thrusts.

The geometric relationships of this upper crustal structure and the basin filled with Cenozoic deposits allow us to recognize three major deformation stages reflecting the evolution of the western Mediterranean region since the beginning of the Africa-Eurasia convergence. These main stages are: 1) the latest Cretaceous-early Oligocene inversion of the pre-existent Mesozoic extensional basins that occurred during the development of the Pyrenees at the Iberia-Eurasia boundary; 2) the late Oligocene to Langhian stage in which the Valencia Trough area was affected by extensional deformations linked to the back-arc processes generated by the subduction of the Maghrebian Tethys beneath the Iberian plate; subduction that also generated the building of the thrust system in the Betic-Balearic domain; 3) a post-Langhian stage, developed after the collision of the Iberian-Africa continental realms, in which the tectonic activity in the Valencia Trough attenuated considerably and became restricted to the motion of some faults along the Iberian margin.

Regional geophysical data

The Valencia Trough has been the target of extensive geophysical investigation by the oil industry and academic institutions. During the 1970s and 1980s, the Iberian Continental Platform was extensively explored by the hydrocarbon industry. The recording of reflection-seismic surveys and the drilling of over 110 exploration wells resulted in the discovery of one small and one large oil field (mainly near the Tarragona coast) and provided valuable information on the sedimentary record of the trough and its structure, subsidence and thermal evolution.

In this section we mainly focus on seismic data acquired by the academy from the early 1970s to 1990s, as well as on regional and world data bases that provide information on the Valencia Trough heat flow, and gravity and geoid signatures.

Reflection and refraction seismic data

Fig. 3 shows the location of the compiled refraction/wide-angle reflection and multichannel academic reflection profiles that are discussed in this study.

The first geophysical experiments started at the beginning of the seventies (Hinz, 1973) with the acquisition of two profiles of refraction seismic data, using a small number of Ocean Bottom Seismic surveys (OBSs). In 1976, deep seismic soundings were conducted along the Balearic Promontory. Twenty-four stations, 4-5 km apart, were installed on the islands to record the wave propagation resulting from ten depth charges fired at sea by the Spanish Navy. In addition two offshore shots near the Catalan coast were recorded on a north-south line across the island of Majorca (see Banda *et al.,* 1980 for further details).

In 1988, within the framework of the French-USA VALSIS-II experiment, a 2-ship seismic survey was carried out to determine the lithospheric structure of the Valencia Trough. The seismic experiment consisted of 12 deep multichannel seismic reflection profiles (CDPs), 8 wide-aperture multichannel profiles (COPs) and 6 expanding spread profiles (ESPs). For a detailed discussion of CDP results the reader is referred to Mauffret *et al.* (1992), Maillard *et al.* (1992) and Torne *et al.* (1992). The ESP results are discussed by Pascal *et al.* (1992) and Torne *et al.* (1992), while COP data are discussed by Collier *et al.* (1994).

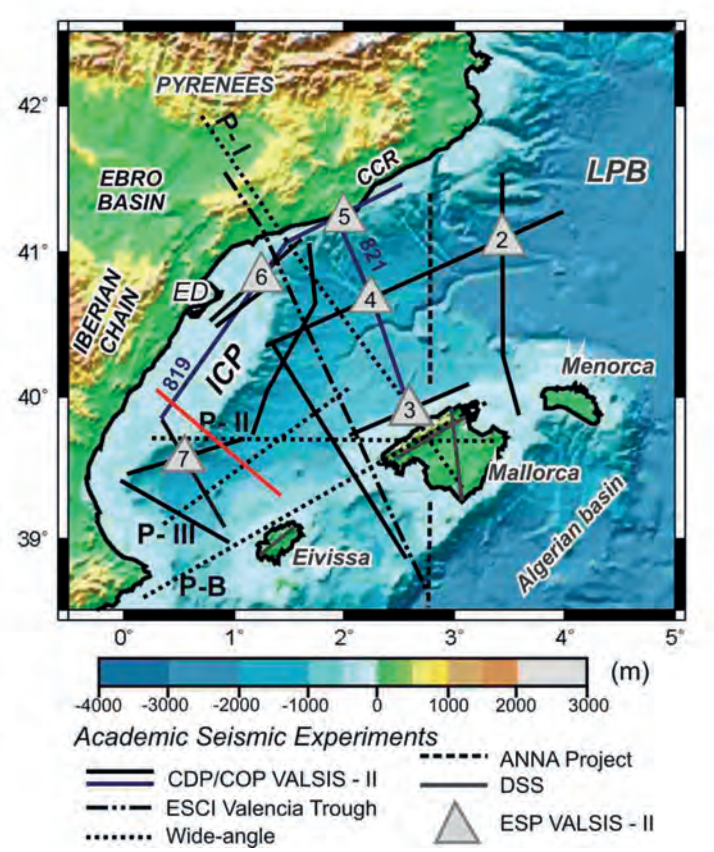

Figure 3. Location of the seismic experiments discussed in this paper. The red line is the location of the seismic section in Fig. 5A. CCR: Catalan Coastal Ranges; ED: Ebro river delta; ICP: Iberian Continental Platform; LPB: Liguro-Provençal Basin. Numbers within the triangles: ESP VALSIS – II. Background: Elevation (m). Numbers in dark blue indicate the location of the reflection seismic sections shown on Figs. 5b and 5c. This figure has been generated with GMT (Generic Mapping Tools, Wessel and Smith, 1998).

Figura 3. *Situación de los experimentos sísmicos que se discuten en este artículo. La línea roja es la localización de la sección sísmica de la Fig. 5A. CCR: Cordillera Costero Catalana; ED: Delta del Ebro; ICP: Plataforma continental de Iberia; LPB: Cuenca Liguro-Provenzal. Los números dentro de los triángulos indican los ESP del proyecto VALSIS-II. De fondo: Elevación en m. Números en azul oscuro indican la localización de los perfiles de sísmica de reflexión que se muestran en las Figs. 5b y 5c. Esta figura se ha generado con GMT (Generic Mapping Tools, Wessen and Smith, 1998).*

The marine seismic data was complemented with on land recordings (Gallart *et al.,* 1990) which provided additional information on the crustal structure at the offshore-onshore transition of the NW margin. In the summer of 1989, three wide angle refraction-reflection profiles were acquired, covering an area from NE Iberia to the Balearic Islands (Dañobeitia *et al.,* 1992).

In 1992, within the ESCI Programme (*Estudios Sísmicos de la Corteza Ibérica-Seismic* Studies of the Iberian Crust), a new NW-SE oriented multichannel profile was recorded, crossing the entire trough from the coast of Tarragona to the Algerian Basin (Gallart *et al.,* 1994, 1995; Vidal *et al.,* 1995, 1998). The main target of the ESCI-Valencia Trough profile was to investigate the deep lateral variations in velocity and reflectivity at the transition between NE Iberia and the trough.

Free air and Bouguer anomaly

Offshore free-air gravity anomalies (Fig. 4a) were obtained from the global satellite altimetry data model V16.1 (see Sandwell and Smith, 2009, and references therein). On land, Bouguer anomalies (Fig. 4a and b) were computed from Casas *et al.* (1987) and from Ayala (2013), whilst at sea (Fig. 4b), simple Bouguer anomalies were calculated from the free-air grid with the FA2BOUG software (Fullea *et al.,* 2008).

As observed in Figure 4a, the deeper areas of the Valencia Trough are characterized by values that oscillate from -10 to 10 mGal, which may suggest that the area is close to isostatic equilibrium, whereas towards its margins free-air anomalies increase, reaching maximum values in the range of 40-60 mGal. Of particular interest is the observed relative high located along the Iberian Continental Platform which is likely to be related to the thick accumulation of Plio-Quaternary sediments. Watts and Torne (1992) have demonstrated that the thick Plio-Quaternary sedimentary pile is not in isostatic equilibrium. These authors conclude that the sedimentary pile related to the Ebro delta, which has prograded more than 60 km into the trough since the Pliocene, requires that the lithosphere beneath the Iberian continental platform has a high elastic thickness (60 to 80 km) which they attribute to incomplete stress relaxation of the lithosphere during loading. South of the Columbretes Islands, negative values of -10 to -20 mGal are probably associated to the Mesozoic successions and are less dense than the basement. The observed positive gradients around the Balearic Islands coincide with steep continental slopes towards the Valencia Trough and Algerian Basin which characterizes the flanks of the Balearic Promontory.

Bouguer gravity data (Fig. 4b) shows that the deeper regions of the trough are associated with a gravity high that increases from its SW end (60 to 80 mGal) to its NE border at the transition with the Liguro-Provençal Basin where values of up to 180 mGal are observed. Towards the margins of the Valencia Trough, Bouguer anomalies decrease to values up to 20-60 mGal on its NE margin to 60-80 along the Balearic Promontory. The regional pattern of the gravity anomalies, therefore, shows a significant crustal thinning from SW to NE towards the Liguro-Provençal Basin and points to a change in the style of thinning across the trough.

Geoid anomaly

The residual geoid has been used to investigate the deep structure of the lithosphere by Ayala *et al.* (1996; 2003) and Carballo *et al.* (2014), amongst others. The residual geoid shown in Figure 4c has been obtained by subtracting (Arabelos *et al.,* 1991; Brovelli and Sansó, 1993; Sevilla, 1992) a regional field calculated from the Global Geopotential Model EGM96 from the Mediterranean geoid (Lemoine *et al.,* 1997) developed up to degree and order 12, which corresponds to wavelengths of c. 3300 km, thus removing the regional trend of the geoid containing information on the sublithospheric lateral-density variations to depths exceeding 580 km. (Ayala *et al.,* 1996, 2003).

Some areas of the Valencia Trough are associated with a long wavelength geoid anomaly of 0.5 m with a magnitude decreasing towards the NE, reaching values of up to -0.5 m, and increasing to the SW where it attains values of 1.5-2 m. In the SW region of the trough and on the Balearic Promontory, the anomalies become even more positive with amplitudes as high as 2.5 m around the islands of Majorca and Ibiza. As already observed in the Bouguer anomaly map, a qualitative interpretation of the geoid anomalies suggests a thinning of the lithosphere towards the centre of the trough as well as towards the Liguro-Provençal Basin. Geoid anomalies also show the asymmetry of the lithosperic thinning across the Valencia Trough.

Heat flow

Until the VALSIS-I experiment (Foucher *et al.,* 1992) information on the thermal regime was limited to temperature gradients obtained from on-shore and off-shore water and oil wells. These data indicate that

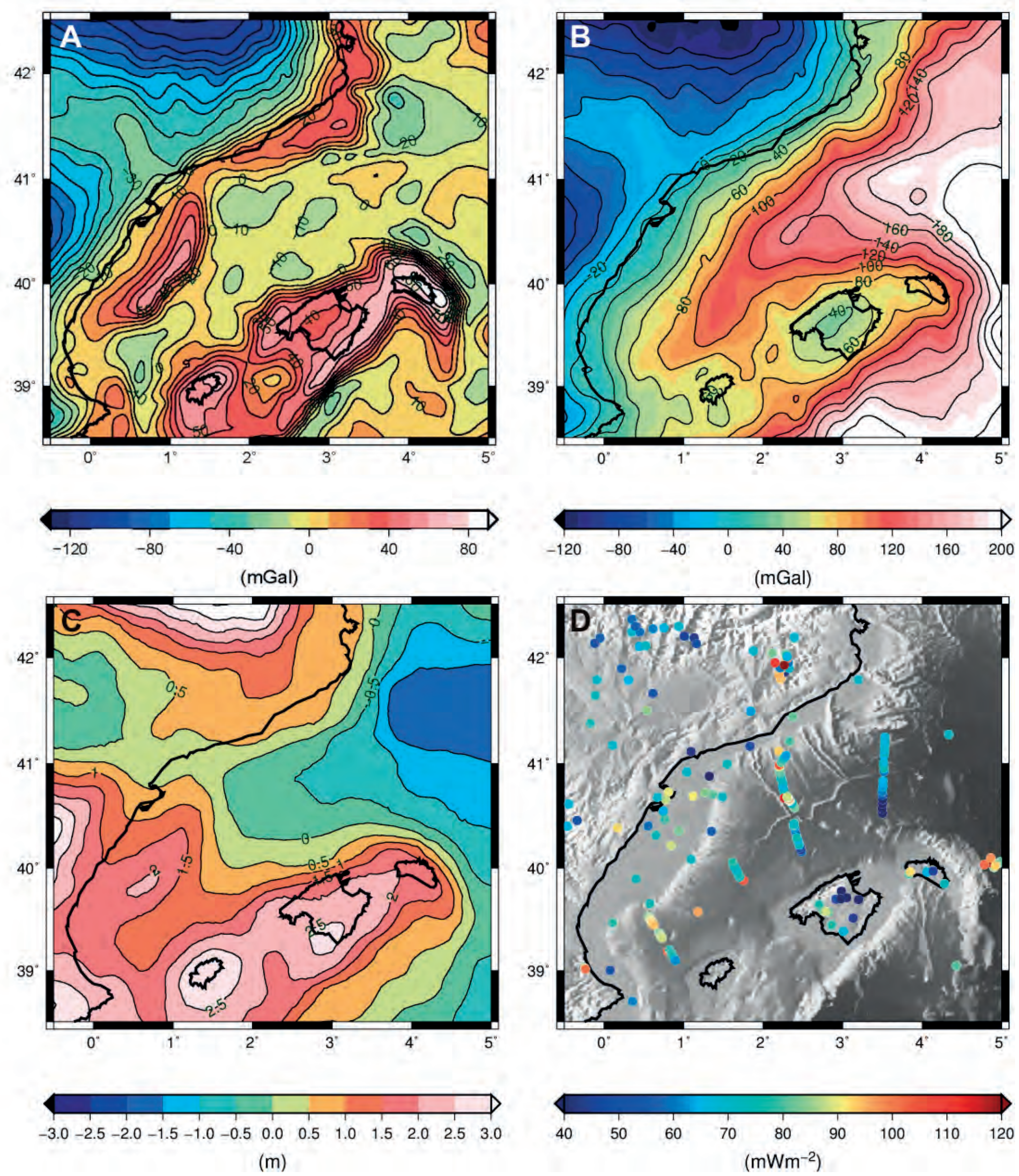

Figure 4. Geophysical observables: A: Bouguer on land and free air at sea; B: Bouguer anomaly; C: Residual geoid anomaly; D: Heat flow (background: image map of the elevation). This figure has been generated with GMT (Generic Mapping Tools, Wessel and Smith, 1998).
Figura 4*. Observables geofísicos: A: Bouguer en tierra, aire libre en el mar; B: Anomalía de Bouguer; C: Anomalía de geoide residual; D: Flujo de calor (fondo: Imagen de la elevación). Esta figura se ha generado con el GMT (Generic Mapping Tools, Wessel and Smith, 1998).*

the Iberian Continental Platform and adjacent mainland areas are characterized by significant temperature gradient variations that Fernandez and Banda (1989) and Fernandez *et al.* (1990) attribute to groundwater circulation.

Results of the VALSIS-I cruise show that, along the axis of the Valencia Trough, heat flow values decrease from 88 mW m^{-2} at its SW end to 66 mW m^{-2} in the NE at the transition to the Liguro-Provençal Basin (Fig. 4d), coinciding with deepest bathymetry and thinnest crust. Throughout the Iberian Continental Platform heat flow values are highly variable ranging from 55 to 90 mW m^{-2} (Negredo *et al.,* 1999), while in the Balearic Promontory (the islands of Majorca and Minorca) values oscillate from 70 to 80 mW m^{-2} and 75 to 90 mW m^{-2}, respectively (Fernandez and Cabal, 1992).

As already pointed out by Carballo *et al.* (2014) heat flow data show a large scatter around a mean value of 65 mW m^{-2} onshore and about 70-80 mW m^{-2} in the Valencia Trough and the Balearic Promontory (Fig. 4d).

The crustal structure

Information about the crustal structure of the Valencia Trough comes primarily from the interpretation of both academic and industry seismic data, further refined through potential field modelling. In this section we discuss the main results of the crustal structure of the Valencia Trough as deduced by available academic seismic profiles and potential field modelling, with particular reference to the thinning differences between the upper-middle and lower crust as well as their relationship with the observed Alpine upper-crust structure.

The upper and middle crust

Below the sedimentary cover, the upper and middle crust of the Valencia Trough is of continental nature with P-wave velocities (Vp) oscillating from 5.4-6.4 km s^{-1} (Pascal *et al.,* 1992; Torne *et al.,* 1992; Dañobeitia *et al.,* 1992). The crust can be characterized by a "crystalline" almost non-reflective basement with a reflective Mesozoic cover above. The top of the Mesozoic cover usually corresponds to a well-defined reflector that marks the bottom of the overlying Valencia Trough basin infill (e.g. Stoeckinger, 1976; Maillard *et al.,* 1992; Roca and Desegaulx, 1992).

Seismic and gravity data show that the thickness of the upper-middle crust decreases from about 18 km beneath the Iberian mainland to about 6-12 km at the axial part of the Valencia Trough and increases again towards the Balearic Promontory where it is again close to 18 km thick (Banda *et al.,* 1980; Pascal *et al.,* 1992; Torné *et al.,* 1996). Along the axis of the trough, the upper-middle crustal thickness decreases gradually towards the NE. It is nearly 12 km thick between the Iberian Peninsula and the island of Ibiza, and only 5-6 km thick at the boundary between the Valencia Trough and the Liguro-Provençal Basin.

The available seismic reflection profiles, as well as the COP and CDP data, indicate that the structure and characteristics of this thinned upper-middle crust are not constant but change significantly throughout the Valencia Trough. Two areas, separated by a transitional zone located in front of the Ebro river delta can be distinguished:

a) In the northeastern one, the much thinner upper and middle crust thins suddenly along the Iberian Continental Platform where large low-angle extensional faults, late Oligocene to Neogene in age, are present (e.g. the Barcelona Fault, Roca *et al.,* 1999). In this area it is difficult to distinguish the Mesozoic cover from the underlying "crystalline" basement, except close to the Iberian coast where relatively thick Mesozoic successions have been identified both seismically and by exploration wells (Lanaja, 1987). At the centre of the trough, however, the 5.9 to 6.4 km s^{-1} velocities of the ensemble of the upper and middle crust suggest that, if it exists, it is probably very thin.

b) On the other hand, southwest of the Columbretes Islands, abrupt changes in the upper-middle crustal thickness and the top of the crust are not observed. Although the crust in this area has been thinned, it does not appear to be affected by significant Cenozoic extensional structures (Roca and Guimerà, 1992) and contrary to the NE region, the middle and upper crust is mainly made up of Mesozoic successions which are seismically well defined, forming a 50 km wide syncline-shaped basin. This basin, called Columbrets Basin (Fig. 5a; Roca, 1996, see Fig. 1 for location, C. I.) is filled with up to 6-8 km of Jurassic to Cretaceous sediments with velocities increasing from 4.4 km at the top to 6.6 km s^{-1} atthe bottom. Underneath, the crystalline crust is as thin as 4-5 km with relatively high P-wave velocities (6.7 to 6.9 km s^{-1}; Mauffret *et al.,* 1992; Torne *et al.,* 1992).

Consequently, seismic reflection and also refraction data (see also Dañobeitia *et al.,* 1992; Gallart *et al.,* 1995; Vidal *et al.,* 1995, 1998) denote that firstly,during the Cenozoic formation of the Valencia Trough, the middle and upper crust was only significantly thinned in its north-eastern part; and secondly during the Mesozoic, the Variscan middle and upper crust had already been thinned, especially in its south-western part.

The lower crust

Seismic reflection profiles show that the lower crust is highly reflective under the Iberian Continental Platform (e.g. COP Line 819, Fig. 5b) and has a thickness of 6-7 km with average Vp values of 6.6 km s^{-1} (Torne *et al.,* 1992; Collier *et al.,* 1994). Conversely, the lower crust beneath Majorca is variably reflective with disrupted reflectors that are difficult to identify (e.g. COP Line 821, Collier *et al.,* 1994, see Fig. 5c). The lower crust has a thickness of 9 to 10 km with P-wave velocities similar to those recorded along the Iberian Continental Platform. Towards the axis of the trough, the lower crust is very thin (up to 1-2 km thick) or even absent in some places (Torne *et al.,* 1992), whereas Vp values remain around 6.4-6.5 km s^{-1} (Dañobeitia *et al.,* 1992; Gallart *et al.,* 1995; Torne *et al.,* 1992; Vidal *et al.,* 1995). Some authors (e.g. Watts *et al.,* 1990; Collier *et al.,* 1994) suggest that the

Cenozoic extension notably weakened or even destroyed the lower crustal reflectivity (e.g. Fig. 5c).

The Moho topography

The Moho topography (Fig. 6) is well constrained by seismic (see Torne *et al.,* 1996, and references therein) and gravity data (e.g. Ayala *et al.,* 1996, 2003). These data shows that, in a NW-SE direction, the Moho rises steadily from a depth of 27-32 km beneath the Iberian mainland to 20-22 km below the Iberian Continental Platform, achieving minimum values of 14 km in the axis of the Valencia Trough. An asymmetric crustal thickening, when compared to that of the NW margin, is observed towards the Balearic Promontory where the base of the crust is found at depths of 23-25 km. Along the axis of the trough, the Moho rises gradually from 18-19 km at the SW end to 8-10 km at the NE end, at the limit with the Liguro-Provençal Basin. This significant crustal thinning at its NE end suggests the presence of a transition zone to the oceanic/transitional crust of the Liguro-Provençal Basin. As already mentioned, the configuration of the Moho is slightly asymmetric across the Valencia Trough (NW-SE direction). Thus, we observed that the gradient of the crustal thinning is more abrupt towards the Balearic Islands than towards the Iberian Peninsula. Figure 6 shows the depth-to-Moho map as deduced from 3D gravity and geoid modelling, using seismic data as a constraint (e.g. Dañobeitia *et al.,* 1992; Gallart *et al.,* 1995; Vidal *et al.,* 1995, 1998).

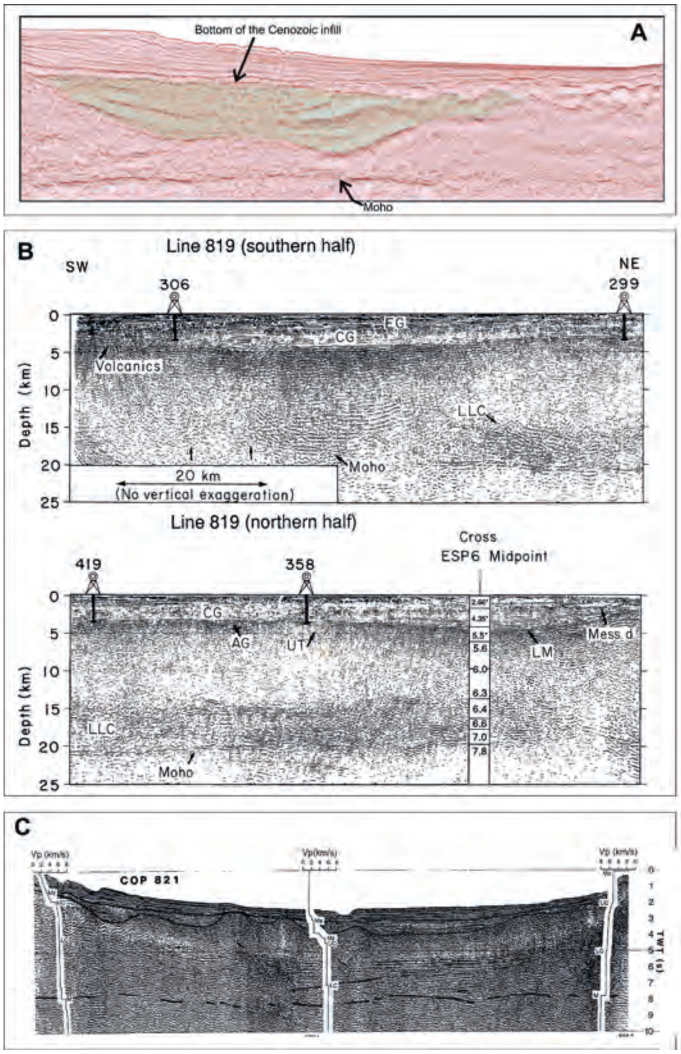

Figure 5. A: Reflection seismic profile showing the Mesozoic Columbrets Basin (shaded on the image); B: CDP line 819 (from Torne *et al.,* 1992); C: COP line 821 (from Collier *et al.,* 1994). See location in Fig. 3 and text for moredetails.

Figura 5. *A: Perfil sísmico de reflexión mostrando la cuenca Mesozóica de Columbrets (sombreada en la imagen); B: Línea CDP 819 (de Torne et al., 1992); C: Línea COP 821 (de Collier et al., 1994). Ver situación en la Fig. 3 y el texto para una explicación más detallada.*

The lithospheric mantle estructure

Information about the lithospheric mantle and, in particular, the geometry of the lithosphere-asthenosphere boundary (LAB) comes mainly from thermal modelling of 2D lithospheric profiles (Zeyen and Fernandez, 1994; Carballo *et al.,* 2014), and 2D and 3D gravity and geoid modelling, with the constraint of the 2D available seismic data (Ayala *et al.,* 1996, 2003) (see Fig. 7 for location of the modelled profiles). Since the mid 1990s several methodologies in 2D and 3D based on potential field data have been used to determine the geometry of the LAB. In parallel, 2D algorithms have been developed to further study the thermal regime of the lithosphere. Recently, Carballo *et al.* (2014) have studied the thermal, compositional, density and seismological structure of the lithosphere and upper mantle down to 410 km depth, using the LitMod finite-elements algorithm code developed by Afonso *et al.* (2008).

The first 2D thermal lithospheric model was carried out in the early 1990s by Zeyen and Fernandez (1994) using a finite-element code. The model was based on surface heat flow, Bouguer anomaly and local isostatic elevation assuming a thermal steady state. Its main goal was to determine the thickness of the lithosphere and its temperature distribution. The authors, using the same crustal structure, assessed the use of two different density models for the lithosphere mantle: the first assumes a linear decrease of density with increasing T, using the density of the

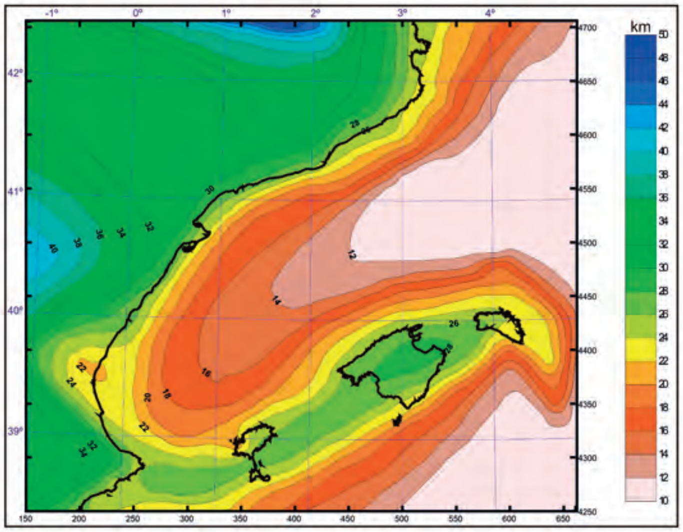

Figure 6. Depth of the Moho (in km) obtained from 3D gravity and geoid modelling by Ayala *et al.* (2003).

Figura 6*. Profundidad del Moho (en km) obtenida de la modelización 3D de gravimetría y geoide por Ayala et al. (2003).*

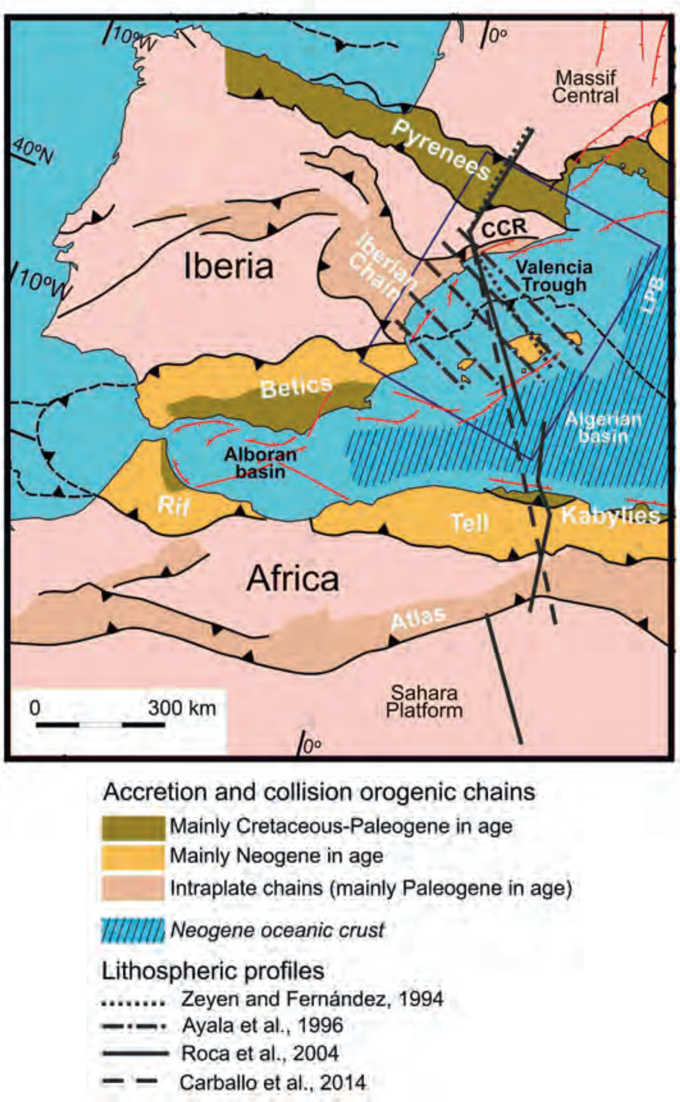

Figure 7. Lithospheric profiles which cross the Valencia Trough and the surrounding areas discussed in this paper. CCR: Catalan Coastal Ranges; LPB: Liguro-Provençal Basin. Geological sketch modified from Roca (2004).

Figura 7*. Perfiles litosféricos que cruzan el Surco de Valencia y las áreas circundantes que se discuten en este artículo. CCR: Cordillera Costero Catalana; LPB: Cuenca Liguro-Provenzal. Esquema geológico modificado de Roca (2004).*

asthenosphere as reference; whilst the second assumes a constant density. The authors concluded that although conceptually the two density models differ substantially, no major differences were obtained in terms of lithosphere structure (see Zeyen and Fernandez, 1994 for further details).

Ayala *et al.* (1996) published the results of the density distribution and the geometry of the lithosphere asthenosphere boundary (LAB) along five NW-SE lithosphere profiles crossing the Valencia Trough perpendicularly to the main crustal trends. The modelling was carried out using a 2D join gravity and geoid forward modelling and covered the trough from the SW to the NE, at its transition with the Liguro-Provençal Basin. Densities were considered constant for each modelled layer-sediment, upper crust, lower crust, anomalous mantle, lithospheric mantle and asthenosphere (see Ayala *et al.,* 1996 for details). One of the main results was to find that the base of the lithosphere remains at an almost constant depth of c. 60 km along the axis of the Valencia Trough (SW-NE direction), whereas the crust thins from 19 km at its south-westernmost border to 12 km at its NE end. Based on these results, and in agreement with previous seismic data, Torne *et al.* (1992) and Collier *et al.* (1994) also proposed an asymmetrical-style thinning across the trough.

The results obtained along these profiles, i.e. the LAB geometry; differential thinning of the crust and upper lithosphere mantle and an asymmetric thinning, were confirmed some years later by a 3D gravity and geoid modelling of the Western Mediterranean performed by Ayala *et al.* (2003) (Fig. 9).

During the first years of this century, the lithosphere structure has been investigated again by Roca *et al.* (2004) and Carballo *et al.* (2014). Roca *et al.* (2004) presented a transect running from the Aquitaine Basin to the southern Sahara platform, within the framework of the TRANSMED Atlas project (Cavazza *et al.,* 2004). This transect, representing an

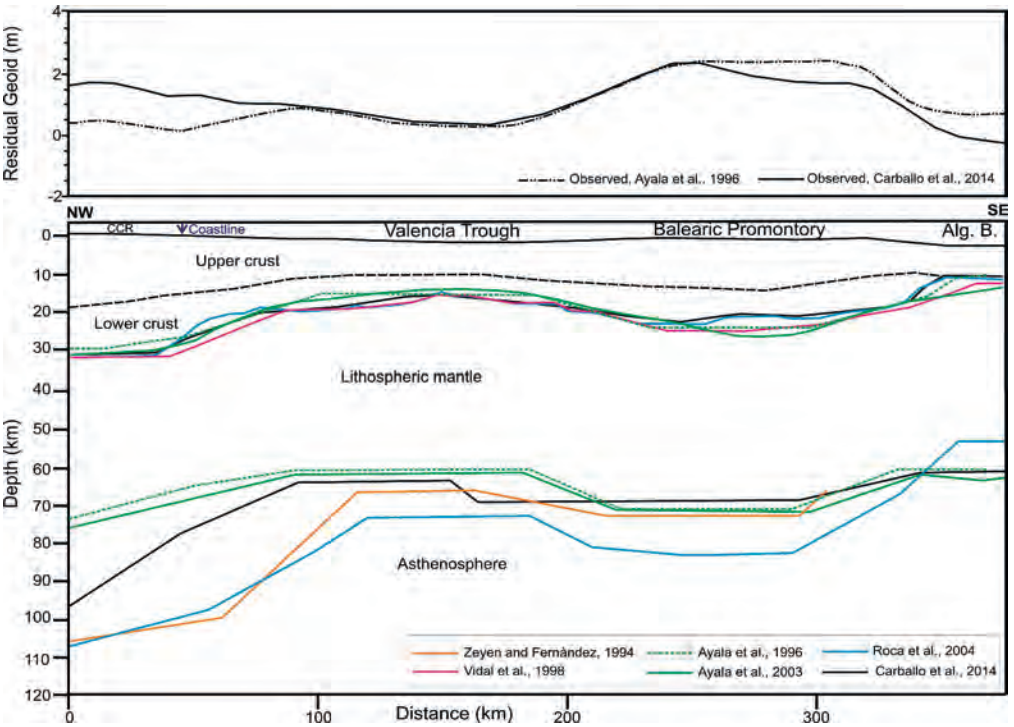

Figure 8. Upper panel: Comparison between the residual geoid from Ayala *et al.* (1996) and Carballo *et al.* (2014). Lower panel: Comparison between the depth of the Moho and the lithosphere-asthenosphere boundary obtained by the authors listed in the legend. The profile extracted from the 3D model by Ayala *et al.* (2003) runs at the same coordinates as the one from Carballo *et al.* (2014) from the Catalan Coastal Ranges (CCR) to the NE part of the Algerian Basin (Alg. B).

Figura 8. *Panel superior: Comparación entre el geoide residual de Ayala et al. (1996) y Carballo et al. (2014). Panel inferior: Comparación entre la profundidad del Moho y la frontera litosfera-astenosfera obtenida por los autores que se listan en la leyenda. El perfil extraído del modelo 3D de Ayala et al. (2003) pasa por las mismas coordenadas que el perfil de Carballo et al. (2014) desde la Cordillera Costero Catalana (CCR) hasta la parte NE de la Cuenca de Argelia (Alg. B).*

updated compendium of the current geological and geophysical knowledge of the area, included a preliminary lithospheric model that combined thermal, gravity, geoid and local isostasy analyses. The transect provides an overview of the geological and geophysical features of the area from crust to mantle (see Fig. 7 for location and Fig. 8 for summarized results).

Finally, Carballo *et al.* (2014) performed a new 2D model of the lithosphere along a transect that runs parallel to the TRANSMED transect of Roca *et al.* (2004). The novelty of this approach is that it is based on an integrated geophysical-petrological method that combines elevation, gravity, geoid, surface heat flow, seismic and geochemical data, and thus permits the investigation of possible changes in mantle composition. Unlike previous models, where the density of the lithospheric mantle is only temperature-dependent, this method allows us to infer seismic velocities and density in the mantle down to a depth of 410 km from its chemical composition through self-consistent thermodynamic calculations. Like previous models, the thermal equation is solved by the finite elements method in steady-state with the following boundary conditions: 0 °C at the surface; 1330 °C at the LAB; and no heat flow across the lateral boundaries of the model (for further details on the modelling approach the reader is referred to Afonso *et al.,* 2008).

Among the conclusions reached by Carballo *et al.* (2014) we highlight the point that the lithospheric mantle of the Valencia Trough and its SE margin, the Balearic Promontory, are characterized by a primitive upper mantle composition (PUM, Pm_2) as defined by Jagoutz *et al.* (1979), which is in agreement with the continental highly intruded continental nature of the lithosphere in the area. In terms of crustal and lithosphere structure, their results confirm previous findings of differential thinning (e.g. Watts and Torné, 1992; Collier *et al.,* 1994), although they show some major differences regarding the style and the amount of mantle lithosphere thinning, particularly along the Iberian margin.

We now go on to discuss the results obtained by the referred models with particular attention to the

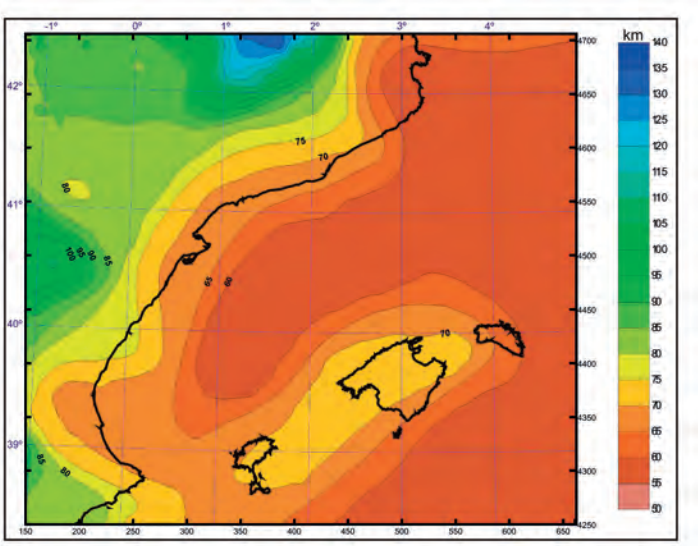

Figure 9. Depth to the base of the lithosphere (in km) obtained from 3D gravity and geoid modelling by Ayala *et al.* (2003).
Figura 9*. Profundidad de la base de la litosfera (en km) obtenida de la modelización 3D de gravedad y geoide por Ayala et al. (2003).*

geometry of the lithosphere-asthenosphere boundary and the presence of an anomalous low-velocity uppermost mantle.

The anomalous uppermost lithospheric mantle

One of the most distinctive features of the Valencia Trough is that the uppermost mantle is characterized by anomalously low P-wave velocities (7.6-7.8 km s^{-1}). These low velocities were first recorded within the Anna Project (Hinz, 1973) and have been observed in each seismic experiment ever since (e.g. Gallart *et al.,* 1990; Watts *et al.,* 1990; Dañobeitia *et al.,* 1992). The anomalous mantle seems to extend further inland, as observed by Zeyen *et al.* (1985) along two seismic reflection-refraction profiles that cross the Iberian Range from the Central Meseta to the Valencia Trough. The results of Zeyen *et al.* (1985) show the presence of an anomalous mantle characterized by a Vp of less than 7.9 km s^{-1} together with a thinned crust of c. 20 km extending further inland beneath the SE Iberian Range where thick Mesozoic basins exist. Low Vp values for the uppermost mantle have also been found in places in the Gulf of Lions (Le Douaràn *et al.,* 1984) and further to the southeast and south in the Algerian and Alboran basins.

These results indicate that the uppermost mantle of the Western Mediterranean is characterized by low P-wave velocities the origin of which is still under debate (see the discussion in section 6).

The geometry of the lithosphere-asthenosphere boundary

All the studies referred to coincide in that the thinning of both the crust and mantle lithosphere are asymmetric across the Valencia Trough with a slight thickening below the Balearic Promontory relative to that obtained below the NE margin (Fig. 8). The most outstanding discrepancies arise in the geometry of the LAB as well as the amount and style of mantle lithosphere thinning, since, as already mentioned, the crustal structure is well constrained at a regional scale according to seismic experiments.

Figure 8 shows that inland the LAB depth ranges from c. 76 to 69 km in Ayala *et al.* (1996, 2003) and between c. 105 to 100 km in Zeyen and Fernandez (1994) and Roca *et al.* (2004), whereas the results from Carballo *et al.* (2014) are somewhat in between.

From the coastline towards the centre of the Valencia Trough, the thinning is much gentler in Ayala *et al.* (2003) and Carballo *et al.* (2014) than that proposed by Zeyen and Fernandez (1994) and Roca *et al.* (2004), whereas from the Valencia Trough to the Algerian Basin significant differences in the style of thinning arise, since the total width of the thinned area below the trough as well as the lithospheric thickness underneath the Balearic Promontory vary among the four models referred to (Fig. 7).

From the 2D and 3D lithospheric models, the main mantle lithosphere features of the Valencia Trough can be summarized as follows:

In the NW-SE direction, there is an important lithospheric thinning from the Iberian Peninsula to the centre of the basin. The asymmetry observed at crustal levels also affects the entire lithosphere. Underneath the Ebro basin the LAB attains depths of about 80-90 km, thinning towards the Spanish coastline, the lithosphere is placed at c. 66-75 km depth and the axis of the trough 60-65 km. Towards the Balearic Promontory the lithosphere thickens with a more abrupt gradient, attaining depths of 65-70 km beneath the islands. An important thinning occurs towards the Algerian Basin, where the base of the lithosphere is located at about 55 km, possibly already within the oceanic domain.

Along the axis of the Valencia Trough, the thickness of the lithosphere remains almost constant 60-65 km, shallowing slightly in the transition zone to the Liguro-Provençal Basin, were the thickness of the crust suggests either a transitional or an oceanic type domain.

Discussion and concluding remarks

The Valencia Trough has been studied for the last 40 years but there are still some unresolved issues under debate that require further investigation.

Crustal structure

One of the main features of the configuration of the crust in the Valencia Trough is the different seismic structure observed from south to north and from its NW and SE margins. Seismic data combined with available geological and other geophysical data indicate that the crustal structure is quite complex reflecting the geodynamic scenario that has affected the study region since the Mesozoic. At upper-mid crustal levels, we observe that there are major differences from its margins and also from the SW and NE region. Along its margins, the Valencia Trough infill and the underlying crust (upper and middle crust) show a complex late Oligocene-Miocene structure with extensional structures in its NW region and contractional ones in its SE margin, the Balearic Promontory, which has resulted in the definition of two domains, the Catalan and the Balearic domain. There is wide consensus in that both domains show very different tectonic styles, and that these tectonic styles are the result of the late Oligocene to Langhian stage in which the region was affected by extensional deformation linked to the back-arc extensional processes generated by the subduction of the Maghrebian Tethys beneath the Iberian plate; subduction that also generated the building of the thrust system in the Betic-Balearic domain.

More puzzling, however, are the differences in the crustal configuration from its SW half region when compared to what it is observed in its NE half. As stated, in the SW parts of the Valencia Trough seismic data show that underneath the Cenozoic sedimentary infill there are clearly marked dipping reflectors that indicate the presence of thick Mesozoic series that are not observed further to the north. the “crystalline crust” in this region is also much thinner than the one recorded in the central and even northern parts of the trough, indicating that the southern areas were much more affected by the Mesozoic rifting phase that affected wide areas of NE and S Iberia.

On the other hand, there is no clear evidence of significant extensional structures on the Cenozoic cover. Major extensional structures are confined to the NE parts of the Iberian margin, becoming less noticeable or even imperceptible towards its southern and central regions.

The amount of Oligocene and younger lithospheric stretching has been obtained by different authors (e.g. Watts and Torne 1992; Collier *et al.,* 1994) mainly based on crustal geometry and subsidence studies. Their results indicate that stretching factors, B, for the crust vary from 1.4-1.55 in the western flank of the Trough and 3.15 +/- 0.25 at the centre of the region, whereas upper crustal thinning factors are c. 2.1; this value is greater than the one deduced from structural analysis by Roca and Guimerà (1992), who obtained values up to1.4-1.5. It is difficult to conciliate the distribution of these B values, especially at the centre of the region (Collier *et al.,* 1994) with the absence of major extensional features. Thus, the differences between the observed extension and the calculated thinning ratios could be explained if the thinned crust is in part inherited from one or several Mesozoic rifting events, although the effect of a reworked Moho as a result of the Neogene extension cannot be ruled out completely.

The Moho and LAB geometry

Overall, the referred models are in agreement on the style of crustal thinning and on the depth of the Moho (Fig. 8) since they are quite well constrained by the available seismic data. Some local differences, however, are observed locally on the Moho depth, particularly below the Balearic Promontory. These differences, which coincide with areas where seismic information is not conclusive enough, are likely to be related to the slightly different density-depth distribution for the crust and lithospheric mantle chosen by the different authors.

Major discrepancies are observed in the geometry and depth to the LAB (Fig. 8). As already pointed out in previous sections, the geometry of the LAB differs considerably amongst the different authors, particularly from the Iberian mainland, to the axial regions of the Valencia Trough. Ayala *et al.* (1996, 2003), based on 2D and 3D gravity and geoid modelling, propose a very smooth and continuous thinning; Zeyen and Fernandez (1994) propose a step-like thinning located mainly underneath the Iberian Continental Platform, while Carballo *et al.* (2014) postulates an intermediate model in which thinning from the Iberian mainland to the axis of the trough is mainly taken by a two-step smooth gradient. Major mantle lithosphere thickness differences (35 to 20 km) are also seen underneath the Iberian mainland and the Ebro continental platform. In the axis of the trough and Balearic Promontory there is agreement on the depth of the LAB amongst the different authors, with the exception of Roca *et al.* (2004).

These dissimilarities could be explained by the modelling approaches used by the authors and also by the differences in the calculation of the residual geoid anomaly. Differences in the model approaches may result in significant different lateral density distribution within the lithosphere mantle and along the LAB. In this regard, note that Ayala *et al.* (1996, 2003) used a constant density contrast across the whole model, whereas Zeyen and Fernandez (1994) and Roca *et al.* (2004) based on thermal, gravity and local isostasy modelling, used a density profile in the lithospheric mantle that varies according to temperature. It is worth noting that Zeyen and Fernandez (1994) conclude that a constant density profile vs. a temperature-dependent profile may result in differences of as much as 20-25 km of the LAB depth. The same argument can be used to explain the results of Carballo *et al.* (2014), since this model integrates pressure and compositional changes within the mantle for the first time, thus taking into account the mantle compositional heterogeneities. The assumption of local isostasy might also play an important role in the differences observed along the Iberian Continental Platform since, as stated previously, Watts and Torne (1992) demonstrate that the Iberian Continental Platform is far from a local isostatic equilibrium.

An additional factor that should be considered is that the observed residual geoid anomaly used by Ayala *et al.* (1996, 2003) was obtained by subtracting a spherical, harmonic development up to degree and order 12 from the geoid, which removes wavelengths greater than 3,300 km and density anomalies below 580 km, whereas Carballo *et al.* (2014) had removed a spherical, harmonic development up to degree and order 8, which filters wavelengths greater than 5,000 km and density variations at depths below 900 km. As observed in Figure 8, this results in differences between the two observed residual geoids up to 1.5 m at the Catalan Coastal Ranges and up to 0.5 m between the centre of the Balearic Promontory and the transition to the Algerian Basin.

Figure 8 also shows that the geoidal response from the models fits the observations. However, it is worth noting that the calculations of the minimum wavelength to be removed and the maximum depth to anomalous sources do not take into account the inherent non-uniqueness of the geoidal features in relation to the distribution of mass anomalies at depth (Featherstone, 1997). In the 90s there was an ongoing debate on the best degree and order to be removed to obtain the residual geoid. Some authors, such as Bowin (1994) support the view that a spherical harmonic development up to degree and order 10 can be considered as an appropriate regional field, whereas other authors (e.g. Souriau, 1984; Featherstone, 1992) suggest a spherical harmonic development up to degree and order 12-16. Cazenave (1994) proposed a development up to degree and order between 10 and 16, depending on the geology of the study area.

Low uppermost mantle P-wave velocities

Low P-wave velocities (Vp) in the uppermost lithospheric mantle (7.7-7.9) have been found all around the Neogene West Mediterranean basins with the exception of the Liguro-Provençal Basin (e.g. Contrucci *et al.,* 2001).

In the Valencia Trough, some authors attribute these low Vps to the presence of partial melts at the base of the crust (Collier *et al.,* 1994) or to mantle rock intrusions within the lower crust (Martí *et al.,* 1992) originated during the rifting process. Another possible explanation that has been explored is that the crust-mantle boundary is not a first-order discontinuity but rather a transition zone, as has been postulated in other rift zones with similar Vp configurations (e.g. in Kenya rift, Novak *et al.,* 1997)

Recently, Carballo *et al.* (2014) have investigated different causes for the low P-wave velocities at the uppermost mantle region. These authors conclude that transient thermal effects are not enough to explain the low measured Vp. They invoke either moderate serpentinization in the first 3-4 km of the lithospheric mantle, due to the hydration of the uppermost mantle during the extension related to the slab roll-back, or to the presence of seismic anisotropy (up to 4.5 %) with almost orthogonal fast polarization directions, as shown by Díaz *et al.* (2013)

There is still no conclucisve evidence to identifya unique mechanism to explain the low Vp in the Valencia Trough or to exclude any of the mechanisms already mentioned. Nonetheless, according to Carballo *et al.* (2014), the most plausible explanation is a combination of a small amount of serpentinization together with seismic anisotropy, although they do not rule out a certain influence of transient thermal effects.

The current knowledge of the Valencia Trough still does not allow the full explanation of its geodynamic evolution, particularly regarding how much the Mesozoic rifting has influenced its present day lithosphere configuration. Therefore, further studies are needed to better define the crustal structure, especially in the central part and along the axis of the Trough, as well as the extent and character of the uppermost anomalous mantle and the geometry of the lithosphere-asthenosphere boundary for the whole region.

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