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La Maladeta and Bono granites at depth from geophysical data (Central Pyrenees)

Los granitos de La Maladeta y Bono en profundidad a partir de datos geofísicos (Pirineo Central)

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ABSTRACT

This work aims to show a compilation of geophysical data (gravity, magnetic and magnetotelluric data) to determine the upper crustal structure and geometry at depth of the La Maladeta and Bono granites (Central Pyrenees). La Maladeta granite is interpreted as an asymmetric granitic complex 8 km-thick formed by two differentiated bodies and with a clearly northwards deepening. By contrast, the Bono granite shows a laminar geometry and its thickness does not reach 1.5 km. Both granites show higher areal extension at depth than that showed by their outcrops at surface.

Key-words: *La Maladeta granite, Bono granite, gravity, magnetotellurics, magnetic anomalies.*

RESUMEN

Este trabajo tiene como principal objetivo mostrar una compilación de datos geofísicos (datos gravimétricos, magnéticos y magnetotelúricos) para caracterizar la estructura de la corteza superior y la geometría en profundidad de los granitos de La Maladeta y Bono (Pirineo Central). El granito de La Maladeta se interpreta como un complejo granítico asimétrico de 8 km de espesor y formado por dos cuerpos diferenciados. Por otro lado, el granito de Bono presenta una geometría laminar y un espesor menor de 1.5 km. Ambos granitos presentan un volumen en profundidad mayor que el que se observa en superficie.

Palabras clave: *Granito La Maladeta, granito de Bono, gravimetría, prospección magnetotelúrica, anomalías magnéticas.*

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Introduction

La Maladeta granite is one of the largest granitic massifs outcropping in the Pyrenean Axial Zone. Its petrology, magnetic fabric and geochemistry are relatively well-known (e.g. Leblanc *et al*., 1994), but its geometry at depth has not received much attention. The Bono granite, located to the South, represents a smaller granitic body (Fig. 1).

The aim of this work is to compile different geophysical studies (gravity, magnetic and magnetotelluric methods) to infer the upper crustal structure and geometry at depth of the La Maladeta and Bono granites.

Geological setting

The Pyrenean Axial Zone represents the core of the Pyrenees. It is formed by several south-verging thrust sheets mainly composed by Paleozoic rocks. One of the features of the Axial Zone is the presence of several granitic bodies dated Late Carboniferous-Permian (Esteban *et al*., 2015) that intruded Cambrian to Carboniferous rocks. Around the La Maladeta granite, the country-rocks show very low-grade regional metamorphism and an aureole of contact metamorphism (sillimanite zone) (Leblanc *et al*., 1994). Both the La Maladeta and Bono granites are located close to major Alpine thrusts (Figs. 1, 2).

In the study area the following Late Variscan granites outcrop (Figs. 1, 2): La Maladeta, Artiés, Marimanha, Bono and Lys granites.

Methods

The Bouguer gravity data were obtained from the compilation done by Ayala *et al*. (2021) using the geodetic reference system GRS80 and a reference density of 2670 kg/m^3. Information about the data processing and gridding of the Bouguer anomaly can be found in Ayala *et al*. (2016, 2021). The residual Bouguer data were obtained after subtracting a regional gravity anomaly that consists of a third order polynomial surface (see Ayala *et al*., 2021; Soto *et al*., 2022) (Fig. 3A,B).

The magnetic data derives from the EMAG2v2 (Maus *et al*., 2009). From the total magnetic intensity map (Fig. 3C), we calculated the reduced to the pole (RTP) map (Fig. 3D). The RTP transforms an observed magnetic anomaly into the anomaly that would be measured at the north magnetic pole. This relocates asymmetrical magnetic anomalies to be over their sources, thus making magnetic interpretation easier.

The magnetotelluric (MT) data and resistivity model come from Piña-Varas *et al*. (2023). Broadband magnetotelluric sites were recorded in 2019 in the La Maladeta granite area along a NNE-SSW profile (Figs. 2,4).

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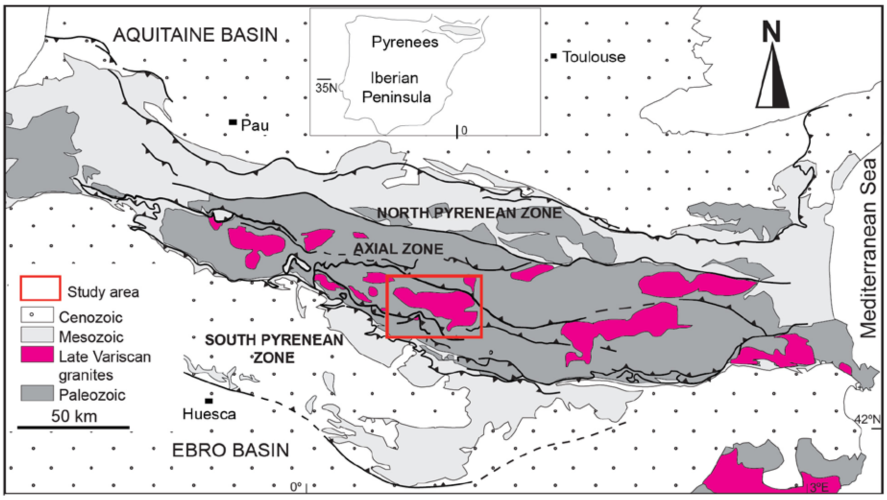

Fig. 1.- Location of the study area showing the main Late Variscan granites in the Central Pyrenees. Color figure in the web.

Fig. 1.- Localización del área de estudio mostrando los principales granitos tardi-Variscos del Pirineo Central. Ver figura en color en la web.

Results

Gravity

The Bouguer anomaly over the La Maladeta granite coincides with a relative gravity minimum of negative values and shows variations in amplitude of only 12 mGal (Fig. 3). Within the La Maladeta granite, the smaller gravity values define a minimum located at its central part and elongated in a NNE-SSW direction towards the North.

Two smaller granites in the study area are also associated with gravity minima; (i) the Artiés granite that coincides with the above mentioned relative minimum and shows values ranging between -100 and -108 mGal, and (ii) the Bono granite that coincides with a relative minimum of -100 to -104 mGal elongated towards the South also in a NNE-SSW direction (Fig. 3A,B).

The residual Bouguer anomaly map shows roughly the same gravity trend than the Bouguer one highlighting the relative gravity minimum located to the North of La Maladeta granite and coinciding with the Artiés granite (Fig. 3). The Bono granite also coincides with a relative gravity minimum elongated in a NNE-SSE direction that extends towards the South of its outcrop. Both the Marimanha and Lys granites do not show a remarkable gravimetric response.

Magnetic response

The total magnetic intensity anomaly map showed in Figure 3C shows several small magnetic anomalies with values raging between -14 and 0 nT. The reduced to pole magnetic intensity values range between 0 and -15 nT (Fig. 3D). The preferred orientation of magnetic anomalies is NNW-SSE and NNE-SSW. The La Maladeta and smaller granites as the Bono one outcropping in the study area do not show a remarkable magnetic response (Fig. 3D) reflecting their paramagnetic character (i.e. negligible contribution of ferromagnetic minerals; Bouchez, 1997).

The southern margin of the La Maladeta granite is characterized by the presence of two relative maxima (Fig. 3D). Both maxima coincide with the limit of the granite with Devonian rocks at surface and probably reflect higher magnetic signal related to metamorphism and/or deeper sources.

2D MT resistivity model

The 2D MT resistivity model shows three striking high-resistivity bodies

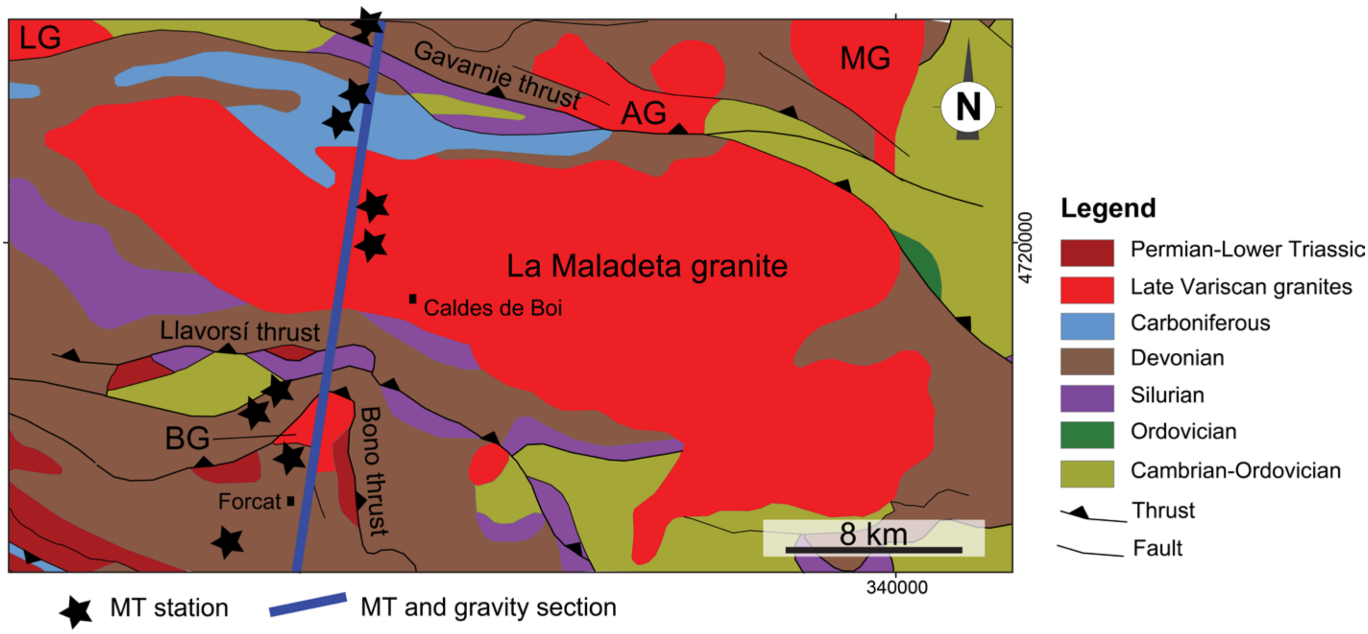

Fig. 2.- Geological map of the study area with the location of the MT sites and gravity section. LG: Lys granite, AG: Artiés granite, MG: Marimanha granite, BG: Bono granite. Modified from Ternet et al. (2008). Color figure in the web.

Fig. 2.- Mapa geológico de la zona de estudio con la localización de los sitios MT y perfil gravimétrico. LG: granito de Lys, AG: granito de Artiés, MG: granito de Marimanha; BG: Granito de Bono. Modificado de Ternet et al (2008). Ver figura en color en la web.

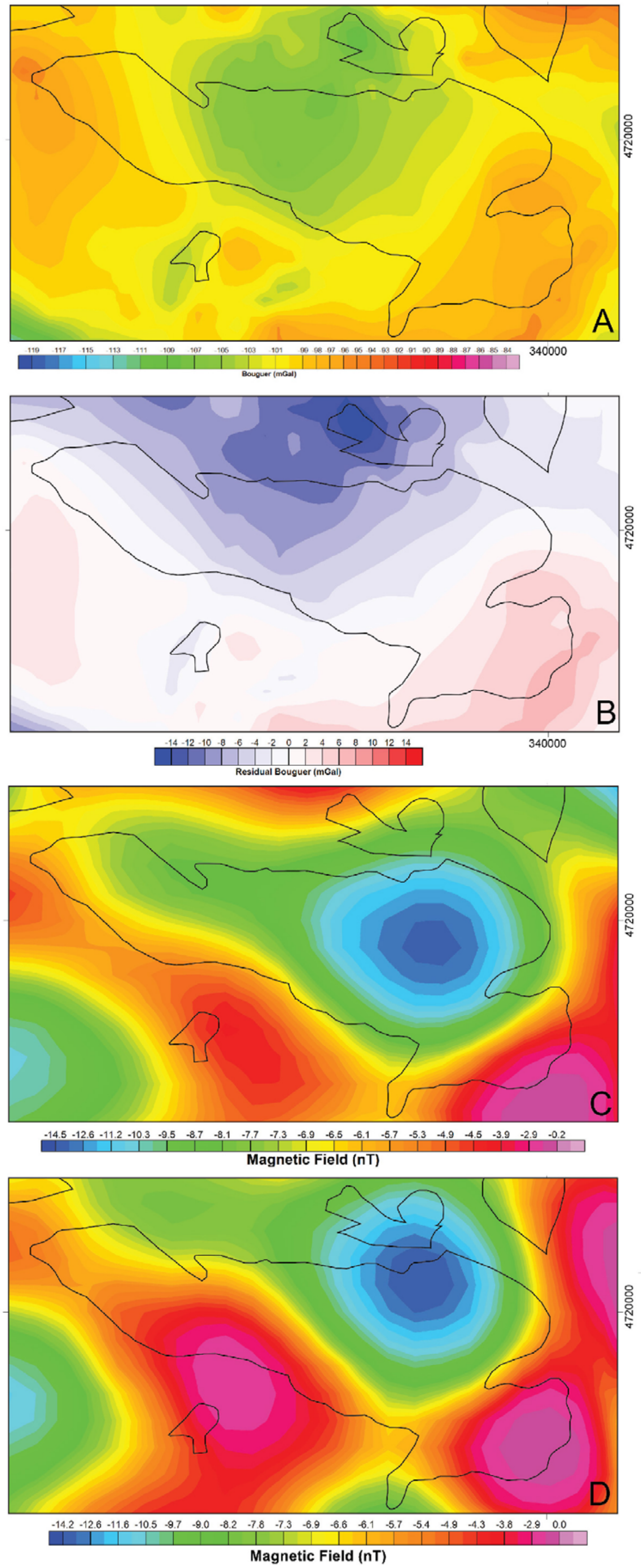

Fig. 3.- A,B. Bouguer and residual Bouguer anomaly map of the study area, respectively. C. Total magnetic intensity anomaly map. D. Reduced to the pole magnetic anomaly map. See text for details. Color figure in the web.

Fig. 3.- A. Mapa de anomalías de Bouguer del área de estudio. B. Mapa de anomalías residual de Bouguer. C. Mapa de anomalías de intensidad magnética total. D. Mapa de anomalías magnéticas reducidas al polo. Ver texto para detalles. Ver figura en color en la web.

(Fig. 4) (see Piña-Varas *et al*., 2023 for details). The highest resistivity values, up to 4000 Ω·m, correspond to two differentiated bodies (R1 and R2 in Fig. 4) separated by a lower resistivity zone. They coincide with the La Maladeta granite and are observed to depths of ~4-5 km below sea level (b.s.l). To the South, similar resistivity values are imaged by a body with shallower depth extent and slightly dipping to the South (R3) that partly coincides with the outcrop of the Bono granite.

Interpretation

The final geometry at depth of the study area was interpreted taking into account the input of geophysical data. The initial model of the La Maladeta granite, deduced only by gravimetric data (see Clariana *et al*., 2022; Soto *et al*., 2022) depicted an unique body of c. 10 km in depth dipping to the North with a batholithic shape. The geological cross-section of Fig. 5 was subsequently modelled with the constraints of gravity and MT data (see Piña-Varas *et al*., 2023 for details).

The geometry of the La Maladeta granite at depth is, therefore, interpreted as an asymmetric granitic complex formed by two differentiated bodies. Its thickness reaches more than 8 km and shows a clearly northwards deepening. With respect to the Bono granite, it shows a laminar geometry probably controlled by the Bono thrust and its thickness does not reach 1.5 km. Both La Maladeta and Bono granites show higher volume at depth than that showed by their outcrops at surface.

Interpretation of the source of the small magnetic anomalies appearing in the study area would need further rock magnetic analyses (both magnetic susceptibility and magnetic remanence).

Conclusions

The geometry at depth of the La Maladeta and Bono granites has been constrained by means of gravity and magnetotelluric methods due to density and resistivity contrasts between the granitic and host rocks, respectively. The magnetic anomaly maps do not show prominent magnetic anomalies coinciding with both the La Maladeta and Bono granites, confirming that they show a negligible contribution of ferromagnetic minerals.

Authors' contribution

Soto, R.; Paper Structure, editing, figures, research/analysis, coordination, supervision.

Clariana, P., Ayala, C., Piña-Varas, P.; Methodology, figures, manuscript review, research/analysis.

García-García, A., Martín-León, J.; Methodology, figures.

Gamisel-Muzás, A., Mochales, T, Rey-Moral, C., Rubio, F.; Methodology, manuscript review.

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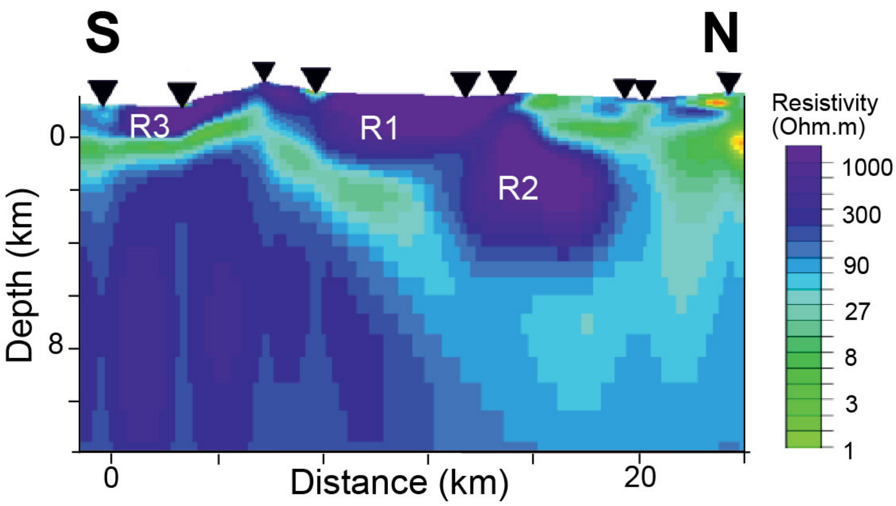

Fig. 4.- 2D MT resistivity model of the study area. R1, R2 and R3 represent main geoelectrical features of high-resistivity. Modified from Piña-Varas et al. (2023). Color figure in the web.

Fig. 4.- Modelo 2D de resistividades de MT. R1, R2 y R3 representan zonas de alta resistividad. Modificado de Piña-Varas et al. (2023). Ver figura en color en la web.

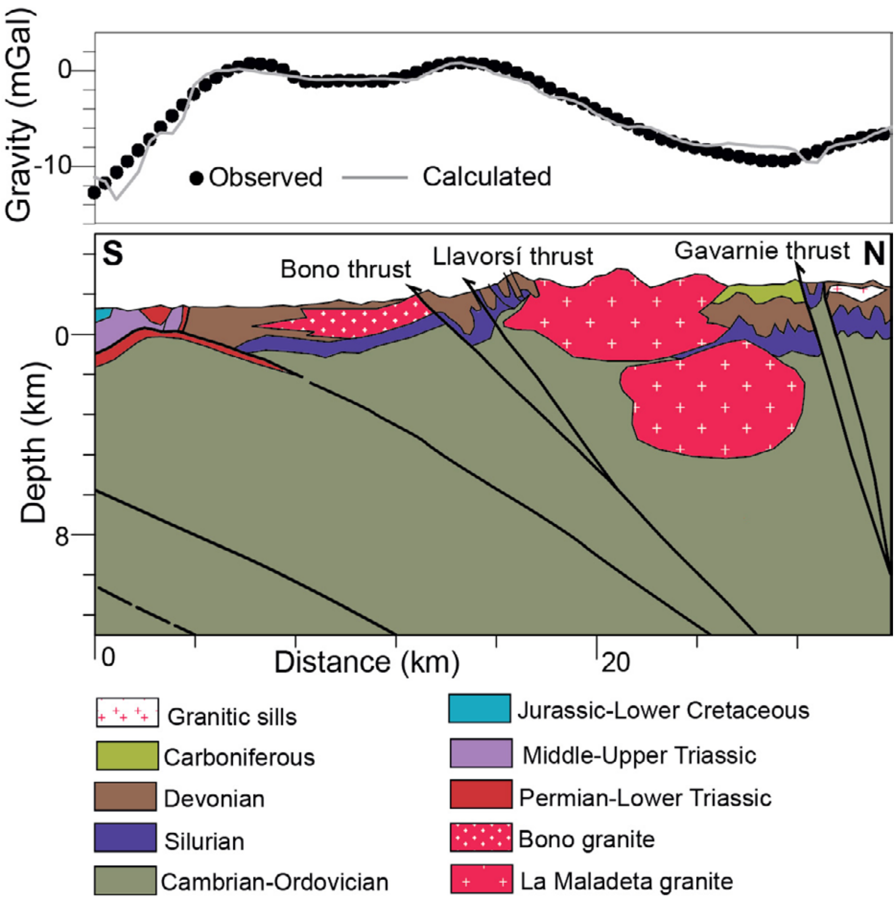

Fig. 5.- Geometry at depth of the La Maladeta and bono granites. Modified from Piña-Varas et al. (2023). Color figure in the web.

Fig. 5.- Geometría en profundidad de los granitos de La Maladeta y Bono. Modificado de Piña-Varas et al. (2023). Ver figura en color en la web.

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