Gravity applied to La Garriga-Samalús geothermal system

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Abstract: Geophysics is a transverse science field which aims to explore and characterize the surface and subsurface of the Earth. There are different geophysical methods based on different physical parameters that can be applied in geological and geothermal exploration. In this work we apply the gravity method to the Vallès-Penedès Basin (NE of Spain), which is based on the density differences of the subsurface. In order to differentiate the basin of its surroundings we calculate the Bouguer anomaly of the area from the filtered acquisitioned data. Not only there is the Vallès Basin as an interesting geological item but also the Vallès Fault, which we show using the horizontal derivative. We also do a gravity inversion-which gives the density in depth- tracing a profile along the basin in a NW-SE direction. The geological characterization of the area, and specifically, the characterization of the fault, is the first step for a better understanding of the geothermal system.

I. INTRODUCTION

The studied area is located in the eastern part of the Catalan Coastal Ranges (NE of Spain). The Catalan Coastal Ranges (CCR) display a horst and graben structure which includes two mountain ranges (horst) and one basin (graben). These mountain ranges have a NE-SW orientation, and from NW to SE, they include the Pre-Coastal Range, the Vallès-Penedès Basin and the Coastal Range.

In a horst and graben structure, different faults can limit the different geological units. In the case of study, in the eastern part of the CCR, the Vallès Fault limits the Pre-coastal Range and the Vallès Basin. This fault has been previously defined as a crustal normal fault which act as the path for hot fluids in a geothermal system,[1].

By the use of the gravity method, we will determine the limits between these 3 main geological items that conform the studied area. It is expected to get a resulting map with a similar trend with FIG. 1, which shows clearly the basin situated between both pre-coastal and coastal ranges, the Vallès normal fault and the different types of the subsurface rocks.

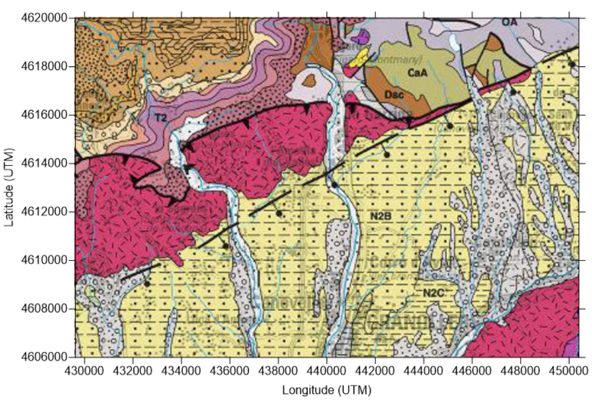

FIG. 1: Geological map of the studied area[2].

The Vallès Fault localization and characterization is the main goal of this project. The presence of the fault leads to a natural canal for the subterranean hot water to go up to the surface, pushed by the higher pression of the interiors of the crustal. This process takes place as fast as the hot water has no time to cool so it springs up in very high temperatures. These are called thermal waters and there are a few in La Garriga and Caldes de Montbui, which are locations situated just above the Vallès Fault.

By the use of the gravity method the densities of the subsurface units can be labelled, giving useful information about the crust structure of a zone. In the study area, higher densities are expected in both range zones and lower densities are expected in the basin, according to the type of rocks that conform each area.

The Vallès Basin is conformed mainly of clastic sediments, as sandstones and conglomerates[2, 3], which according to FIG. 2, have lower densities than granite, igneous and metamorphic rocks, which are vastly present in the mountain ranges[2, 3].

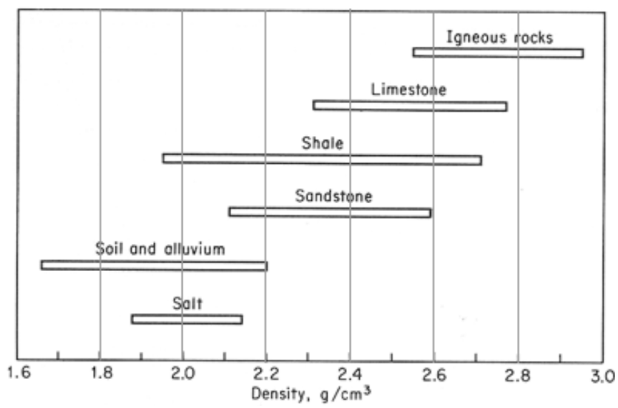

FIG. 2: Density of rocks[4].

II. DATA ACQUISITION

The gravity map covers an area of 210 km^2 over the entire Vallès Basin and it contains 781 measurement points, 25 of which have been added in the present study. The new acquired data, measured in March 2022, cover the western zone of FIG. 1 and FIG. 3, surrounding Caldes de Montbui town.

The field campaign was prepared in advance by locating the measurement points homogeneously distributed over the target area. The distance between the measurement points were ranged between 500 and 1000m, which combined with the previous points gave enough precision to calculate the Bouguer anomaly of the zone.

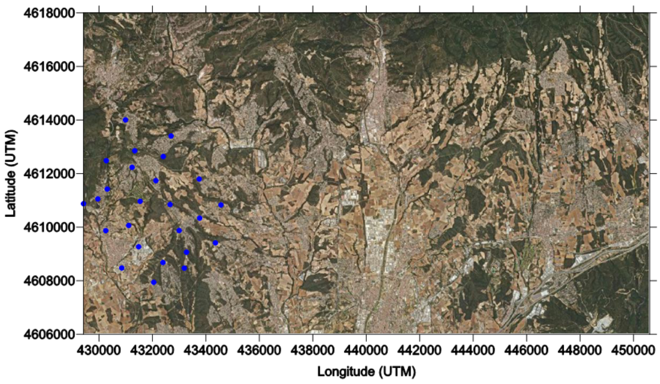

FIG. 3: Position of the new measurements added to those already studied in previous studies located over the rest of the Vallès Basin.

For the acquisition we used a relative gravity measuring device (Lacoste & Romberg). This means that instead of giving the local and instantaneous gravity as the absolute ones do, it measures gravity differences between observation sites. These differences combined with a measure in an official known gravity point -called the base- allow to get the absolute gravimetric profile of all the studied points. In this study the base was located near the Physics school at Barcelona University.

Whenever a gravimetric work is done, some conditions have to be taken into account, such as the latitude, the longitude, the time of measurement and of course the measurement itself. All these features have to be known as they will be needed for applying the gravimetric corrections. After the data review and corrections the aim was to get a Bouguer anomaly value for every site.

III. GRAVIMETRIC CORRECTIONS

The corrections are mainly distributed in two groups: those referred to the observed gravimetric data and those related to the theorical gravity values. In fact, the Bouguer anomaly is the difference between the observed and the theorical gravity's value.

First of all, the conditions of the gravimeter have to be taken into account, since each one has its own constants and they're unique. This means that the lecture itself have to be corrected. The second aspect to be considered is the tide correction, since its effects change through the day -that's why we had to take notes of the time of measurements-. In order to apply this correction, solid.exe software was used, as it gives you information of the tide variation during the day. The instrument height correction is programmed in these kinds of studies, but we calibrated the gravimeter on a plate instead of some taller support, so this correction isn't necessary in the current study.

The gravimeters work thanks to a group of springs that are very sensitive. This allows to detect tiny differences of gravity values but it also implies a huge sensitivity on temperature changes since the springs deform themselves easily in these situations. Because of this, after having measured all the points in the studied zone, another measurement was made in the base, so that the drift correction could be calculated in the gravimeter during the day. This drift effect is shown in FIG. 4

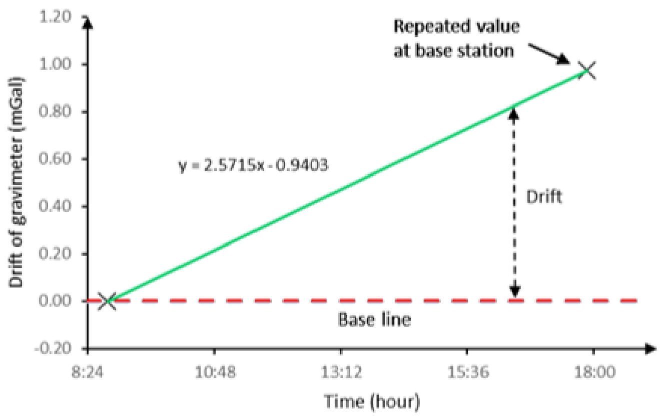

FIG. 4: This figure shows the drift effect on the gravimeter during the day. This effect follows a growing linear function so that it continues increasing until the last measurement on the base.

At this point, the first corrections can be applied to the observed gravity values, so the last step to achieve the absolute gravity's values observed is adding these filtered relative gravity data to the official absolute gravity measurement at the base [5].

$$g_0 = g_{B1} + (r_c - t - d) - (r_{B1} - t_{B1} - d_{B1}) \qquad (1)$$

This formula summarizes the corrections referring to the observed data, where g_0 is the corrected absolute gravity observed, g_{B1} is the official absolute gravity measurement at the base, r_c is the corrected reading, t is the tide correction, d is the drift and the subindex "$B1$" refers to the corrections in the base.

As it is been said, so as to get the Bouguer anomaly not only the observed gravity's values are needed but the theoretical ones too. The ones of this kind are affected by the local and regional topography besides of the latitude.

As a matter of fact, the first correction that has to be made is the latitude one. It's well-known that the earth is a spheroid due to its rotation movement. This causes a significant difference of gravity's value depending on the latitude, in such a way that the more the latitude the less the gravity there is. There exist three formulas that applies this correction, in this study the 1980 one is been used.

During the data processing we had to take into account the topographic altitude of each point since it also affects the gravity's measurement. This effect is called the free air anomaly, and depending on the height the gravimeter measures higher or lower gravity's values.

Not only is important the height where the measurements are done but also the density of the rocks in its ground. This is called the Bouguer correction itself and for this research a constant density of 2,67 g/cm^3 is been used for calculations since the homogenous presence of granite rocks under the basin.

Lastly there has been applied the terrain correction, which contains the effect of the orography of the surroundings in a local and regional scale. Based on two digital topographic models, a local one ($5 \times 5m$) and a regional one (45×45) the correction has been calculated using the Geosoft Oasis Montaj software (©Seequent)[5], which follow the methodology proposed by Nagy (1966) and Kane (1962).

$$BA = g_0 - (g_n - FAC + BC - TC) \qquad (2)$$

Once all the corrections are done the Bouguer anomaly can be calculated for each measurement point applying Eq. (2), where BA is the Bouguer anomaly, g_0 the result of Eq. (1), g_n the theoretical gravity, FAC the free air correction, BC the Bouguer correction and TC the terrain correction.

IV. BOUGUER ANOMALY

As it has been already said in a previous section, the main aim of this study was to examine the major geological features related to the Vallès Basin. That's the reason why the Bouguer anomaly of this zone has been calculated, since it contains information of the gravimetric effects of the surface i.e. information of the geological structure itself[6]. However, Bouguer anomaly is caused by anomalous objects situated both close and far from the surface, and as the objective of geophysical surveys is to examine the structures close to the surface some distinctions are needed.

The anomalous objects closer to the surface studied are the source of the residual effect, and those ones which are further cause the regional effect. Thus, separate regional and residual effects have to be calculated. Now, for this study the principal information is given by the residual Bouguer anomaly, and giving the fact that the Bouguer anomaly is the sum of both effects, the residual effect is found by this formula:

$$BA_{res} = BA - BA_{reg} \qquad (3)$$

Therefore, according to this formula the regional anomaly needs to be calculated apart. This anomaly searches the effect of the terrain of the surroundings of the area. In this study we searched a lineal tendency as there's the effect of the Catalan Coastal Ranges. This is been made manually using Surfer Software ©Geosoft, which allows to draw a contour map by applying a polynomial regression of the studied points as a gridding method.

Finally, we were able to get the residual Bouguer anomaly according to Eq. (3). This calculation was carried by the Surfer software itself since it lets combining different maps following mathematical operations, in this case a subtraction.

V. RESULTS AND DISCUSSION

A. Bouguer anomaly maps

Once the needed calculations have been made, the graphic representations have been drawn as well. After getting the Bouguer anomaly data of every site, we have used the interpolation method of Krigging in Surfer software in order to finally get the Bouguer anomaly map (FIG. 5). The observed Bouguer gravity anomaly field consists of two components, a regional and a residual, which can be expressed by the simple relation of (3). We have obtained three maps corresponding with the three anomalies, represented respectively in FIGs. 5,6,7.

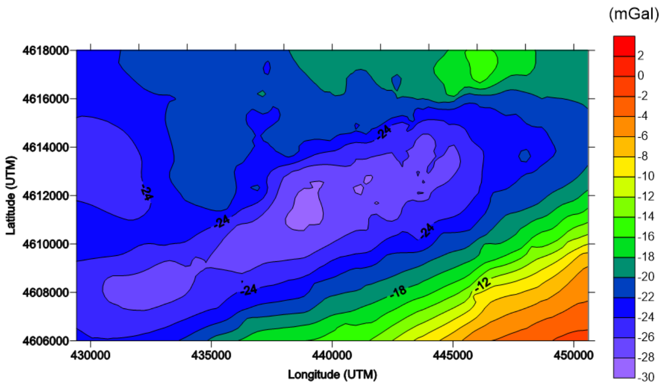

FIG. 5: Bouguer anomaly map of the Vallès Basin.

The Bouguer anomaly map shows a clear gravimetrical depression as a negative anomaly in the NE-SW direction which can be interpreted as the Vallès Basin. Furthermore, it can also be appreciated the beginnings of the Catalan Coastal Range at the left bottom of the map. However, this figure doesn't give enough information of the limits of the basin, i.e. where the Vallès Fault is located. That is the reason why the separation into residual and regional anomalies had to be done.

As mentioned in Eq. (3), in order to get the final residual anomaly map (FIG. 6), we need to rest the regional trend to the Bouguer anomaly map. The first-degree polynomial regression of the data resulted in a map which follows the general trend of the Catalan Coastal Ranges. In other words, the regional map has a linear pattern with a NE-SW trend, with increasing values towards the SE.

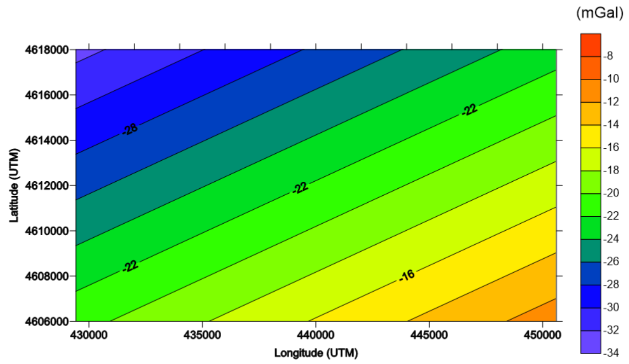

FIG. 6: The pattern of regional Bouguer anomaly.

The residual map obtained after substracting the regional map to the Bouguer anomaly map is plot in FIG. 7. This map clearly shows the delimited zone of the Vallès Basin, with a negative gravimetric anomaly in its area and a positive one in its surroundings. Some interesting information can be extracted from this map since not only the basin can be seen but also the fault located between La Garriga and Caldes de Montbui villages can be calculated with the horizontal derivative. In fact, this is exactly what is shown in FIG. 8, where besides some major slopes due to the Coastal Range it can be seen the result of the Vallès Fault.

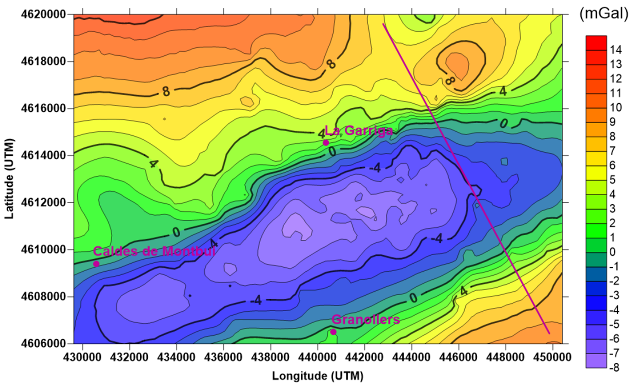

FIG. 7: Residual Bouguer anomaly pattern with the inversion profile.

B. Horizontal derivative of the residual anomaly map

In order to better image the Vallès Fault trace we have used the Gradient Operator of Surfer software to apply an horizontal derivative to the residual Bouguer anomaly map [7]. This operator generates a grid of steepest slopes at any point on the surface using Eq. (4). This gives valuable information about the change of the gravity anomaly, which considering that the bigger this change the bigger difference of density there is we can clearly locate the Vallès Fault.

$$||\vec{g}|| = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2} \quad (4)$$

The formula above describes the gradient of the gravity anomaly, being $\vec{g}$ the gravity gradient, and both $\frac{\partial z}{\partial x}$ and $\frac{\partial z}{\partial y}$ the partial derivatives with respect to the x and the y coordenates. Here the z coordenate stands for the gravity anomaly values.

The results shown in FIG. 8 reveals a segmented fault with a line of green shades in the NE-SW direction. This isn't random since is the delimitation of the Vallès Basin. The segmentation of the fault evidence the structure complexity of the area.

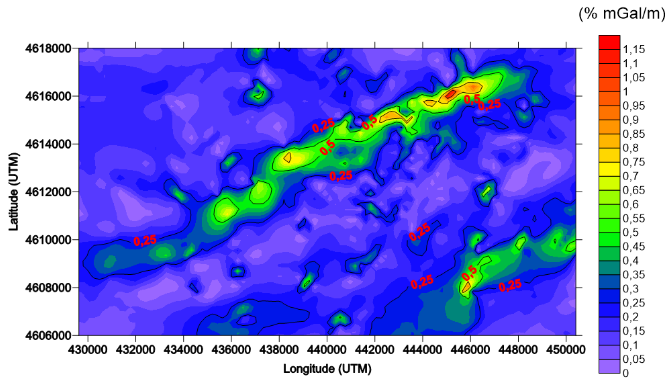

FIG. 8: Horizontal derivative map. Green zones correspond to those where there is more horizontal derivative. The slope is represented in percentage of mGal/m.

C. Gravity inversion profile

In order to extract more data from this study a gravity inversion of a profile extended over the basin in the NW-SE direction (shown in FIG. 7) has been calculated using the ZondGM2D software. The length of the profile is about 14 km and the depth about 1500 m, which is enough to show the horizontal density variations.

The results show a lack of density in the basin as it was expected. Meanwhile, mountain zones have higher densities, being the Pre-Coastal one the densest. This difference between both mountain ranges is probably caused because of the presence of metamorphic rocks in the Pre-Coastal one, which compared with the dominant granite in the Coastal Range is denser.

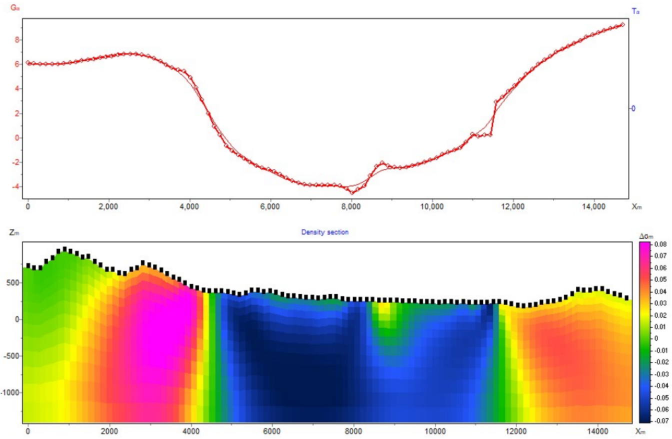

FIG. 9: Gravity inversion profile in the NW-SE direction of the Vallès Basin. High densities are represented in a red color range and low densities in a blue color range.

Even though it is the result we were expecting, the density variations are quite small and they should be higher according to FIG. 2. In addition, the RMS error is too high and this might lower the quality of the inversion. Thus, the data and some parameters of the inversion should be revised.

VI. CONCLUSIONS

The gravity method used in this study allows to characterize the different geological items, specifically the horst and graben structure, as well as the Vallès Fault, as long as the density contrast is enough. The residual anomaly map shows a clear gravity negative anomaly in the Vallès Basin, which also changes laterally. This negative anomaly combined with the lower density of the basin rocks compared with the surroundings allows us to clearly locate the limits of the basin.

Moreover, we have been able to display a distinct trace of the Vallès Fault thanks to the horizontal derivative map, which has also allowed us to classified the fault as a segmented one instead of a linear continuous plane. The identification and characterization of the Vallès Fault would be also relevant in terms of geothermal exploration, as it had been previously defined as the key parameter of this system.

Lastly, the gravity inversion profile has shown the difference of densities that were expected between the basin and the ranges. However, as it has been said, in order to optimize the inversion some improvements in the parameters characterization can be done.

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