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SCIENCE



Gravity data on the Central Pyrenees: a step forward to help a better understanding of the Pyrenean structures

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ABSTRACT

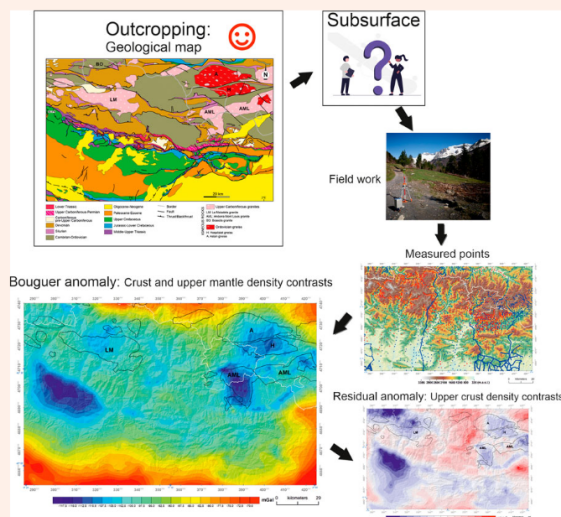
In this work, we present new Bouguer and residual Bouguer anomaly maps of the Central Pyrenees calculated from 3590 stations, of which 1141 are new observations acquired from surveys performed between 2018 and 2019. The most prominent feature of the Bouguer anomaly is the long wavelength elongated minimum in its central part that continues to the W and ends towards the E with a positive gradient that seems to envelope the minimum. Other short and medium wavelength minima are superimposed, some placed over the batholithic outcrops. In the residual Bouguer, the main relative minima are related with outcrops of batholiths or interpreted buried granites except for the prominent minimum South of La Maladeta Granite, associated with Triassic evaporitic accumulations. These maps (shown on the Main Map) will help characterizing the Permo-Carboniferous batholiths of the Central Pyrenees, in particular La Maladeta and Andorra Mont-Louis granites in order to add constraints to the mechanism of their emplacement.

ARTICLE HISTORY

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Bouguer anomalies; residual anomalies; Central Pyrenees; igneous rocks



1. Introduction

Bouguer anomalies reflect the changes in the gravity field produced by the subsurface density distribution and its lateral variations. The raw measurements are acquired with a gravimeter on the surface, airborne or on a vessel and then corrected to obtain the Bouguer anomalies (e. g. [Hinze et al., 2005](#)). Broadly speaking, maximum values on the Bouguer anomalies show a

mass excess. Depending on its wavelength they can be related to a thinning of the continental crust, a basement high, the presence of denser materials as basic igneous or metamorphic rocks, ore deposits, etc. Minimum values are in general associated to a mass deficit caused by, e.g. a thicker continental crust, sedimentary basins, acid igneous rocks and/or salt deposits.

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Bouguer anomalies can be used to address a broad range of geological unknowns by defining the subsurface geometry of outcropping geological structures previously unknown (e. g. Santolaria et al., 2020, Ayala et al., 2019) and/or adding constraints on the characterization of the crust and upper mantle (Peral et al., 2018, Pedrera et al., 2017). In local studies, the applications include studies as diverse as research related to natural hazards (seismotectonic studies, volcanoes, faults) or natural resources (such as geothermal energy, minerals, etc.) (e.g. Hinze and Hildenbrand, 1988; Hildenbrand et al., 2000; Mishra, 2011), and also, basic research on the structure and dynamics of the Earth's interior.

The gravity method is cost effective and gives reliable results when the density contrasts between the lithologies found in the study area are high enough to be correlated with the mapped anomalies. Once the relationship is established, we can build up 2D, 2.5D and/or 3D models showing the geometry and density distribution of the targeted geological features. In this regard, we have acquired new gravity data in the context of a basic research project funded by the Spanish Ministry of Science and Innovation whose acronym is GeoPiri3D.

One of the goals of the GeoPiri3D project is to obtain a 3D model of two of the main batholiths of the Central Pyrenees (NE Spain) (Figure 1): La Maladeta batholith, that crops out in an area of c. 42×18 km and the Andorra Mount Louis batholith, whose outcrop extends in an area of c. 10×20 km

(Figure 2). This detailed characterization of granitic complexes aims to discern their relationship with coeval igneous rocks and with all the surrounding materials, including the host rocks. Gravity interpretation will help reconstructing the Pyrenean history before the Alpine orogeny.

The available gravity data from the Institut Cartogràfic i Geològic de Catalunya (ICGC) database was quite scarcely distributed in the study area. For this reason, new gravity surveys were accomplished by IGME and ICGC in 2018 and 2019 to improve the spatial distribution of these data to better constrain the 3D geometry and density variation of the intrusive bodies and host rocks. A total of 1141 new points were acquired, processed, and integrated in the database. The joined set of stations was carefully revised to ensure the quality of the complete dataset.

2. Location and geological setting

The Pyrenees consists of a WNW-ESE striking, narrow asymmetric chain with a mainly southward vergence. The deep structure of the Pyrenean belt responds to the north-dipping continental underthrusting of the Iberian lithosphere underneath the European upper plate (e.g. Choukroune and ECORS Team, 1989; Muñoz, 1992; Roure et al., 1989). The present-day crustal thickness in the Pyrenean region is the result of the complex evolution of the mountain belt characterized by several

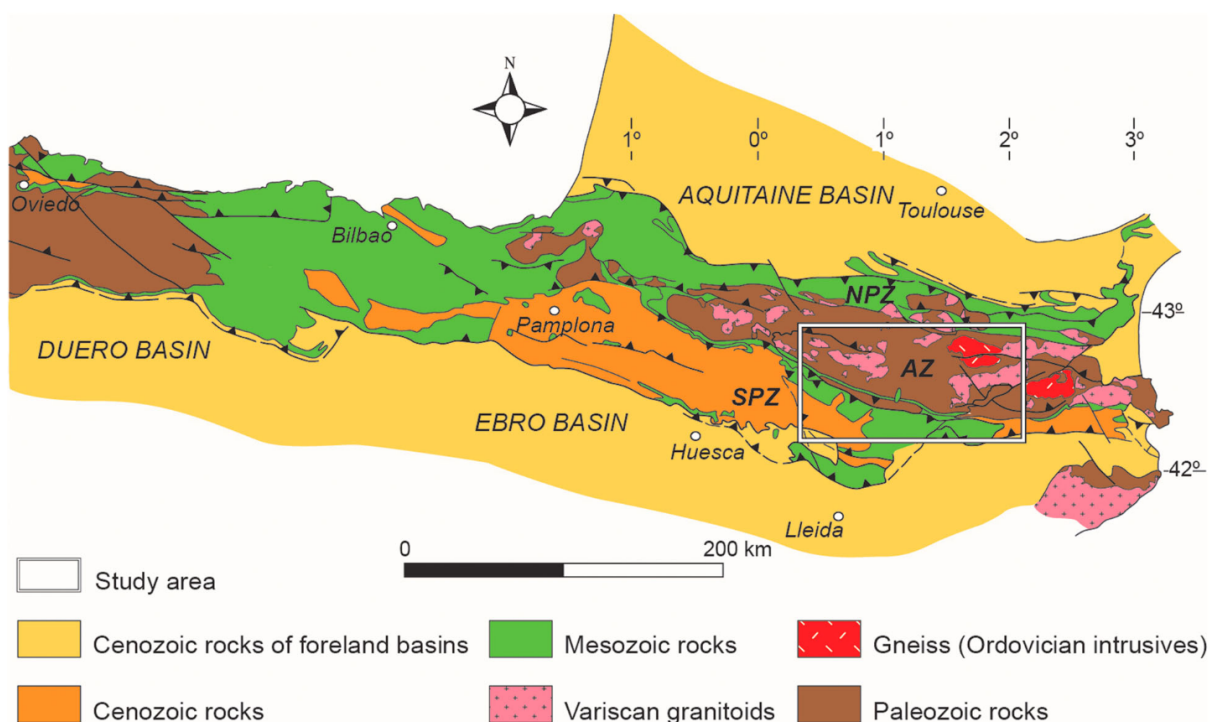


Figure 1. Geological sketch of the Pyrenees with the location of the study area (white rectangle) and some of the main cities. Structural units: SPZ, South Pyrenean Zone; AZ, Axial Zone; NPZ, North Pyrenean Zone.

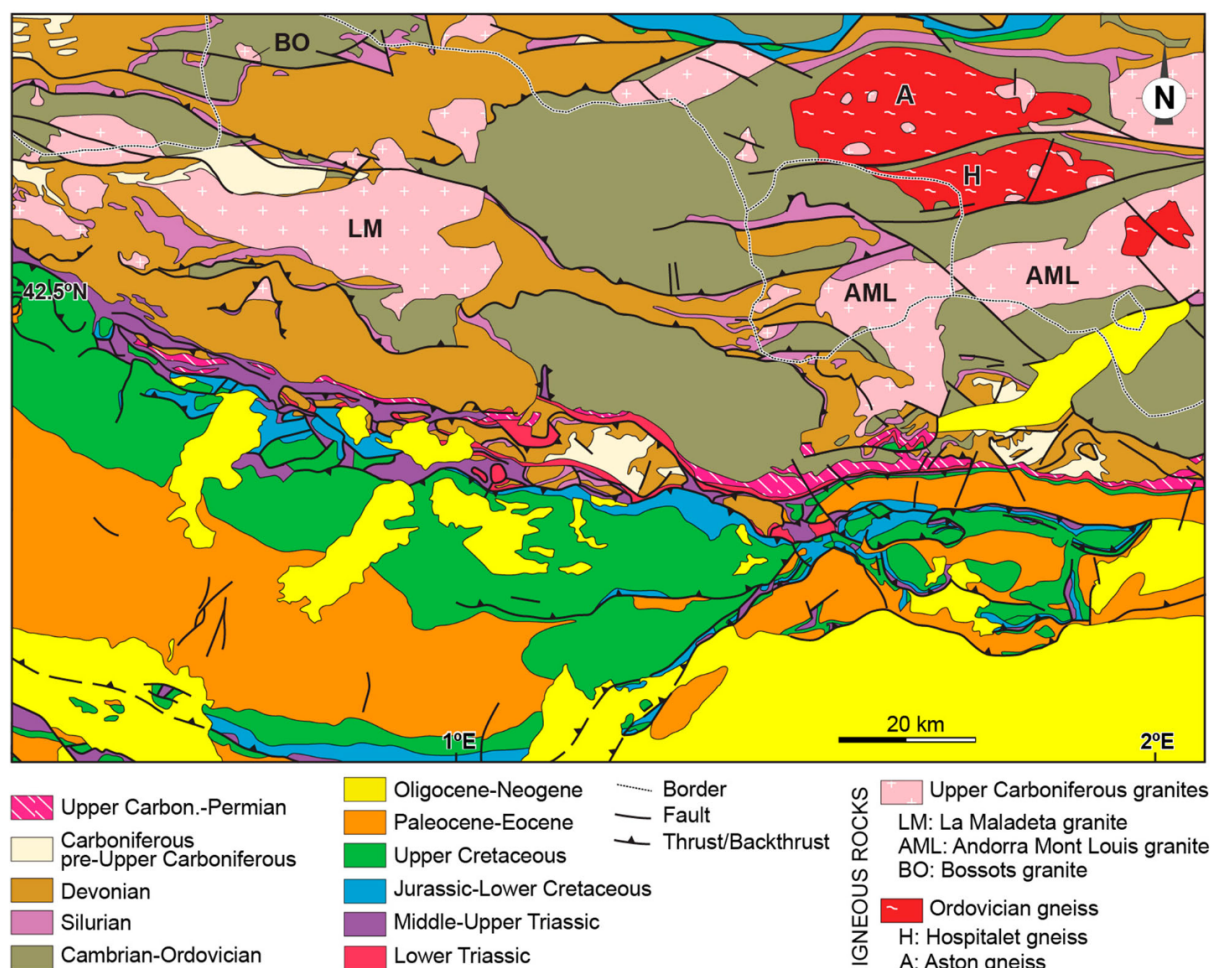


Figure 2. Geological map of the studied area showing the location of the granites and gneisses mentioned in the text. Modified from Rodríguez-Fernández et al. (2015), Autran and García-Sansegrundo (1996) and Muñoz et al. (2018).

tectonic stages (e.g. Barnolas and Pujalte, 2004; Muñoz, 2019 and references therein); the Variscan (Carboniferous) and Alpine (Late Mesozoic-Miocene) orogenies and two rifting stages (Triassic and Late Jurassic-Early Cretaceous). From North to South the Pyrenees include (e.g. Muñoz, 1992): the Aquitaine foreland basin, the North Pyrenean Zone, the Axial Zone, the South Pyrenean Zone and the Ebro foreland basin (Figure 1). Maps based on gravity data compiled in this work are located within the Axial Zone and the northern part of the South Pyrenean Zone of the Central Pyrenees, where the structures show south vergence (Figure 2). The Axial Zone (the backbone of the chain) consists of an antiformal stack of thrust sheets involving mainly Paleozoic basement rocks affected by the Late Carboniferous intrusion of granitic bodies (as La Maladeta and Andorra Mount Louis granites) (e.g. Barnolas et al., 1996; Porquet et al., 2017; Casas et al., 2019). The South Pyrenean Zone consists of a south-verging thrust stack involving Mesozoic and Cenozoic rocks decoupled from the Paleozoic basement along the

Triassic evaporites, a significant detachment level playing a major role on the Pyrenean Alpine deformation (e.g. Séguret, 1972).

3. Materials and methods

3.1. Source data and methodology

Out of the 3590 data points compiled in the study area, 2449 come from the ICGC-CATAGRAV database (IGC/ICC/ICTJA, 2012; Marzán & Fernandez, 2010) that already integrates and harmonizes data from IGN and IGME (Mezcua et al., 1996; SIGEOF by IGME, 2010), Bureau Gravimétrique International (BGI, 1951) and BRGM (2009) in the French part as well as from previous compilations of Catalunya (ICC, 1987) including some academic works (Casas et al., 1987, 1997; Torné et al., 1989; Rivero-Marginedas, 1994, etc.). The 1141 new stations come from the surveys carried out in 2018 and 2019 by IGME and ICGC.

The new gravity data were acquired using three different gravimeters: A Scintrex CG5 (with an

accuracy of 0.001 mGal), a Lacoste & Romberg G582 (with an accuracy of 0.005 mGal) and a Scintrex CG6 (with an accuracy of 0.001 mGal). 63% of the stations were measured with the Scintrex CG5; 25% were measured with the Lacoste & Romberg and 12% with the Scintrex CG6. To calibrate the measurements made by the three instruments and ensure consistency, 12 stations were measured simultaneously with the three instruments and 78 stations with the Scintrex CG5 and the Lacoste & Romberg.

Gravity measurements were performed in itineraries with an estimated duration of less than 8 h to control and minimize the effect of the instrument drift that in each case was corrected, together with the tidal correction (Longman, 1959; Rudman et al., 1977), prior the Bouguer anomaly reduction. Four different gravimetric IGN bases, Sort, Vielha, Puigcerdà and La Seu d'Urgell (<https://www.ign.es/web/ign/portal/grv-consultas-2007>) have been used to obtain the observed gravity and tie up the stations to the International Gravity Standardization Network 1971 (IGSN71 network). To evaluate the uncertainty of the data, about 10% of the stations were repeated with an average root mean square (RMS) of the differences between lectures at the same location of 0.02

mGal for the Scintrex CG5 and CG6 gravimeters and 0.06 mGal for the Lacoste & Romberg gravimeter. The location of the stations, i.e. horizontal coordinates (X, Y) and elevation (Z) was measured with a differential GNSS instrument (TRIUMPH from JAVAD) that has centimetric precision. Due to the steep orography of the study area, with elevations above 2000m and without easy accessibility (Figure 3), it has not been possible to have a homogeneous coverage of the measurements.

3.2. Gravity data homogeneization

As part of the quality control of the gravimeters to ensure best performance, IGME uses some of the stations of the Santander-Málaga IGN calibration line (<http://www.ign.es/web/resources/docs/IGNCnig/GRV-Teoria-Gravimetria.pdf>), to supervise the stability, calibration factor and its proper functioning. Before the beginning of the surveys, measurements were taken in these stations with both gravimeters. The results show that both instruments are stable. Nevertheless, the values measured with the Scintrex CG5 are more similar to the IGN values of the calibration line than the ones measured with

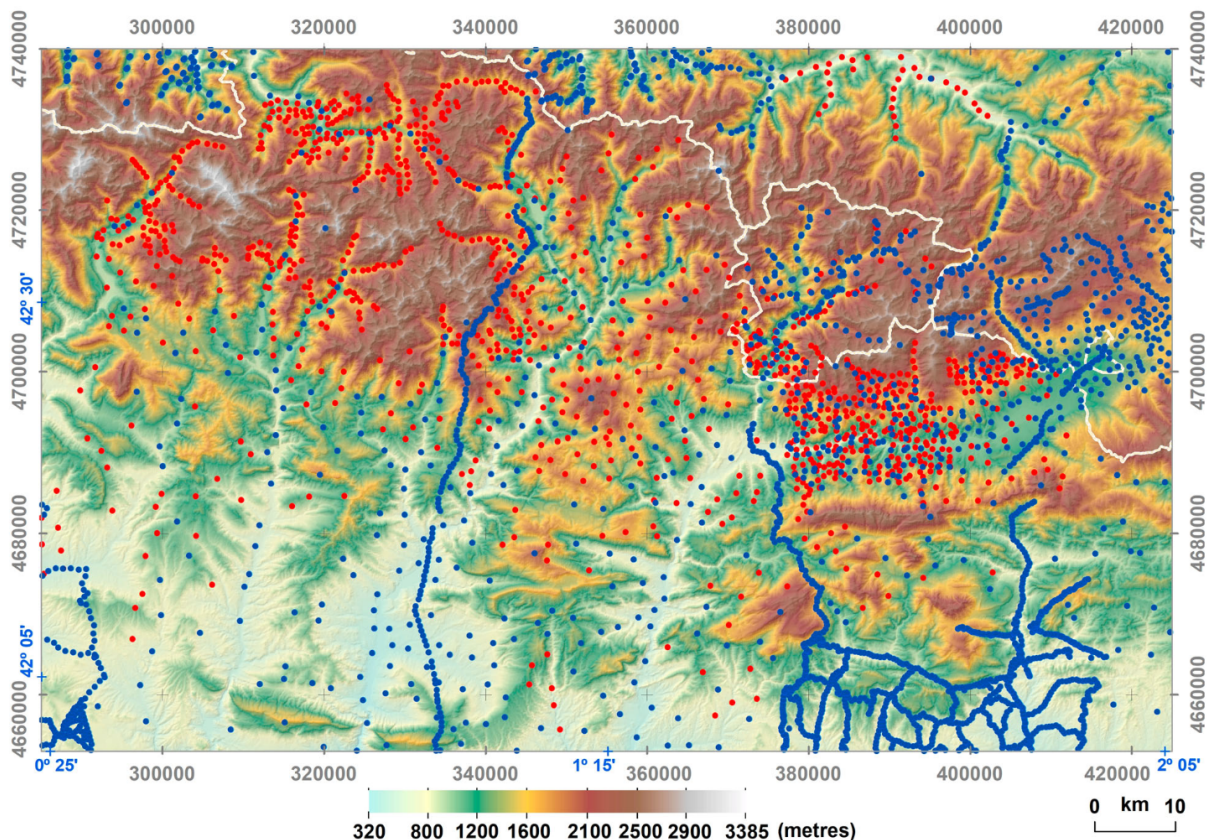


Figure 3. Relief map of the study area. Color scale in m. Red points are the new gravity stations measured in the project. Blue points are stations from CATAGRAV database. Color scale are in meters above sea level. Gray labels: UTM coordinates in m, zone 31N, datum ETRS89; Blue labels: Geographical coordinates.

the Lacoste & Romberg. Please note that the Santander-Málaga calibration line is linked to the Spanish Fundamental Gravimetric Network (RGFE 73) which is also linked to the IGSN 71 network. The procedure followed by the IGN is explained in the International Gravity Standardization Net 1971 UIGG-IAG Special Publication (Morelli et al., 1972). IGN is the official Spanish body in charge, among other responsibilities, of maintaining the RGFE 73.

Once the stability of the gravimeters has been established and in order to homogenize the measures taken in the surveys, we have carried out seven programs at different days measuring the same points with the two gravimeters. The analysis of these measures has allowed us to make the corresponding corrections. The graph showing the correlation between both gravimeters together with the regression equation and adjusting parameters is shown in Figure 4, where the X-axis corresponds to Lacoste & Romberg values and the Y-axis to Scintrex CG5 values.

This regression equation is used to correct the Lacoste & Romberg values and make them more homogeneous with the Scintrex values. After the correction, the mean square error of the differences between the repeated values with the two gravimeters has decreased from 0.59 mGal to 0.20 mGal which is acceptable for a regional gravity survey. The regression equation and its parameters are as follows:

$$Y = 1.006705289 * X - 6571.835954$$

Number of points used = 78

Coefficient of determination, R-squared = 0.999802

3.3. Bouguer anomaly calculation

Prior to interpret the results of the gravity surveys in terms of geological structures, it is necessary to correct the variations in the Earth's gravity field that are not related to the subsurface density distribution (Hinze et al., 2005). The calculations have been made using the same formulae as those of the ICGC database:

- (1) Latitude correction: This correction consists of subtracting from the observed gravity (which is the sum of the gravitational attraction of all the Earth's masses and its rotation) the theoretical gravity G_N (the gravitational attraction of a homogeneous ellipsoid with the same semi axes as the Earth) determined on the surface of the reference ellipsoid GRS80. It is calculated using the Somigliana formula (Somigliana, 1930; Heiskanen and Moritz, 1967).
- (2) Free air correction, G_{CF} , accounts for the elevation h of the measurement location respect to the reference ellipsoid:

$$G_{CF} = - (0.3087691 - 0.0004398 \sin^2(\varphi)) * h + 7.2125 \cdot 10^{-8} * h^2$$

(Heiskanen and Moritz, 1967), where h is the orthometric height in m and φ is the latitude.

- (3) The space between the ellipsoid and the observation point is filled with material so the Bouguer anomaly correction, G_{CB} , accounts for the gravity attraction of a slab of constant thickness located between the ellipsoid and the observation point:

$$G_{CB} = 4.192 \cdot 10^{-5} * h * \rho$$

where h is the orthometric height and ρ is the reduction density in kg/m^3

- (4) The slab does not consider the topography (mountains and valleys).

In theory, the terrain correction should extend to the radius of the Bouguer slab. In practice, the effect of the elevation diminishes very rapidly with distance and becomes negligible for distances further than 166.7 km. However, the influence of the nearby topography is particularly important.

In this work the terrain correction has been applied up to 166.7 km, in order to be consistent with the calculations made by the ICGC. We have used the Oasis Montaj terrain correction module, based on Kane (1962) and Nagy (1966). We use a combined 5 m DTM from Spain, France and Andorra that were re-gridded to 20×20 m as local grid and a joint grid from the SRTM database (e. g. Farr et al., 2007) and Bathymetry data from GEBCO database (Sandwell et al., 2002) re-gridded to 100×100 m as regional grid.

For the calculation we use the geodetic system GRS80 with orthometric heights with a reduction density of $\rho = 2670 \text{ kg/m}^3$; all the terms are expressed in mGal.

The new map of Bouguer anomalies (Figure 5) is characterized by a long wavelength elongated relative minimum that occupies the central part of the map with values lower than c. -95 mGal . It extends towards the W, outside of the study area, but it closes to the E with a positive gradient at the edges whose value reaches about -70 mGal . This minimum can be associated with the cortical root of the Pyrenees (e. g. Torné et al., 1989). Superimposed to this minimum, some relative maxima and minima of medium and short wavelengths are depicted. They have variable amplitudes that are associated with outcropping structures and their different extension at depth.

The two main granite bodies (La Maladeta and Andorra-Mount Louis, LM and AML respectively) provide different gravimetric responses. The anomaly on the granite outcrop of LM has variations in amplitude of only 5 mGal, while the outcrop of the AML batholith is characterized by a relative minimum whose variation is 15-20 mGal which extends towards the NE in an area where there is no granitic outcrop. The relative minimum located to the SW of LM is interpreted as the gravimetric response of Triassic evaporitic accumulations (low density rocks) in the subsurface that are covered by Mesozoic sediments.

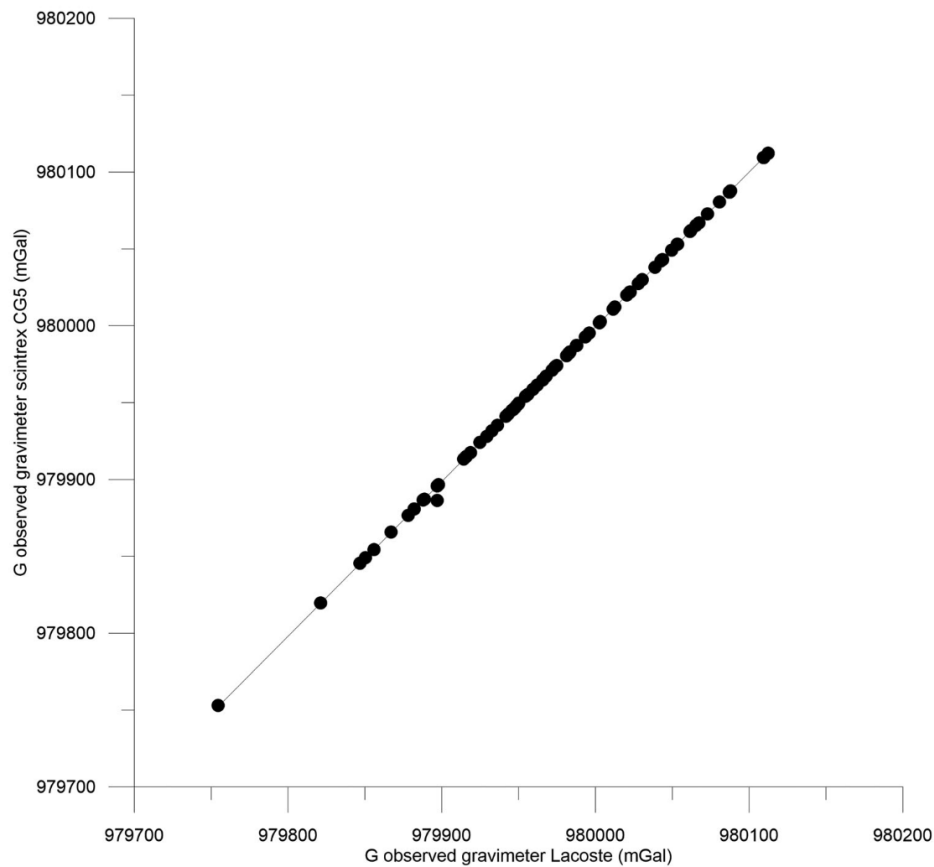


Figure 4. Correlation between L&R values and Scintrex CG5 values. A straight line has been adjusted to these values with the adjustment parameters shown below: Equation: $Y = 1.006705289 * X - 6571.835954$; Number of points used = 78; Coefficient of determination, $R\text{-squared} = 0.999802$.

3.4. Regional-residual separation residual bouguer anomaly

The residual anomaly (Figure 6) was calculated assuming a regional anomaly corresponding to a third-degree polynomial that reflects the density distribution of the mid to lower crust and upper mantle structures. This polynomial was calculated using Surfer software. The equation and coefficients are as follows:

$$Z(X,Y) = A00 + A01*Y + A02*Y^2 + A03*Y^3 + A10*X + A11*XY + A12*XY^2 + A20*X^2 + A21*X^2Y + A30*X^3$$

$$A00 -11500987.429613$$

$$A01 7.4620895971381$$

$$A02 -1.6126536833881 \cdot 10^{-6}$$

$$A03 1.1607085548261 \cdot 10^{-13}$$

$$A10 -0.78320248964874$$

$$A11 3.1357264521318 \cdot 10^{-7}$$

$$A12 -3.0559172480929 \cdot 10^{-14}$$

$$A20 1.289920232212 \cdot 10^{-7}$$

$$A21 -3.7089474940754 \cdot 10^{-14}$$

$$A30 4.3679212592231 \cdot 10^{-14}$$

The pattern of the anomalies shows a zonation coinciding with the LM batholith characterized by a succession of a gravity high and a gravity low of small amplitude (4–6 mGal), which is consistent with lateral lithological changes on the surface (Debon et al., 1996) and at depth, and a possible granitic contact dipping towards the N. Towards the NW of LM granite another minimum appears coinciding with the Bossòst granite located at border of the study area (see Figure 2 to locate this body). It is worth noting that the amplitude and extension of this minimum suggest that the major part of this granite is buried. The relative minimum (with values of –6 to –8 mGal) over the AML batholith that extends towards the NE with an amplitude of c. 10 mGal coincides with the outcrops of the Hospitalet-Aston gneisses (see also Figure 2). South of the LM batholith, in the South Pyrenean Zone, there is a prominent relative minimum that can be associated to the accumulation at depth of the Triassic evaporites that crop out as slivers between the thrusts and as diapiric bodies (Figure 2). Its S-SE extension seems to indicate that these rocks also extend in that direction.

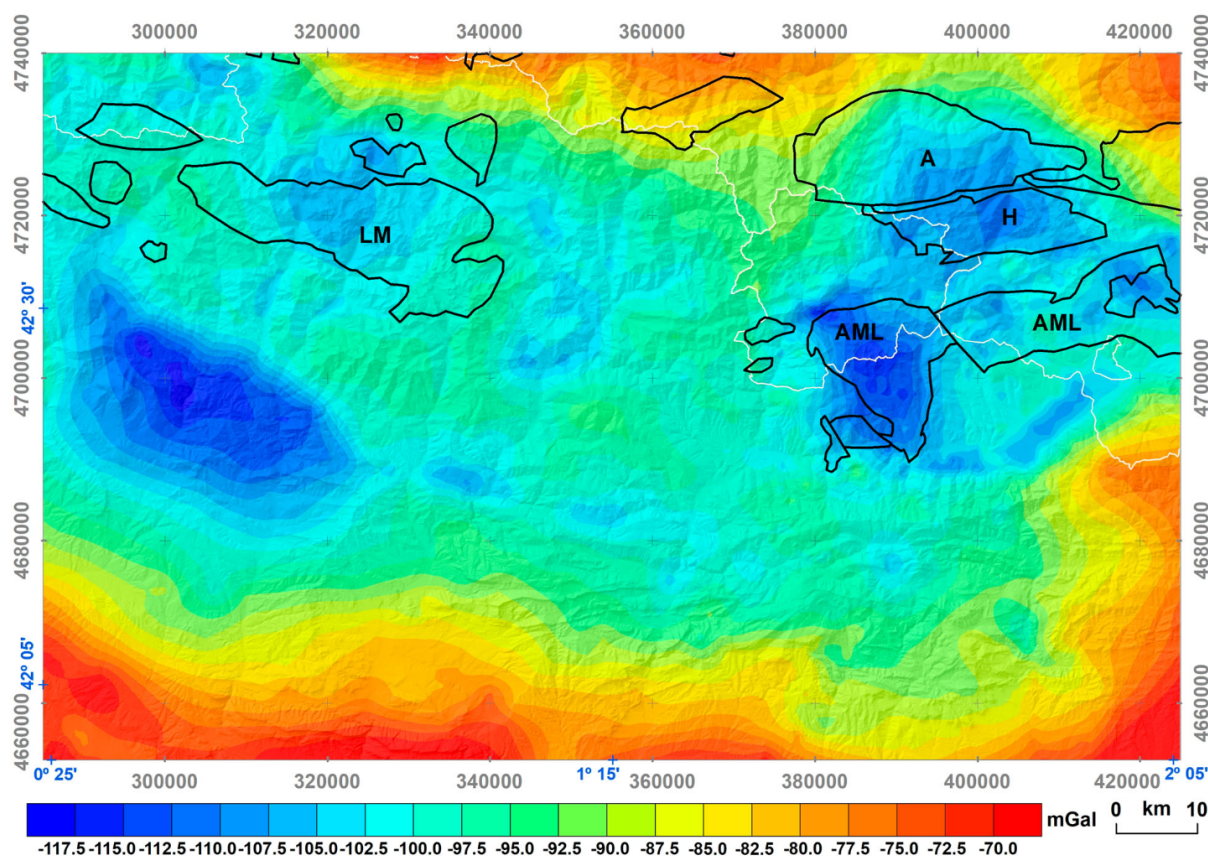


Figure 5. Bouguer anomaly map. Gray labels: UTM coordinates in m, zone 31N, datum ETRS89; Blue labels: Geographical coordinates. Intrusive bodies are outlined in black. LM – La Maladeta granite; AML – Andorra Mont-Louis granite; H – L'Hospitalet gneiss; A – Aston gneiss.

4. Results and conclusions

This new Bouguer anomaly map of the Central Pyrenees improves the spatial resolution respect to the existing map of the Iberian Peninsula (Ayala et al., 2016) and Catalonia (CATAGRAV database, IGC, ICC, ICTJA-CSIC 2012). Therefore, it allows to carry out more detailed geological studies, in particular those aiming to investigate the upper crust and to gain knowledge on the structure of the thrust system, the geometry of the Late Carboniferous granites and the volume of the Triassic evaporitic rocks.

Regarding the interpretation of the maps, in addition to the high amplitude minimum associated with the outcropping granites, the Bouguer and residual anomaly maps show three more outstanding minima.

- (1) The one located to the NE of the Andorra Mont-Louis granite that coincides with the outcrops of the Hospitalet-Aston gneisses (labels H and A in Figures 5 and 6).
- (2) To the SW of the La Maladeta granite, the minimum is associated with the low density Triassic evaporites whose inferred thickness is greater

than that shown by their outcropping area. The geological setting of this anomaly rules out the presence of buried granitic bodies in this sector (Clariana et al., under revision IJES, 2020).

- (3) The one located NW of La Maladeta granite, at the border of the study area, is related to the Bossòst granite (see Figure 2 for location); the amplitude and extension of this minimum suggests that the major part of the granitic body is buried.

It is also noteworthy the fact that the gravity lows are surrounded by relative gravity highs that correspond with outcrops of metasedimentary rocks (i.e. the host rocks for the emplacement of the igneous bodies) of the Axial Zone, showing higher density than the granitic massifs.

In the Central Pyrenees, where no seismic data is available, gravity data is a valuable tool to better constrain 2D and 3D geological models. This geophysical method allows defining the geometry and density distribution of granitic bodies and their host rocks based on their density contrasts and inferring the volume of evaporitic rocks (lower density rocks) at depth. The combination of gravity, petrophysical data of sampled rocks from the studied area and geological data constitutes a powerful tool to infer the architecture of

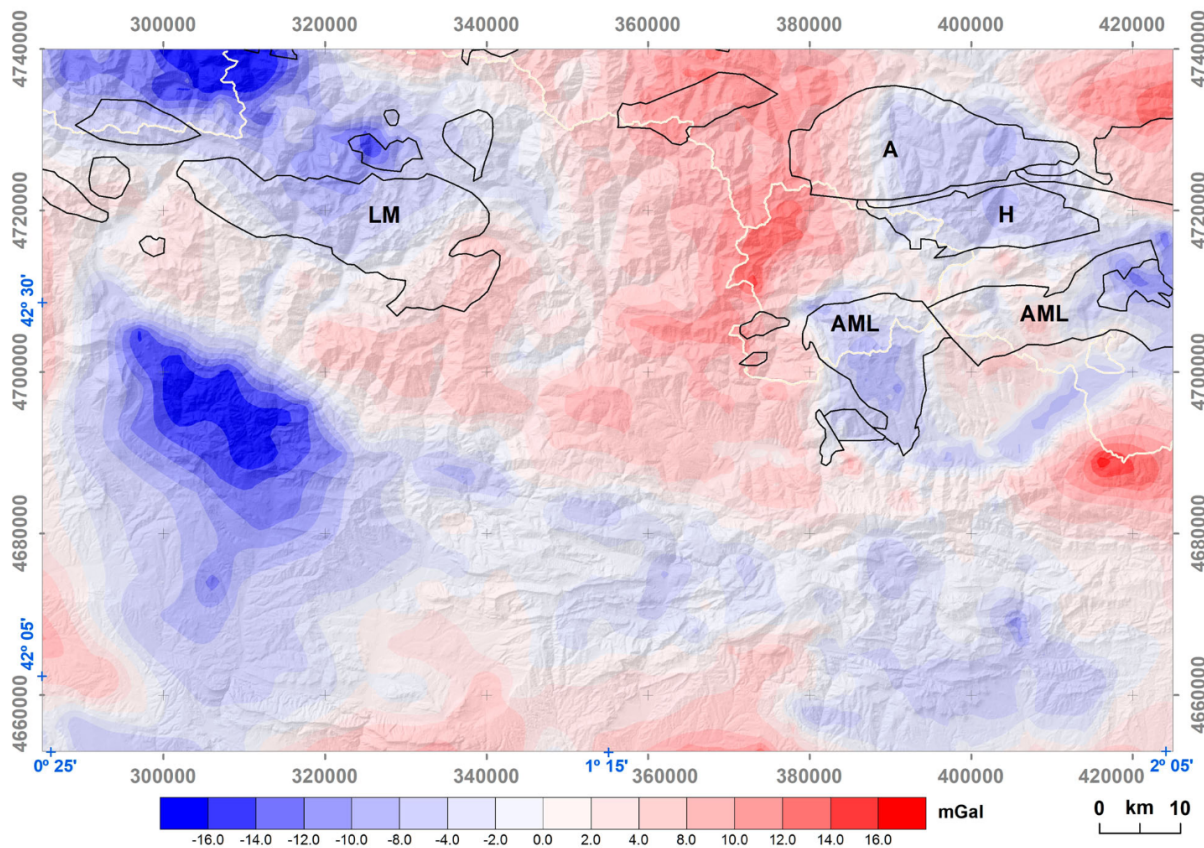


Figure 6. Residual anomaly map. Gray labels: UTM coordinates in m, zone 31N, datum ETRS89; Blue labels: Geographical coordinates. Intrusive bodies are outlined in black. LM – La Maladeta granite; AML – Andorra Mont-Louis granite; H – L'Hospitalet gneiss; A – Aston gneiss.

orogenic belts toward a further understanding of their geodynamic evolution.

Software

The gravity data have been processed to obtain Bouguer and residual anomalies using Oasis Montaj v. 9.7 from Geosoft. The gridding method has been minimum curvature and with a grid spacing of 1000 m. To avoid border effects in the gridding process, the area has been extended 20 km in all directions. Once the grid has been calculated, it has been cut to the study area.

Regional gravity anomaly was calculated using Surfer v. 13 by 3rd degree polynomial adjust with a grid spacing of 1000 m.

GPS coordinates have been calculated using Justin software.

Figures 1 and 2 have been produced with Adobe Illustrator CS2 12.0.0.

The graph displayed on Figure 4 has been built using Grapher v. 11.

Figure 3, Figures 5 and 6 have been created using a combination of Geosoft v.9.7 mapping and ArcGIS Desktop 10.8.1.

The map design and output display have also been built up using ArcGIS Desktop 10.8.1.

GEOLOCATION AND GEOGRAPHICAL INFORMATION.

The study area is located in the Central Pyrenees, between approximately 0° 25' E and 2° 05' E, 42° N and 42° 40' N.

We have used ETRS89 as the geodetic reference system with the associated GRS80 ellipsoid (as established in Spain by law, RD 1071/2007 BOE-A-2007-15822). Furthermore, Bouguer anomalies have been calculated using the geodetic system GRS80 (with orthometric heights) and with a reduction density of 2670 kg/m³. In this way, we have created maps that are consistent with European standards.

- EU-DEM digital surface model (DSM) and EAA Coast Line are available at https://www.eea.europa.eu/eu_dem_v11_E30N20.TIF: <https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1>

EAA Coast Line <https://www.eea.europa.eu/data-and-maps/data/eea-coastline-for-analysis-2>

- Emodnet Bathymetry E4_2018.asc and F4_2018.asc are available at <https://portal.emodnet-bathymetry.eu/>
- Spanish geographic reference information are available at Instituto Geográfico Nacional (IGN) <http://>

centrodedescargas.cnig.es/

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- Andorra's country limit is available at <https://www.iaea.ad> <https://www.iaea.ad/cartografia/cartografia-sig>

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The newly acquired data for this study will be uploaded to the IGME (Spanish Geological Survey) repositories. To access the data, use the web application SIGEOF – Geophysical Information System: <http://info.igme.es/SIGEOF/#>. The data is available under request and free of charge. It will also be uploaded to the DIGITAL.CSIC public repository (<https://digital.csic.es/>).

Gravity data from the Institut Cartogràfic de Catalunya (CATAGRAV) database used to complete the gravimetric maps are available in the web <https://www.icgc.cat/Administracio-i-empresa/Descarregues/Cartografia-geologica-i-geotematica/Mapes-geofisics-i-sismics> where these data can be request by e-mail and will be free of charge for research purposes.

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