The Iberian thermal lithosphere and perspectives on deep geothermal studies.

La litosfera térmica de la Península Ibérica y perspectivas sobre estudios geotérmicos profundos.

M. Torne[1], I. Jiménez-Munt[1], A. M. Negredo[2,3], J. Fullea[2], J. Vergés[1], I. Marzán[4], J. Alcalde[1], E. Gómez-Rivas[5] and C. García de la Noceda[6].

1 GEO3BCN-CSIC. The Spanish National Research Council (CSIC), Solé i Sabaris, S/N, 08028 Barcelona, Spain
2 Department of Physics of the Earth and Astrophysics, Universidad Complutense de Madrid (UCM), Madrid, Spain
3 Institute of Geosciences IGEO (CSIC-UCM), Madrid, Spain
4 Instituto Geológico y Minero de España, IGME-CSIC, Rio Rosas, 23, Madrid, Spain
5 Departament de Mineralogia, Petrologia i Geologia Aplicada, Facultat de Ciències de La Terra, Universitat de Barcelona, Barcelona, Spain
6 GEOPLAT. Plataforma Española Tecnológica y de Innovación en Geotermia. Cedaceros, 11, 2º C. 28014 Madrid

Abstract: Renewable energy sources are key to achieve the transition toward clean energy system. Among them, geothermal energy has a production whose effectiveness requires sufficient understanding of the temperature distribution and fluid circulation at depth, as well as of the lithological and petrophysical properties of the crust. Based on the compilation of available modelling results, we present the depth of the thermal Lithosphere–Asthenosphere Boundary (LAB) of the Iberian Peninsula and the temperature distribution at crustal depths of 5, 10, and 20 km, and at Moho level. At 5 km depth, the temperature is above 110 °C with local anomalies (> 130 °C) located in the Iberian Massif and Cenozoic volcanic provinces. A similar pattern is observed at 10 and 20 km depth, where temperatures are above 190 °C and 350 °C, respectively. At 20 km depth, anomalies above > 500 °C, delineate the SE and NE Cenozoic volcanic provinces. At Moho depths, temperature ranges from 450 to 800 °C with hot regions mainly located along the Iberian Massif and the SE and NE volcanic provinces. The compiled results do not show any lithospheric anomaly that could give rise to high temperatures at shallow depths, but they do show an acceptable exploitation potential at intermediate depths.

Key words: Thermal lithosphere, geothermal potential, temperature distribution in the Iberian crust, integrated geophysical–petrological numerical modelling.

Resumen: *Las fuentes de energía renovable son clave para la transición hacia un sistema de energía limpia. Entre ellas, la energía geotérmica tiene una producción cuya efectividad requiere conocer la distribución de la temperatura y la circulación de fluidos en profundidad y las propiedades litológicas y petrofísicas de la corteza. Basándonos en resultados publicados, analizamos la profundidad del Límite Litósfera–Astenosfera (LAB, en inglés) de la Península Ibérica y la distribución de la temperatura a profundidades de 5, 10 y 20 km y en la Moho. A 5 km, la temperatura supera los 110 °C con anomalías locales (> 130 °C) localizadas en el Macizo Ibérico y en las zonas volcánicas Cenozoicas del SE y NO. A 10 y 20 km de profundidad, se observa un patrón similar con T superiores a 190 °C y 350 °C, respectivamente. A 20 km de profundidad, las anomalías superiores a 500 °C delimitan las zonas volcánicas Cenozoicas. A profundidades de la Moho, la temperatura varía entre 450 y 800 °C, con zonas calientes principalmente a lo largo del Macizo Ibérico y las zonas volcánicas Cenozoicas. No se observan anomalías litosféricas que pueda generar altas temperaturas a poca profundidad, aunque sí muestran un potencial de explotación aceptable a profundidades intermedias.*

Palabras clave: *Litosfera térmica, potencial geotérmico, distribución de temperaturas en la corteza de Iberia, Modelización numérica integrada geofísica-petrológica.*

THE THERMAL STRUCTURE OF THE IBERIAN CRUST

In this work, we summarize the regional trend of the structure and temperature distribution at crustal depths in the Iberian Peninsula. This study is based on the compilation of seismic data and the available results from 2D profiles and 3D regional thermal models located in Figs. 1 and 2. The models integrate geophysical and petrological data to determine the thermo-chemical structure of the crust and upper mantle down to 400km (e.g., Kumar et al., 2021). For more detailed information the reader is referred to the work of Torné et al. 2023.

The compilation of seismic data from Diaz et al., 2021) and the results of the thermal modeling of the Iberian Peninsula (Fig. 3) shows that, in general, both the Variscan and Alpine crust are structured in three layers: the upper and middle crust of variable thickness with velocities between 5.4–6.2 and 6.2–6.5 km/s, respectively, and the lower crust with velocities between 6.5–7.2 km/s, velocities that are slightly higher on average (6.9–7.0 km/s) in the Variscan crust (Díaz and Gallart, 2009). Thermal modelling results show that this stratification is also reflected in variations of the values of radiogenic heat production and thermal conductivity obtained from the best fit model that are summarized in Figure 3.

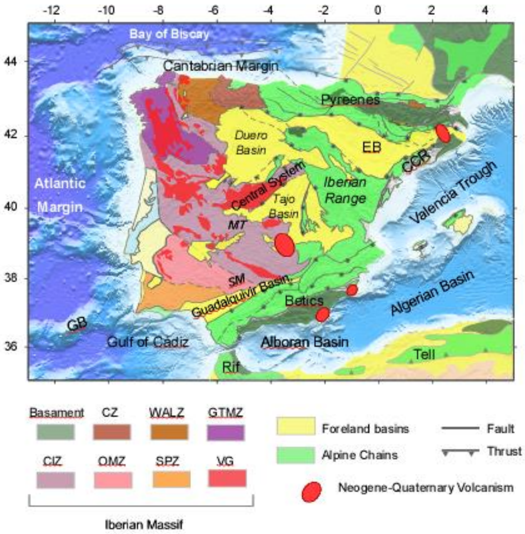

FIGURE 1. *Simplified geological map of the Iberian Peninsula. Modified form Torné et al. (2015).*

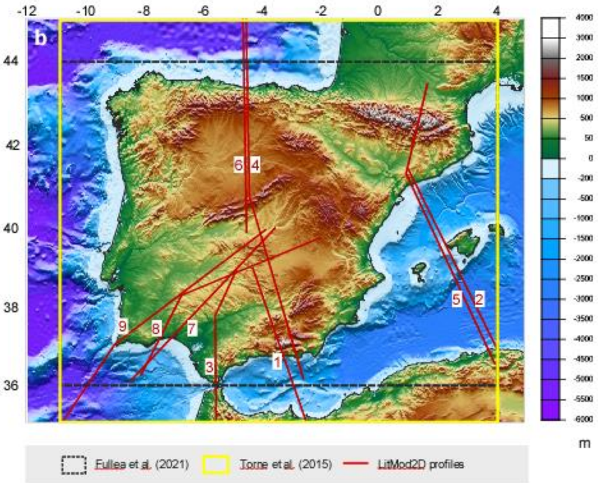

FIGURE 2. *Location of thermal models carried used in this study. Thick red lines show location of 2D profiles. Thick yellow and dashed grey lines show location of regional models. 2D profiles: 1 and 2—Kumar et al. (2021); 3—Jiménez-Munt et al. (2019); 4—Carballo et al. (2015a); 5—Carballo et al. (2015b); 6—Pedreira et al. (2015); 7 and 8—Palomeras et al. (2011); 9—Fernàndez et al. (2004). Modified from Torné et al. (2023).*

In Figure 3 we observe how, along the Pyrenean orogen, the conductivity is slightly higher in the middle/lower crust of the Alpine zone (3.1 and 2.5 W/m.K) than in the Variscan zone (2.1 and 2.0 W/m.K), while for the rest of the Peninsula, the conductivity values remain constant (2.4, 2.1, and 2.0 W/m.K), except for the SW Iberian Massif, which shows slightly higher values (Fig. 5). On the contrary, in the northern margin, radiogenic heat production is lower in the Alpine upper crust than in the Variscan one (1.0 and 1.65 µW/m3), while this trend is reversed for the lower crust (0.3 and 0.2 µW/m3, respectively). We also highlight the differences observed at the level of the middle/lower crust between the northern half of the Iberian Peninsula (Duero Basin) and its southern half (Tajo Basin) with values of radiogenic heat production for the middle/lower crust being slightly higher in the northern part (1.0 and 2.4 versus 0.5 and 0.2 µW/m3, respectively). With regard to the upper crust, a nearly constant value is obtained throughout the area (1.65 µW/m3), except for the Axial Zone of the Pyrenees and the SW Iberian Massif. We raise some caution with these results since the thermo-physical parameters obtained from thermal modelling should be taken as proxies that result from the best fit model, but they cannot replace in-situ or lab measurements. Site-specific values of crustal radiogenic heat production and thermal conductivity are essential to constrain the shallow geotherm and, hence, to evaluate regions of elevated geothermal gradients with the potential for geothermal energy exploitation

Figure 4 shows that at 5 km depth crustal temperatures range from 75–150 ºC with local maxima located in the Iberian Massif and SE and NE Volcanic Provinces. A similar pattern is observed at 10 km depth where temperatures range from 200 ºC to 275 ºC, with local anomalies up to 290 ºC. Results from 2D models mainly differ from 3D regional models in the Betics and Alboran Sea where they register temperatures above 275 °C. These high temperatures are likely related to the lithospheric thinning obtained in the transition from the Iberian Margin to the Alboran Basin, which is not so well constrained in the regional models. The temperature anomalies of the Iberian Massif and SE Volcanic Province proposed by Fullea et al. (2021) mainly trace the outcrops of the Variscan granitoids of the Iberian Massif and the volcanic rocks of the Calatrava and SE Volcanic Provinces (Figs. 1 and 4). In the volcanic provinces they are supported by the measured surface heat flow. Some differences are seen in the temperature distribution at Moho depths between the 3D regional thermal models. Fullea et al. (2021) model, which is based on the Bayesian geophysical-petrological inversion of surface waves, surface heat flow, elevation, and geoid anomalies, obtains higher temperatures (75-100 ºC on average), than those deduced by the model of Torne et al. (2015), which is based on geoid and elevation inversion integrated with 3D inversion gravimetric modeling (Fig. 4). The differences observed between the model of Fullea et al. (2021) and the model of Torne et al. (2015) and 2D profiles are related to the different information they use and their lateral resolution, which results in differences in the topography of the Moho and LAB depths, e.g., at the western regions.

The differences and similarities observed between the analyzed thermal models are largely controlled by the depth of the thermal LAB, the assumed isotherm, and to a lesser extent, by the values of the thermal parameters used. 2D thermal models permit a more detailed definition of the structure of the crust and the lithospheric mantle, and in turn, of their thermophysical properties. Fullea et al. (2007) assess the effect of varying the thermal parameters within geologically meaningful ranges and conclude that the lithospheric thickness, and hence the lithospheric geothermal gradient, is mostly affected by changes in the linear thermal expansion coefficient in the mantle, and to a lesser extent by changes in crustal thermal conductivity and radiogenic heat production. Changes in thermal conductivity and radiogenic heat production are more relevant at upper crustal levels since they have a greater influence in the shallow geotherm.

CONCLUSIONS

1. Integrated geophysical-petrological thermal modeling allowed us to study and propose a first approximation of the temperature distribution, composition, and density distribution in the Iberian Peninsula.
2. Lithospheric thermal models show no evidence of lithospheric anomalies giving rise to high temperatures at shallow depths, but they do show a suitable geothermal potential at intermediate depths.
3. The potential for direct use of geothermal energy for district and greenhouse heating, and industrial processes, seems to be excellent throughout the Iberian Peninsula, the main challenges being the availability of groundwater and drilling costs.
4. Regarding electricity production, hot dry rock (HDR) systems would be located mainly in the Iberian Massif, while hot sedimentary aquifer (HSA) systems, with the greatest potential, would be located in the eastern areas with a thin lithosphere and on the Mediterranean Margin of Iberia.
5. Site-specific values of crustal radiogenic heat production and thermal conductivity as well as an even distribution of surface heat flux measurements are essential to better constrain the shallow geotherm on the Iberian Peninsula and, hence, to evaluate regions of elevated geothermal gradients with the potential for geothermal energy exploitation.
6. The Iberian Massif and the Mediterranean Margin show the highest potential geothermal resources and should be therefore prioritized in future resource estimation investigations.

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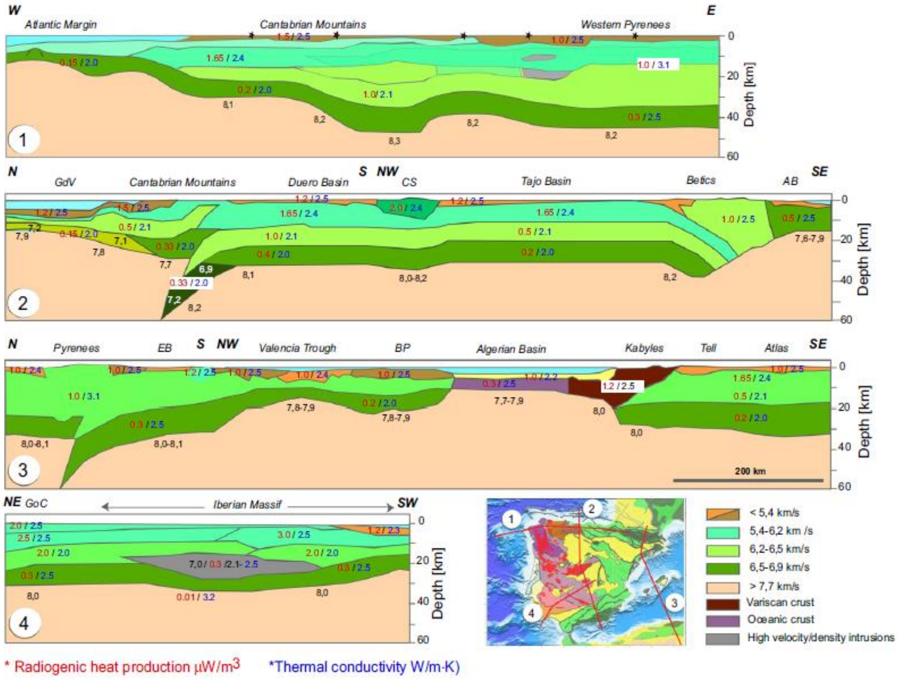

FIGURE 3. *Crustal profiles showing the distribution of Vp, thermal conductivity and radiogenic heat production in the crust and uppermost lithospheric mantle. The map in the lower right corner shows the location of the profiles. Crustal structure from Díaz and Gallart (2009), Pedreira et al. (2007), Carballo et al. (2015 a, b) and Palomeras et al. (2011). Modified from Torné et al., 2023.*

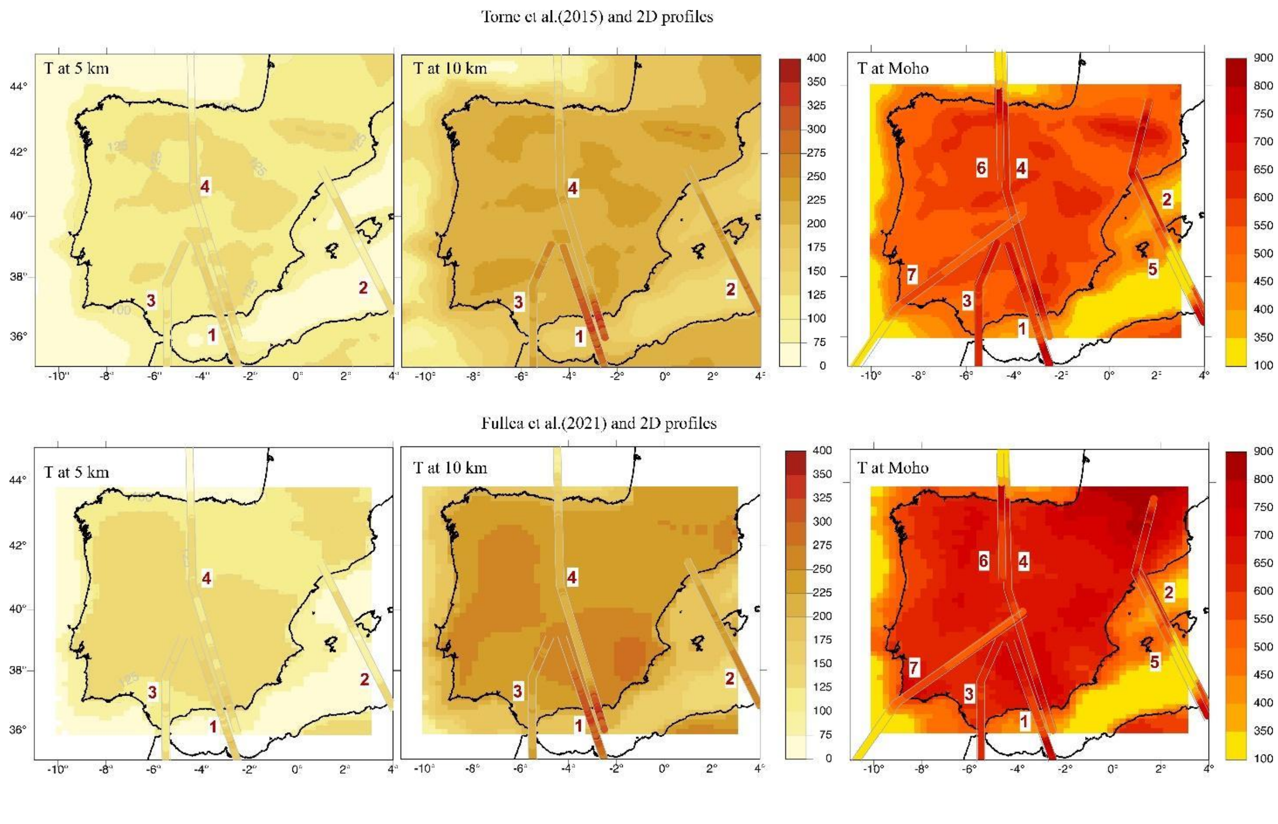

FIGURE 4. *Temperature distribution at 5, 10 km crustal depths and at Moho depth based on the models of Torne et al. (2015) and Fullea et al. (2021) and on the 2D profiles of Kumar et al. (2021) (1 and 2), Jiménez-Munt et al. (2019) (3), Carballo et al. (2015a) (4). Modified from Torné et al., 2023.*