Gravimetric Modelling and Geological Interpretation of Argemela-Panasqueira Area

Ricardo Fernandes Ribeiro

Mestrado em Geologia

Departamento de Geociências, Ambiente e Ordenamento do Território

2017

Orientador

Alexandre Martins Campos de Lima, Professor Auxiliar, Faculdade de Ciências da Universidade do Porto

Coorientador

Rui Miguel Marques Moura, Professor Auxiliar, Faculdade de Ciências da Universidade do Porto

Todas as correções determinadas pelo júri, e só essas, foram efetuadas.

O Presidente do Júri,

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MSc

Acknowledgments

I would like to extend sincere thanks to a number of people that contributed to this project, and to the ones that conveyed moral attributes in the completion of my Master's thesis project. First and foremost, I would like to thank Professor Doctor Alexandre Lima and Professor Doctor Rui Moura for the opportunity to include me in this project and extend the research in the Argemela and Panasqueira region.

I would like to thank Professor Doctor Charles Gumiaux, from Orleans University, for his leadership and expertise in the field and for receive me in Orleans. The experience that I had in France was great, he was important for the interpretation of the 2-D profiles and show me how to use the Geomodeller software.

I would like to thank the two PhD students from the Orleans University, Launay Gaetan, Julie Michaud and BRGM researcher. Thanks for the availability they had to help me interpreting the profiles and provide me information about the lithology and the density of rocks.

I would like to thank Sara Leal for all the help in the field with the equipment. She is a really important friend that help me keeping moving and keeping focus during my work.

I would like to thank my colleague from Geographical Engineering, André Pinhal, for his time and expertise in the use of Trimble R6.

I would like to thank my friend Pedro Fernandes for is patience and for helping me keeping focus during this project.

And lastly, I would like to thank my friends and family for their patience and support during the completion of this project.

Resumo

A gravimetria é um método geofísico que permite determinar a geometria, quer em duas dimensões, quer em três dimensões, das estruturas geológicas a ser estudadas. Este método baseia-se essencialmente nas diferenças de densidade entre uma estrutura geológica e as estruturas encaixantes. É um método utilizado quer em prospeção geológica, quer em geologia estrutural.

Durante março de 2017 foi levada a cabo uma campanha de gravimetria na Argemela e na Panasqueira, com o principal objetivo de estudar os corpos graníticos existentes nestas regiões.

Os dados obtidos em campo foram processados e analisados usando o Oasis Montaj software. Foram criados mapas de Anomalias de Bouguer, estes mapas exibem anomalias negativas associadas aos corpos graníticos e anomalias positivas associadas as rochas encaixantes que apresentam uma densidade maior do que os corpos graníticos.

Mapas residuais foram criados a partir da anomalia de Bouguer com o objetivo de isolar as anomalias causadas pelos corpos graníticos.

Usando o Gravity and Magnetic Modelling Software, foram criados perfis 2-D de ambas as regiões. Os perfis 2-D gravimétricos, efetuados na Argemela, revelaram que o microgranito apresenta uma extensão vertical máxima de cerca de 1000 metros. No caso da Panasqueira, os perfis 2-D mostram que o granito se apresenta como um lacólito, com uma extensão vertical média de 2500 m e com uma extensão lateral de direção N-NE.

Usando como base os perfis 2-D e a cartografia da região, modelos geológicos 3-D foram criados para ambas as regiões. O modelo geológico da Argemela mostra-nos que a instalação ocorreu verticalmente e que o microgranito apresenta uma forma tubular. O modelo 3-D do granito da Panasqueira mostra-nos que a instalação do granito é controlada essencialmente por falhas regionais de direção NE-SW.

Palavras-Chave: Gravimetria, Anomalia de Bouguer, Modelos 2-D, Modelos 3-D, Granitos, Argemela, Panasqueira.

Abstract

Gravimetry is a geophysical method that allows determining the geometry, both in two dimensions and in three dimensions, to depth of the geological structures to be studied. This method is essentially based on the differences in density between distinct rock lithological units or linked to geological structures. This method is used in geological prospecting and in structural geology.

During March 2017, a gravimetric survey was carried out at Argemela and Panasqueira, with the main objective of study the granite bodies existing in these regions.

Field data was processed and analysed using Oasis Montaj software and Bouguer anomalies maps have been created. These maps show relative negative anomalies associated with the granite bodies and the positive anomalies are associated with host rocks that have a higher density than granite bodies.

Residual maps were created from the Bouguer anomaly in order to isolate the anomalies caused by the granite intrusions and to remove effects of deeper structures in the continental crust.

Using Gravity and Magnetic Modelling Software, 2-D profiles were created for both regions. The 2-D gravimetric profiles, performed in the Argemela, revealed that the microgranite has a maximum vertical extension of about 1000 meters. In the Panasqueira case, the 2-D profiles show that the granite is display as a laccolith, with an average maximum depth of 2500 m and with a lateral NNE striking elongated trend.

Based on the 2-D profiles and surface geological data, 3-D geological models have been computed for both regions. The Argemela geological model highlights a vertical tubular shape of the granite body suggesting a pipe like intrusion. The 3-D model of Panasqueira granite shows that the granite installation was essentially controlled by regional faults trending NE-SW.

Keywords: Gravimetry, Bouguer anomaly, 2-D models, 3-D models, Granites, Argemela, Panasqueira.

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Abbreviations

µGal – microgal

ALZ – West Asturian Leonese Zone

B – Betics

BRGM - Bureau de Recherches Géologiques et Minières

BGI – Bureau Gravimetrique Internationale

CIZ – Central Iberian Zone

CM – Cantabrian Mountains

CS – Central System

DB – Duero Basin

DEM – Digital Elevation Model

EB – Ebro Basin

GB – Guadalquivir Basin

GM-SYS – Gravity and Magnetic Modelling Software

GTMZ – Galicia -Trás-os-Montes Zone

Gu – gravity unity

IC – Iberian Chain

IM – Iberian Massif

mGal – mGal

OMZ – Ossa Morena Zone

PY – Pyrenees

TB – Tajo Basin

1. Introduction

The gravity survey conducted for this project covers two distinct areas: the Panasqueira Mine and the Argemela microgranite. The Argemela microgranite is in the region of Beira Baixa, Portugal and is situated between the villages of Barco and Lavacolhos, in the municipality of Fundão, in the district of Castelo Branco.

Like Argemela, Panasqueira is located in Beira Baixa. The localization of the mine covers the districts of Coimbra and Guarda. The concession of the mine integrates more precisely the villages of São Jorge da Beira, Barroca Grande, Dornelas do Zêzere, Silvares and Aldeia de São Francisco de Assis.

These areas are covered by map N^{os} 244 and 245 – S. Jorge da Beira (Covilhã) and Silvares (Fundão) of the Military Charter of Portugal at scale 1:25,000.

Figure 1 shows the location of Panasqueira and Argemela relatively to Fundão and Covilhã.

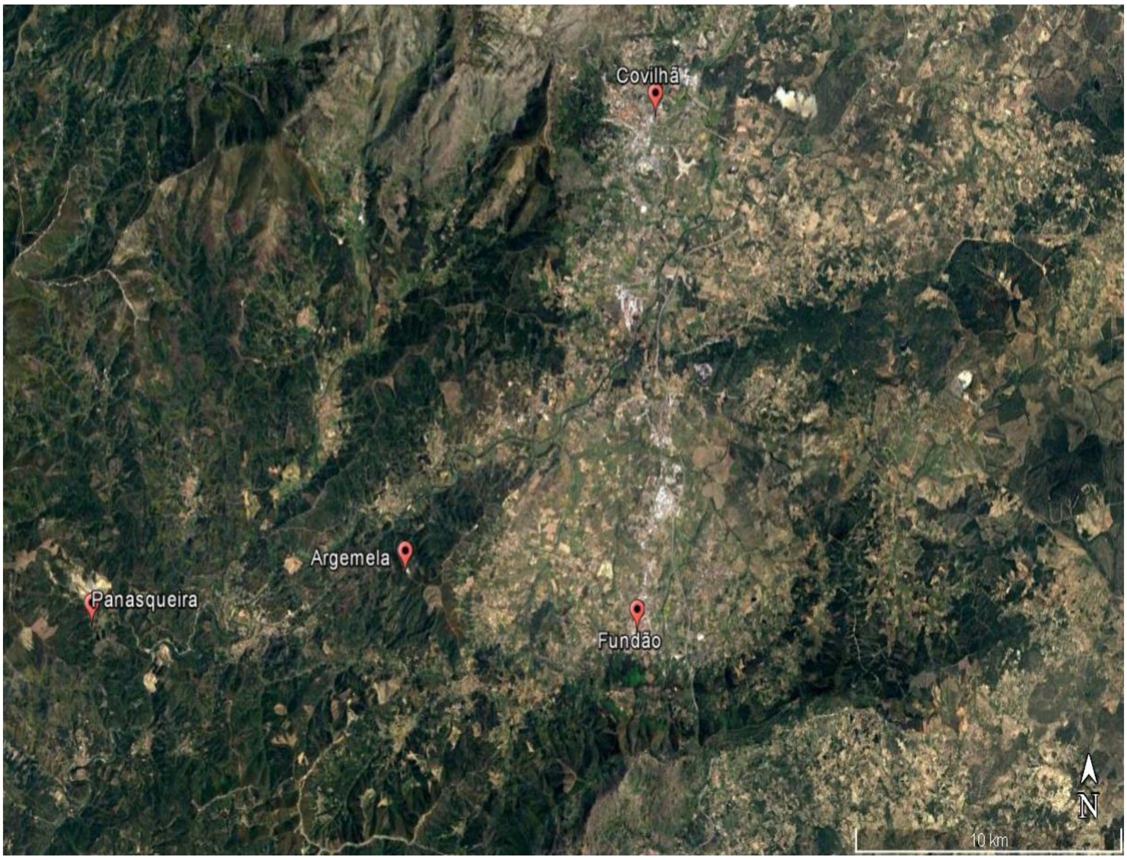

Figure 1 – Localization of Panasqueira and Argemela relatively To Fundão and Covilhã (Google Earth)

The gravimetry is a geophysical method that allows determining the geometry, both in two dimensions and in three dimensions, of a geological structure of interest. This process is essentially based on differences in density between the different lithologies of rocks units forming the crust or variations in the density due to alteration, hydrothermalism, grain reduction during deformation. It's a method used in structural geology and geological prospecting.

In this thesis, the main goal is to compute a 2-D and 3-D models of the Panasqueira granite and the Argemela microgranite, and compare with previous works that were performed in this area.

The Argemela microgranite makes part of the "Rare Metals granites". This means that some specific geochemical elements that should be found in surrounding late veins around the pluton are purely included within the granitic rock itself. To have a better understanding of this phenomenon, it's important to have a better image of the structure, volume and vertical special extension of this intrusion. Argemela is pretty exposed at surface but the few deep boreholes are not sufficient to properly image the 3-D shape of the microgranite. We thus propose to perform gravity modelling.

The Sn-W mineralization in Panasqueira is associated to flat veins around the granitic cupola. The top boundary of the granite has been image locally along the boreholes or in the mine, but the general lateral extend of the pluton and its thickness is not known. In order to better constrain the spatial links between the pluton and the vein system we also propose here to use gravimetric profiles to image the shape to depth.

This thesis is structured in seven chapters:

1. **Introduction –** it will be described the propose and the area of the study.
2. **Geology Setting** – it describes the lithology that is found in Panasqueira and Argemela.
3. **Gravity Signatures in the Iberian Peninsula** – a small description of the gravity signatures in Iberian Peninsula and its meaning.
4. **Field Survey and Methodology –** intended to describe the theoretical principal behind the method, describe what was made in the field and the corrections that are necessary to processing the gravimetric data.
5. **Results –** explain how the results were obtained and the results themselves.

6. **Interpretation** – discussion and interpretation of the 2-D profiles and 3-D models and comparison with previous works.

7. **Conclusion**

2. Geological Setting

2.1 Regional Geology

Both Argemela and Panasqueira are located in the "Iberian tin-tungsten-Metallogenic Province" (Neiva, 1944 e Thadeu, 1979 *In* Ribeiro & Pereira, 1982), where W and Sn mineralization occurs. It extends from the shear zone Porto-Coimbra-Tomar in the West to the Juromenha thrust fault at Northeast. With the exception of the deposits linked to the St. Eulalia granite (OMZ – Ossa Morena Zone), the rest is located in the Central Iberian Zone (CIZ), Galicia -Trás-os-Montes Zone (GTMZ) and West Asturian Leonese Zone (ALZ) (Figure 2).

The CIZ, where is located Argemela and Panasqueira (Figure 2), is characterized by two main phases of the Variscan Orogeny (F_1 and F_3). The structures formed during the first phase are characterized by folds with a predominant orientation NW-SE. The second phase of deformation produced thrust structures (e.g., "Olho de Sapo" Anticlinorium) and in the central and meridional domain, the CIZ has large zone of ductile shear zones. The last phase of the Variscan Orogeny is characterized by a refolding of the initial F_1 folds. This phase is also related with the emplacement of voluminous plutons, in this case two-mica granites and biotite granites. Most of the outcrops founded in CIZ are granites and schists from the Beira schist unit.

To a lesser extent, we can found rocks from the Upper Precambrian, Ordovician and Silurian (Noronha, 1983) (Figure 3).

The hydrothermal mineralization is associated with the Argemela and Panasqueira granites. This mineralization of W and Sn are parallel to the alignment of the Variscan structures. The mineralization occurs along the contact zone between intrusive granites and metasediments, and can also be found over the contact zone of intrusive granites in other older granites (Thadeu, 1965).

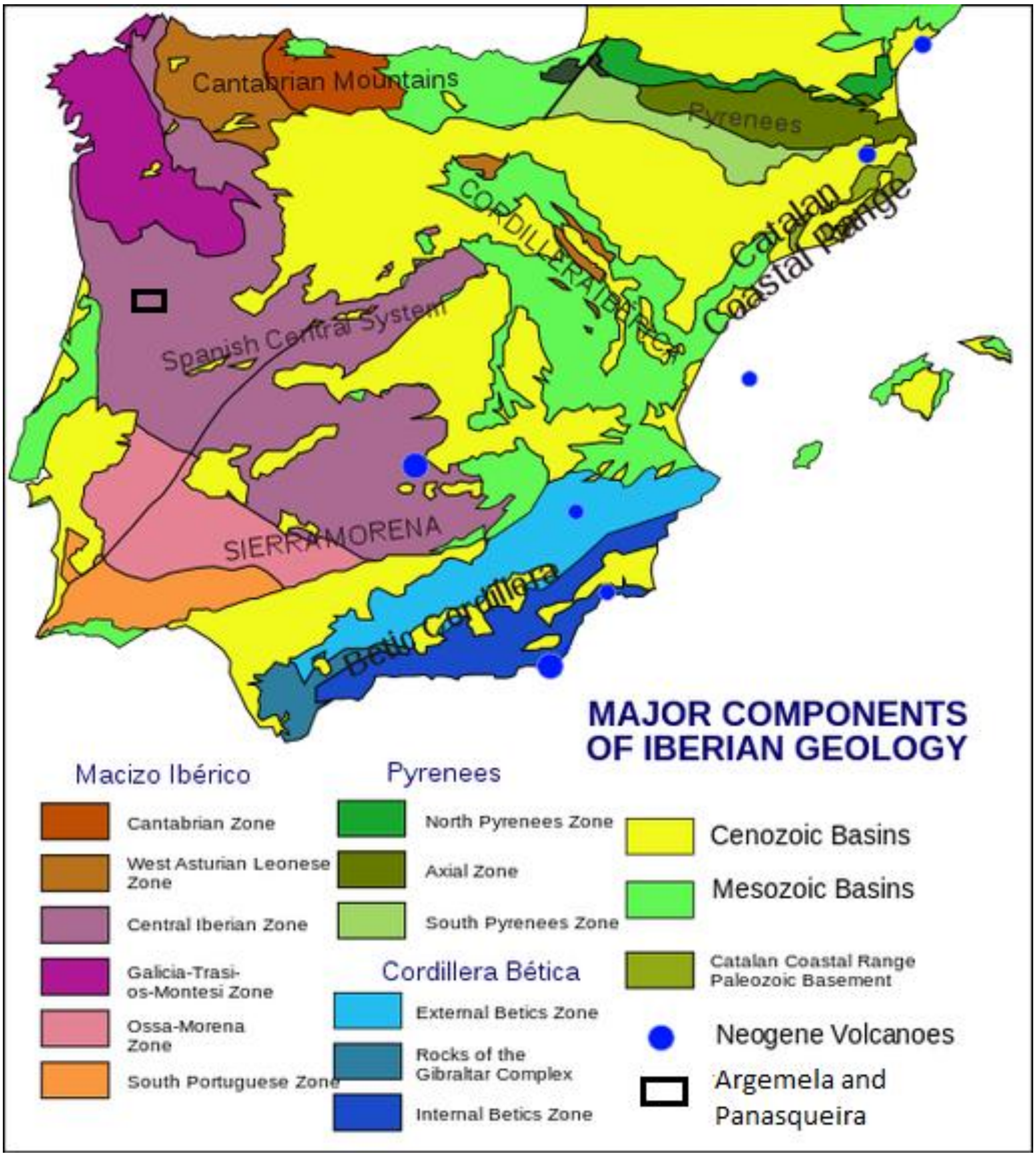

Figure 2 – Morpho structural Units of Iberian Peninsula and the location of Argemela and Panasqueira.

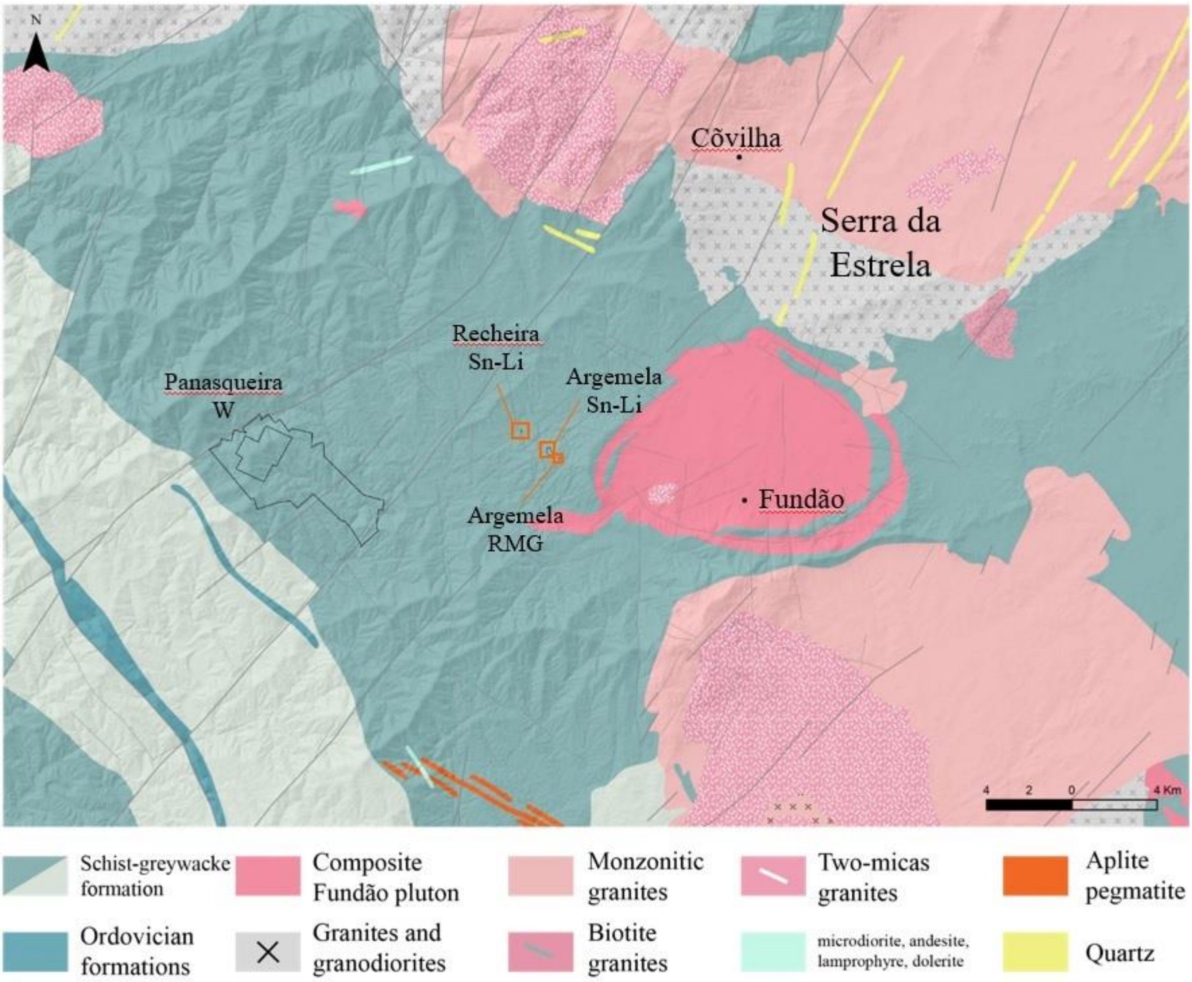

Figure 3 – Geological Map of Argemela and Panasqueira region with the locations of Serra da Estrela batholith and Fundão pluton (Michaud, 2017 unpublished).

2.2 The Argemela granite

The Argemela microgranite is a leucocratic rock and presents a porphyritic texture. In hand specimen, it’s only possible to recognize the quartz and white mica (Sant'Ovaia, et al., 2015). On the petrographic level, it’s showed the occurrence of quartz, albite and white mica, the last one is partly replaced by lepidolite and amblygonite. It´s possible to find some minerals of beryl and cassiterite (Charoy & Noronha, 1996).

The microgranite of Argemela, in Central Portugal, displays as a small elliptical shape intrusion (300 m by 200 m). This body crosscuts the low-grade metamorphosed schist-greywacke complex of the Beira series (Figure 4).

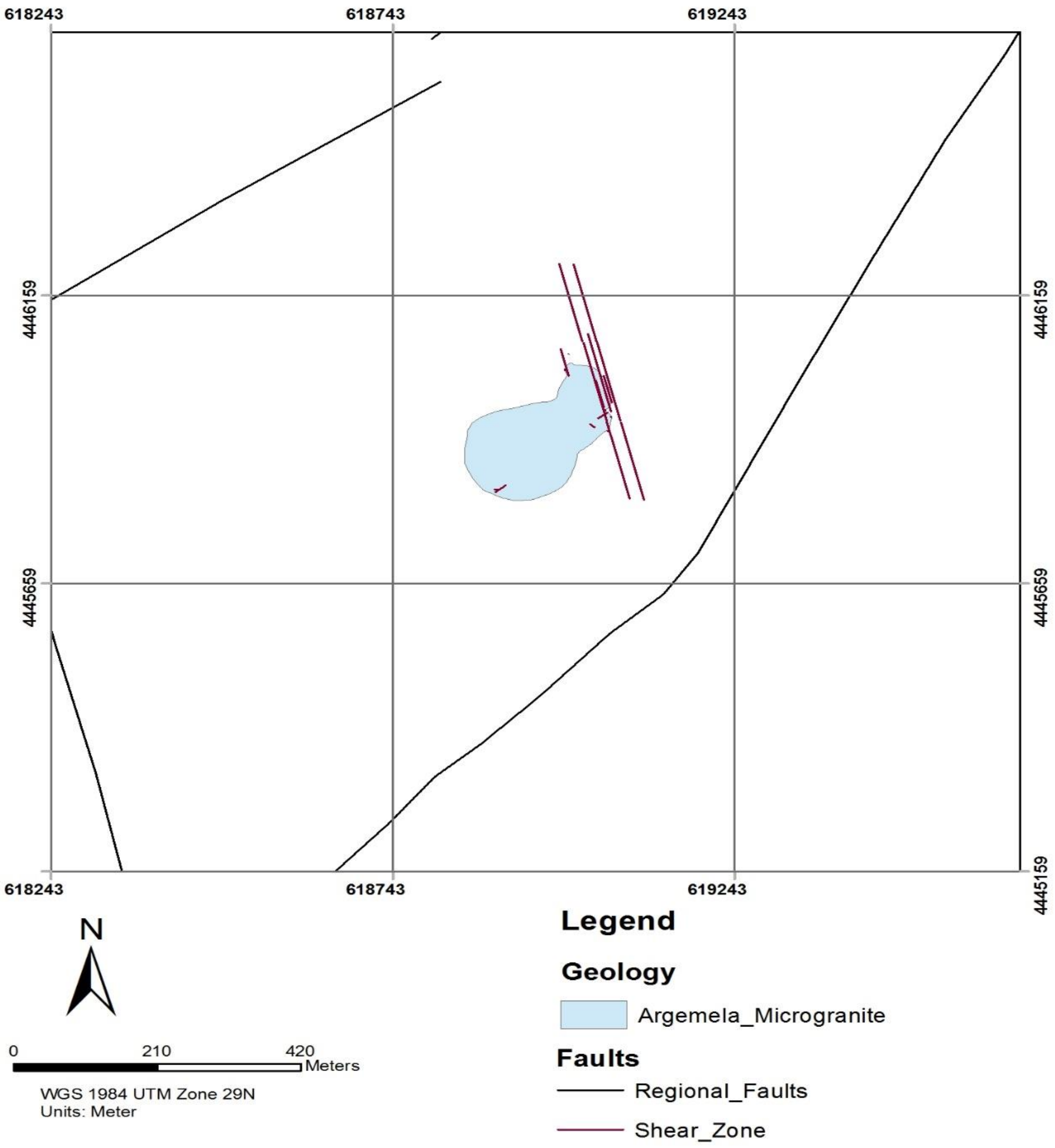

Figure 4 – Geological map of Argemela, in white we have the rocks of schist-greywacke complex (adapted from Michaud, 2017 (unpublished)).

Few kilometres North of this microgranite there is the Serra da Estrela batholith, which is a two-mica granite (Neiva et al., 1987). Nearly this microgranite, in the Southeast part, there's the thermal aureole border of the syntectonic Fundão pluton (Figure 3).

In the quarry is possible to see that this intrusion has a sharp and a vertical control, with N160 trending shear zone with the schist-greywacke complex. Does not show any signs of structural disturbance, alteration or thermal metamorphism (Charoy & Noronha, 1996).

2.3 Panasqueira Geology Setting

The Late Hercynian ore deposit of Panasqueira is located in the Central-Iberian Zone. This zone is dominated by the low-grade metamorphic schist-greywackes complex of the Beira series. These metasedimentary formations consist of "xistos gressosos", quartzites and greywackes. These formations are dated from the Cambrian or Precambrian age (Conde *et al.,* 1971).

During underground works, in 1948 (Thadeu, 1951), a non-outcropping two-mica granite intrusion was intercepted. This granite (Panasqueira Granite) has a porphyritic texture with feldspar megacrystals and, as accessory minerals, zircon, monazite, apatite, ilmenite and pyrite (Clark, 1964). On the apex of the granite, there's a cupola composed of a massive muscovite-quartz greisen, which presents a medium equigranular grain (Figure 5).

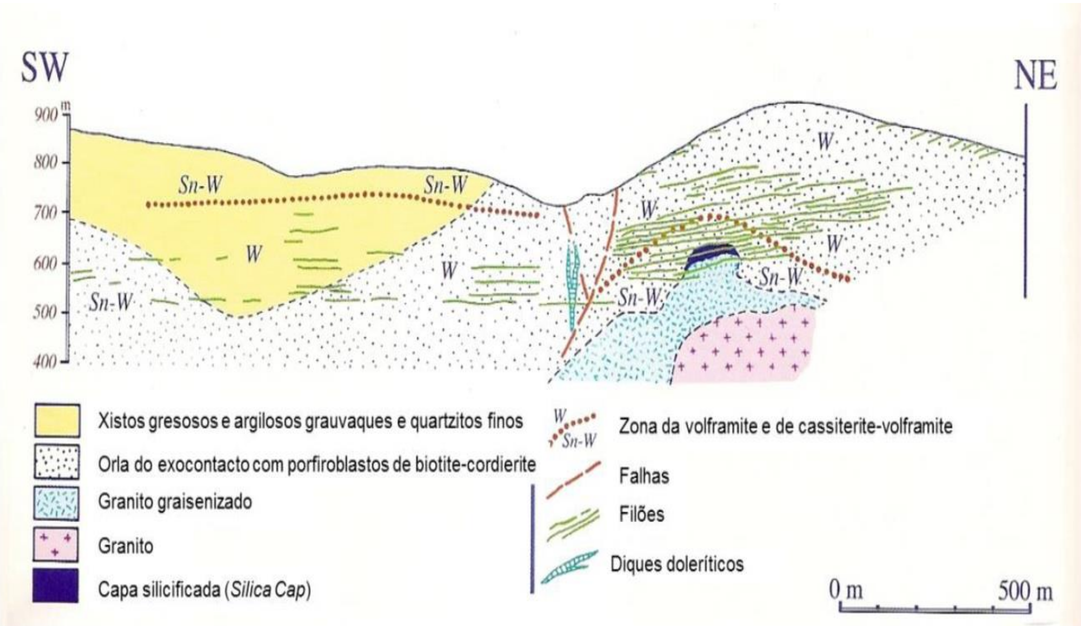

Figure 5 – A Southwest – Northeast profile from the regions of Panasqueira. Here we can see the different lithologies that are described in the text. (Adapted from Thadeu, 1979)

The intrusion of the granite induced a contact metamorphism that transformed the schist as spotted schist. This spotted schist can be found at surface (Figure 6).

In this area, was found basic rocks identified as dolerites (Thadeu, 1951). These rocks present a grey tone, with a thin grain and are constituted by labradorite, hornblende, chlorite and amphibolitized pyroxene.

The W-Sn (Cu) mineralization occurred in sub-horizontal quartz veins. These veins are related with the cupola, and the mineralized veins in the greissen cross cut the contacts between granite and spotted schist. These veins contain wolframite, cassiterite, chalcopyrite and sphalerite.

This region is affected by regional faults that can be grouped in two systems: The N-S and the NE-SW to ENE-WSW.

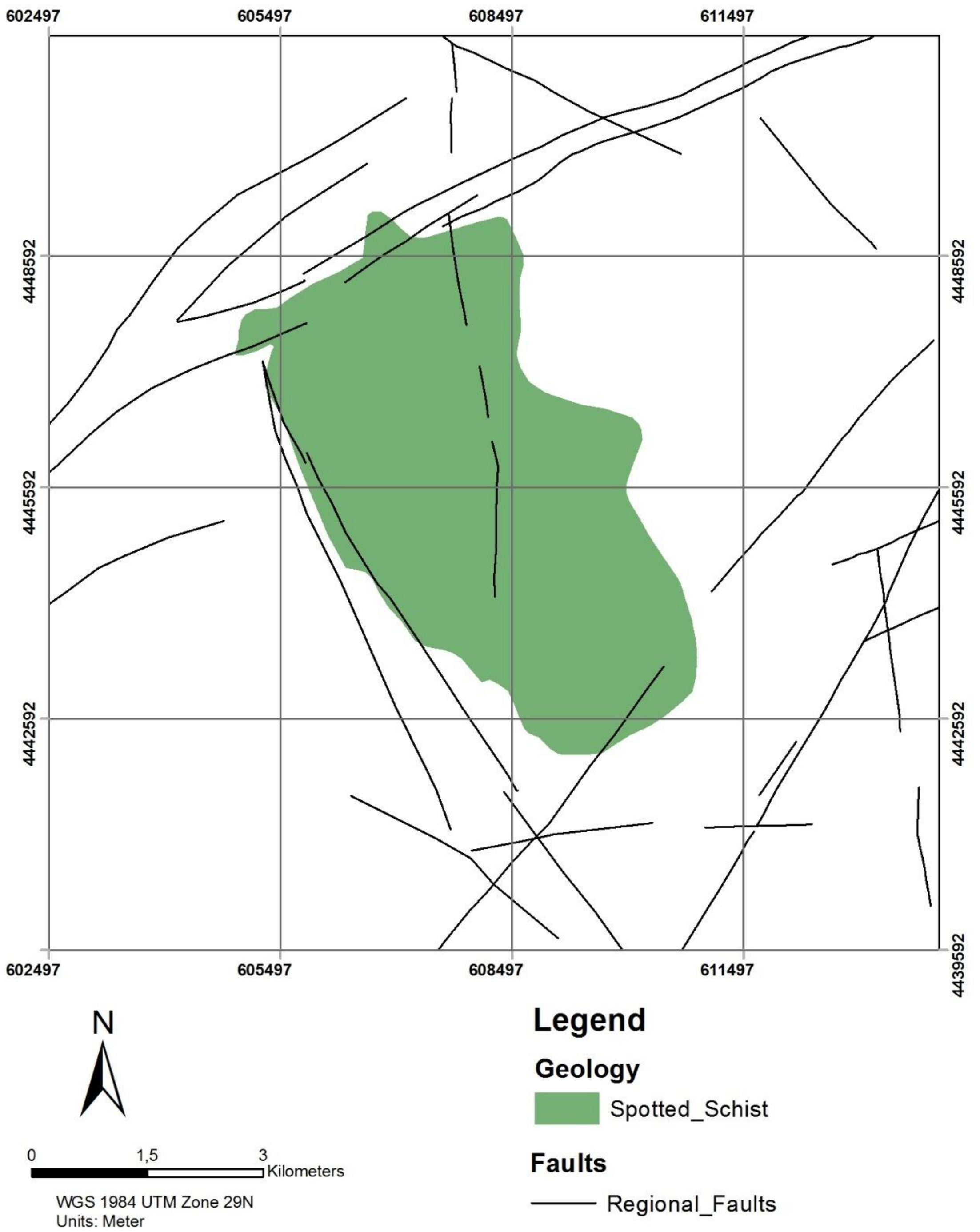

Figure 6 – Geological map from Panasqueira, in white we have the rocks that constitutes the schist-greywackes complex (Adapted from Launay, 2017 (unpublished)).

3. Gravity Signatures in the Iberian Peninsula

3.1 Geological Setting

The Iberian Peninsula can be divided into two major parts, the Eastern that the predominant geology are Mesozoic and Cenozoic sediments and the Western part with rocks of Paleozoic and Proterozoic age. The Iberian Massif, in the Western part is composed by metamorphic and igneous rocks. This region has several tectono-stratigraphic zones. These zones correspond to diverse microcontinents involving during the collision between Gondwana, Laurentia and Baltica during the Paleozoic (Matte, 1991). The geodynamic evolution of the Iberian plate was controlled by the opening of the North Atlantic and the Tethys cycles during Mesozoic and Cenozoic (Ribeiro 2006). The basis formed during early Mesozoic, were formed by a large scale stretching. In the Northern part of Iberian plate, we have the Pyrenean belt. This belt was developed during a collisional orogen that extends from Mediterranean Sea to the Atlantic Ocean, and is composed by the Pyrenean Mountains and the Cantabrian Mountains. In the Southern margin of this belt, two foreland basins ca be recognized. These basins infill, Douro and Ebro Basins, were the result of the erosion related to the uplifted orogen. The converge of the African and Iberian plates formed the Betics belt in the Southern part of the Iberian plate. The Guadalquivir Basin was created during the formation of the Betics belt, and is filled with Neogene to Quaternary rocks. In the Iberian Massif, we have a mountain chain that was developed in the Cenozoic. This mountain chain, Iberian Chain, consists in an uplift of the crust and is bounded by two reverse faults with a NE-SW direction. In the Figure 7 we can see the lithology described in the text.

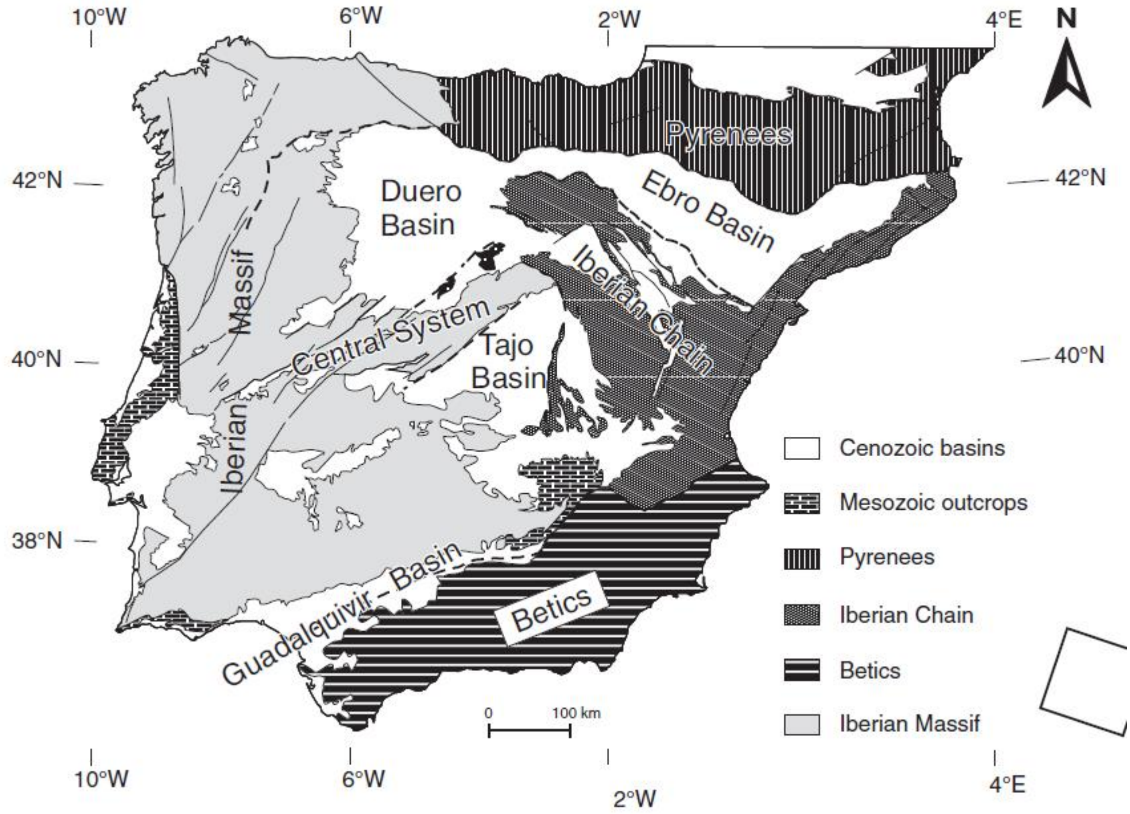

Figure 7 – Geological Map of the Iberian Peninsula (Gómez-Ortiz et al., 2011).

3.2 Bouguer anomaly and Thickness of the crust

In 2011, Gómez-Ortiz et al, conducted a gravimetry investigation to study the thickness of the crust in Iberian Peninsula. A Bouguer Anomaly map was made using three different sets of gravity data. These data are composed by 2892 gravity stations in Central Spain, 28202 data points from the Bouguer Anomaly map of the Iberian Peninsula (Mezcua *et al.,* 1996) and data from the Bureau Gravimetrique Internationale (BGI) for France, Morocco and Algeria. This data was interpolated to generate the Bouguer Anomaly map. The Bouguer Anomaly map was subjected to spectral analysis, low-pass filtering, and inversion to create a Gravity Anomaly map that reflects the effects of Moho undulations in the Iberian Peninsula.

The Figure 8 shows the variations in the gravity field. These variations have a range from -200 to +378 mGal, and over the Iberian Peninsula, it varies from -140 to +220 mGal. The lowest gravity anomalies are located in the Pyrenees chains and can be also linked to the Douro and Tejo Basins. The positive anomalies are observed in SW Iberia and are associated with crustal thinning in a seaward direction from the coast.

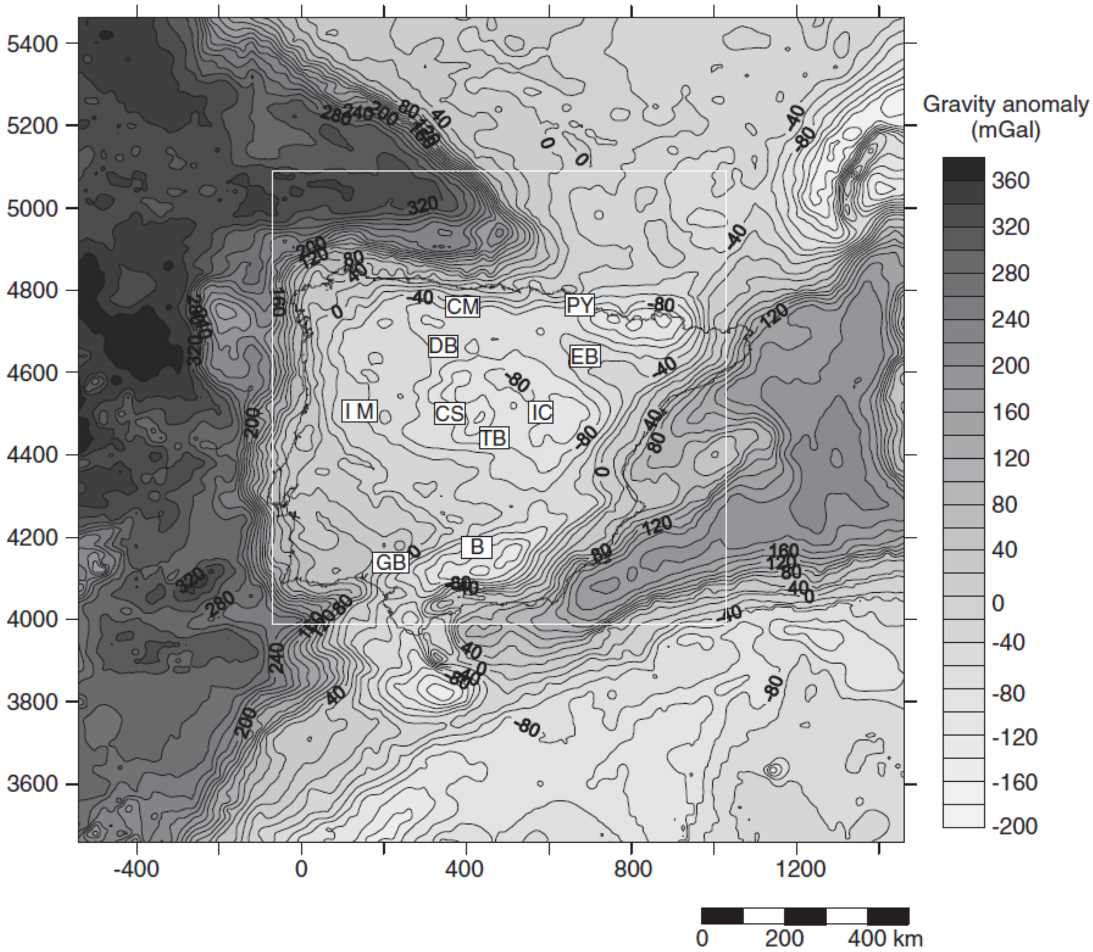

Figure 8 – Bouguer gravity anomaly map of the Iberian Peninsula. UTM coordinates in kilometres, zone 30N. The abbreviations used are: CM-Cantabrian Mountains; PY-Pyrenees; DB-Duero Basin; EB-Ebro Basin; CS Central System; TB-Tajo Basin; IC-Iberian Chain; GB-Guadalquivir Basin; B-Betics; IM-Iberian Massif (Gómez-Ortiz et al., 2011).

The Gravity map associated with Moho undulations (Figure 9), shows that the areas that have a low gravity anomaly are associated with the deepest Moho. These areas are the Alpine Chains, the Betics chain and the Central System. In these locations, the range of Moho is between 45 to 33 kilometres. Towards the coast, gravity anomalies are higher, and the Moho is shallower.

The information from the seismic profiles gives information on the Moho depth. Thus, the only other mean to compute the Moho depth is to inverse gravity anomaly maps. It is thus normal to have this correlation when the different treatment of the data gives the larger wavelength from the signal. Using this information's, we could conclude that in Portugal the anomaly is more positive towards the coast. This can be explained due to the crust thinning due to the extension during the opening of the Atlactic.

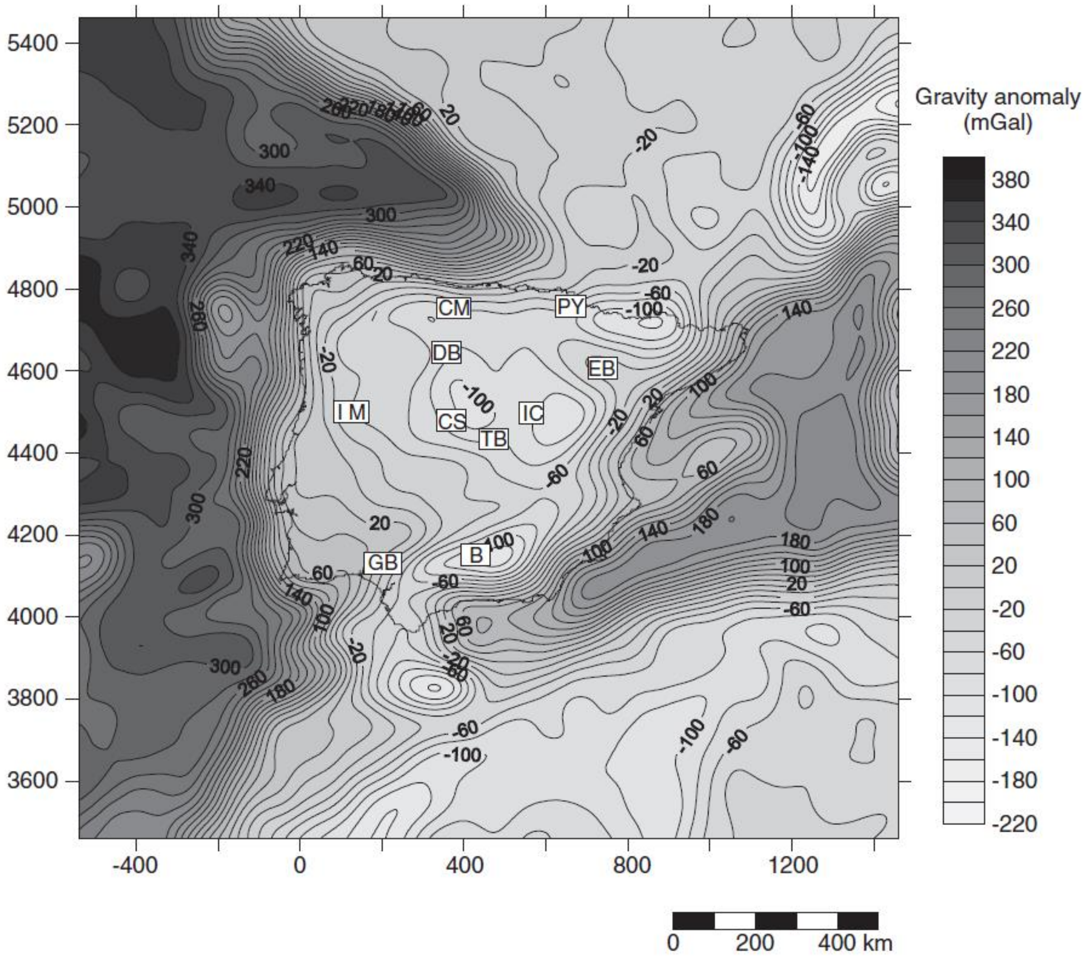

Figure 9 – Gravity anomaly map created to retain wavelengths greater than 150 km corresponding to Moho undulations in Iberian Peninsula. Coordinates and abbreviations are in Figure 7 (Gómez-Ortiz et al., 2011).

4. Field Survey and Methodology

4.1 Introduction to Gravimetry

The gravity method is an important tool to solve problems that involve subsurface mapping. This method is used in various geological studies, as example in mapping near-surface voids, quantitative studies of metallic ore bodies and characterizing salt structures. It's also an important tool in regional characterization of the Earth, cause with this method it's possible to determinate the structure of the crust, identifying potentially favourable regions for resource exploration and developing conceptual explorations models (Hinze *et al.,* 2013).

The gravity method is a passive exploration method that is based on gravitational force field (F=mg). The acceleration can be related to the movement of a point at the surface of the Earth but also to the acceleration due to the Earth attraction. Attraction slightly varies according to the different mass in depth.

4.2 Units of gravity

The value of gravity at the Earth's surface is about 9.81 ms^{-2}. Because of the different density values on the subsurface, some variations of the Earth's surface acceleration exist with the order of 1000 μms^{-2} (Kearey, *et al.,* 2002). This unit of micrometre per second is referred as the gravity unity (gu). In geophysical exploration, the unit that is used is the miligal (mGal). In high-sensibility studies the unit used is the microgal (µGal).

1 Gal = 0.001 mGal =10-6 µGal = 10000 gu

4.3 Field work

During the field campaign, two surveys have been made for two study areas, Panasqueira and Argemela.

In Panasqueira 4 long profiles have been made along the roadside plus a grid in a restricted area (Figure 10). The space between the gravity stations along the four profiles was between 200 and 500 meters. The gravity stations on the grid have a space between 100 to 150 meters. The profiles were made to better understand the spatial lateral extension of the body and the depth. The grid was made to see if there is another cupola as suggested by Póvoa, 2011.

The total number of stations was 123. Of these 123 stations, there's 6 base stations. These base stations are important for quality insurance and drift corrections.

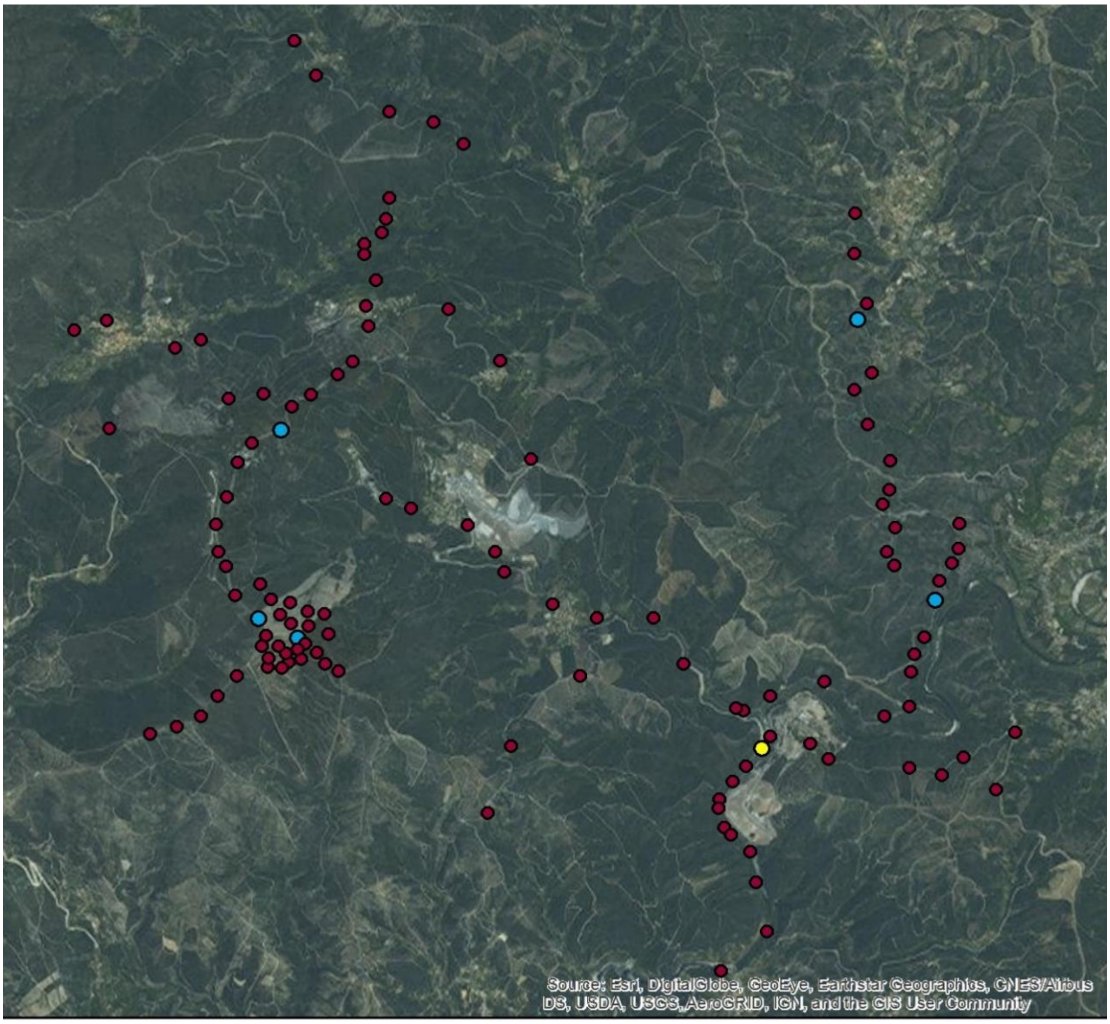

Figure 10 – All the measured station in Panasqueira. In red the normal stations, in blue the base stations and in yellow the base station that was measured every day.

It’s important to explain that the sites for measurement in Panasqueira have been chosen in order to be in hard ground and to avoid the tellings that can exist.

In Argemela were made 2 profiles along dirt roads, where the space between the gravity stations was 50 to 150 meters. The resolution used where was determinate due to the exposed surface and in order to perform a more detailed survey (Figure 11).

The total number of gravity station was 43, and from these 43 stations, one was a base station.

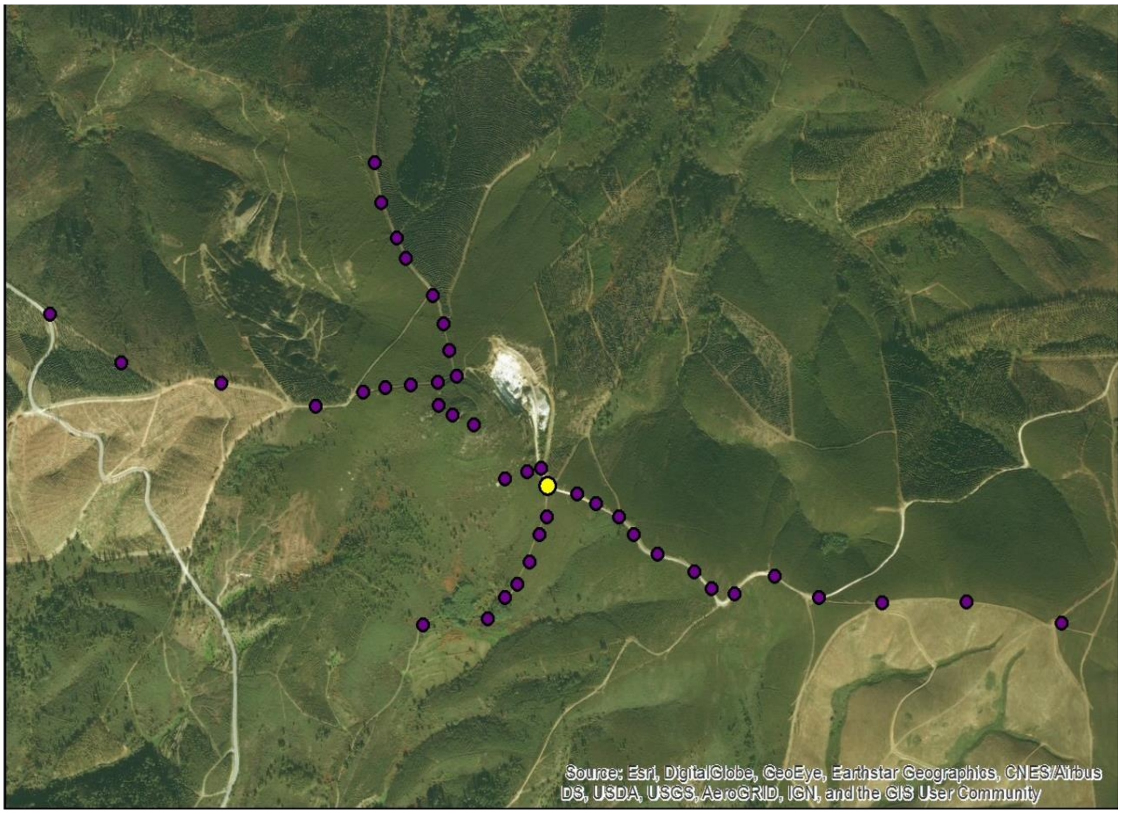

Figure 11 – All measured stations in Argemela. The stations on purple are the normal and the yellow is the base station in Argemela.

In every station we made 3 measurements with a duration of 90 seconds each, this was made to decrease the error in each station. If there were bad measurements, we could do another measurement on the field.

The only base station that was measured every day was the base 0. This station was measured at the begging of the day, every time that we changed a base station along the profiles and at the end of the day. Is propose was to be a reference station for the corrections during post processing. The table 1 shows all the locations of the Base stations.

Table 1 – Localizations of the base stations. The datum is ETRS89.

	Name	Lon_ETRS89	Lat_ETRS89
Central Base	Base 0	-7,714472	40,130648
Panasqueira	Base A	-7,766936	40,159023
	Base C	-7,769692	40,142532
	Base F	-7,695186	40,143342
	Base G	-7,703275	40,167966
	Base GC	-7,765395	40,140827
Argemela	Base ARG	-7,601523	40,153821

To be able to accurately measure elevation, latitude and longitude at each station, and to apply the corrections we used the SYSTEM GNSS Trimble R6. The accuracy of this equipment is important, especially for the elevation, because the acceleration decreases with increasing distance. The gravimeter used during this survey was a Scintrex CG-5 Autograv.

4.4 Equipment

The gravimeter used in this gravimetric survey was the Scintrex CG-5 Autograv (Figure 12). This Autograv have a microprocessor that automatic reads the measurements. It has a range over 8000 mGal and a reading resolution of 0.001 mGal. The gravimeter has the capacity to do measurements in a cycle mode. This is an important feature, because with this we can make a series of reading in the same place and decrease the error of the measurements. A quartz elastic system operates in an extremely stable environment, and combined with the software, the drift error is reduced to less than 0.02 mGal per day.

The software-based tilt sensors help the increase of stability during the readings, cause these sensors provides a greater accuracy that the conventional bubble levels.

Figure 12 - Scintrex CG-5 Autograv gravimeter set up for measuring gravity at a station.

The SYSTEM GNSS Trimble R6 (Figure 13) was used to accurately measure the elevation, latitude and longitude of each gravity station in the field. The elevation error averaged was about 0.02 meters, in other words, the precision of this equipment is extremely accurate for this survey. Differential correction uses a ground base station (with a rigorous and precisely location) that broadcasts the difference between the position indicated by satellites relative to the position in the field.

Figure 13 - SYSTEM GNSS Trimble R6 set up for measurements of the localization of the station.

4.5 Gravity Corrections

The principal objective in gravity surveys is to obtain a map of the Bouguer Anomaly. Therefore, it necessary to make corrections for all the variables that influence the variation of the gravity acceleration. The gravity reduction is the process to normalize the measured gravity data. This process is essential for a great accuracy of the anomalies.

4.5.1 Drift correction

Due to the elastic stretching in the spring, the gravimeter readings change through time. The instrumental drift (Figure 14) can be measured through repeating readings at different times of the day on a base station (usually 2-4 hours). Once the differences are calculated they are subtracted from the observed gravity measurements at each station.

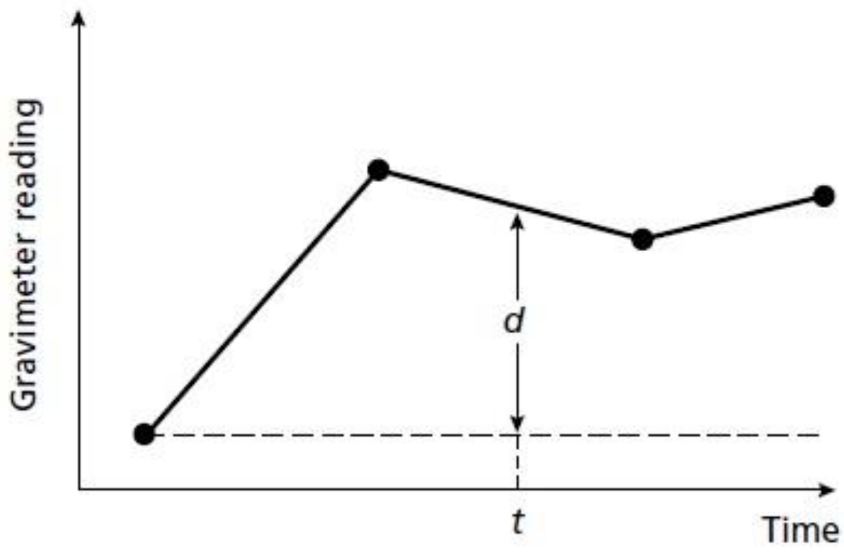

Figure 14 – A gravimeter drift curve. The drift correction, d, is subtracted from a reading at time t (Kearey, et al., *2002).*

4.5.2 Tidal corrections

The relative positions of the Earth, Moon and Sun influence the gravimeter readings, due the gravitational forces. These gravitational forces cause a variation in the shape of the earth and causes tidal variations. These corrections can be made through values found in specific bibliography. In this case the gravimeter used in the survey, have a specific software that can calculate this variations by setting the correct UTC/GMT time. Because the survey was made in Portugal, the correct UTC/GMT is +1h (West).

4.5.3 Latitude correction

The gravity acceleration changes with the latitude. This happens because of the shape of the Earth. To do this correction it is necessary use the next equation

$$gt = 978{,}031.85(1 + 0.005278895 sin2\,(\pi\phi) + 0.000023462 sin4\,(\pi\phi)) \text{ mGal}$$

Where, ϕ is the latitude observed at each station.

The Datum used in this survey was the *ETRS89.*

4.5.4 Free Air Correction

The free air correction considers the changes in altitude between the gravity measured in witch station and the sea level. The rate of decrease of the gravity with the elevation is 0.308 mGal per meter. The free air correction is,

$$Free\ Air\ Correction = h0.308 \text{ mGal}$$

Where, h is the elevation of the station above a sea level datum. This rate of gravity decreases with increasing elevation highlights that it is crucial to measure or estimate precisely the elevation for each measurement site.

4.5.5 Bouguer Correction

The Bouguer corrections form the basis for the interpretations of gravimetric data. This correction accounts for the gravitational effect between the station and the sea level datum. This is done by assuming a slab of uniform density (2.67g/cm^3) and an infinite horizontal extent, whose thickness is the elevation of the station.

$$Bouguer\ Correction = 0.0419\,\rho h \text{ mGal}$$

Where, ρ is the density of the slab (2.67g/cm^3) and h is the station elevation. This density is called the reference density for reduction and is fixed as the average density estimated for a standard continental crust.

4.5.6 Simple Bouguer Gravity Anomaly

The Simple Bouguer Anomaly reduces the gravity data by subtracting the effects of an infinite horizontal slab, with density from the Free Air Gravity Anomaly

$$Simple\ Bouguer\ Anomaly\ =\ Free\ Air\ Anomaly - Bouguer\ Correction$$

Where, Free Air Anomaly is the subtraction of the Latitude Correction (g_n) from the observed gravity (g) and adding the Free Air Correction (g_{fa}).

$$Free\ Air\ Anomaly\ =\ g\ -\ g_n\ -\ g_{fa}\ \text{mGal}$$

4.5.7 Terrain Corrections

The regions of Panasqueira and Argemela have considerable variations in elevation, and with profiles made in mountainous terrain and in valleys, it’s necessary to perform a terrain correction to accurately reduce the gravity data. The Bouguer Correction assumes that the topography between the station and the sea level datum is flat. A gravity measurement obtained next to a hill or a valley requires a correction to be added to the data, having in account the excess of mass above the station or missing mass below it.

In order to correct the data, we have to choose one of the two existing methodologies, the Hammer chart or a software correction using a Digital Elevation Model (DEM) or a combination of the two.

The Hammer chart (Figure 15) consist of a series of segmented concentric rings that are divided in a large number of compartments (Hammer, 1939). This chart is laid on a topographic map with the centre on the gravity station and the average elevation of each compartment is determined. After that, was apply an equation that determinates the Gravitational effect in each compartment (Reynolds, 1997).

$$Terrain\ Correction = 0.4191\frac{\rho}{n}\ (r_2\ -\ r_1 +\ \sqrt{r_1^2 + z^2} - \sqrt{r_2^2 + z^2})\ \text{gu}$$

Where, n is the number of segments in zone, ρ is the Bouguer correction density (2.67g/cm^3), z is the difference in the elevation between the gravity stations and the mean elevation of compartment (m), r_1 is the inner radius of zone (m) and r_2 is the outer radius of zone (m).

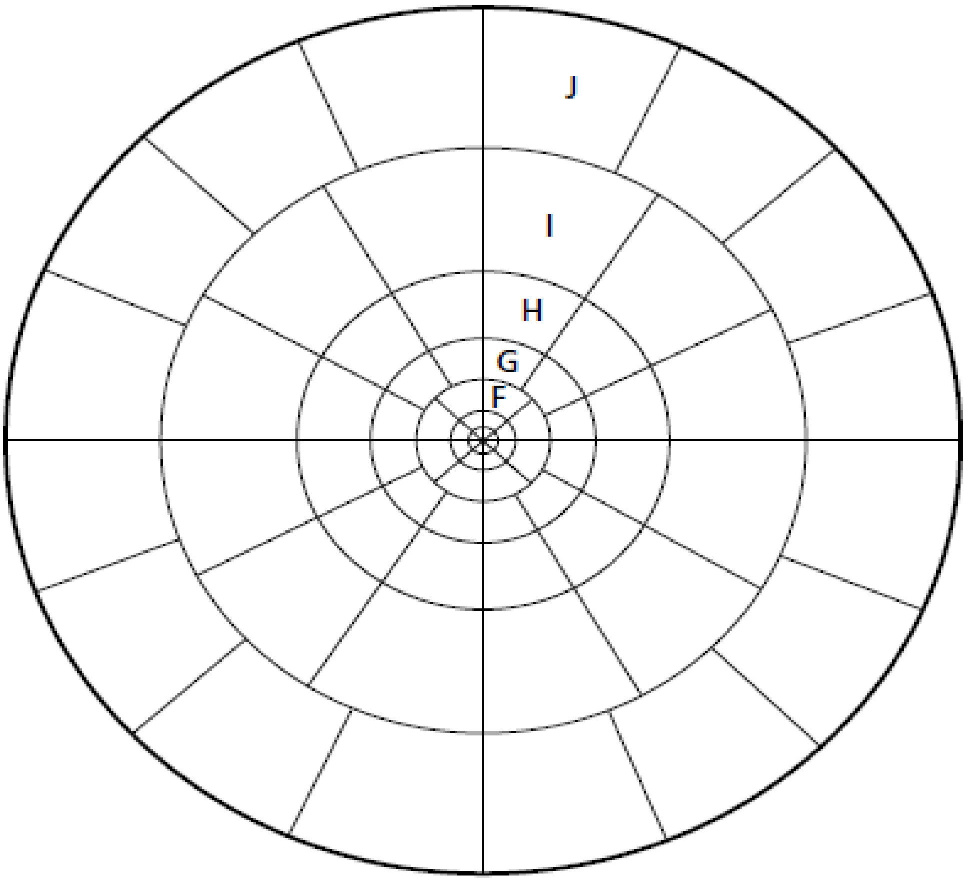

Figure 15 – A typical graticule used in terrain corrections. The chart with zones carrying in radius from 2 meters to 21.9 kilometres is used with topographic maps (Kearey, et al., *2002).*

The Oasis Montaj software was the possibility of applying terrain corrections using a DEM. The software Gravity and Terrain Correction system calculates the terrain correction using a regional DEM, that is draped over a sampled local DEM model. This produces a regional correction grid that represents terrain corrections beyond a local correction distance. With this we can calculate the corrections for each gravity stations.

The terrain corrections in this thesis were made using the two methods. The DEM that we used was the Portuguese DEM 20x20 metres, and because we wanted a more detailed correction, we used the zone B and C from the Hammer chart, in order to considering more detailed topographic variations at distance less than 20 meters around measurement points. In the field, we took the measurements of these two zones. Then, the terrain corrections, were calculated using the terrain correction equation. The rest of the correction were made in Oasis Montaj Gravity and Terrain Correction system.

4.5.8 Complete Bouguer Anomaly

In order to obtain the Complete Bouguer Anomaly, the Terrain correction must be added to the Simple Bouguer Anomaly.

$$Complete\ Bouguer\ Anomaly\ =\ Terrain\ Correction\ +\ Simple\ Bouguer\ Anomaly$$

With this anomaly, it’s possible to calculate the residual and the regional Bouguer anomaly.

4.5.9 Residual and Regional Bouguer Anomaly

Generally, in gravity surveys, the anomalies of interest are derived from a shallow source or from a deeper source. These anomalies are called the residual anomalies. Although the definition of residual anomaly is not very precise (e.g. Nettleton, 1954; Skeels, 1967), is normally defined as the anomaly derived from a source of interest. The anomalies that are larger than the anomaly of interest, are called regional anomalies. The amplitude of the regional anomaly is greater that the amplitude of the residual anomaly (Figure 16).

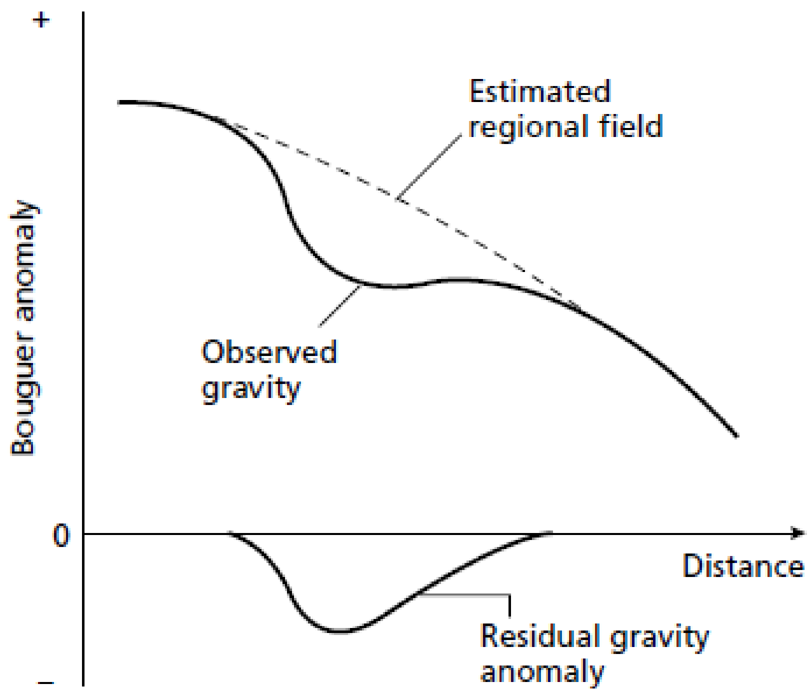

Figure 16 – The separation of the regional and residual anomalies from the observed Bouguer anomaly (Kearey, et al., *2002).*

It's possible to separate the residual-regional anomaly using two types of techniques, the isolation or enhancement techniques (Hinze, 1990). The isolation techniques try to eliminate all the anomalies that do not have interest for the objectives of the survey. With that, the isolated anomalies are the residual anomalies. The fundamental premise of isolation approach is that geologically significant anomaly is minimally modified by the regional gravity field and by the process.

Enhancement techniques, are a group of methods which accentuate characteristics that defines the anomaly that is important for the survey. In this process, the anomalies are accentuated to increase their perceptibility. Using these methods, we are promoting a distorted anomaly that may no longer be useful for quantitative analysis and inversion.

There are various isolation and enhancement methods. These methods are described in Hinze, 2013. In this case, we separate the residual-regional anomaly using the Bouguer Anomaly of Iberian Peninsula and subtracted to the Complete Bouguer Anomaly from our data. This method is used in various works (see in Martínez-Moreno, 2015) and was an easy way to calculate the residual anomaly in the study area. The data of the Bouguer Anomaly of Iberian Peninsula was retired from airy.ual.es. The file used was a ASCII file that was treated on ARGIS software.

4.5.10 Density

While density of the different lithologies was not used in the calculations of the Bouguer Anomaly map, these measurements were necessary for the interpretation and modelling of the data. The densities were determinate by colleagues in France, Michard J.and Launay G., 2017 (unpublished) that used fresh sample to determinate the densities. The next table shows the densities that were used during the modelling

Table 2 – Density adopted during the 2-D and 3-D modelling.

Lithology	Mean (g/cm^3)
Spotted_schist	2.763
Granite	2.673
Greisen	2.777
Schist (Panasqueira)	2.776
Schist (Argemela)	2.75
Microgranite	2.566

5. Results

In order to make the final density models of Argemela and Panasqueira that are compatible with the gravity data, its needed to remove the regional trend of the Bouguer anomaly from the Complete Bouguer Anomaly. The result will be the residual gravity anomaly. All the Bouguer maps were interpolated using the Oasis Montaj software. The maps were made with the Kriging algorithm. The coordinate system used was WGS84/UTM zone 29N.

5.1 Argemela Results

5.1.1 Complete Bouguer Anomaly

The complete Bouguer Anomaly map (Figure 17) corrects the anomaly for topography in vicinity of the stations. This map was produced from the reduced data, with all the corrections discussed in Chapter 4 and using the standard crustal density of 2.67g/cm^3. The map was a spatial resolution of 50 meters, that is because of the minimum space between stations. The anomaly values range between -73.117816 and -75.546985 mGal. In the west part of the map it’s possible to see the lowest anomaly, that is caused by the possible underground extension of the Fundão pluton, as shown by outline of the thermal aureole extension, at surface. On the centre of the map it’s possible to observe another lower anomaly. This anomaly is caused by the Argemela microgranite. The highest anomaly value (-73.117816 mGal) is present in the east part of the map. Here the influence of the Fundão pluton or the Argemela microgranite is low, so these anomalies are presumably related only to the schist or with basement rock density changes, with no influence of any granite body that would be hidden, to depth.

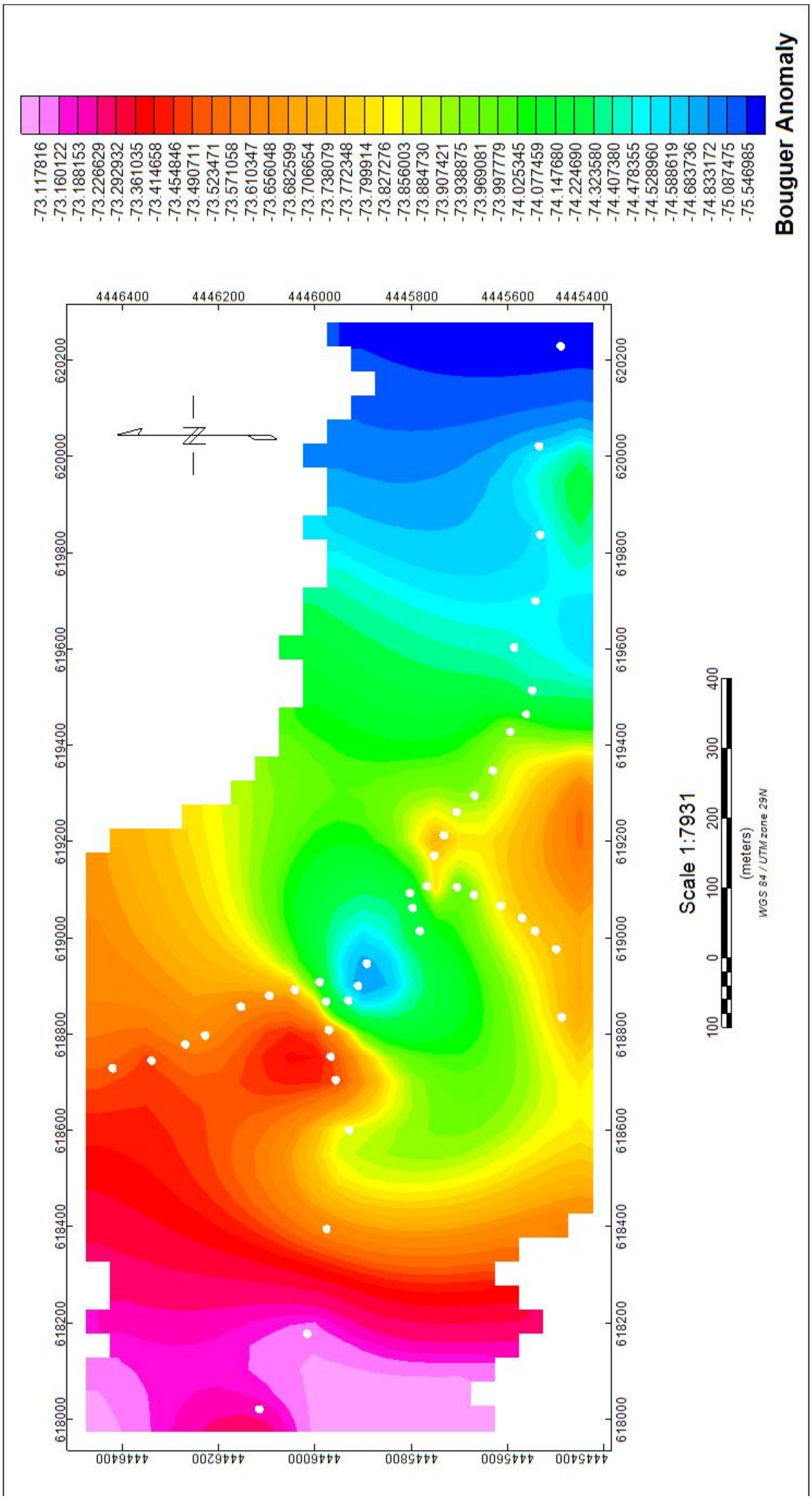

Figure 17 – Complete Bouguer Anomaly Map of Argemela, with the gravimetric stations (white dots) overlaid.

5.1.2 Regional and Residual Gravity Map

For the determination of the residual map in Argemela, it was necessary to subtracting the regional gravity from the complete Bouguer anomaly, thereby isolating the anomaly from regional trends that usually have a deeper source than that of the residual anomaly we are interested in for our propose. To produce the residual anomaly, we used a large scale Bouguer gravity map of Iberian Peninsula. This Bouguer map of Iberia shows the regional trends of the deep sources and it's better explained in the chapter 4. The regional map was treated on a GIS software and used in Oasis Montaj to create the Residual Bouguer Anomaly map of Argemela.

In the residual map, the anomalies are about 10 mGal higher than the ones that we can observe in the Bouguer map (Figure 18). The residual map isolates the gravity anomaly in the central part of the map (the Argemela Microgranite) with a gravity low of about -64 mGal. The boundaries of this anomaly are similar with the contact boundaries that we can found on surface between the microgranite and the host rocks.

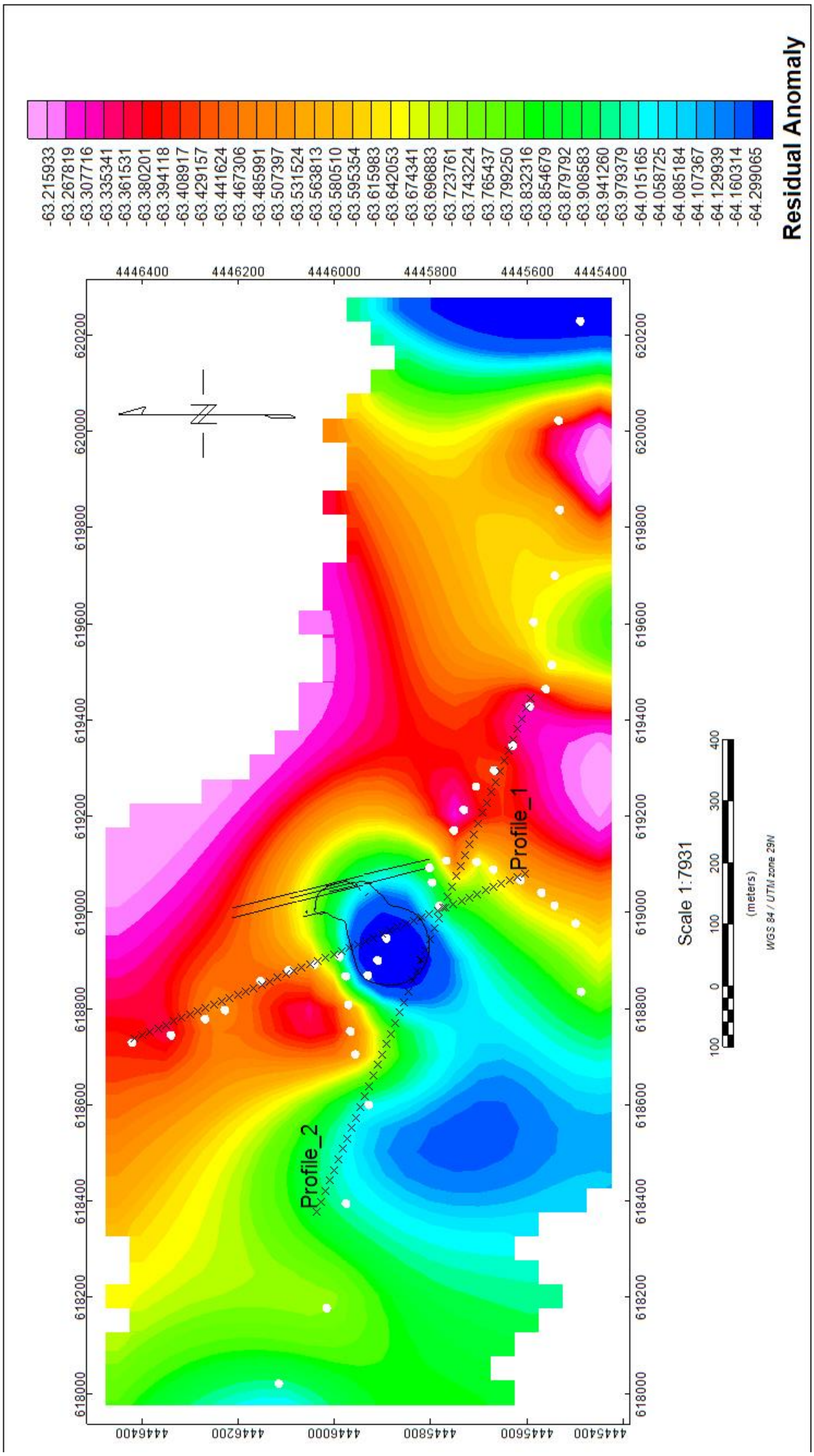

Figure 18 – Residual Gravity Map of Argemela, with the outline of the microgranite and shear zone, the gravimetric stations (white dots) and the profiles (black crosses) overlaid.

5.2 Panasqueira Results

5.2.1 Complete Bouguer Anomaly

To interpolate the gravimetry data from Panasqueira, we used the same methods like we did in Argemela (Figure 19). The only difference was the special resolution, in this case the special resolution was 170 meters. The anomaly values range between -61.921577 and -72.613769 mGal. In the center of the map we can see the lowest anomaly, this anomaly is apparently related with the Panasqueira granite. In the south and west it is possible to observe the highest anomalies. This type of anomaly can show us that the influence of the granite is minimal and presumably it’s related only with the schist.

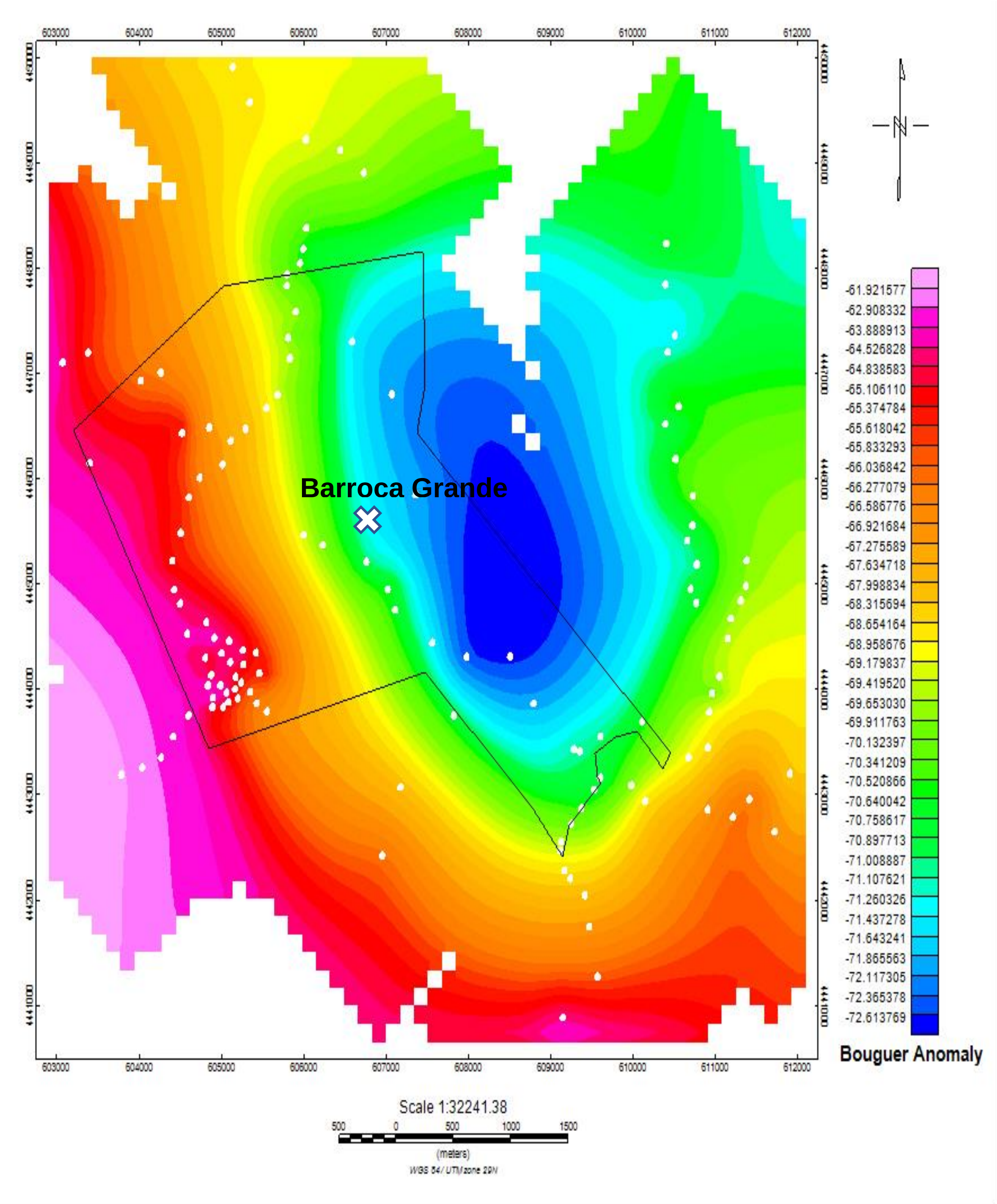

Figure 19 – Complete Bouguer Anomaly Map of the Panasqueira, with the outline of the mining concession and the gravimetric stations (white dots).

5.2.2 Regional and Residual Gravity Map

Like in Argemela, we adopted the same method for Panasqueira. We used the Bouguer map of Iberian Panasqueira. In terms of the differences in anomalies between the Complete Bouguer map and the Residual map, we can see they are small. The highest anomaly in the Residual map is -63.847928 mGal and the lowest anomaly is -72.212759 mGal (Figure 20). The anomaly caused by the granite is more noticeable that in the Complete Bouguer map, and have a shape similar to the boundaries of the spotted schist at surface. The granite apparently has a continuity to the north part of this region.

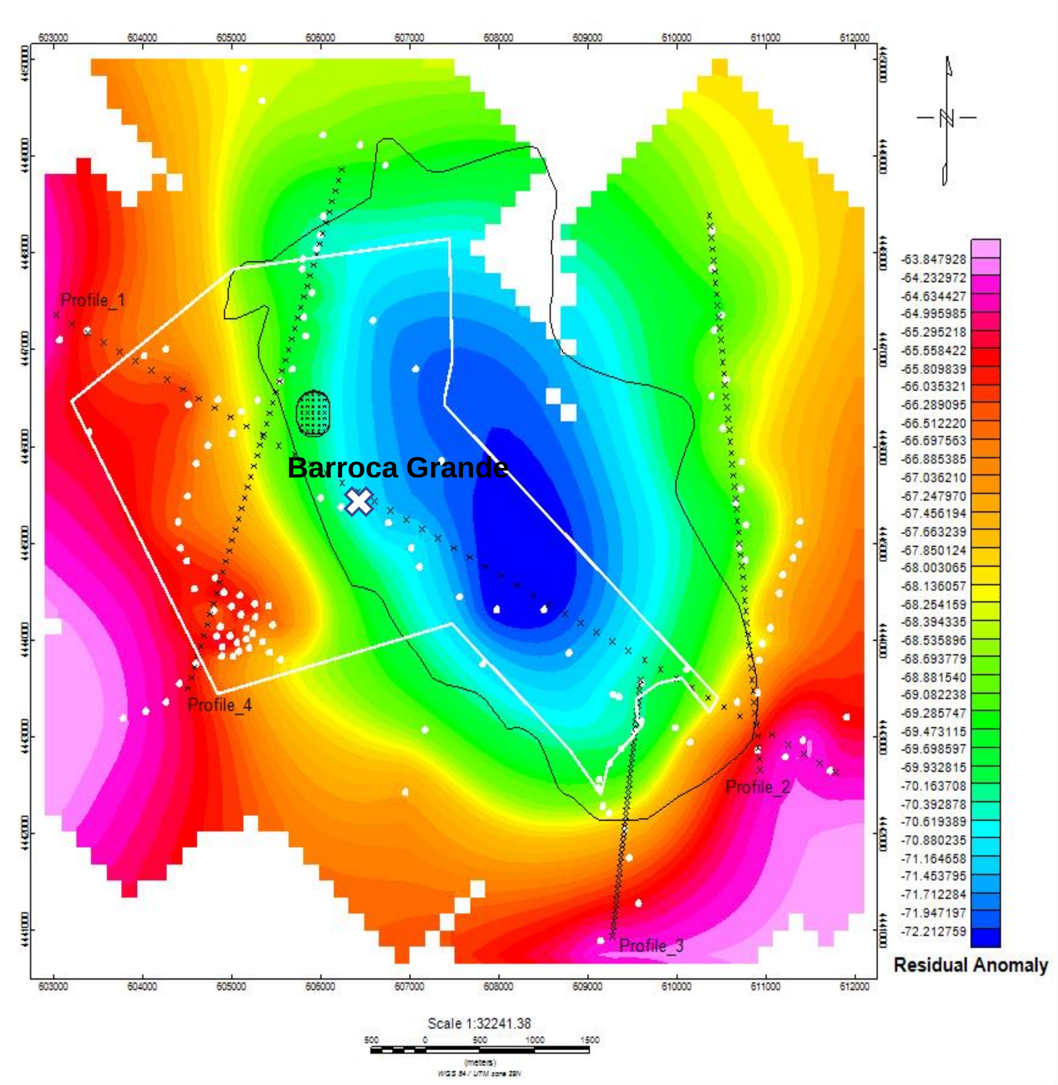

Figure 20 – Residual Anomaly Map of the Panasqueira, with a black outline of the spotted schist and of the granite cupola, a white outline of the mining concession, the gravimetric stations (white dots) and the profiles (black crosses) overlaid.

5.2.3 Gradient Map

Due to the large amount of data in this area, we made a gradient map to see if we could recognise and trace some sharp discontinuities (sharp and sub-vertical intrusive contacts, steep faults, etc). In this map (Figure 21), we can see one SW-NE trending zone with high gradient. High gradient tells us that in that zone we have a big step and that the contacts are sharp and vertical. In the southeast part of the map we can observe a high gradient and we know traces of a NE-SW fault zone have been recognised there. In the southwest part, we have another high gradient. In this zone, we don't have geological information about any fault. The Cebola Fault is not visible in this gradient map, maybe because that, given the steepness of the topography, there is only too few data measured in this part of the study area.

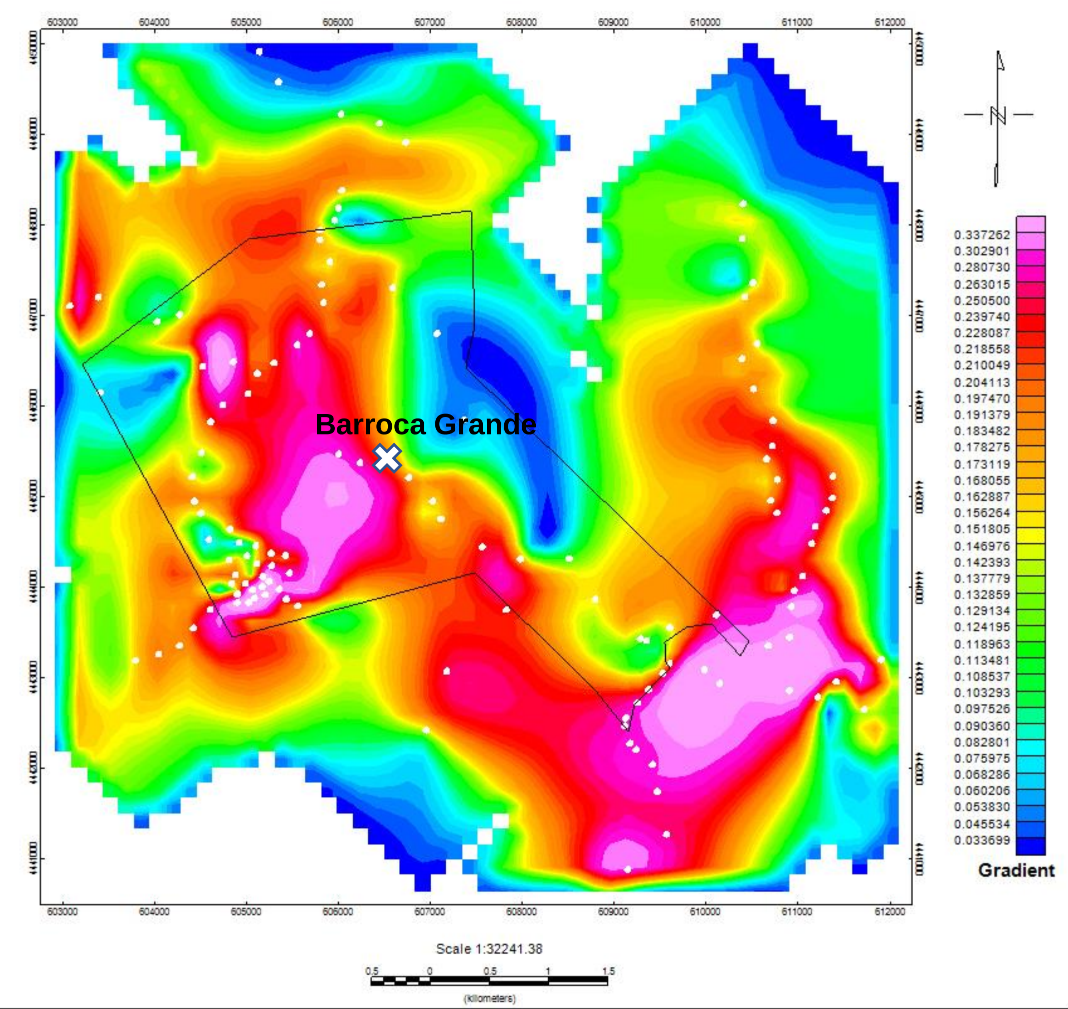

Figure 21 – Gradient Map of the Panasqueira, with the outline of the mining concession and the gravimetric stations (black dots) overlaid..

6. Results on Gravity Modelling

Forward modelling is an essential step in gravity interpretation. The forward models, were produced from the residual Bouguer map for Argemela and Panasqueira. For Argemela it was made from two transects and for Panasqueira was made four transects. The profiles of this transects have been made along the profile measurements in the field to compare modelled values directly to the measurements and not to the interpolated map values. Forward modelling involves calculating the gravity field from an assigned density and comparing the calculated field with the observed residual gravity, then by trial and error adjusting the subsurface model. The final result is a determination of the shape and extent of the geological structures that provides the best fit to the observed gravity. However, such a model is not unique, as a great number of models may fit the same data. This can be overcome be the use of other information, as the use of borehole data, mapping of surface contacts, density measurements of samples and a sound geological conceptual model based on the geological cartography. In the case of Argemela and Panasqueira we have the densities of the lithology and the mapping of surface contacts, and for Panasqueira we have data from boreholes. It is also that important to refer that the densities used are fixed and that the values came from some measurements made in the lab.

The Gravity Profiles were produced using the Gravity and Magnetic Modelling Software (GM-SYS). This program is used for calculating the gravitational response from a geological model. It provides the option to create and manipulate the density models to fit the observed gravity data, either in 2-D or 2¾-D models. The 2-D models assume the Earth is two dimensional. So, the only affected directions are the Z direction (depth) and the direction of the profile (X axis). The blocks and surfaces are presumed to extent to infinity in the strike direction. In this case, all the information about the structure and density of the intrusions and the host rocks was used. The density used for each of the lithological units are based on data collected by Michaud J. and Launay G., 2017 (unpublished) and the geological data from boreholes and bibliography.

In this process, systematic changes are made in the subsurface geometry consistent with the know surface geology, borehole data and rock density. With this, the number of models were reduced, and the only variables were the depth of the intrusions and subsurface geometry.

Each profile in Argemela was produced with a homogeneous granite having a density of 2.566 g/cm^3, a basement having a density of 2.67 g/cm^3 and a schist having a density of 2.75 g/cm^3. During the modelling, the density of the schist was changed in some points in order to fit the observed gravity data. The outcropping boundary of the granite at surface is known and was used in the model. Moreover, the orientation of the East contact can also be fixed as we have the observation of the vertical shear zone there.

In the case of Panasquieira, the profiles were produced with a homogeneous granite having a density of 2.663 g/cm^3, a spotted schist having a density of 2.753 g/cm^3, a schist having a density of 2.776 g/cm^3 and a basement having a density of 2.67 g/cm^3. The data of the boreholes was interpolated to get the top the pluton and this parameter was also introduced in the profiles.

6.1 Interpretation of the 2-D profiles of Argemela

6.1.1 Profile 1

Figure 22 is a profile with the direction NNW-SSE. It depicts a calculated residual gravity low of -64.5 mGal. The microgranite, depicted in pink, has a density of 2.566 g/cm^3. The horizontal extent of the microgranite is proximality 220 meters in the subsurface and with a maximum vertical extend of 1000 meters. The surrounding schists, depicted in green colour, has an average density of 2.75 g/cm^3. In the surface the geological map was used in order to limit the microgranite.

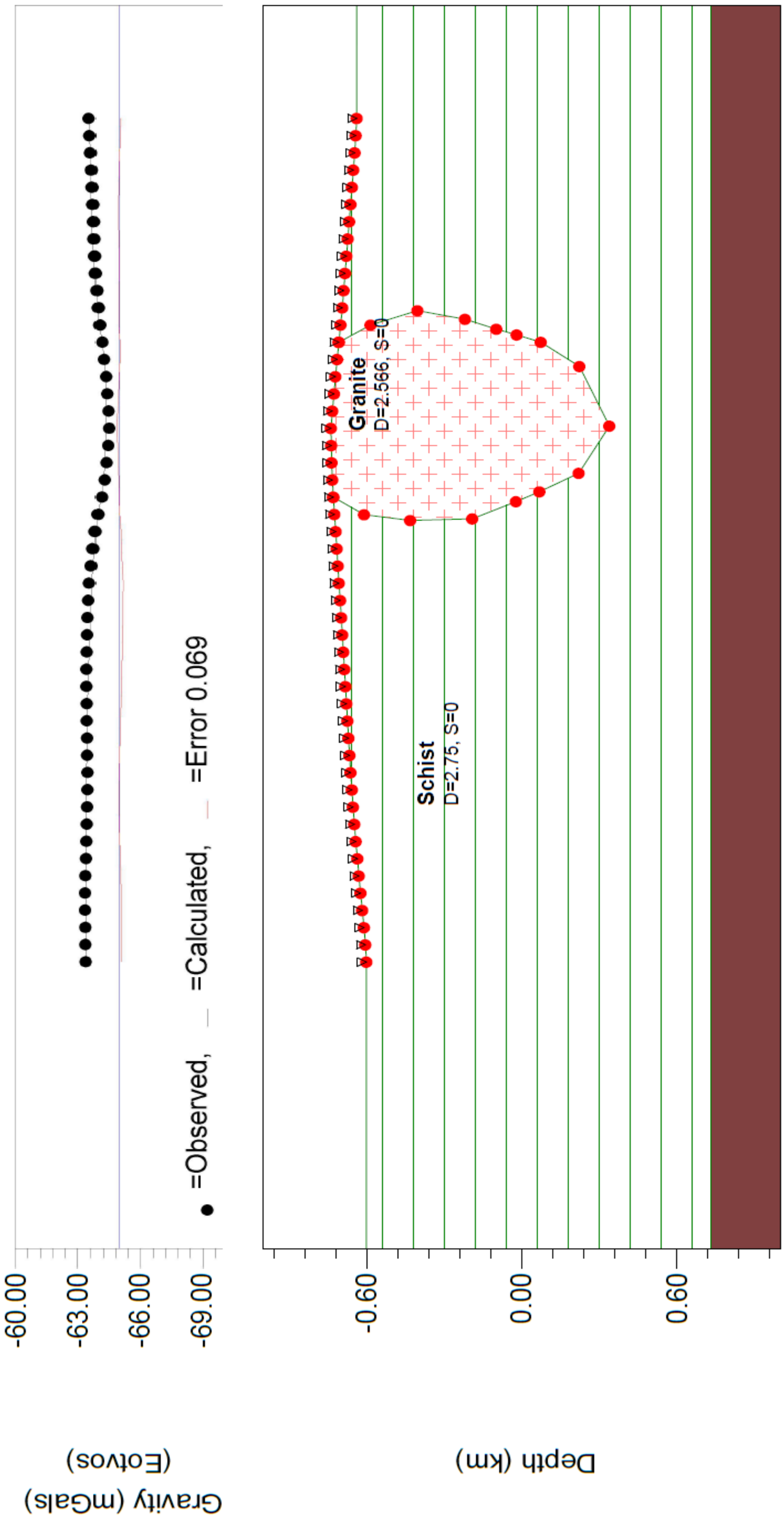

Figure 22 – The profile Profile_1 and model from NNW-SSE.

6.1.2 Profile 2

Figure 23 is a profile with the direction ESE-WNW. It depicts a calculated residual gravity low of -64.5 mGal. The microgranite, in a pink colour, have a density of 2.566 g/cm^3. The horizontal extent of the microgranite is proximality 180 meters in the subsurface and with a maximum vertical extend of 700 meters. The surrounding schist, in green colour, in order to fit the residual anomaly was divided into three parts. In the ESE side, we have an average density of 2.76 g/cm^3, this is where the residual anomaly is higher. In the central part, near the microgranite, an average density of 2.75 g/cm^3. In the WNW part of the profile, an average density of 2.74 g/cm^3.

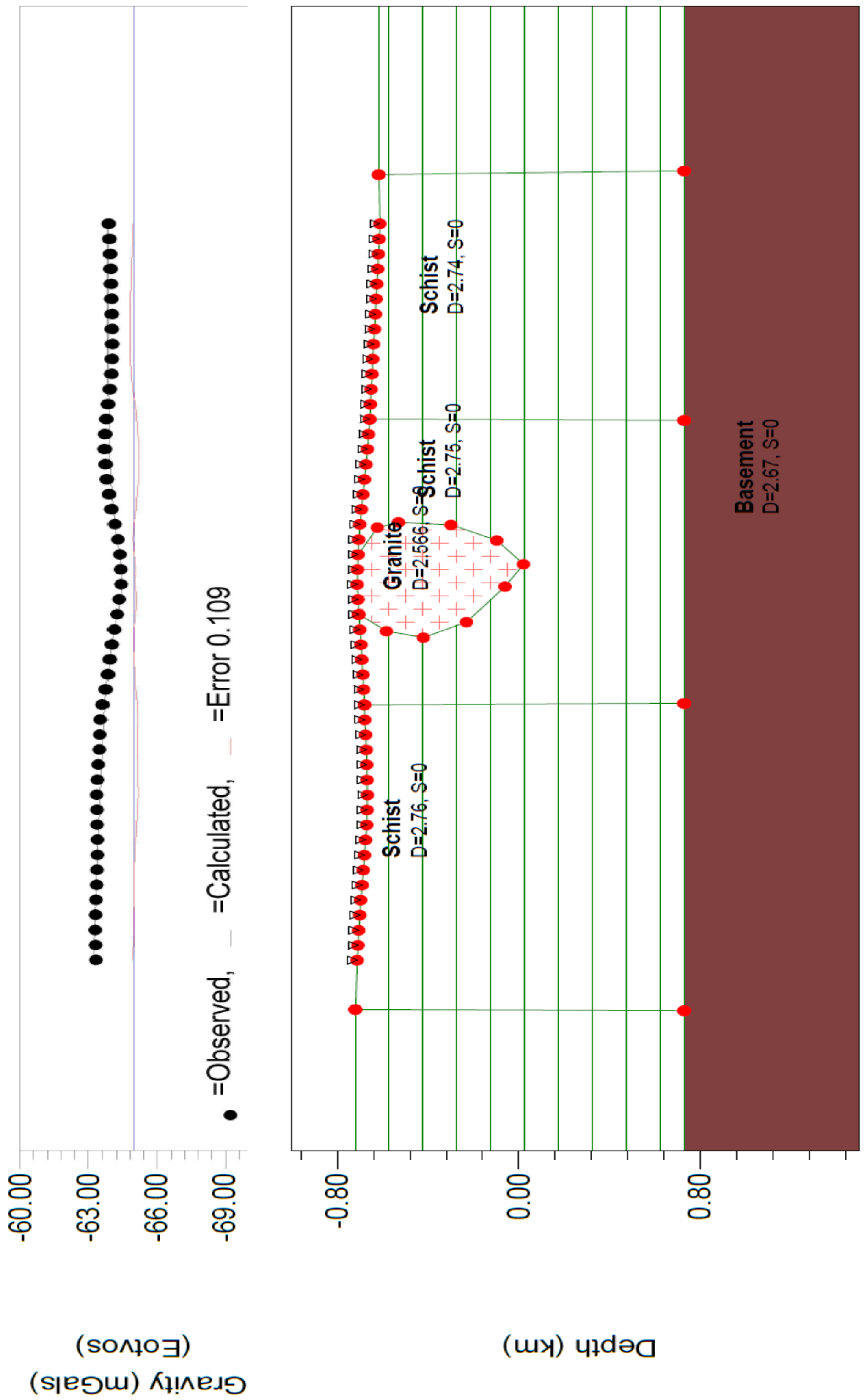

Figure 23 - The profile Profile_2 and model from ESE-WNW.

6.2 Interpretation of the 2-D profiles of Panasqueira

6.2.1 Profile 1

Figure 24 is a profile with the direction ESE-WNW, in the south part of the region. It depicts a calculated residual gravity low of -72 mGal. The granite, in a pink colour, have a density of 2.663 g/cm^3. The horizontal extent of the microgranite is proximality 7000 meters in the subsurface and with a maximum vertical extend of 2500 meters. The surrounding spotted schist, in light green colour, have an average density of 2.763 g/cm^3. The "normal" schist, in a dark green, was divided in three parts. In the NNW side, we have an average density of 2.79 g/cm^3, this is where the residual anomaly is higher. In the central part, near the granite, an average density of 2.776 g/cm^3. In the SSE part of the profile, an average density of 2.773 g/cm^3. This was made because of the differences on the residual anomaly. The granite is bounded by two regional faults and it cannot be followed on the other sides, suggesting some magma stopping or controls of these structures during the magma ascent and emplacement in the upper crust. The topography was restricted with the data from the boreholes, so the only variable was its thickness. The data of the boreholes was applied in all profiles.

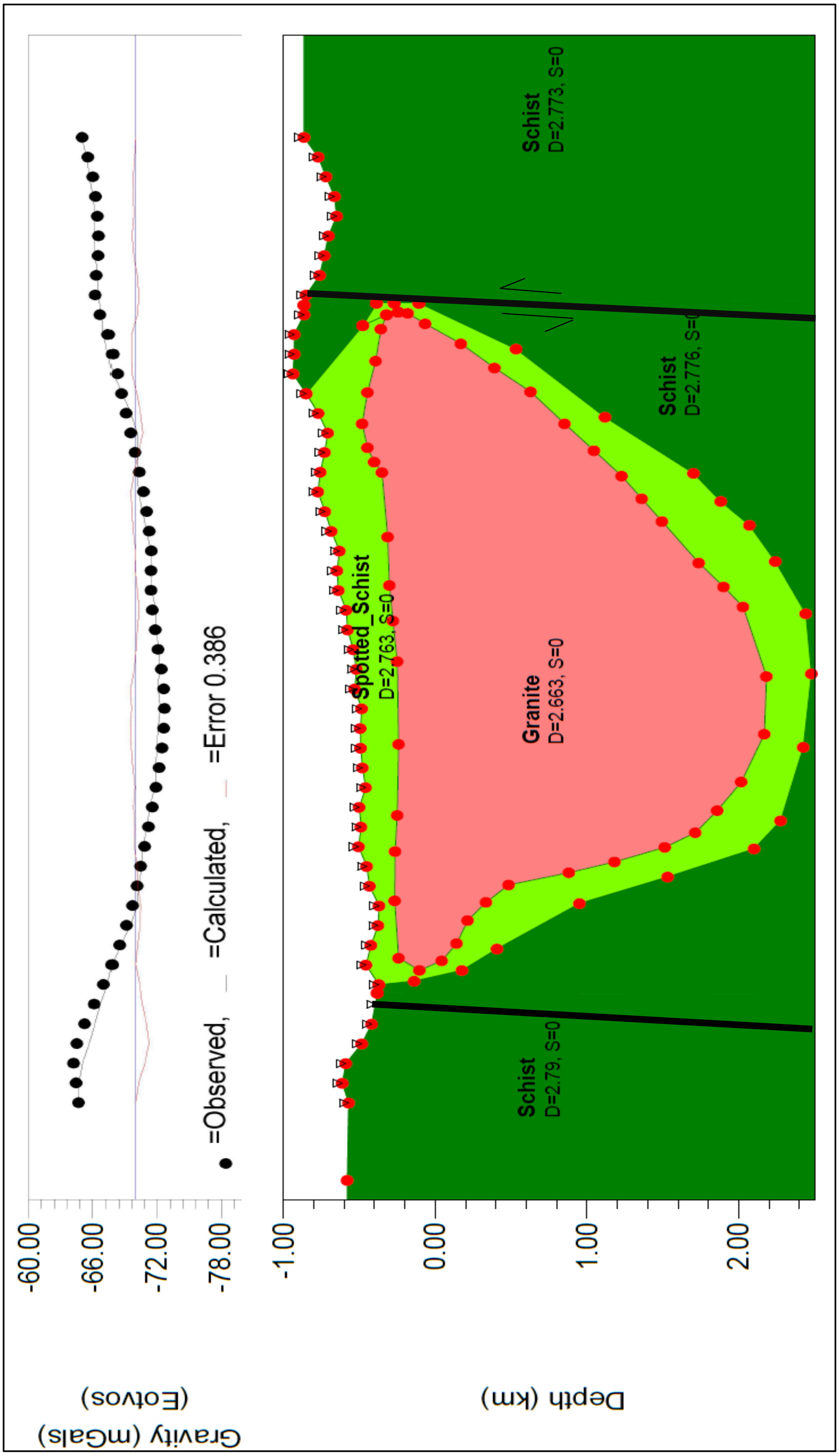

Figure 24 – The profile Profile_1 and model from ESE-WNW.

6.2.2 Profile 2

Figure 25 is a profile with the direction N-S and is situated in the east part of the region. It depicts a calculated residual gravity low of -69.5 mGal. The granite, in a pink colour, has a density of 2.663 g/cm^3. The horizontal extent of the microgranite is proximality 4500 meters in the subsurface and with a maximum vertical extend of 1000 meters. The surrounding spotted schist, in light green colour, have an average density of 2.763 g/cm^3. The normal schist, in a dark green, was divided in two parts. In the south part, the schist has an averaged density of 2.79 g/cm^3 and the other part of the schist have a density of 2.776 g/cm^3. The granite is restricted by a regional fault in the south part of the profile.

Based on this profile and the residual gravity map, the granite is inferred to extend to the north side of the region in the subsurface.

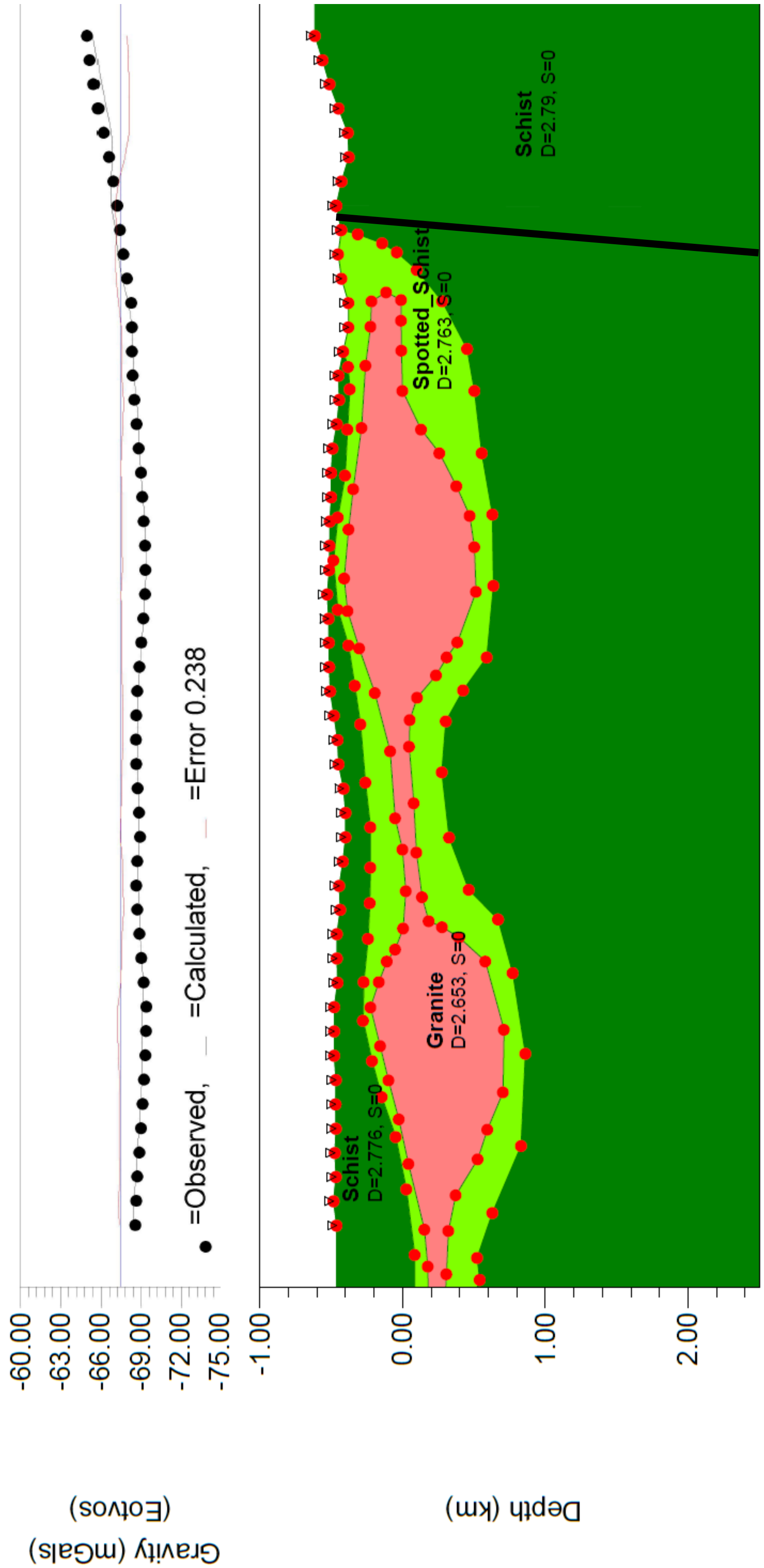

Figure 25 - The profile Profile_2 and model from N-S.

6.2.3 Profile 3

Figure 26 is a profile with the direction N-S and is located near the second profile, but below the profile 1. It depicts a calculated residual gravity low of -70 mGal. The granite, in a pink colour, have a density of 2.663 g/cm^3. The maximum vertical extend is 1000 meters. The surrounding spotted schist, in light green colour, have an average density of 2.763 g/cm^3. The normal schist, in a dark green, was divided in two parts. In the south part, the schist has an averaged density of 2.79 g/cm^3 and the other part of the schist have a density of 2.776 g/cm^3. In this profile, the granite is restricted by the same regional fault that we can see in the profile 2.

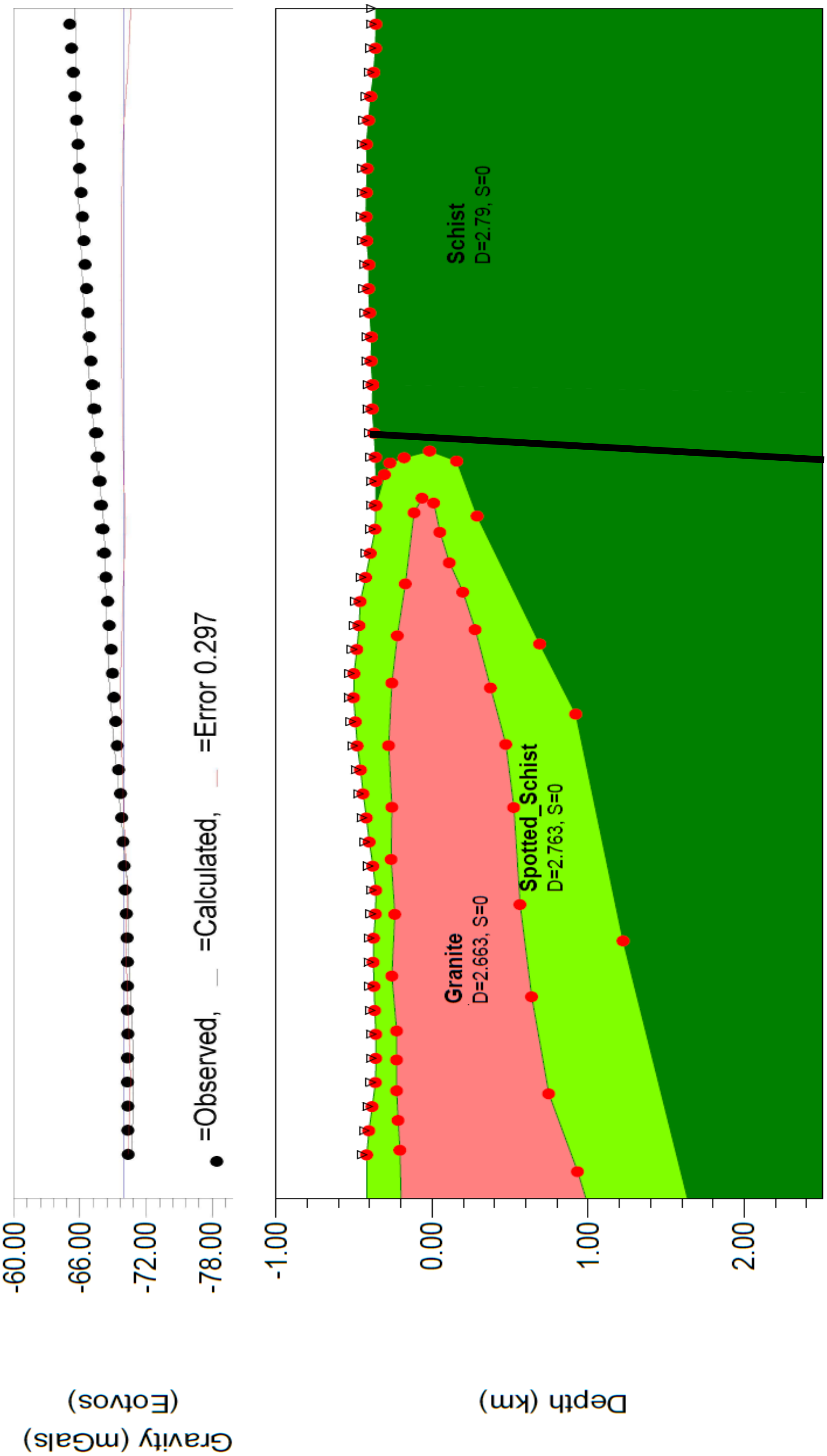

Figure 26 - The profile Profile_3 and model from N-S.

6.2.4 Profile 4

Figure 27 is a profile with the direction N-S and is located in the west part of the region. It depicts a calculated residual gravity low of -71 mGal. The granite, in a pink colour, have a density of 2.663 g/cm^3. The horizontal extent of the microgranite is proximality 4400 meters in the subsurface and with a maximum vertical extend of 1000 meters. The surrounding spotted schist, in light green colour, have an average density of 2.763 g/cm^3. The normal schist, in a dark green, was divided in two parts. In the south part, the schist has an averaged density of 2.773 g/cm^3 and the other part of the schist have a density of 2.776 g/cm^3. The granite extends to the north part of the region and is bounded by a fault.

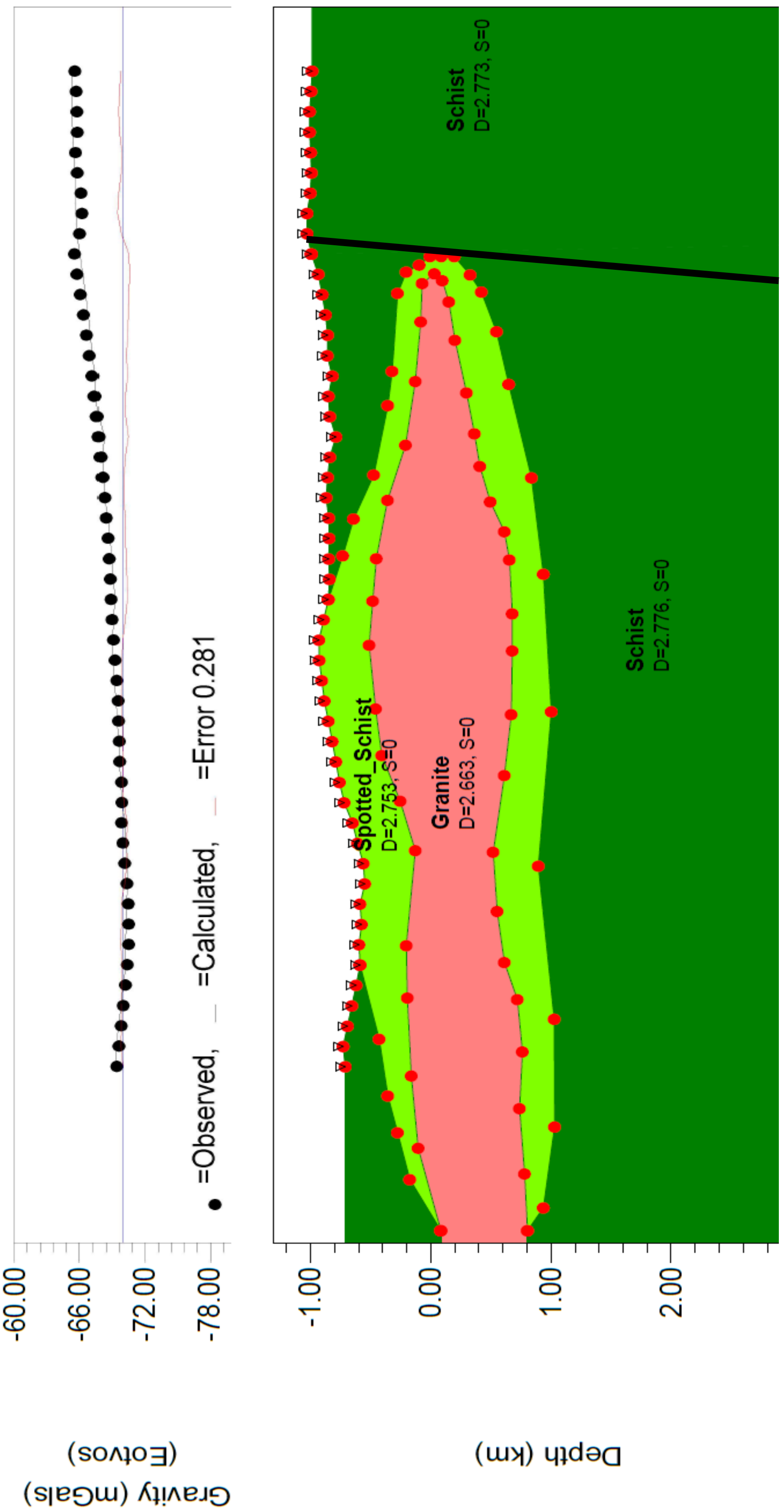

Figure 27 - The profile Profile_4 and model from N-S.

7. Interpretation

After producing the best in section views, these were introduced in a 3-D software. The 3-D software used was the Geomodeller. With this software, we have the opportunity to do forward modelling and inverse modelling using the density and geological data. In this case, we just introduced the 2-D profiles, the surface geology and, in the case of Panasqueira, the depth of the top of the granite. The program interpolates the profiles, the geological information that included either geological boundaries and orientation, boreholes and the trace of the major shear zones or faults, and produce a 3-D model. This 3-D models can be modified to improve the geological model.

7.1 Interpretation of the 3-D model of Argemela

After the modelling of the 2-D profiles, we introduced them in the 3-D software, as well, the geological surface mapping. The final result was the geological model. In this model, we can see that the microgranite has a tubular form and some small lateral inflations. In fact, this intrusion does not display a typical shape for a granite with no stock chamber (bubble shape) as was expected. Our model better shows a shape corresponding to a pipe system (Figure 28). Near the shear zone, we can see a small deformation of the microgranite (Figure 29). This could have happened after the emplacement, whilst the magma was cooling. Sant'Ovaia et al, 2000, proposed that the magma emplacement was vertical and had a lateral inflation due to the magma pressure. Charoy and Noronha, 1996, proposed that the microgranite was fed by subvertical dykes and was rootless. This model agrees that the emplacement was a subvertical injection, but currently there is no information to prove or disprove that the microgranite was fed by subvertical dykes

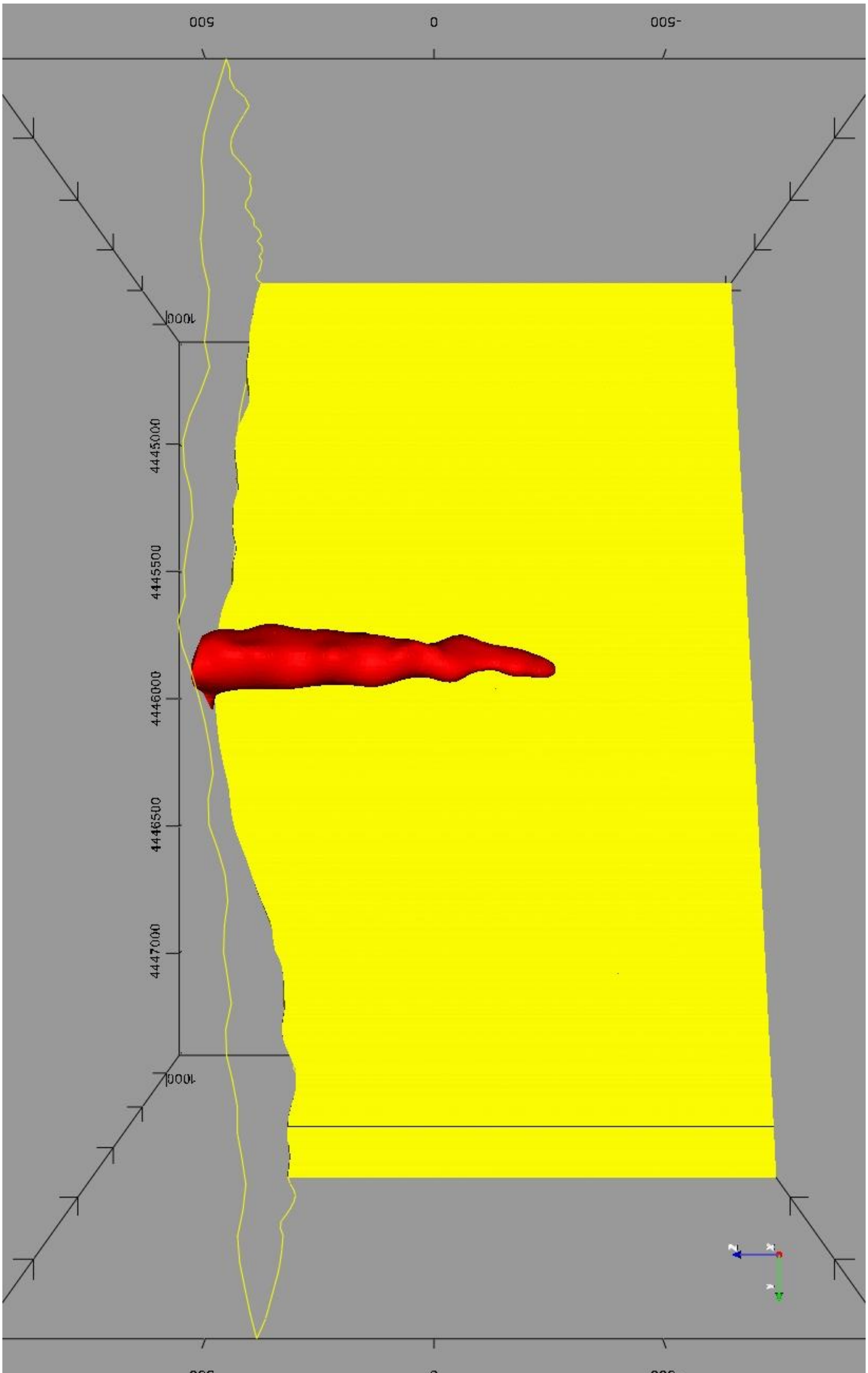

Figure 28 – Argemela microgranite with a shape corresponding to a pipe system.

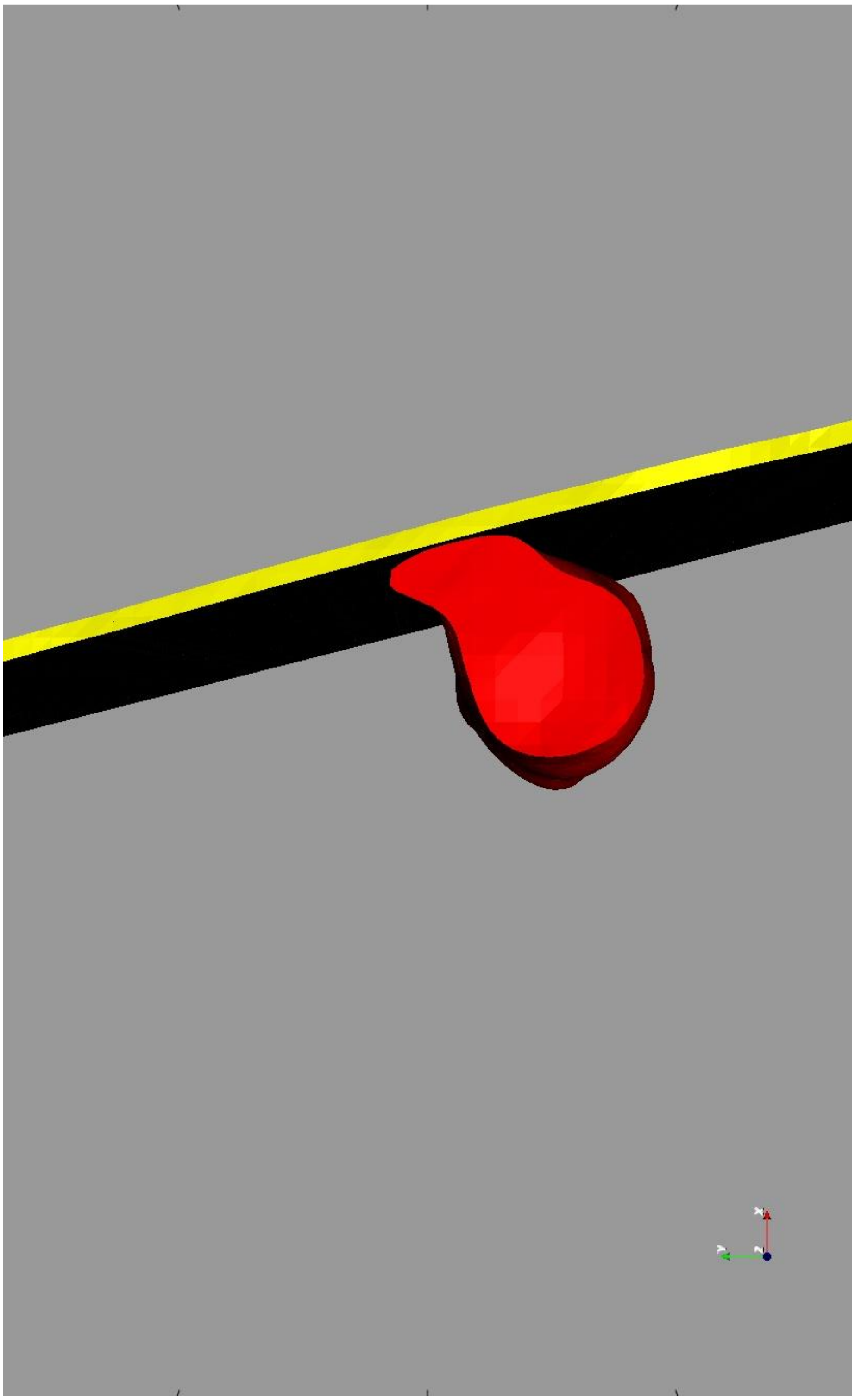

Figure 29 – Deformation of the Argemela microgranite near the shear zone.

7.2 Interpretation of the 3-D model of Panasqueira

Using the data from the boreholes, the geological surface map and the 4 profiles, it was possible to obtain a 3-D geological model (Figure 30). In this model we have three faults, two depicted in orange (NE-SW) and one depicted in red. The fault towards the north of the region (orange) corresponds to the Cebola Fault, as mapped at surface. The east fault (orange), is a regional fault that is near the Zêzere River and is recognised and traced in the Gradient Map. The red fault, is a fault that we propose based on the Gradient Map.

The emplacement of the granite occurred in the central part of the region extended to the North and Northeast part of the region (Figure 30 and 31). The emplacement was controlled by the three faults. These faults may have existed before the magma emplacement and restricted the shape of the granite.

In 2011, Póvoa, using a passive electromagnetic method (Magnetotellurics), proposed that south of the known cupola could exist another cupola with mineralizations. In this we carried out some gravimetric measurements and based on the obtained gravimetric 2D anomalies, as well as on the modelled profiles, we can infer that the referred cupola may not exist.

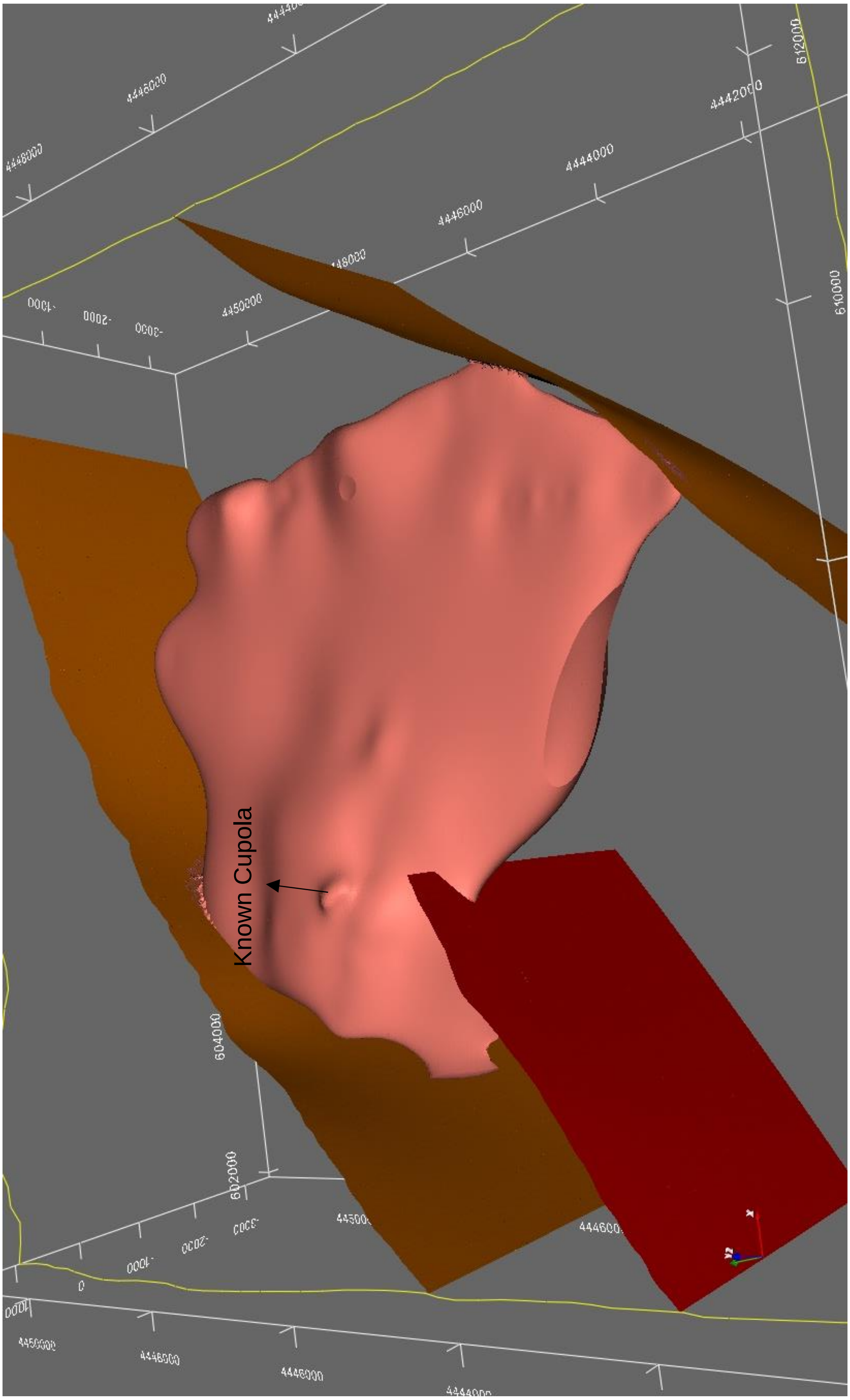

Figure 30 - Geological model of the Panasqueira granite with the localization of the known cupola.

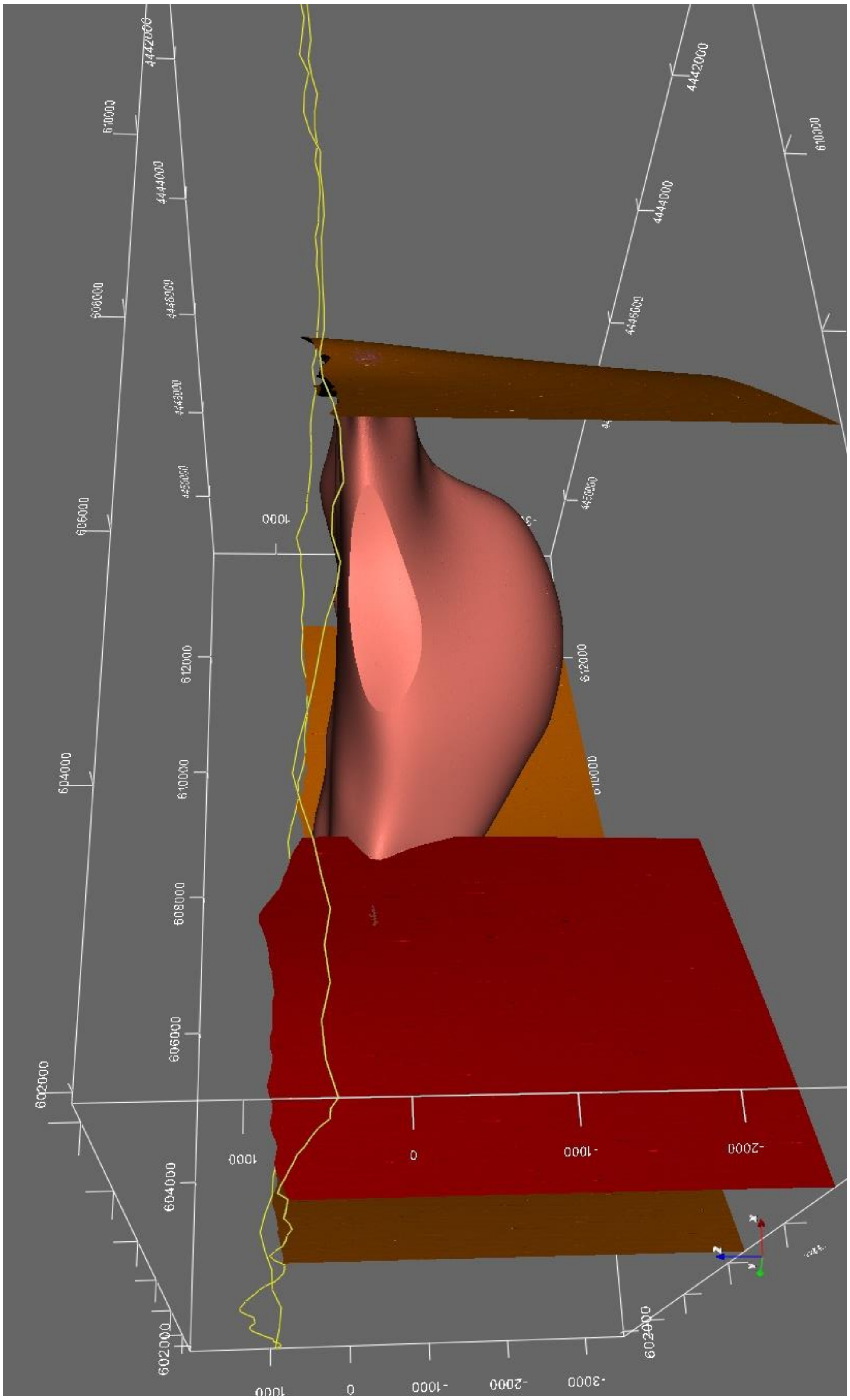

Figure 31 – Geological model of Panasqueira granite showing us where the emplacement occur.

8. Conclusions

The gravimetric method used during this research provided a means to obtain better understanding of the subsurface configuration and a more conclusive estimate of the depth extent of the microgranite of Argemela and the granite of Panasqueira. The outcome from the primary objective is a result of maps, sections and 3D models produced from reduced observed gravity data collected on the field.

It is important to refer that in both regions, Argemela and Panasqueira, were never performed studies using the gravimetric method. With our study, we can point that using a gravimeter like Scintrex CG-5 Autograv or one with superior quality, we can perform a gravimetric campaign where is possible to evidence relative low contrast anomalies, especially in Argemela region.

8.1 Argemela

The residual Bouguer anomaly map for Argemela (Figure 18) shows a gravity low in the central portion of the map. This anomalous feature represents the microgranite of Argemela. In the South part of the maps we can see another low anomaly, but we did not study this anomaly because of the low amount of gravimetric stations in that part of the region.

The geological 3-D model produced with the 2-D profiles for Argemela allows a reasonable interpretation of the microgranite in terms of the depth and shape. The intrusion has an estimated vertical extend of about 1000 metres and presents a tubular shape. This shape fits the model proposed by Sant'Ovaia et al (2015) in which the magma emplacement was vertical.

During the campaign with had some limitations, especially because of the terrain. In Argemela the topography is very irregular and steep, and in some parts of the region, the vegetation is very closed. With these limitations, the selection of the stations was not easy and it was impossible to make more transects around the microgranite.

In a future, it can be conducted another gravimetric survey, especially in the Southwest part of the Argemela microgranite, in order to comprehend and study the low anomalies that we can see in the residual Bouguer anomaly map.

8.2 Panasqueira

The residual Bouguer anomaly map of Panasqueira (figure 20) shows gravity low in the central part of the region. This anomaly represents the granite intrusion extending to its greatest depth (2000 Km) in the subsurface. The form of the low anomaly suggests that the intrusion extends toward north. It’s also possible to identify some of the regional faults existing in the region, due to the differences in density.

The 3-D geological model shows that the granite was fed in the central part of the region and has an estimated vertical extension of 2000 metres. It’s possible to infer that the emplacement was controlled by regional faulting and it extends toward the N-NE part of the region.

In Panasqueira we have large tellings because of the Panasqueira mine. This fact was a limitation, because of the unstable terrain and because of the great amount of heavy metals, that have a great density and can influence the measurements. To work around this problem, we tried to choose station that where distant from the tellings.

The terrain, like in Argemela, is very irregular and steep, what created another problem with the localizations of the stations. The vegetations high density was another limitation to this survey. Because of that we could not perform more measurements around the region in order to improve the interpretation of the gravimetric data.

It’s important to refer, in the case of Panasqueira, that can be conduct a new survey in the north part of the region, in order to have a better understanding of the intrusion in that part of the region and thus further improve the geological model.

9. References

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