Updated Bouguer anomalies of the Iberian Peninsula: a new perspective to interpret the regional geology

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ABSTRACT

Bouguer anomaly maps are powerful cartographic tools used mainly by geoscientists and natural resources’ companies (oil, mining, etc.) since they reflect rock density distribution at different depths, allowing the identification of different tectonic features. At upper crustal levels, Bouguer anomaly maps can help, for instance, in characterizing possible ore deposits, ground water reservoirs, petroleum resources, CO₂ storage sites and sedimentary basins; at deeper crustal levels they can help to further refine seismic velocity models or other integrated geophysical models and thus help in deciphering the lateral density variations within the crust and the geometry of the base of the crust. This new Bouguer anomaly map at a 1:1,500,000 scale is based on the compilation of 210,283 gravity stations covering the Iberian Peninsula (c. 583,254 km²). The new map upgrades previous maps in two ways: (1) it is built up from a database with a 15% more spatial coverage than previous compilations and (2) it is freely available. This map show shorter wavelengths than previous published maps thus allowing investigation of smaller geological features.

1. Introduction

Density distribution within the Earth is one of the most important physical parameters to determine the structure and dynamics of the Earth’s interior. Lateral variations in density are responsible for gravity anomalies that can be measured on the surface or airborne and then corrected to obtain the Bouguer anomalies. These anomalies can be used to identify subsurface geological structures that can be of interest from natural resources’ companies to researchers looking for a better understanding of the Earth’s dynamics. In general terms, positive anomalies indicate a mass excess (e.g. a thicker crust, the presence of denser rocks as metamorphic or basic igneous rocks, a basement high, ore deposits, etc.) whereas negative anomalies suggest a mass deficit (e.g. a thinner crust, the presence of sedimentary basins with potential oil reservoirs, etc.). One of the advantages of gravity data is that it allows going from two-dimensional studies along a cross-section based on the interpretation of seismic, electric, magnetotelluric profiles, etc. to 3D models of the geometry and density distribution of the causative bodies in selected areas of interest. A Bouguer anomaly map is the first step needed prior to building up 2D or 3D models (please note that throughout the text, when talking about the Bouguer anomaly, we mean the complete Bouguer anomaly, that is, the Bouguer anomaly with topographic correction).

The story of the construction of gravimetric maps from gravity data surveys in the Iberian Peninsula goes back as far as 1877 (see http://www.ign.es/ign/layoutIn/gravimetriaPeriodo1.do, Álvarez, 2002; Inglada, 1923; Mezcua, Gil, & Benarroch, 1996 for more historical information). The first Bouguer anomaly map covering the Iberian Peninsula and the Balearic Islands was obtained and published in 1996 by the National Geographical Institute (Mezcua et al., 1996) using 32,976 stations in the GRS80 Geodetic Reference System (Moritz, 1984). In the late 1990s and early 2000s, a thorough compilation of gravity data was carried out by the Area of Geophysics at IGME (Spanish Geological Survey); a total of 119,200 stations from 393 different surveys were revised and standardized using the GRS67 Geodetic Reference System and a density reduction of 2600 kg/m³. The resulting database was made available to the public through a web-based interface called SIGECO (http://cuarzo.igme.es/sigeco/default.htm) that allows free access to public geological and geophysical data held at IGME. In 2006, within the framework of the Topolberia project (a Consolider-Ingenio project financed by the Spanish government, see http://www.igme.es/Topolberia/default.html) a new gravity data compilation for the Iberian Peninsula was carried out in order to generate the Bouguer anomaly map presented here. For this purpose, several Institutions (the Spanish Geological Survey (IGME), the University of Granada,
the University of Oviedo, and the Bureau Gravimétrique International) contributed their data (Figure 1). The final database consists of 210,283 gravity stations unevenly distributed (Figure 1) that were used to calculate a new Bouguer anomaly map using the geodetic reference system GRS80 and a reference density of 2670 kg/m³. The choice of this value for solid-earth reference system GRS80 and a reference density of late a new Bouguer anomaly map using the geodetic unevenly distributed (Figure 1) that were used to calculate with the one from IGN (National Geographical institute) published by Mezcua et al. (1996) as the database contains 15% more stations than previous compilations (e.g. Gómez-Ortiz, Agarwal, Tejero, & Ruiz, 2011, with a total of 180,930 stations) with the additional advantage that, unlike other compilations, the data and the Bouguer anomaly map are publicly available through the SIGECO web server (http://cuarzo.igme.es/sigeco/default.htm and http://geodb.ictja.csic.es/BBDD_TopoIberia/). Detailed information and technical aspects about how the data were compiled and homogenized in order to obtain the final database from which the Bouguer anomaly map is generated can be found in Ayala (2013) (http://geodb.ictja.csic.es/BBDD_TopoIberia/).

The map published in this paper can only be compared with the one from IGN (National Geographical institute) published by Mezcua et al. (1996) as the IGME database was never published as a map. The most recent gravimetric compilation, from (Gómez-Ortiz et al., 2011), presents the data as Figure 2 in the paper, which does not have much detail. Neither the database from Gómez-Ortiz et al., 2011 nor the figure in the aforementioned paper is freely available to the public.

The Bouguer anomaly map of Mezcua et al. (1996) is based on a network of 32,976 gravity stations. From this point of view, the map presented in this paper has 630% greater coverage. It shows, in general terms, the same pattern of anomalies as the IGN but because our map has a greater coverage and therefore better spatial resolution, high-frequency anomalies are better displayed. Our map can therefore be used to investigate smaller geological features (in this case, as small as 4 km across) that can be easily identified from the anomaly pattern.

The final Bouguer anomaly map at the 1:1,500,000 scale is composed of one map sheet (see supplementary map), with the main map colour coded from blue (gravity minima) to red (gravity maxima) with a histogram equalized colour scale in order to highlight the main anomalies. Also displayed are the stations with the data sources for the Bouguer anomaly (same as Figure 1) and the Bouguer anomaly map with the main thrusts and fault traces superimposed and the zero isoline depicted in white. In this way, this map constitutes a valuable tool for geoscientists in order to interpret Bouguer anomalies in terms of tectonics and regional geology.

### 2. Methods

#### 2.1. Source data and methodology

A gravity anomaly at a given point on the Earth’s surface is the difference between the observed gravity (the combined effect of the gravitational attraction of the Earth’s masses and the rotation of the Earth) and a theoretical gravity (the gravimetric effect of a homogeneous ellipsoid). When the gravity anomaly is: (a) corrected for the elevation h of the measurement site (Free-air correction) with respect to the reference ellipsoid; (b) corrected for the gravitational attraction of a plate of constant thickness h (Bouguer plate correction) and (c) corrected for the gravity attraction of the terrains around the measurement site (Terrain correction), we obtain the Bouguer anomaly.

We have calculated the Bouguer anomaly using the geodetic system GRS80 formula, which, for each point of observation, is given by:

\[ G_{BA} = G_{obs} - G_N + G_{cF} - G_{cB} + CT, \]

where \( G_{BA} \) is the Bouguer Anomaly; \( G_{obs} \) is the observed gravity, tied to International Gravity Standardization Network 1971 (IGSN71); \( G_N \) is the normal gravity determined on the surface of the reference ellipsoid WGS84 using the Somigliana formula (Heiskanen & Moritz, 1967; Somigliana, 1930); \( G_{cF} \) is the free air correction (Heiskanen & Moritz, 1967)  \( (G_{cF} = - (0.3087691-0.0004398 \sin^2(\phi))h + 7.2125 \times 10^{-11} \times h^3, \) where \( h \) is the orthometric height in m); \( G_{cB} \) is the Bouguer correction  \( (G_{cB} = 4.192 \times 10^{-8} h \rho \) where \( \rho \) is the reduction density in kg/m³); \( CT \) is the topographic correction.

For this map, the density reduction is \( \rho = 2670 \) kg/m³, and all the terms are expressed in mGal.

The topographic correction has been calculated at least up to 21,943 m using Hammer tables and a digital terrain model from the National Geographic Institute (IGN). Please note that Fullea, Fernández, and Zeyen (2008) demonstrate that in order to attain an accuracy of 0.1 mGal in the Bouguer anomaly calculation, the minimum distance required for the topographic correction is 20,000 m even in rough areas, so there is no need to extend further the calculations of the topographic correction because it will not improve the accuracy of the Bouguer anomaly.

From uncertainties in the observed gravity at a given station, and in the horizontal (latitude and longitude) and vertical (height) positions of the station, we estimate that the accuracy of the new Bouguer anomaly map is in the range of 2–5 mGal.

To build up the map, the uneven distribution of the Bouguer anomaly point data has been gridded using the minima curvature algorithm with a 2000 m grid spacing and internal tension \( T = 0 \). The optimum grid spacing has been calculated using Esri ArcMap. As
the stations of the database have extremely inhomogeneous distribution, to grid the data we have followed the steps described in Sambridge, Braun, and McQueen (1995): (a) create a triangulated mesh (called TIN, Triangular Irregular Networks); (b) estimate the best grid spacing and (c) grid TIN using the Natural Neighbour algorithm. In our database, the distance between points varies from 200 to c. 50,000 m. According to Sambridge et al. (1995), the optimum grid spacing ranges between 100 and 25,000 m. If we used the former grid spacing, some artefacts would be created whereas using the latter would result in an appreciable loss of information. The adopted solution was to calculate the grid spacing from the weighted average distance between TIN nodes, which is 2000 m. See Ayala (2013) for a complete explanation of the procedure; further discussions about gridding can be found in previous work, for example, Rubio and Plata (1998); Smith and Wessel (1990); Sambridge et al. (1995). The data are stored in both geographical coordinates (Longitude/Latitude; 10°W to 5°E, 35°50′ N to 44°N) and rectangular coordinates (UTM 30N in m; −75,000 to 113,600 easting, 3,980,000 to 4,871,000 northing), using the ETRS89 datum. The grid was constructed using the rectangular coordinates.

### 2.2. Data representation

The Bouguer anomaly map of the Iberian Peninsula is a composite sheet made of three maps (see Main Map) at a 1:1,500,000 scale, colour shaded using a histogram equalization method in order to highlight patterns and features that can be useful for geological and geophysical exploration. The anomalies range from c. −120 mGal to c. 80 mGal. The raster grid can be represented at any other scale taking into account that the smallest structures that can be resolved have a minimum wavelength of c. 4000 m (defining the structure with three points) or 6000 m (defining the structure with 4 points).

When comparing the Bouguer anomalies with the tectonic map, there is a good correlation between the main tectonic features and the anomaly patterns. In general terms, the negative anomalies can be correlated with mountain ranges (the minima generated by their crustal roots) and sedimentary basins, whereas positive anomalies mainly correspond with outcrops of the Variscan basement, mostly high-density basic rocks.

### 3. Conclusions

We present a new Bouguer anomaly map that has been built based upon an improved gravity database using ETRS89 as the geodetic reference system with the associated GRS80 ellipsoid (as established in Spain by law, 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 a map that is consistent with European standards.

The Bouguer anomaly is displayed as a colour-shaded map represented with the histogram equalization colour method in order to reveal the most...
important features of the Iberian crustal and lithospheric structure. The scale of the map presented in this work is 1:1,500,000, but the 2,000 m × 2,000 m grid could be represented at other scales bearing in mind that it can resolve structures with wavelengths as small as 4,000 m.

The map reflects lateral variations in density distribution within the crust and upper mantle, allowing geoscientists and commercial companies to use the Bouguer anomaly map for geophysical exploration and also to target zones that could be of further interest for more detailed investigations. The clear relationship between the main geological structures and the Bouguer anomalies in the Iberian Peninsula implies that this map represents a first-order product in the study of the geological evolution of the region.

The gravity data have been imported, managed and processed using Oasis Montaj v.8.0 from Geosoft. The grid was built with Generic Mapping Tools V4 (GMT V4; Wessel, Smith, Scharroo, Luis, & Wobbe, 2013). The map design and output display has been built up using a combination of GMT V4, Global Mapper V16, ESRI ArcGIS 9.2 and Adobe Illustrator CS3. Figures 1 and 2 have been made using Adobe Illustrator CS3.

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