A Journey into Iberia’s Depths: Geometry of Plutons in the Central Pyrenees and Iberian Massif

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IMAGYN

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GEO3BCN
Geosciences Barcelona - CSIC

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Resumo

Os plutões graníticos variscos preservam um importante registo da evolução crustal, dos processos de instalação magmática e da reativação tectónica no Maciço Ibérico e na Zona Axial dos Pirenéus. Este estudo investiga a geometria tridimensional e os mecanismos de instalação de quatro plutões representativos: Vila Pouca de Aguiar e Águas Frias-Chaves, no Norte de Portugal, e La Maladeta e Andorra Mont-Louis, nos Pirenéus Centrais. Foi utilizada uma metodologia integrada que combina dados gravimétricos, medições de densidade, Anisotropia da Suscetibilidade Magnética, cartografia geológica, modelação 2D e modelação geológica 3D, com o objetivo de reconstruir a arquitetura destes plutões em profundidade.

Para os plutões portugueses, um conjunto de dados gravimétricos previamente publicados foram reprocessados através da utilização de softwares mais recentes e expeditos, tendo sido construídas em Oasis Montaj novas secções geológicas e geofísicas posteriormente integradas no GeoModeller. Para os plutões pirenaicos, foram incorporados e refinados modelos geológicos, gravimétricos e magnetotelúricos existentes, recorrendo a interpretações geofísicas recentes. A modelação direta e a inversão gravimétrica foram aplicadas de forma iterativa para minimizar a discrepância entre os dados observados e calculados, assegurando simultaneamente a plausibilidade geológica dos modelos.

Os resultados revelam variações significativas na geometria dos plutões, com corpos lacolíticos pouco profundos, estruturas batolíticas e estruturas em cunha profundamente enraizadas. Estas diferenças refletem a influência combinada das propriedades das rochas encaixantes, das estruturas crustais que permitiram a instalação, da arquitetura das zonas de origem e da evolução tectónica regional. A comparação entre os exemplos portugueses e pirenaicos demonstra que os controlos litológicos e estruturais exercem uma influência mais determinante na morfologia final dos plutões do que o contexto tectónico por si só. Este trabalho evidencia a importância da integração de dados geológicos e geofísicos na redução das ambiguidades inerentes à interpretação do subsolo e no aprofundamento do conhecimento sobre os processos de instalação de magmas graníticos.

Palavras-chave: Plutões Variscos, Gravimetria, Modelação Geológica 3D, Geofísica, Instalação de Granitos.

Abstract

The Variscan granitic plutons preserve an important record of crustal evolution, magma emplacement processes, and tectonic reactivation in the Iberian Massif and the Axial Zone of the Pyrenees. This study investigates the three-dimensional geometry and emplacement mechanisms of four representative plutons: Vila Pouca de Aguiar and Águas Frias–Chaves in northern Portugal, and La Maladeta and Andorra–Mont-Louis in the Central Pyrenees. An integrated methodology combining gravity data, density measurements, Anisotropy of Magnetic Susceptibility (AMS), geological mapping, 2D modelling and 3D geological and gravity modelling and stochastic inversion was employed to reconstruct the subsurface architecture of these plutons.

For the Portuguese plutons, a previously published gravity dataset was reprocessed using more recent and efficient software, such as Oasis Montaj instead of Surfer, allowing the construction of new geological and geophysical cross-sections in Oasis Montaj, which were subsequently integrated into GeoModeller. For the Pyrenean plutons, existing geological, gravity, and magnetotelluric models were and some cross-sections were added to better constraint the models. 3D Forward gravity modelling and stochastic gravity inversion were applied iteratively to minimize the misfit between observed and calculated gravity anomalies while ensuring the geological plausibility of the resulting models.

The results reveal significant variations in pluton geometry, including shallow laccolithic bodies, batholithic structures, and deeply rooted wedge-shaped intrusions. These differences reflect the combined influence of the properties of the host rocks, the crustal structures that facilitated the emplacement, the architecture of the subsurface structures, and the regional tectonic evolution. Comparison between the Portuguese and Pyrenean plutons demonstrates that lithological and structural controls exert a more significant influence on the final morphology of these bodies than the tectonic setting alone. This work highlights the importance of integrating geological and geophysical data to reduce the ambiguities inherent in subsurface interpretation and to advance our understanding of the emplacement processes of granitic magmas.

Keywords: Variscan plutons, Gravity, 3D geological modelling, Geophysics, Granite emplacement

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List of Abbreviations

FCUP	FACULTY OF SCIENCES OF THE UNIVERSITY OF PORTO
UP	UNIVERSITY OF PORTO
VPA	VILA POUCA DE AGUIAR
AF	ÁGUAS FRIAS
LM	LA MALADETA
AML	ANDORRA MONT-LOUIS
VPAP	VILA POUCA DE AGUIAR PLUTON
AFP	ÁGUAS FRIAS PLUTON
AFG	ÁGUAS FRIAS GRANITE
SAMG	SANTO ANTONIO MONFORTE GRANITE
PRVF	PENACOVA-RÉGUA-VERIN FAULT
VPAG	VILA POUCA DE AGUIAR GRANITE
PSG	PEDRAS SALGADAS GRANITE
GSG	GOUVÃES DA SERRA GRANITE
CSB	CHAVES SEDIMENTARY BASIN
AMS	ANISOTROPY OF MAGNETIC SUSCEPTIBILITY
MT	MAGNETOTELLURIC
LMP	LA MALADETA PLUTON
AMLP	ANDORRA MONT-LOUIS PLUTON
CIZ	CENTRAL IBERIAN ZONE
PAZ	PYRENEAN AXIAL ZONE
D1	FIRST VARISCAN DEFORMATION PHASE
D2	SECOND VARISCAN DEFORMATION PHASE

D3	THIRD VARISCAN DEFORMATION PHASE

1. Introduction

The three-dimensional geometry of granitic plutons provides important constraints on magma emplacement, crustal deformation, and the tectonic evolution of orogenic belts. In the Iberian Peninsula, numerous Variscan plutons were emplaced during the late Paleozoic, yet their subsurface architecture and emplacement mechanisms remain poorly understood.

This study focuses on four representative granitic bodies: the Vila Pouca de Aguiar and Águas Frias-Chaves plutons in northern Portugal, and the La Maladeta and Andorra Mont-Louis batholiths in the Central Pyrenees. Although these intrusions formed during broadly contemporaneous late-Variscan magmatism, they were later affected by different tectonic histories, particularly the stronger Alpine overprint in the Pyrenean region.

To investigate their subsurface structure, this work applies integrated gravimetric modelling, combining residual Bouguer gravity anomalies, density data, and geological constraints to construct 2D cross-sections and 3D geological models. This approach allows the characterization of pluton geometry at depth, including thickness variations, feeder zones, and relationships with major tectonic structures.

The main objectives of this dissertation are to reconstruct the three-dimensional geometry of the studied plutons and evaluate how contrasting geological and tectonic evolutions since their emplacement, approximately 300 Ma ago, influenced their present-day structure. By integrating geological and geophysical evidence, this study aims contributing to a better understanding of Variscan pluton emplacement in both, the Iberian Massif and the Central Pyrenees.

2. General framework

2.1 Geographical Setting

This work covers four different granitic plutons distributed across Iberia (Fig. 1), two of them are located in northern Portugal (Vila Pouca de Aguiar, VPAP, and Águas Frias, AFP), the other two, are in the Pyrenees (La Maladeta, LM, and Andorra Mont-Louis, AML).

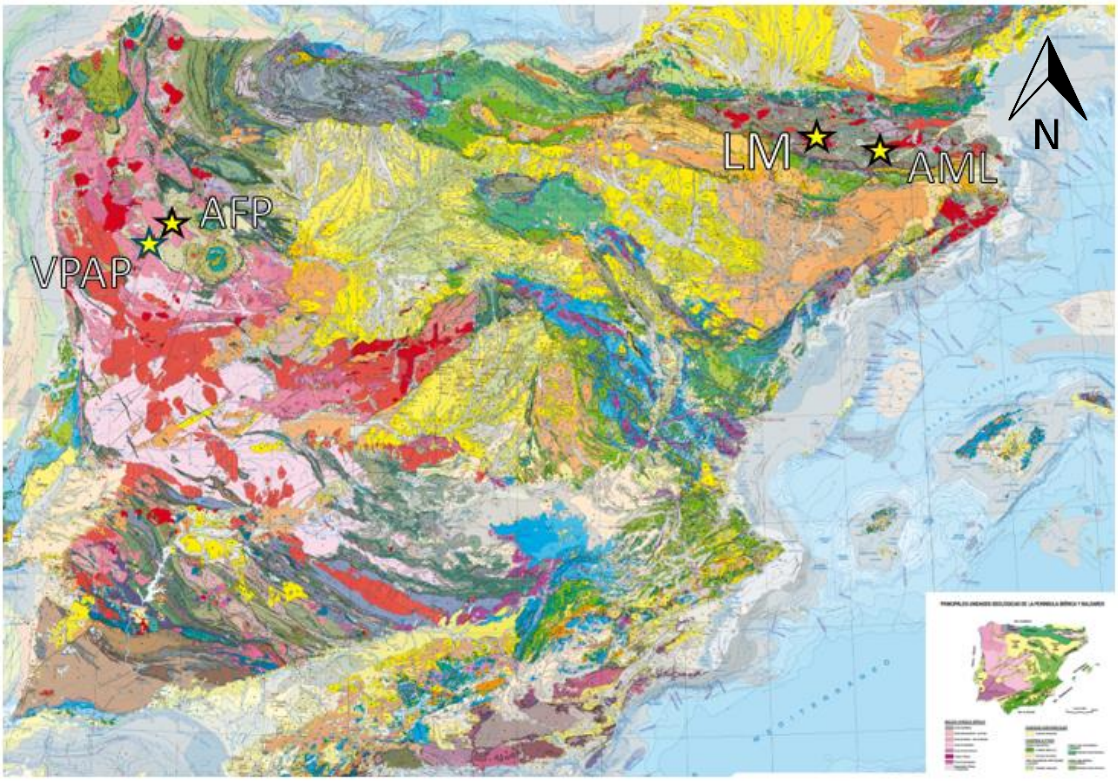

Figure 1 - Geological map of Iberia with pluton locations marked by stars (modified from the "Mapa Geológico de España y Portugal" by IGME and LNEG (scale 1:1.000.000)

Vila Pouca de Aguiar

The Vila Pouca de Aguiar pluton derives its name from the nearby municipality of Vila Pouca de Aguiar. It is located in the north of Portugal, in the district of Vila Real, forming part of the *Trás-os-Montes e Alto Douro* region. The area is in the interior of the country, characterized by a rural landscape and a low population density (INE, 2021).

The landscape of this region is fairly rugged, with moderately high altitudes, ranging between 500 to over 1000 m above sea level. Nearby mountain ranges such as the Serra do Alvão influence the regional topography, contributing to strong contrasts between highlands and valleys (Atlas Ambiental, 2011).

The area is drained by tributaries of the Tamega River, flowing North to South, to the west of the Vila Pouca de Aguiar. The region is also marked by seasonal watercourses, streams and the presence of small rivers, with some of them following the Penacova-Régua-Verin fault, eventually becoming the Corgo River (Atlas Ambiental, 2011).

Águas Frias

The Águas Frias pluton is located near the civil parish of Águas Frias, in the municipality of Chaves, within the district of Vila Real, near the Spanish border. It lies in the north of the Trás-os-Montes e Alto Douro region. Águas Frias is located to the northeast of the urban setting of Chaves, having a rural and sparsely populated setting. It is also located north-east of Vila Pouca de Aguiar, at just almost 40 km of distance, and therefore shares many geographic features (INE, 2021).

Águas Frias sits on a moderately elevated landscape, but with more gentle terrain than Vila Pouca de Aguiar and lower altitudes than the surrounding mountainous areas (Topographic map, https://pt-pt.topographic-map.com).

There are no major waterways in the area. It is mostly drained by small streams and minor tributaries, flowing towards the Tâmega river basin. Watercourses are generally short and seasonal, contributing to local drainage networks and small alluvial areas used for agriculture (Município de Chaves, 2022).

La Maladeta

The La Maladeta pluton derives its name from the Maladeta Mountain. It is located in the Central Pyrenees (northeastern Spain), in the provinces of Huesca and Lleida, within the autonomous communities of Aragón and Catalunya, respectively. It lies close to the French-Spanish border and forms part of the highest sector of the Pyrenean Mountain range (Gobierno de Aragón, https://www.aragon.es/-/parque-natural-de-posets-maladeta).

The La Maladeta area comprises the Maladeta-Aneto massif, one of the most prominent Pyrenean mountainous regions. It is surrounded by the Aran Valley to the northeast and the Ribagorza region to the southwest, occupying a high-altitude alpine environment with marked relief contrasts (Encyclopaedia Britannica, www.britannica.com/place/Pyrenees).

The landscape is dominated by high mountain terrain, with sharp ridges and steep slopes, deep glacial valleys and high-altitude plateaus. Elevations are among the highest in the Pyrenees, with numerous peaks exceeding 3,000 m, including Aneto, the highest peak in the range. The relief is rugged and strongly vertical, with limited flat areas (Posets-Maladeta Natural Park, https://www.turismodearagon.com/en/ficha/parque-natural-posets-maladeta/).

La Maladeta forms an important headwater region, with meltwater and streams feeding major river systems. Northward-flowing streams drain toward France, while southward-flowing tributaries contribute to the Ebro River basin. Numerous small mountain lakes and streams are present, particularly in high-altitude areas (Posets-Maladeta Nature Reserve, https://www.spain.info/en/nature/posets-maladeta-natural-park/).

Andorra - Mont Louis

The Andorra - Mont Louis pluton extends across Andorra, Spain and France, in the border regions of the three countries. It is defined by rugged landscape, owing much of it to the central Andorran ranges. Being not too distant from La Maladeta, just about 90 km to the east, they share many geographical features (Government of Andorra, https://www.govern.ad/ca/tematiques/medi-ambient-i-sostenibilitat/).

The region is characterised by rugged mountainous terrain with steep slopes and sharp ridges. Elevations in the area typically vary between 2500 and 2900 meters above sea level (Encyclopaedia Britannica, https://www.britannica.com/place/Pyrenees).

The area is drained by small mountain streams that feed the Valira river system, Andorra’s main river. The region is also home to numerous seasonal torrents and small alpine lakes. Watercourses follow the steep slopes of the valleys, creating a dense high-altitude drainage network (Government of Andorra, https://www.govern.ad/ca/tematiques/medi-ambient-i-sostenibilitat/).

2.2. Geological Setting

Vila Pouca de Aguiar

The Vila Pouca de Aguiar (VPA) pluton (Fig.1A) is situated in the Galicia-Trás-os-Montes Zone (GTMZ), an area within the autochthonous terrains of the Central Iberian Zone (CIZ) in Northern Portugal. Geologically, it is defined as a post-tectonic (or post-D3) granitic body, meaning that its emplacement occurred after the third phase of ductile deformation of the Variscan orogeny, approximately 299 ± 3 Ma, based on U-Pb zircon dating (Martins et al., 2009). This period corresponds to a distensive or late-brittle stage of the orogeny, which followed the main compressional events (Sant'Ovaia, 2000; Sant'Ovaia et al., 2010).

According to the previous work by Sant'Ovaia (2000) and Sant'Ovaia et al. (2000), the pluton has an elongated shape with a NNE-SSW direction. This shape closely follows the direction of the Penacova-Régua-Verin Fault (PRVF) system. This fault strongly conditions the geometry and emplacement of VPA pluton, with the fault serving as a conduit for magma ascent, essentially functioning as a dike that was subsequently sealed by the granitic intrusion.

The VPA pluton is a composite laccolith characterized by a normal petrographic zoning (Martins and Noronha, 2006). It consists of three biotitic granitic units, suggested to have been emplaced synchronously, that define the pluton's concentric zoning. These are the Vila Pouca de Aguiar Granite (VPAG), a mesocratic, biotite-rich porphyritic granite located at the periphery, representing about 70% of the pluton, the Pedras Salgadas Granite (PSG), a leucocratic, more evolved granite that occupies the core of the massif, and the Gouvães da Serra Granite (GSG), a coarse-grained biotite granite found locally along the southern and eastern borders (Sant'Ovaia, 2000; Sant'Ovaia et al., 2010).

The VPA pluton is a circumscribed, discordant mass that intrudes into two main types of host formations: Metasediments and syntectonic granites. The metasediments are mainly Silurian and Ordovician-Devonian rocks consisting of phyllites, schists, and greywackes. The heat from the intrusion produced a notable contact metamorphism aureole within these surrounding rocks. The pluton also cuts through older, syntectonic two-mica granites, such as the Serapicos, Gralheira, Minheu, and Lagoa massifs (Sant'Ovaia, 2000; Sant'Ovaia et al., 2010).

Águas Frias

The Águas Frias pluton (Fig. 1B) is a post-tectonic (post-D3) Variscan granitic body located in the Galicia Trás-os-Montes Zone (GTMZ) of northern Portugal. It was emplaced during the final stages of the Variscan orogeny, and is similar in age to other post-tectonic biotite plutons in the region, such as Vila Pouca de Aguiar (Cruz et al., 2021, Martins et al., 2009).

The pluton was emplaced approximately 299 ± 3 Ma, according to U-Pb zircon dating (Martins et al., 2009). This timing aligns it with the late brittle stage of the Variscan cycle, occurring in an extensional tectonic regime characterized by large-scale uplift and crustal thinning (Martins et al., 2009).

The pluton is a composite body consisting of two main granitic bodies. The Águas Frias Granite (AFG) is a biotite-rich, porphyritic granite. The Santo António de Monforte Granite (SAMG) is a central two-mica granite. The pluton is specifically categorized as an ilmenite-type (reduced) series and I-type granite, meaning that it is weakly peraluminous and likely derived from the partial melting of a meta-igneous lower crustal source (Cruz et al., 2021, Martins et al., 2009).

Unlike the nearby Vila Pouca de Aguiar pluton, which primarily intruded metasediments, the Águas Frias pluton is mostly surrounded by older two-mica syntectonic granites.

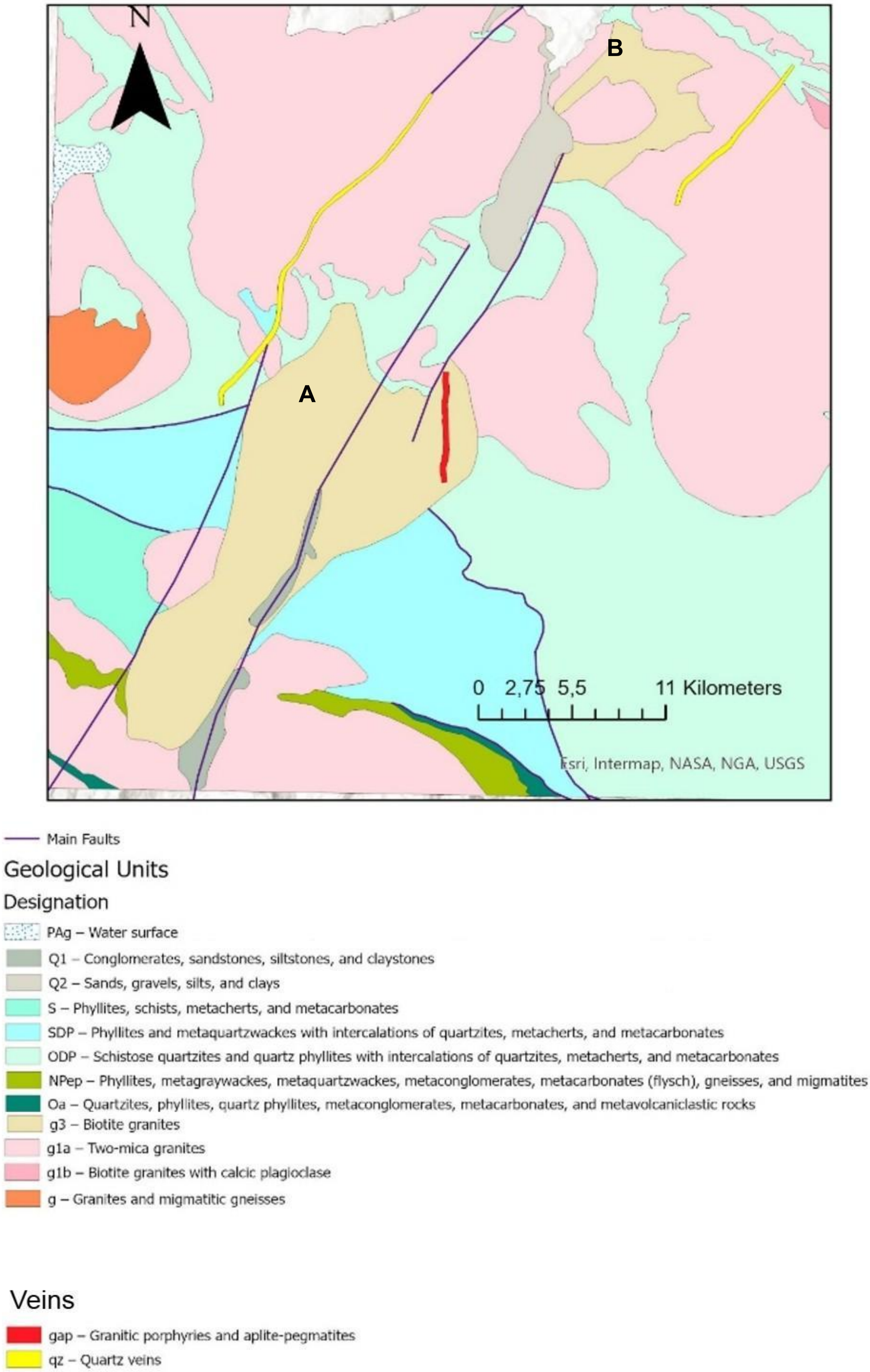

Figure 2 - Geological Map of the Portuguese area. A - Vila Pouca de Aguiar Pluton; B - Águas Frias Pluton

La Maladeta

The La Maladeta (LM) plutonic complex (Fig. 3 LM) is one of the largest Permo-Carboniferous batholiths located in the Axial Zone of the Central Pyrenees, covering an outcropping area of approximately 42 x 18 km (Ayala et al., 2020; Ayala et al., 2021).

With an extension of approximately 42 x 18 km the LM pluton is situated in the "spinal cord" of the mountain range, an area characterized by an antiformal stacking of thrust sheets that mainly involve Paleozoic basement rocks. It is located more specifically in the Orri thrust sheet, one of the main structural units of the Axial Zone, consisting of Cambro-Ordovician quartzite and slates, Silurian slates and Devonian limestones and slates, which are the host rocks surrounding this granitic mass (Clariana et al., 2021; Ayala et al., 2021; Piña-Varas et al., 2023).

The La Maladeta batholith originated during the Late Variscan stage, a post-orogenic magmatism period. It was emplaced into a Paleozoic metasedimentary succession during the Late Carboniferous to Early Permian. The pluton has been dated to be emplaced at around 298 ± 2 Ma, using high-resolution U-Pb zircon dating (Evans, 1993; Ayala et al., 2021; Piña-Varas et al., 2023).

The ascent of the pluton was likely facilitated by E-W trending structural anisotropies that were active during Late Variscan extensional phases. Its lateral expansion may have been also aided by the presence of Silurian shales that acted as an effective decollement level (Clariana et al., 2021; Piña-Varas et al., 2023).

In terms of composition, the complex is predominantly granodioritic, though it is heterogeneous.

The complex is bounded by the Gavarnie thrust to the north and the Llavorsí-Senet thrust to the south. A large subsurface accumulation of low-density Triassic evaporites is also known to be the origin of the gravity minimum a few kilometers southwest of La Maladeta complex (Ayala et al., 2020)

Andorra Mont-Louis

The Andorra Mont-Louis (AML) pluton (Fig.3 AML) is located approximately 90 km east of the La Maladeta batholith in the Central Pyrenees and is one of the main Permo-Carboniferous igneous bodies. Like all other plutons considered here, its origin is Late Variscan (Ayala et al., 2021; Ayala et al., 2020).

With a surface outcrop covering an area of approximately 10 x 20 km, the AML batholith is located in the core of the mountain range, the Axial Zone, which consists of an antiformal stack of basement thrust sheets primarily involving Paleozoic rocks (Ayala et al., 2021; Soto et al., 2022)

The AML pluton is geographically close to and probably structurally related to other basement features such as the Gneiss Domes of Hospitalet and Aston. In addition, it is thought that there are other underlying lower-density gneiss bodies situated underneath the Andorra Mont-Louis granite (Soto et al., 2022). To the South of this pluton, the Neogene La Cerdanya basin is bounded southwards by the La Tet Fault (Ayala et al., 2021; Soto et al., 2022).

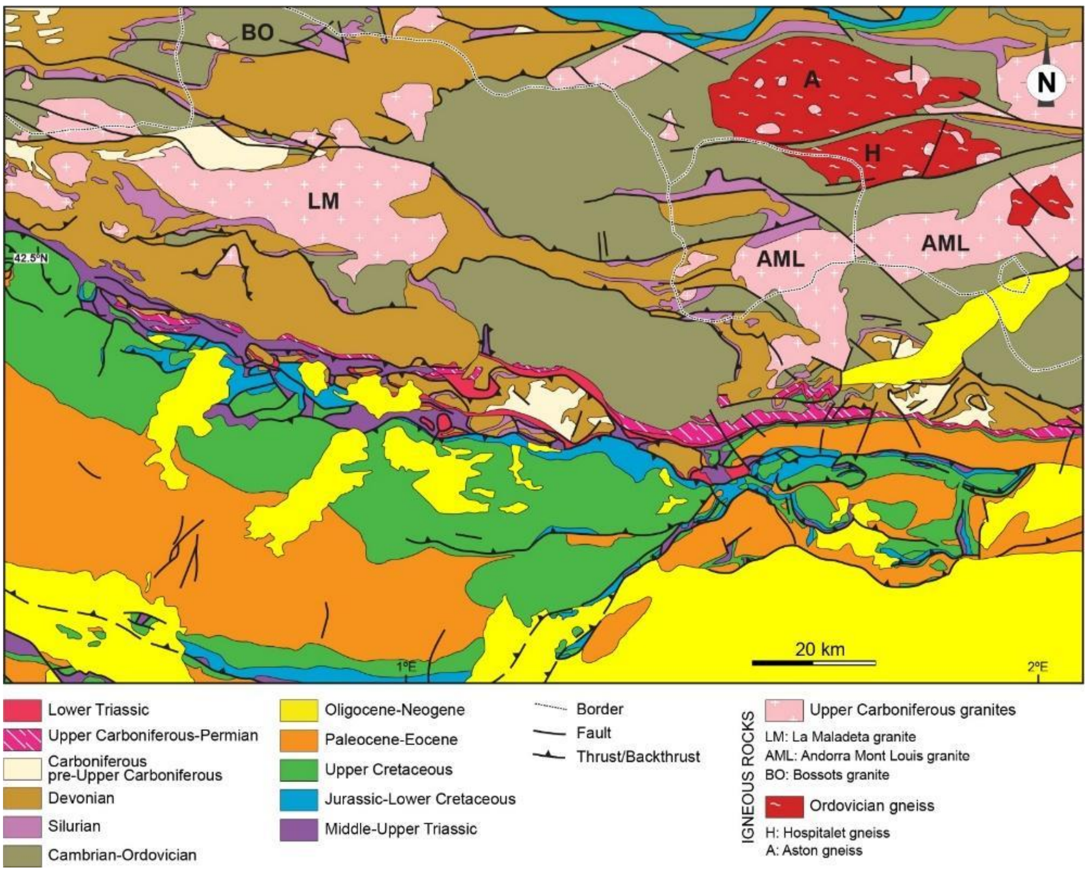

Figure 3 - Geological map of the studied area. LM - La Maladeta granite; AML - Andorra Mont-Louis granite; H - L'Hospitalet gneiss; A - Aston gneiss. Modified from Ayala et al., 2021.

2.3 Geodynamic Framework

The geodynamic evolution of North Portugal and the Central Pyrenees shares a common Variscan foundation, though each region was subsequently shaped by distinct episodes of tectonic reworking. Together, they preserve a record that spans from Late Paleozoic collision through Alpine convergence.

2.3.1 Variscan Orogeny (Late Paleozoic, ca. 290-380 Ma)

The Variscan orogeny arose from the collision between Laurasia and Gondwana, producing a bi-vergent orogenic belt whose crystalline remnants underpin both the Central Iberian Zone (CIZ) and the Pyrenean Axial Zone (PAZ). In North Portugal, deformation unfolded across three main ductile phases: D1 (ca. 360-337 Ma), D2 (337-320 Ma), and D3 (320-310 Ma). The last of these, a NE-SW-trending compressional event, proved particularly influential, as it both established the region's structural grain and created the conditions for widespread biotite and two-mica granite intrusion. In the Pyrenees, the Variscan record is broadly analogous: two phases of crustal thickening and south-verging thrust tectonics (D1 and D2) gave way to an extensional regime (D3) (Casas et al., 2019; García-Sansegundo et al., 2026) and, ultimately, to extensional collapse.

2.3.2 Emplacement of the Variscan Plutons during the Late Variscan stage

The plutons examined in this work were each emplaced during the transition from late-collisional to post-collisional settings, though their individual histories differ in important ways. The Vila Pouca de Aguiar pluton intruded as a composite laccolith in the final stages of the Variscan cycle, its sub-horizontal floor and feeder zones reflecting control by pre-existing subvertical structures. In the Central Pyrenees, the La Maladeta batholith, a large calc-alkaline granodiorite, was emplaced slightly later, around 301-298 Ma, with its elongation and magmatic fabrics recording the influence of the syntectonic regional shear zones active at that time (Evans, 1993). The Andorra Mont-Louis batholith, dated to ca. 305 Ma, was intruded at mid-crustal depths of approximately 12-15 km during a period of local extension linked to the regional dextral strike-slip regime and early orogenic collapse (Bouchez & Gleizes, 1995; Romer and Soler, 1995).

2.3.3 Late-Variscan to Mesozoic Transition

Following the Variscan assembly of Pangea, both regions entered a prolonged phase of tectonic relaxation punctuated by two major rifting cycles. The Permian orogenic collapse brought extension, crustal thinning, and a shift in magmatic character from calc-alkaline to more alkaline signatures as the lithospheric mantle thinned progressively (Lloret et al., 2021). This was followed, during the Aptian-Cenomanian, by a phase of Mesozoic hyper-extension driven by rifting between Iberia and Europe (Lloret et al., 2021; Ford et al., 2022). In parts of the Pyrenees, this extension reached extreme levels, leading to mantle exhumation and the formation of a series of sedimentary basins, including the Arzacq and Parentis basins, whose later tectonic inversion would become a defining feature of the Alpine landscape (Ford et al., 2022).

2.3.4 Alpine Orogeny (Late Cretaceous-Cenozoic)

The onset of Iberia-Eurasia collision marked a fundamental reorganisation of both regions. In the Pyrenees, the Axial Zone was progressively formed as an antiformal stack of basement-involved thrust sheets. The Variscan plutons, including La Maladeta, were pervasively fractured and bounded by Alpine south-verging reverse faults such as the North Maladeta Fault. More recent studies have also identified ductile Alpine deformation within the Axial Zone domes, notably the Garonne Dome, where open folds and penetrative crenulation lineations post-dating Permian markers suggest that the domes' current macrostructural configuration is itself Alpine in age (García-Sansegundo et al., 2026). Further west, the effects of Alpine convergence were felt deep within the Iberian interior, reactivating a network of inherited Variscan structures. Large-scale strike-slip systems such as the Messejana-Plasencia fault were remobilised to accommodate N-S shortening through strain partitioning, while in the Central System, pre-existing mechanical anisotropies, such as those along the Berzosa Fault, controlled the development of Alpine backthrusts and drove upper crustal delamination (Fernández-Lozano et al., 2016; de Vicente et al., 2022).

2.4 Introduction to Modelling

The fundamental aim of geological modelling is to obtain a representation of subsurface formations and their associated structures (Thornton et al., 2018). In the context of granitic plutons, reconstructing geometry at depth is essential for understanding tectonic evolution and magmatic emplacement processes (Bhimavarapu et al., 2023; Thornton et al., 2018). Since the direct observation of the crust is largely confined to surface outcrops and the occasional borehole, gravimetry plays an important role by constraining lateral and vertical density variations that would otherwise remain inaccessible. Integrating structural geology, gravimetric data, and Anisotropy of Magnetic Susceptibility (AMS) substantially reduces the ambiguity inherent in any single dataset, yielding more robust and geologically coherent 3D reconstructions (Sun, 2021; Bhimavarapu et al., 2023; Thornton et al., 2018).

2.4.1 Fundamentals of Applied Gravimetry

Gravimetry measures variations in the Earth's gravitational field caused by density contrasts between different rock bodies. This method is based on Newton's Law of Gravitation, which states that the force of attraction between two masses is proportional to their mass and inversely proportional to the square of the distance between them. In the context of granite studies, it is used primarily because granitic bodies typically have a lower density than their surrounding rocks, creating a detectable negative gravity signature (Sant'Ovaia et al., 2000; Sant'Ovaia, 2000; Cruz et al., 2021).

One of the principal challenges in gravity interpretation is its non-uniqueness: fundamentally different subsurface mass distributions can produce identical surface gravity responses. (Sun, 2021). This is why incorporating geological constraints (foliations, lithological contacts, and structural data) is indispensable. Without them, the range of mathematically valid solutions far exceeds the range of geologically plausible ones (Thornton et al., 2018).

2.4.2 Gravimetric survey

A gravimetric survey consists of measuring variations in the Earth's gravitational field caused by density differences in subsurface rocks. Gravity measurements are obtained using a gravimeter at stations distributed as uniformly as possible across the study area, depending on local topography and accessibility (Sant'Ovaia et al., 2000; Ayala et al. 2021). Raw data must then be corrected for external factors that affect gravity, including latitude, elevation (free-air and Bouguer corrections), topography, and tidal variations. This results in the Bouguer anomaly, which reflects only the structures of the Earth's interior (Cruz et al., 2021). A regional-residual separation is then applied to isolate shallow-sourced anomalies such as those produced by granitic plutons from deeper, regional signals originating deeper in the crust and upper mantle (Bhimavarapu et al., 2023).

2.4.3 Anisotropy of Magnetic Susceptibility

Anisotropy of Magnetic Susceptibility (AMS) is a petrophysical technique used to characterize the internal structure, or fabric, of rocks by measuring how their magnetic susceptibility varies according to direction. This variation is represented mathematically as a tensor and visualized as a triaxial ellipsoid with three principal axes: K_{max} (K_1), K_{int} (K_2), and K_{min} (K_3). In the granitic rocks described in the sources, these magnetic orientations generally parallel the mineral orientations; the K_1 axis represents the magnetic lineation (magma stretching direction), while the K_3 axis is the pole to the magnetic foliation (magma flattening plane) (Sant’Ovaia, 2000; Cruz et al., 2021).

2.4.4 2D and 2.5D Modelling

Profile gravity modelling is the interpretation of gravity data along a 2D profile by building up a density model based on the structures of a geological profile whose calculated gravity response fits the observed gravity anomaly. A distinction is made between 2D modelling, which assumes that the geological model extends infinitely in the direction perpendicular to the profile, and 2.5D modelling, which allows the definition of a finite lateral extent for selected bodies. The latter is more suitable for modelling laterally confined bodies such as plutons (Cruz et al., 2025; Clariana, 2021).

In this work, we have made the calculations by forward modelling using GM-SYS software from Bentley. The modelling begins with the construction of a geological cross-section based on the available surface geological data and other geological or geophysical information, like drillholes, when available. Density values are assigned to the different geological units, and the corresponding gravity response is calculated. Assuming we know the densities of the modelled structures, through an iterative process, the geometry of contacts and faults is progressively adjusted until the calculated gravity curve closely matches the observed response. This modelling approach enables the dip of the pluton margins to be constrained, the identification of potential feeder roots (zones of greater thickness), and a better understanding of the relationship between the plutonic body and the regional fault systems (Cruz et al., 2025; Sant'Ovaia, 2000; Clariana, 2021).

2.4.5 3D Geological and Geophysical Modelling

We have carried out the geological and potential fields’ 3D modelling using 3D GeoModeller, a 3D modelling software used to build up geologically consistent subsurface models from structural, geological, geophysical, and borehole data. It is based on implicit modelling techniques, which allow geological interfaces and faults to be represented as continuous 3D surfaces constrained by observations such as geological contacts, orientations, stratigraphic relationships, and other available subsurface information. Contact data and orientation measurements (foliations) are interpolated using co-kriging algorithms to generate equipotential surfaces that represent geological interfaces. The resulting geological model can also be used for forward modelling and inversion of potential-field data, such as gravity anomalies (Cruz, et al. 2025).

Forward modelling requires manually adjustment to the model and to recalculate iteratively until the pattern of the calculated anomalies is close to the observed ones. Stochastic geophysical inversion, such as Bayesian-MCMC algorithms, takes a different approach, using statistical methods to obtain the probability of different model configurations. This allows for a more systematic evaluation of uncertainty and provides a quantitative basis for assessing the reliability of the interpretation (Cruz, et al., 2025; Sun, 2021).

2.4.6 Software and Workflow

The integrated workflow for the plutons' reconstruction is based on a sequence of specialised tools, each addressing a specific stage of the process. ArcGIS Pro has been used for spatial data preparation, map georeferencing, and geospatial database management. Oasis montaj was used as the main platform for gravity data processing, including grid generation and Euler deconvolution to estimate the depth of the gravity sources. GeoModeller was used for implicit 3D geological modelling and gravity inversion, allowing the construction of geologically consistent volumes that honour stratigraphic superposition rules while being constrained by the observed gravity data (Cruz et al. 2025; Sant'Ovaia, 2000; Clariana, 2021; Bhimavarapu et al., 2023; Sun, 2021).

2.4.7. Tectonic Interpretation and Application to Granitic Plutons

The geometry of a pluton, once resolved, offers important clues about the tectonic conditions under which it was emplaced. Laccolithic bodies and batholiths are frequently controlled by shear zones and regional faults that act as conduits for magma ascent, and the orientation of feeder zones often reflects the structural anisotropy of the host crust at the time of intrusion. Studies of Variscan plutons across the Iberian Peninsula have demonstrated how root geometries and feeding structures are intimately linked to specific crustal deformation episodes, while modelling of Pyrenean complexes illustrates the additional complexity introduced by the reactivation of older structures during Alpine convergence (Sant'Ovaia, 2000; Cruz, et al. 2025; Bhimavarapu et al., 2023).

2.4.8 Limitations and Uncertainties

Any gravity-based model must be interpreted considering its inherent limitations. The resolution of gravimetric data may be insufficient to distinguish thin layers or tightly folded sequences, and undetected lateral density variations can bias depth estimates. Cross-sections modelled in 2D inherently ignore three-dimensional complexity, which can lead to misinterpretation of inclined or plunging structures when treated in isolation.

Ultimately, the distinction between a mathematically optimal solution and a geologically plausible one is the defining criterion of validation, a distinction that no inversion algorithm can make on its own (Thornton et al., 2018; Sun, 2021; Bhimavarapu et al., 2023).

2.5 Current Geological and Geophysical Knowledge of the Study Area

Vila Pouca de Aguiar and Águas Frias-Chaves

Current understanding of the Vila Pouca de Aguiar (VPA) and Águas Frias-Chaves (AFC) plutons rests on the integration of Anisotropy of Magnetic Susceptibility (AMS) with 3D gravimetric inversion, a combination that has proven essential for resolving their internal architecture and feeder systems.

The VPA pluton is now well established as a composite laccolith produced by the successive nesting of two main magma pulses. Gravimetric inversion reveals that the body is relatively thin overall, with roughly 60% of its area extending to less than 1 km depth but reaching a maximum depth of approximately 5 km within discrete Y-shaped feeder zones. The two granitic units record distinct emplacement histories (Sant'Ovaia, 2000; Martins, 2008).

The peripheral Vila Pouca de Aguiar Granite (VPAG) was injected as a sill-like body into a sub-horizontal tensional cavity, with NNE-SSW magnetic lineations documenting the direction of magma transport from the northern roots. The central Pedras Salgadas Granite (PSG), by contrast, represents the main magmatic volume and upwelled above the southernmost root, developing an internal dome-like structure whose WNW-ESE magnetic lineations point to E-W dilation during a ballooning expansion phase. Importantly, the pluton's internal fabric is entirely magmatic in origin; its post-tectonic character means that regional stress played no role in shaping the final structure, which was controlled instead by magma pressure alone (Sant'Ovaia, 2000; Sant'Ovaia et al., 2000; Martins, 2009).

The AFC pluton presents a strikingly different picture. Rather than spreading laterally into a thin sheet, it is modelled as a deeply rooted, wedge-shaped body whose floor generally lies between 10 and 12 km depth (Martins, 2009; Cruz et al., 2025).

A primary feeder conduit descends to approximately 16 km beneath the central Santo António de Monforte granite outcrop, making it considerably more deeply anchored than its Portuguese neighbour. Despite this difference in geometry, the AFC shares the WNW-

ESE magnetic lineation pattern seen in the PSG facies of VPA, suggesting that a broadly similar dilation mechanism governed its ascent and emplacement at depth (Martins, 2009; Cruz et al., 2025).

Synthesising these findings, current research situates both plutons within a regional model of late Variscan magmatism (ca. 299 Ma) structurally controlled by the Penacova-Régua-Verín Fault (PRVF). The fault acted as a major crustal conduit for both intrusions, with the depth and thermal state of different fault sectors explaining their contrasting geometries: the Águas Frias sector, being deeper and hotter, gave rise to a more deeply rooted body, while the shallower VPA sector produced a thinner, more laterally extensive intrusion.

Perhaps the most significant scientific insight to emerge from this integrated modelling is that host rock character exerts a stronger influence on pluton shape than tectonic regime. Where magma invades heterogeneous granitic crust, as at Águas Frias, it tends to develop deep wedge-shaped geometries conditioned by the mechanical complexity of the surroundings. Where it encounters metasedimentary sequences with strong planar anisotropy, as at Vila Pouca de Aguiar, it spreads laterally into flat sill or laccolith forms. Isotopic and geochemical data further suggest that both plutons originated through partial melting of a meta-igneous lower crustal source, with heat likely supplied by ascending mafic magmas (Martins, 2009; Sant'Ovaia, 2000; Sant'Ovaia et al., 2000; Cruz et al., 2025).

La Maladeta and Andorra Mont-Louis

Modelling of the Pyrenean plutons has advanced considerably beyond early 2D interpretations, with modern studies combining high-resolution gravity surveys, magnetotellurics (MT), magnetic derivative analysis, and stochastic 3D inversion to reveal the complex internal architecture and deep roots of both bodies (Piña-Varas et al., 2023).

For La Maladeta, the most consequential recent development has been the recognition that the massif is not a single coherent intrusion but consists of two distinct granitic units separated by a lower-resistivity zone, interpreted as the product of at least two independent intrusive pulses during the Late Variscan (Piña-Varas et al., 2023). Gravity and 2.5D cross-sectional modelling characterise the overall geometry as asymmetrically laccolithic or tabular, with a floor that is far from flat: it tilts and deepens markedly toward the north, where the Gavarnie thrust likely served as a structural pathway for magmatic ascent. Current models place the northern roots at approximately 8 to 8.5 km depth, deeper than previously estimated, and thermochronological data suggest that, prior to Alpine shortening, the base of the system may have extended to as much as 20 km (Soto et al., 2022; Ayala et al., 2020; Ayala et al. 2021).

The Andorra Mont-Louis (AML) pluton tells a different story. Gravity modelling characterises it as having a more traditional batholithic form rather than the asymmetric laccolithic geometry of La Maladeta. A key finding of the GeoPiri3D project is that a substantial portion of the AML body is buried, with gravity minima extending obliquely to the northeast into areas where no granite reaches the surface. The relationship between the AML and the underlying basement is also critical: gravity models have identified a lower-density gneiss dome, associated with the Hospitalet and Aston gneisses, directly beneath the pluton, a feature that proves indispensable for reproducing the observed gravity signal in the eastern Axial Zone (Ayala et al., 2020; Ayala et al., 2021).

Underpinning both Pyrenean models is a suite of advanced methodological tools. Petrophysical datasets drawn from over 500 rock samples (Soto et al. 2022), measured for both density and magnetic susceptibility, provide the constraints needed to reduce the non-uniqueness inherent in geophysical inversion. AMS analysis has been critical in defining the internal magnetostructural fabric of these bodies, confirming their polydiapiric nature and preserving a record of their deformation history (Leblanc et al., 1994; Bouchez & Gleizes, 1995). Meanwhile, the application of vertical and tilt derivatives to magnetic data has enabled more precise delineation of pluton margins (Verduzco et al., 2004; Clariana et al., 2021), even where they are concealed beneath thick sedimentary sequences, an increasingly important capability as modelling efforts push further into the unexposed subsurface (Soto et al., 2022; Ayala et al., 2020; Ayala et al., 2021).

3. Methodology

This thesis builds upon existing geological, geophysical, and petrophysical datasets, which are integrated to develop new 3D models of four granitic bodies, two in Portugal and two in Spain. Therefore, no new gravimetric, AMS and petrophysical data have been collected. The datasets were compiled from previous studies, and, in the case of the Portuguese plutons, gravity data was reprocessed using updated and more efficient software tools. In this work, all data was worked using two systems of coordinates. For Portugal the system of coordinates used was WGS 84 / UTM Zone 29N, for the Pyrenees the coordinate system used was UTM Zone 31N.

3.1 Bouguer and Residual Anomalies. Density Data

For Portuguese plutons:

The Bouguer anomaly data for the VPA and AF plutons comes from Sant'Ovaia (2000), Martins et al. (2009), and Moreira et al. (1992). These geophysical datasets consisted of measured points with the corresponding measured gravity values. The AMS and density for VPA and surrounding lithologies measurements were compiled from Sant'Ovaia, 2000. The density and AMS data used for the AFP were obtained from Martins et al. (2009).

For Pyrenean plutons:

The data used in the modelling of the Pyrenean plutons is taken from three main sources. The gravity anomaly data was taken from Ayala et al. (2021), with density measurements taken from Soto et al. (2022) and references therein.

Densities:

The density values were as thus in Portugal:

Table 1 - Density Values for Lithologies in Northern Portugal

Metassediments	2.72 g/cm3
Two Mica Granites	2.6 g/cm3
Vila Pouca de Aguiar Granite	2.65 g/cm3
Pedras Salgadas Granite	2.6 g/cm3
Chaves Sedimentary Basin	1.4 g/cm3
Águas Frias Granite	2.65 g/cm3
Santo Antonio de Monforte Granite	2.6 g/cm3

These values were directly taken from the previously mentioned literature. When applied to the model some changes were made to these values especially the two mica granites of Vila Pouca de Aguiar. These changes are further explained during the results section.

The density values in the Pyrenees were the following:

Table 2 - Density Values for Lithologies in the Pyrenees

Metassediments	2.68 g/cm3
La Maladeta Granite	2.65 g/cm3
Marimanha Granite	2.65 g/cm3
Lys Granite	2.6 g/cm3
Bassiès Granite	2.65 g/cm3
Arties Granite	2.6 g/cm3
La Fontaneda Granite	2.63 g/cm3
Santa Coloma Granite	2.63 g/cm3
Andorra Mont-Louis Granite	2.65 g/cm3
Hospitalet-Aston gneisses	2.62 g/cm3
La Cerdanya Neogen Sedimentary Body	2.1 g/cm3

For the Pyrenees most values were directly taken from the literature. The exception is the Metasediments which results from a weighted mean of all metasedimentary units. Later the leucogranitic bodies of AML were modelled with a density of 2.6 g/cm3. This too is further explained in discussion.

3.2 Modelling

Modelling is not just only using 3D modelling programs and techniques to achieve the final model; this would lead to models with lack of consistency and unrealistic geological models. Instead, it can be defined by the process of acquiring and compiling information, data processing, integration and interpretation that allows the geologist to create an accurate representation of the studies structures at depth. The workflow for the creation of the 3D models is shown on Fig. 4

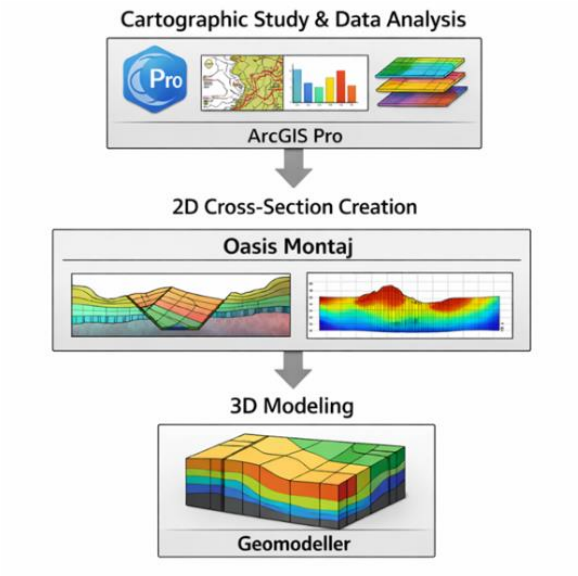

Figure 4 - Simplified modelling workflow.

The modelling workflow consisted of three successive stages. First, an initial geological model was constructed using geological maps, cross-sections, structural data, and density measurements. Second, the model was refined through iterative forward gravity modelling, during which geological contacts and geometries were manually adjusted until the calculated gravity anomaly reproduced the main characteristics of the observed gravity field. Finally, stochastic gravity inversion was applied to further refine the model by automatically exploring geometrically and petrophysically acceptable solutions within predefined geological constraints. The inversion results were then evaluated, and only geologically plausible models with low gravity misfit were retained.

The 2D modelling process required the compilation of geological, geophysical, and cartographic information from existing literature to produce geologically and geophysically consistent cross-sections that served as the basis for the 3D geological models. As the cross-sections for the Pyrenean plutons were adopted from previous studies (Soto et al., 2022; Piña-Varas et al., 2023), 2D gravity modelling was only carried out for the Portuguese plutons.

The modelling process began with the analysis of the pluton geometry and surrounding geology using geological maps together with published interpretations of their subsurface geometry. This was complemented by the interpretation of Bouguer and residual gravity anomaly grids, as well as AMS data, allowing the identification of deeper zones, the lithologies involved, and the overall subsurface geometry of each pluton.

Based on this preliminary interpretation, initial geological cross-sections were constructed to represent the most likely subsurface geometry. These preliminary sections provided a conceptual framework before geophysical modelling. Their location was carefully selected in ArcGIS Pro to intersect the most representative geological features of the Vila Pouca de Aguiar and Águas Frias plutons.

Preliminary cross-sections were initially drafted manually on millimetric paper, but this approach was subsequently abandoned in favour of direct digital construction because iterative modifications during modelling made manual drafting and later digitisation unnecessarily time-consuming.

Modelling in Oasis Montaj consisted of three stages: (1) georeferencing the geological cross-sections, (2) generating the initial GM-SYS model using the Digital Terrain Model (DTM) and the residual gravity anomaly grid, and (3) importing the geological cross-sections into the GM-SYS model. The residual anomaly grid was obtained using the procedures described previously, while the DTM was derived from SRTM data (NASA Shuttle Radar Topography Mission, 2013).

The 2D model was considered complete when the root mean square (RMS) error was reduced to less than one-tenth of the maximum gravity anomaly amplitude (Soto et al., 2022), while remaining geologically consistent. The resulting cross-sections were then digitised into GeoModeller for 3D modelling.

Although Oasis Montaj provides a more convenient environment for editing and visualising 2D gravity models, GeoModeller offers superior capabilities for constructing and visualising three-dimensional geological models. Forward gravity modelling in GeoModeller calculates the gravity response of the geological model and compares it directly with the observed residual gravity field. The software produces both calculated gravity maps and misfit maps, allowing areas where the model overestimates or underestimates the observed gravity field to be readily identified.

Forward modelling therefore acts as both a diagnostic and validation tool. Areas of high misfit indicate inconsistencies between the geological geometry, assigned density contrasts, and the observed gravity field, guiding manual adjustments to lithological boundaries, body geometries, and density values. Once the calculated anomaly reproduced the main characteristics of the observed gravity field, the model was further refined through stochastic gravity inversion.

Stochastic gravity inversion is a numerical optimisation procedure that iteratively adjusts the geometry of geological units and, where permitted, their density distribution to minimise the misfit between the observed and calculated gravity fields. Unlike forward modelling, which relies on manual modification and repeated recalculation, inversion automatically explores acceptable model configurations within predefined geological and petrophysical constraints.

Prior to inversion, permissible density ranges and allowable modifications to lithological boundaries were defined. The proposed changes are therefore mathematically driven and aimed solely at reducing the gravity misfit; they do not, by themselves, guarantee geological plausibility. Consequently, all inversion results were critically evaluated, and the final model was selected based on both its geological consistency and its ability to minimise the gravity residuals (displayed as the "Misfit" in GeoModeller), ensuring that the final interpretation was both geologically and geophysically robust.

4. Results

This section presents the processed gravity data, the 2D cross-sections and the final 3D geological model of each pluton. The results are described following the sections of this work: Gravity Anomaly Patterns, 2D cross-sections, 3D Geological Model. This order follows the workflow of the modelling. Results are then organized by region, with the Portuguese plutons (VPA and AF) presented first followed by the Pyrenean plutons (LM and AML).

4.1 Gravity Anomaly Characteristics

4.1.1 Vila Pouca de Aguiar

The first pluton modelled was the VPAP. Using Oasis Montaj, the point data of the Bouguer anomaly was gridded using the kriging method, which resulted in a map with less "artifacts" than other methods such as Inverse distance weighting (IDW), which was also tested. Four grid spacings were examined, with those being 200-, 250-, 500- and 1000-meter grids. The 500-meter grid was chosen on the basis that it displayed a low amount of artifacts while retaining a good resolution, preserving the information. The residual anomaly grid was then obtained from the Bouguer anomaly grid by removing the regional trend. The regional trend was eliminated using the "remove trend" feature of Oasis Montaj. The trend removed was of a second order polynomial. Other polynomial orders were tested but led to either a worse geological correlation or a worse 2D geophysical modelling result.

Bouguer anomaly grids and residual anomaly grids for the study area are displayed on Figures 5A and 5B.

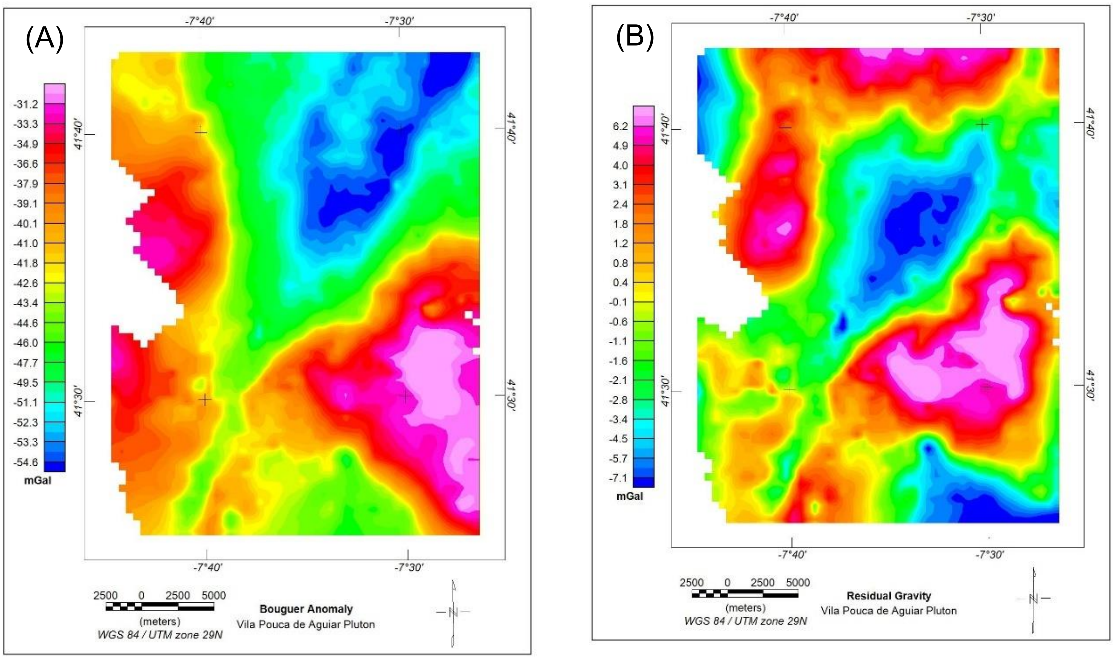

Figure 5 - (A) Bouguer anomaly map, and (B) Residual Bouguer anomaly map of the Vila Pouca de Aguiar Study area.

In the Bouguer anomaly grid (Fig.5A) values vary between -54.6 and -30.5 mGal with a mean value of -44.8 mGal. The residual gravity anomaly varies between values of -8.9 and 9.6 mGal. The residual gravity map displays in its centre a shape of low gravity values following closely the contours of the VPA pluton.

The Bouguer anomaly map is characterized by a broad negative anomaly that extends from the southwest to the northeast across the central part of the area. This elongated minimum is surrounded by higher gravity values, with the strongest positive anomalies located in the western and southeastern parts of the map. The transition between the negative and positive anomalies is abrupt, indicating major changes in rock density across the study area.

The residual Bouguer anomaly map highlights smaller-scale gravity variation. A central elongated negative anomaly, also trending SW–NE, remains the dominant feature. This low is bounded by several positive anomalies, particularly in the northwestern and southeastern parts of the map. Compared with the Bouguer anomaly map, the residual map shows more localized maximum and minimum, revealing the variations in rock density within upper crust.

4.1.2 Águas Frias

As with VPAP, kriging was the method chosen to obtain the Bouguer anomaly grid and a second order polynomial was subtracted to the Bouguer anomaly to obtain the residual anomaly (Fig.6). The residual bouguer anomaly is represented by isolines. Again, the same grid sizes as VPA were tested, with 500 meters remaining the preferred option. In the Bouguer anomaly, values vary between -59.94 and -46.89 mGal with a mean value of -52.66 mGal. Residual Anomaly values range from -9.51 to 5.87 mGal.

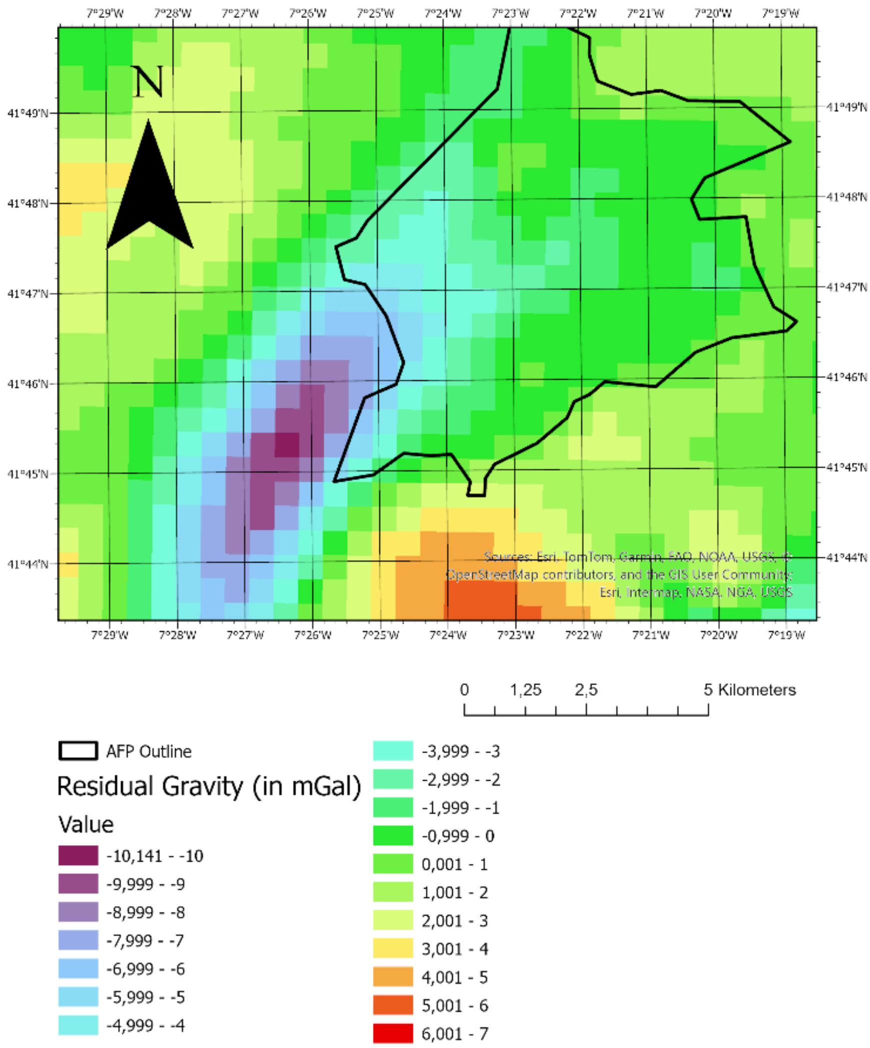

Figure 6 - Residual Bouguer anomaly map of the study area of Águas Frias Pluton.

The residual Bouguer anomaly map of the AFP study area is dominated by moderate anomaly values that range from -10 to 7 mGal. The most prominent features are an elongated negative anomaly in the central part of the study area, extending southwestward, and a positive anomaly in the western and southern sectors, located north and east to the minimum, respectively. The north-northeastern sector is characterized by a small gravity variation with an amplitude of approximately 3 mGal.

4.1.3 La Maladeta

As mentioned before, the LM residual anomaly grid (Fig. 7 (LM)) was provided from Soto et al. (2022). The residual anomaly values for the study area vary from -19 to 7.56 mGal.

In the La Maladeta Zone, the Bouguer anomaly and residual Bouguer anomaly maps display very similar patterns. Both are characterized by a positive anomaly in the southern part of the study area reaching values of around 6 mGal and a more pronounced negative anomaly in the northern sector, which extends northwestward reaching values of up to -16 mGal.

4.1.4 Andorra Mont-Louis

Much like in the case of LM, AML residual anomaly grids (Fig. 7 (AML)) were obtained from Soto et al., 2022. The residual anomaly grid displays values between -12.20 and 15.52 mGal.

In the AML study area, the Bouguer anomaly and residual Bouguer anomaly maps also exhibit similar patterns. Both maps are characterized by a large positive anomaly with values of up to 15 mGal in the northwestern sector and two main negative anomalies both with values in the -6 mGal to -12 mGal range. The larger of these is located in the central part of the study area, while the smaller is a narrow, elongated anomaly that begins in the south and extends northeastward.

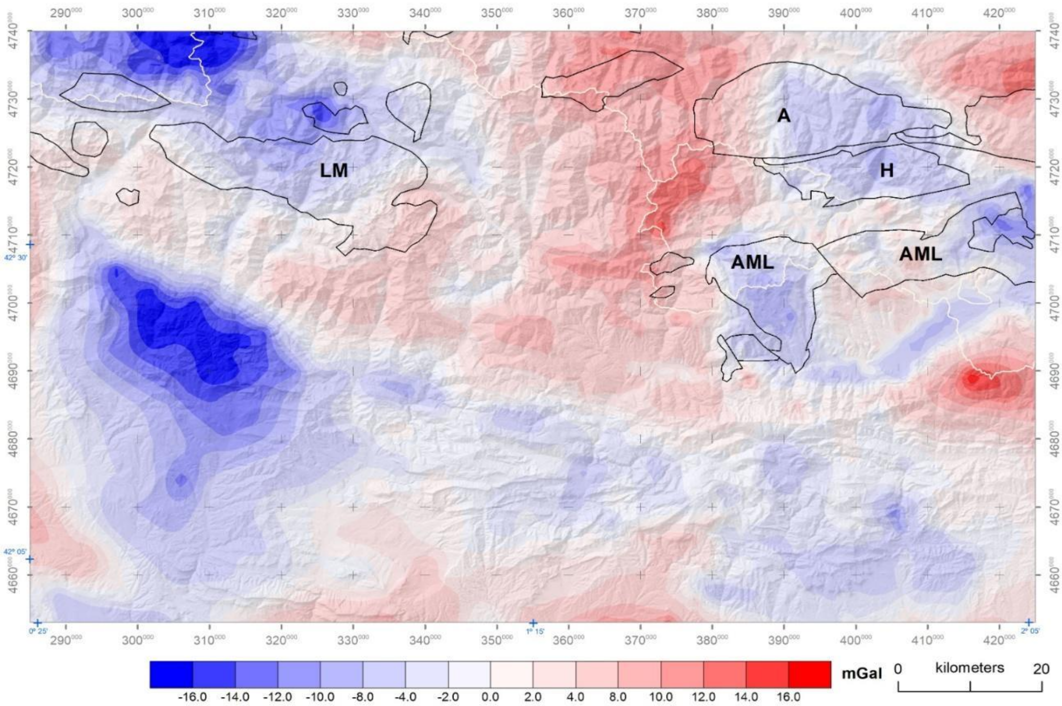

Figure 7 - Residual Bouguer anomaly map of the Pyrenean granites (from Ayala et al. 2021).

4.2. 2D cross-sections and 2D Modelling

4.2.1 Vila Pouca de Aguiar

The first steps towards a 3D modelled VPAP started by 2.5 D modelling of nine cross-sections of the plutonic body and surrounding lithologies (Fig.8). This allowed for a better understanding of the subsurface geology of the pluton. Of these nine cross-sections, eight had a NW-SE direction, perpendicular to the pluton strike and the PRVF direction. The remaining cross-section was built up following the direction of the PRVF and the pluton's extent, tying the other cross-sections together.

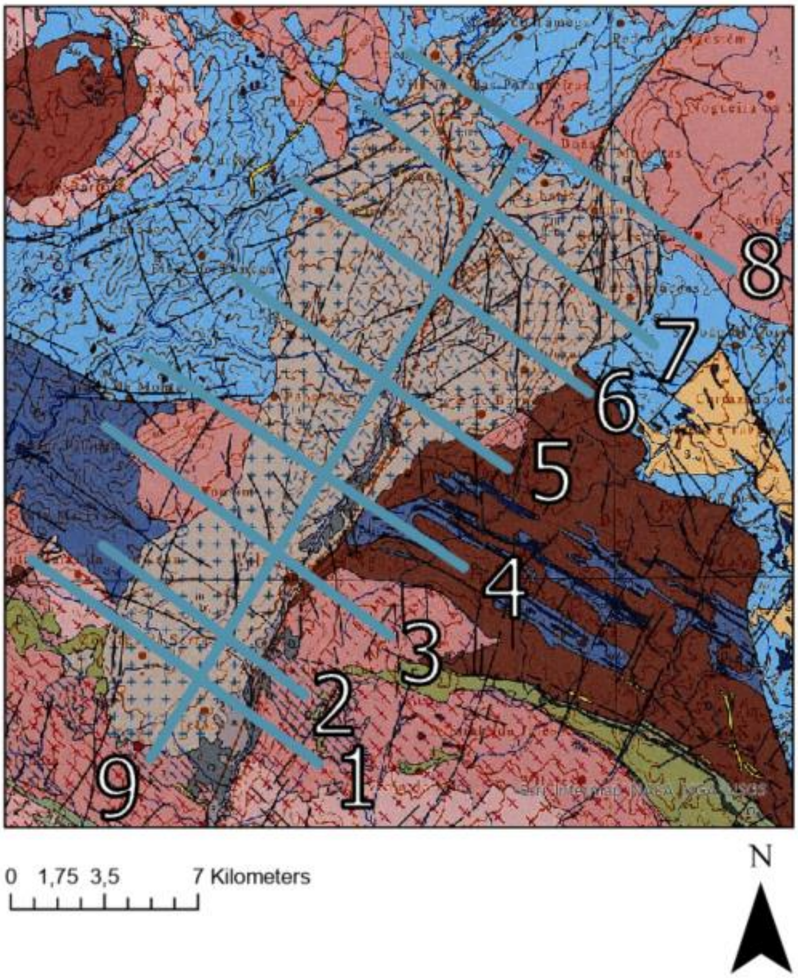

Figure 8 - VPAP's cross-sections mapped on the geological map (cut from Folha 2 - 1:200000, LNEG) numbered 1-9

The eighth cross-section (the most north-eastern one) was discarded due to difficulties during digitisation. These preliminary cross-sections that were first hand-drawn resulted in crude 2D models of the pluton at depth.

While the original paper cross-sections were not very accurated in geological terms, they nevertheless captured the essential geological characteristics of the structures.

After many iterations, the following cross-sections (Fig.9A and 9B) are examples of those modelled in Oasis Montaj:

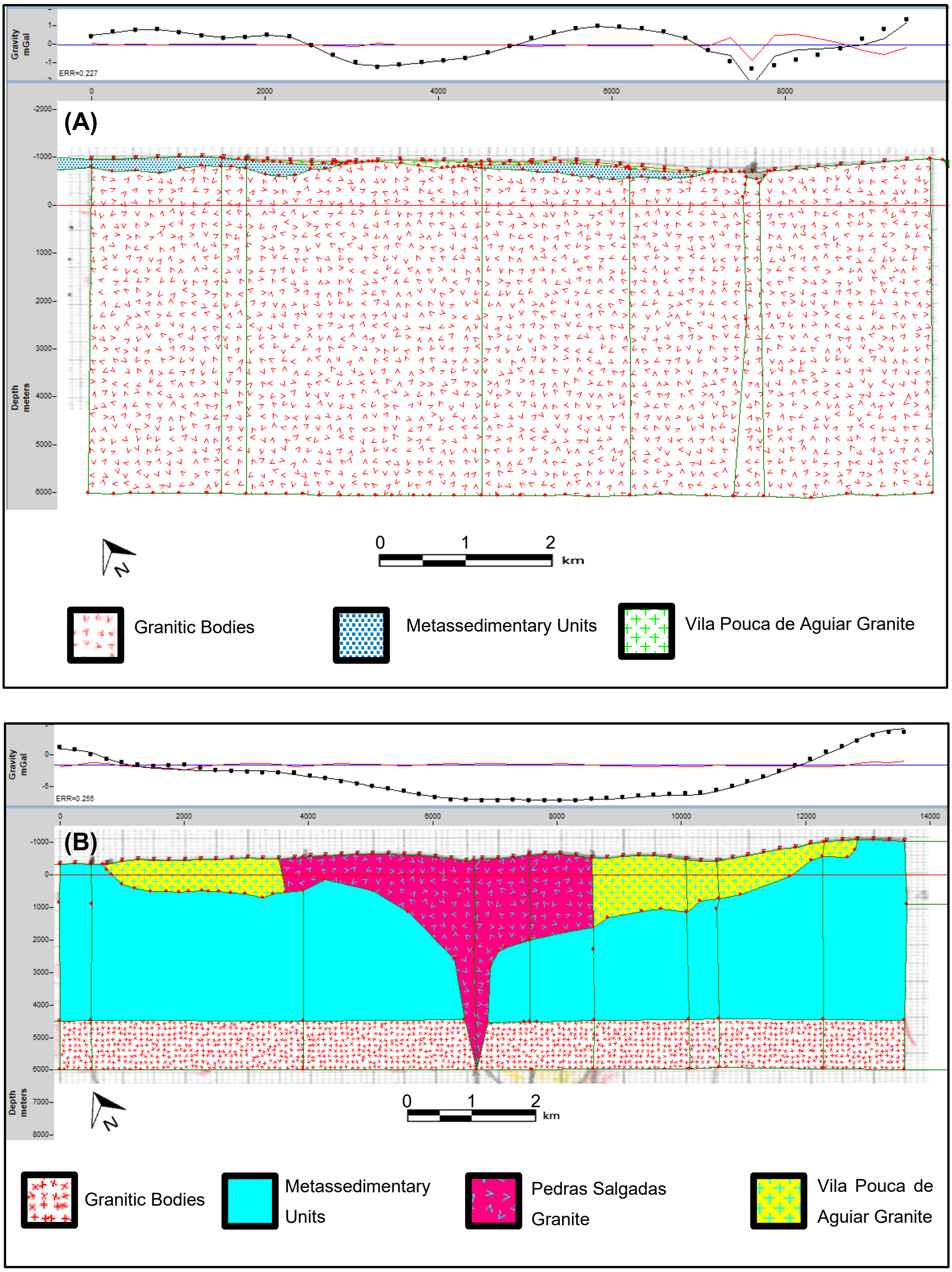

Figure 9 - (A) Cross-Section #2 and (B) Cross-Section #6, performed in Oasis Montaj.

4.2.2 Águas Frias

Much like the process for VPAP, the first step in the 2D modelling of AFP was the creation of cross-sections. Four cross-sections were drawn across the pluton's surface (Fig. 10).

To achieve the best coverage, two had an East-West orientation while the remaining 2 had a North-South orientation. This ensured a coverage of the central SAMG, the AFG rim around it, as well as the surrounding lithologies, notably with section 4 catching a portion of the Chaves sedimentary basin (CSB).

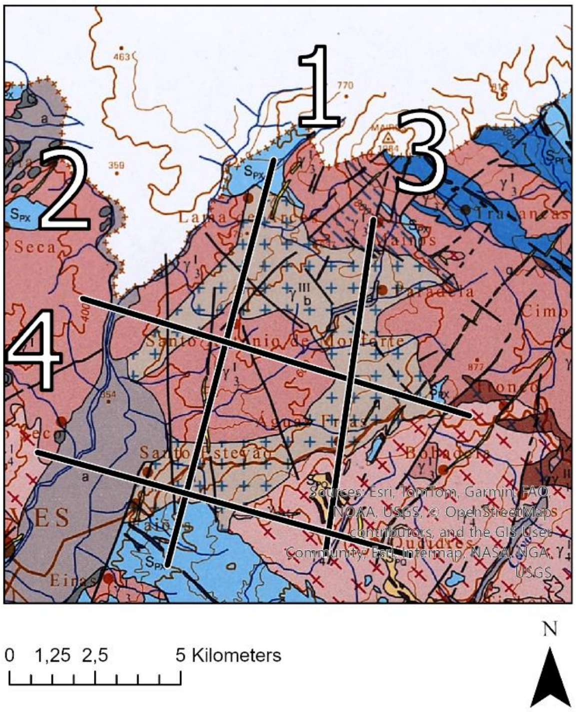

Figure 10 - AFP's cross-sections mapped on the geological map (cut from Folha 2 - 1:200000, LNEG) numbered 1-4

These four cross-sections were created and modelled directly in Oasis Montaj, enabling the gravity modelling to be incorporated into the 2D model from the beginning.

These 2D models displayed a system where the plutons rapidly increased in depth, forming a root system that reaches depths of 18 to 20 kilometers (Figs. 11 and 12).

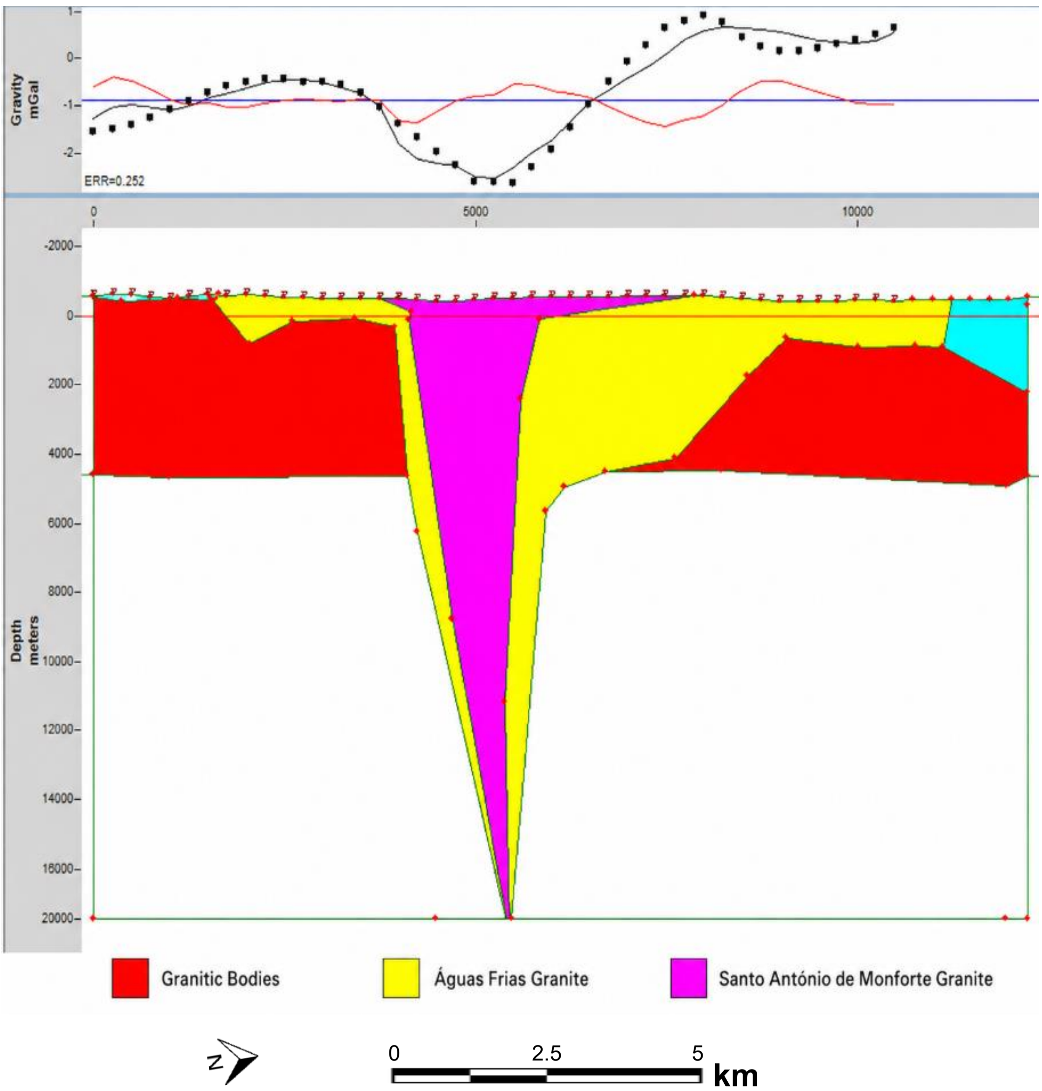

Figure 11 - AFP's Cross-Section #1

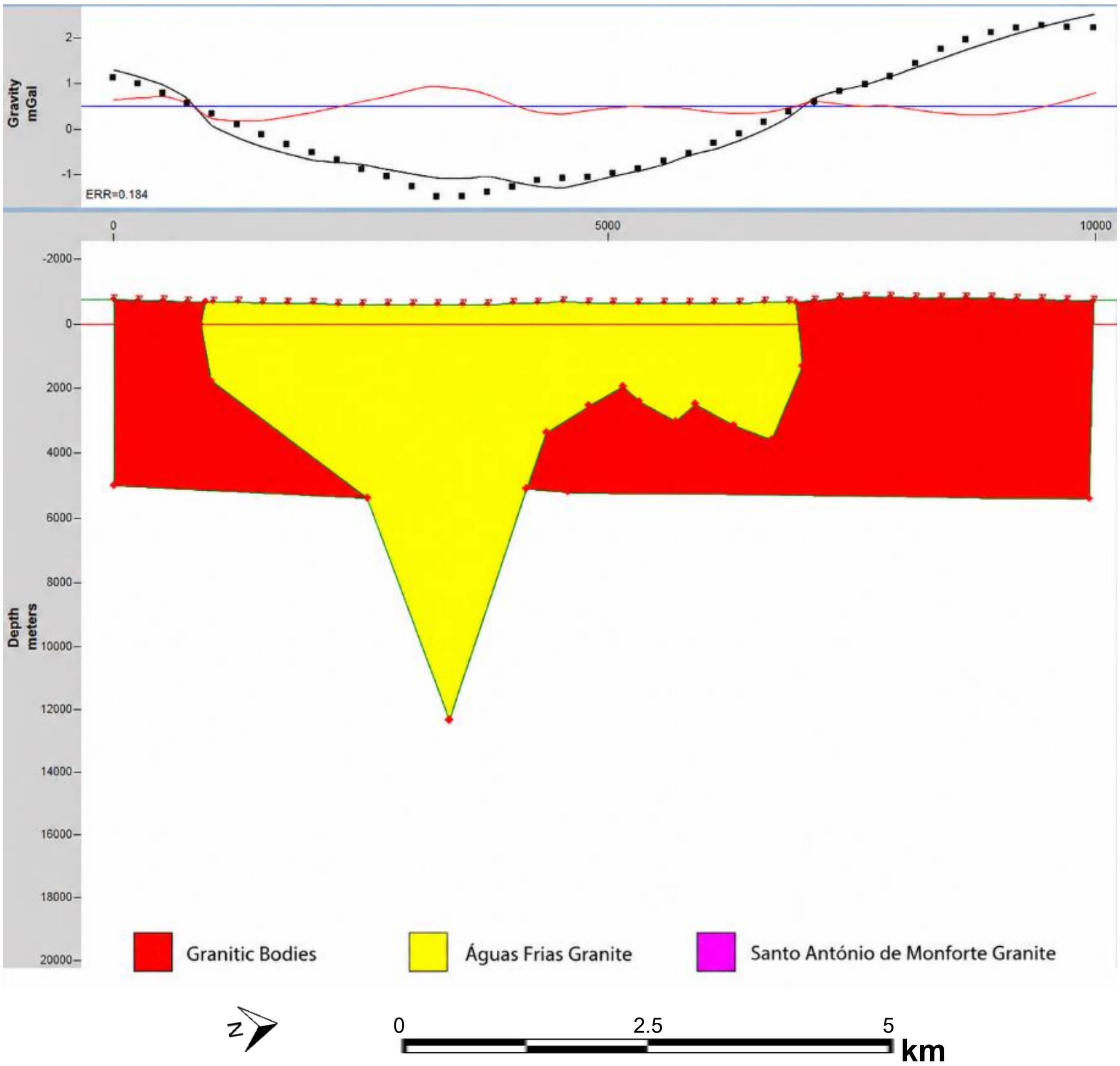

Figure 12 - AFP's Cross-Section #3

4.2.3 La Maladeta

In LM, the 2D cross-sections were compiled from two sources. The AA', BB' and CC' cross-sections (Fig. 13) were obtained directly from Soto et al. (2022) while the cross-section named MT comes from Piña-Varas et al. (2023).

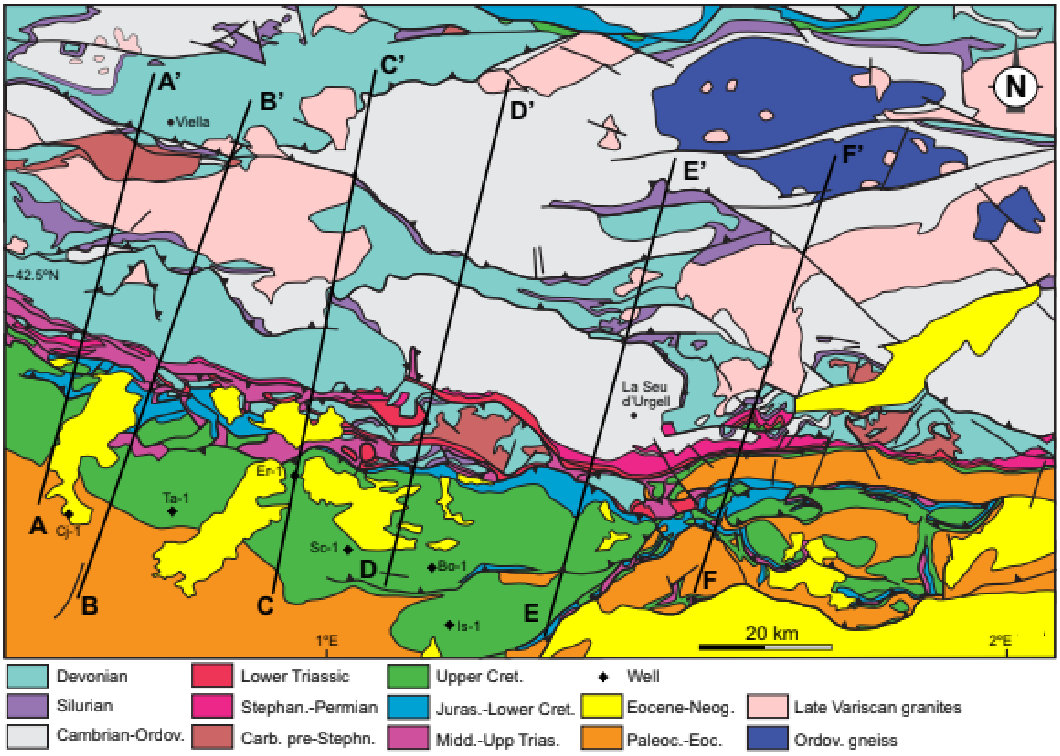

Figure 13 - Pyrenean Cross-Section locations overlaid on a geological map of the region (from Soto et al., 2022)

In Piña-Varas et al. (2023) it is also possible to see new advancements in sub-surface imaging of the La Maladeta pluton not observed in the Soto et al. (2022) so the AA' and BB' had to be altered to fit this new interpretation constrained by gravity and magnetotelluric data. In the cross-sections named AA' and BB', the granite was changed from a single body (Fig.14), with a very well-defined root, to instead, two different bodies (Figs.15 and 16).

The main body cropped out, while the smaller one, previously interpreted as a root, is buried. Changes were applied to the existing cross-sections in Oasis Montaj to support this new interpretation of their geometry. Apart from that, nothing else was changed in LM.

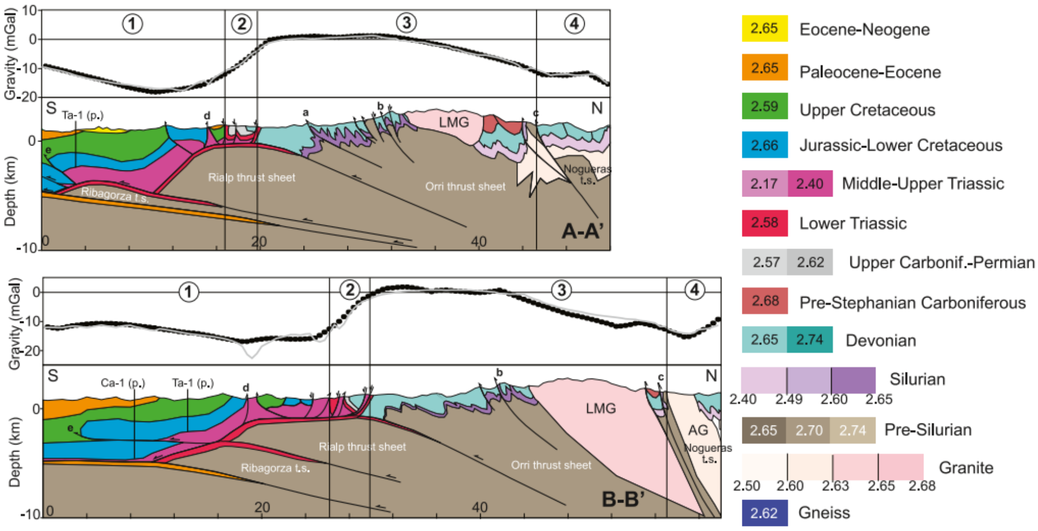

Figure 14 - La Maladeta cross-sections A-A' and B-B' from Soto et al. (2022). Work area corresponds roughly to section number 3. In this work, La Maladeta Granite has been interpreted as a single body.

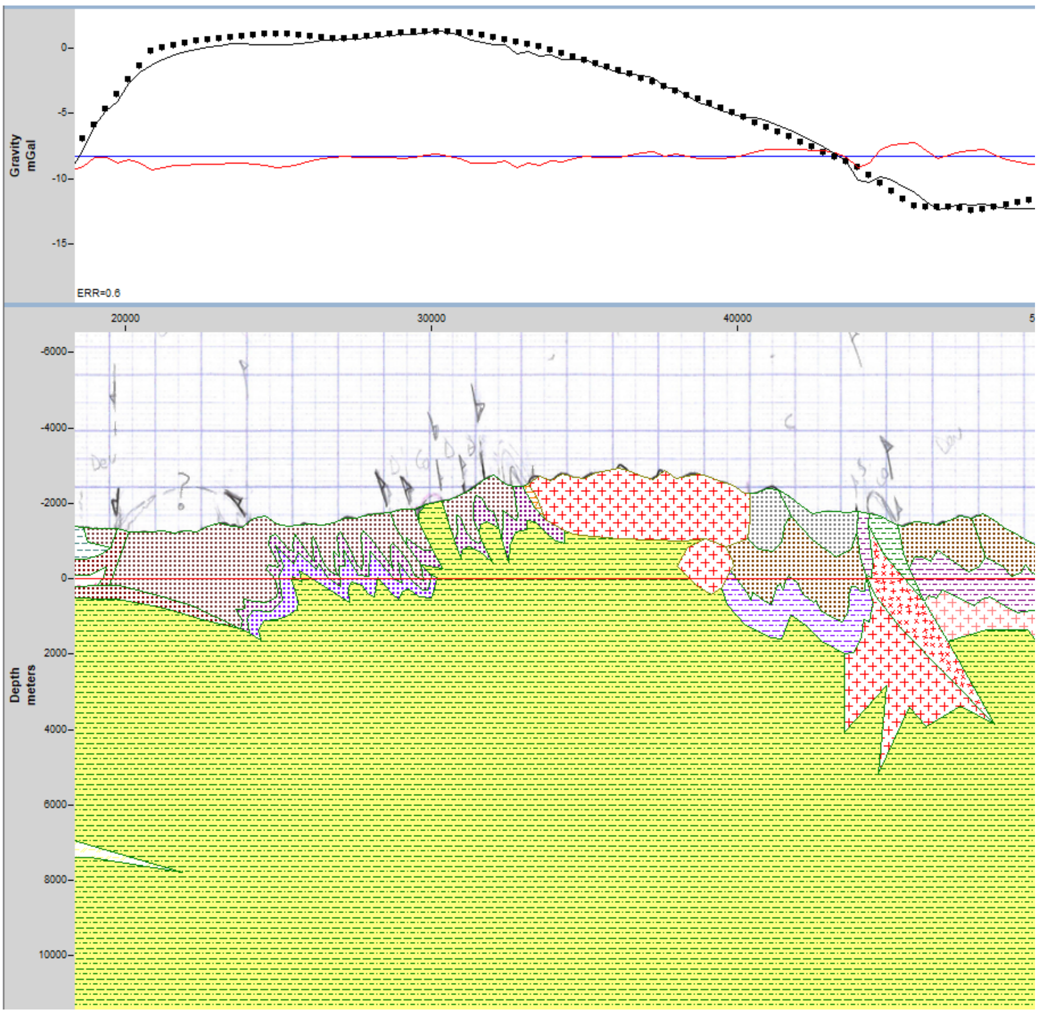

Figure 15 - Updated Cross-Section A-A' on Oasis Montaj. In this interpretation, the pluton has been divided in two to be consistent with Pina-Varas et al., 2023 .

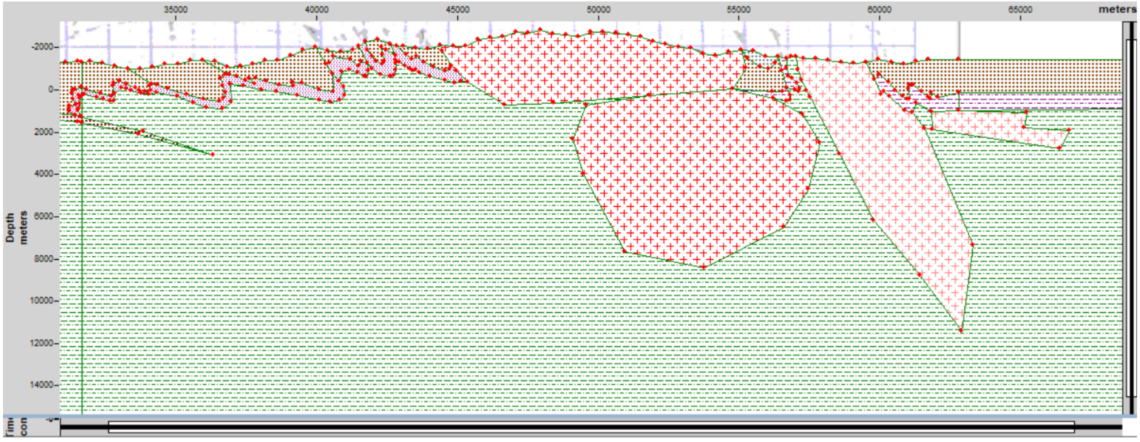

Figure 16 - Updated Cross-Section B-B' on Oasis Montaj. In this interpretation, the pluton has been divided in two following the results from Pina-Varas et al., 2023.

4.2.4 Andorra Mont-Louis

For AML no changes were made to the cross-sections, obtained from the previously cited literature, named EE' (Fig. 17) and FF' (Fig. 18). These were directly digitised in GeoModeller.

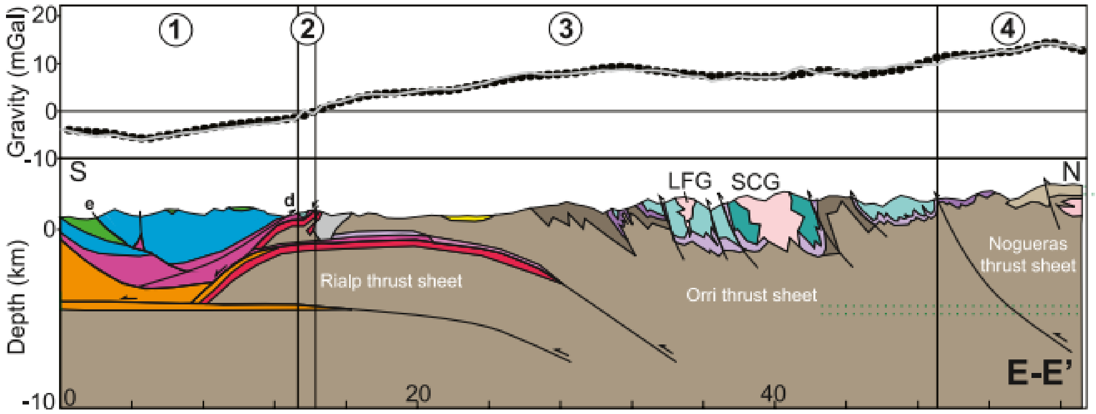

Figure 17 - Andorra Mont-Louis cross-sections E-E' from Soto et al. (2020). The work area corresponds roughly to section number 3.

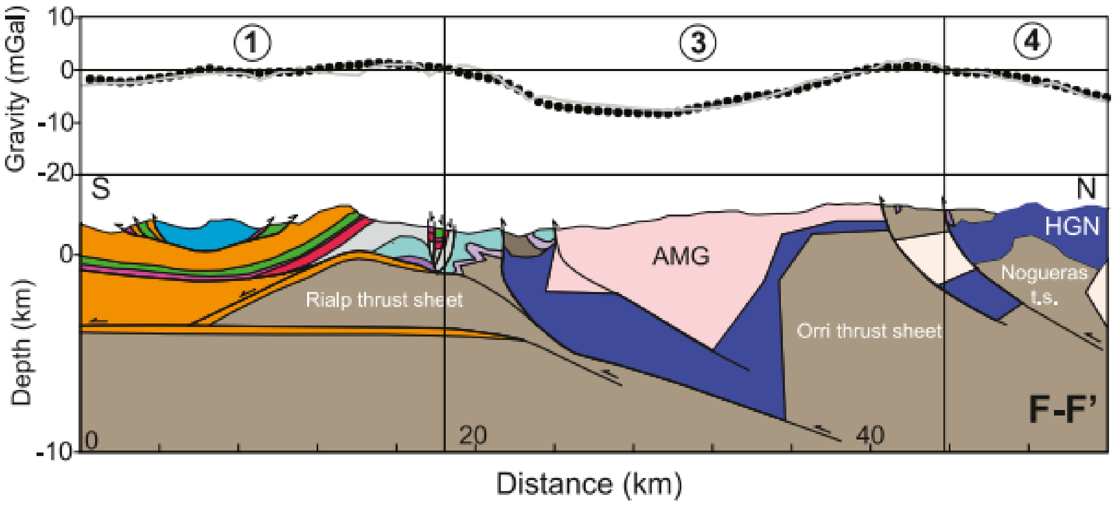

Figure 18 - - Andorra Mont-Louis cross-sections F-F' from Soto et al. (2020). The work area corresponds roughly to section number 3.

4.3 3D Model

4.3.1 Vila Pouca de Aguiar

With all the cross-sections improved with gravimetric data, the project advanced into the next phase: 3D modelling in GeoModeller. In Oasis Montaj, the cross-sections are exported as geo referenced images. These images are then digitised into GeoModeller (Figs. 19 and 20).

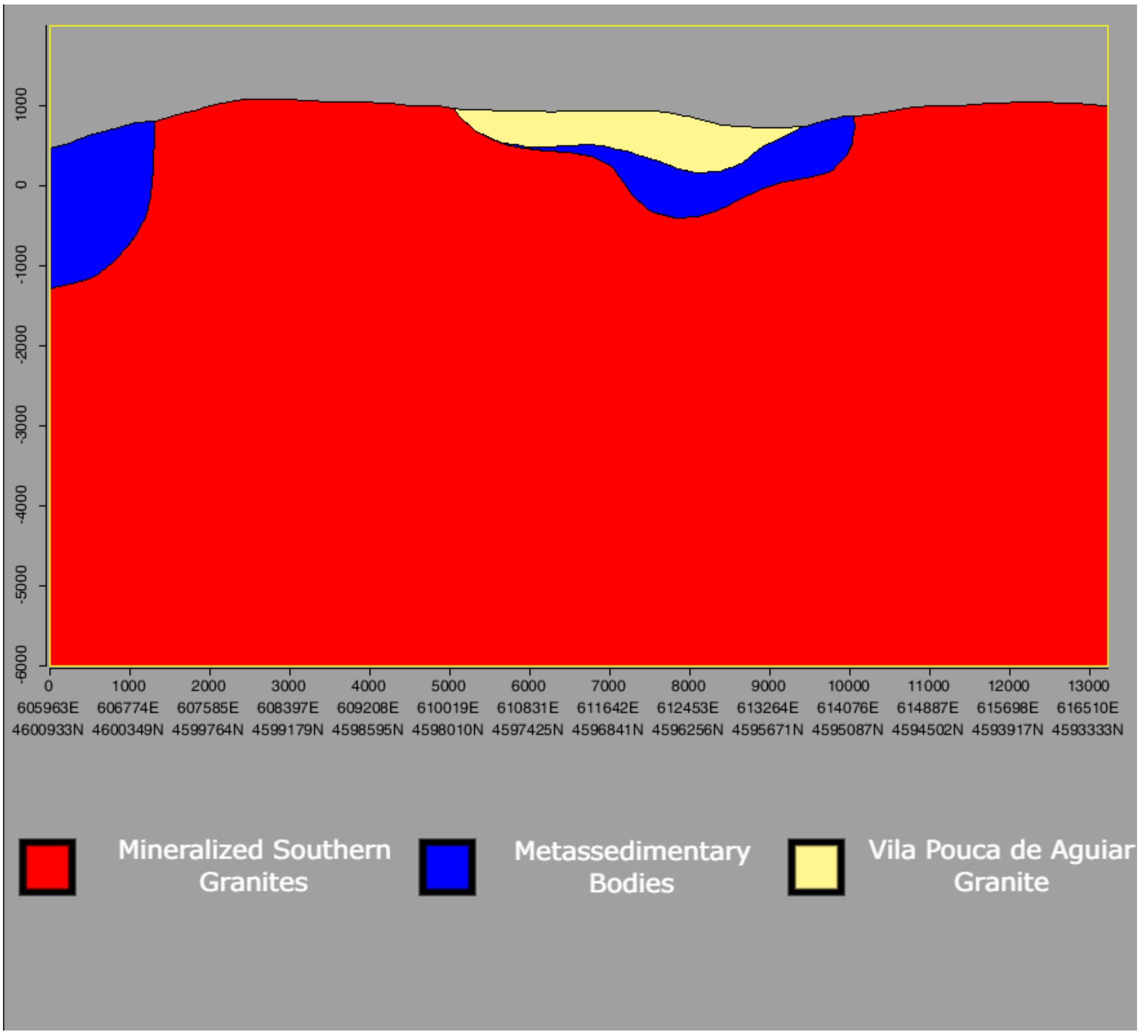

Figure 19 - VPAP's Cross-section #3 in GeoModeller

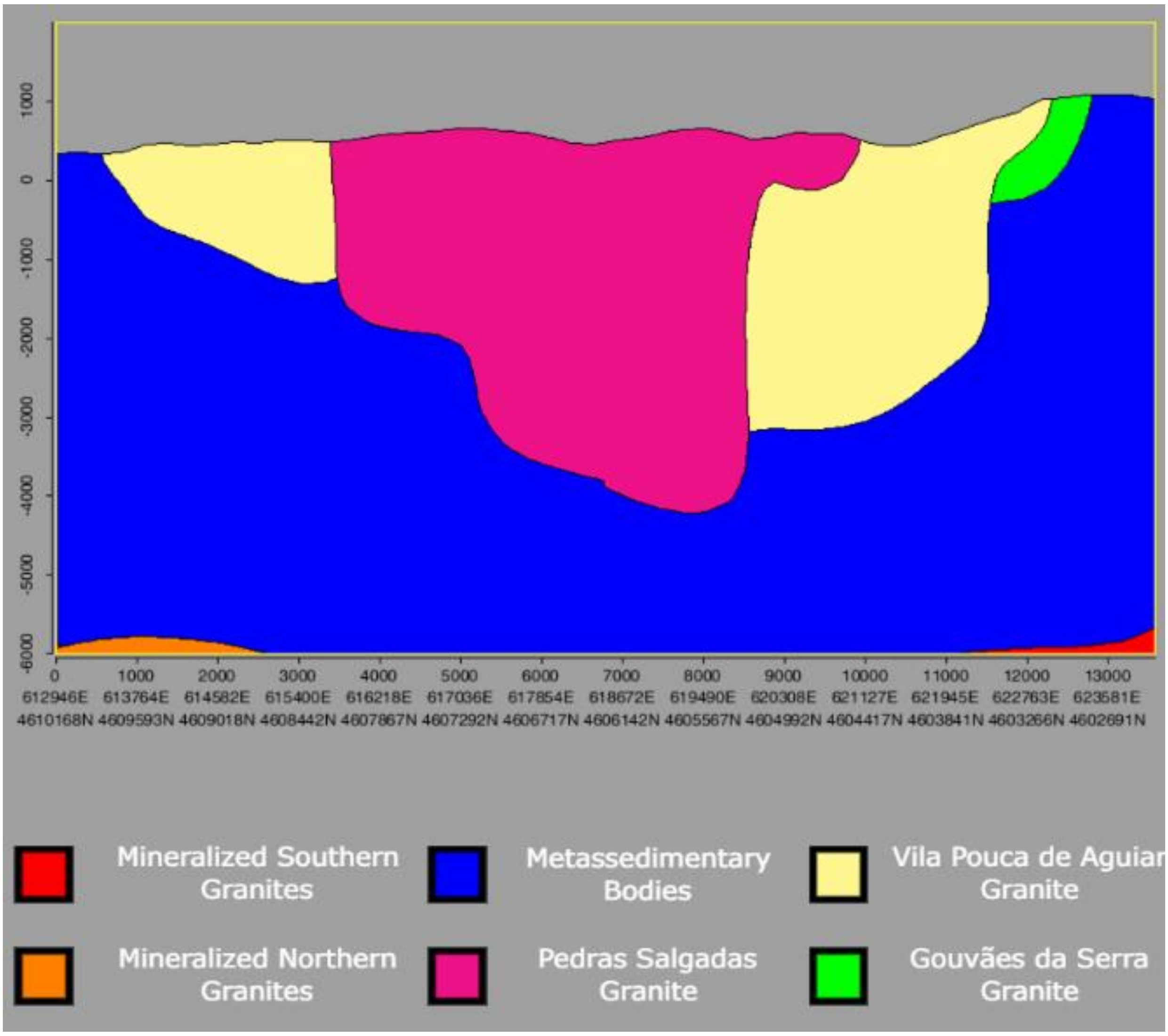

Figure 20 - VPAP's Cross-Section #6 in Geomodeller

The digitised cross-sections were iteratively adjusted to better ensure consistency between adjacent sections and form coherent geological units. Preliminary 3D models were generated at this stage to visualize the spatial relationships between units and to identify geometric inconsistencies or misalignments. These temporary models guided further refinement of contacts and unit geometries across the model volume.

Once all cross-sections were digitized in a coherent and geologically consistent manner, the model was considered sufficiently constrained to proceed to forward gravity modelling.

Each modification made to the model was evaluated through forward modelling to assess improvements in the misfit between calculated and observed gravity, with promising results (Fig. 21).

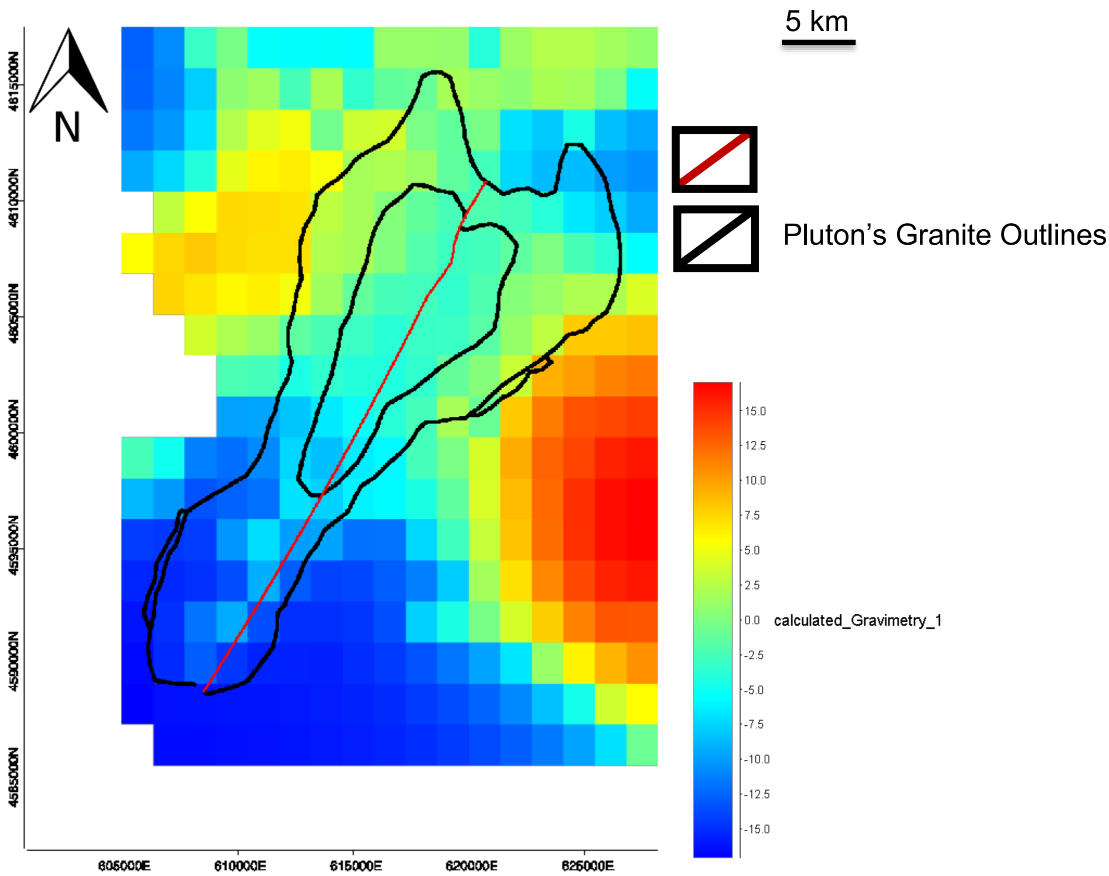

Figure 21 - Preliminary Forwarding Result. (dX: 1362.45; dY: 1768.35)

When comparing the preliminary forwarding results with the observed gravimetry we see the pattern is a bit different, although the core region of the plutons signature is similar, the shape of the pluton is overprinted by a NW and SE relative maxima.

Stochastic inversion was calculated to further refine the model. After several inversion trials, a persistent issue became apparent: regardless of the adjustments made to the southern granitic body, the inversion consistently returned a density value significantly higher than initially expected. This discrepancy is reflected in the pronounced low-gravity response shown in dark blue in Figure 21. A second challenge concerned the definition of geological bodies outside the areas constrained by the original cross-sections, where the model behaviour was more difficult to control.

To address these issues, six additional cross-sections were created. Unlike the original sections, these were not digitised from pre-existing sketches. Instead, they were used to examine how the current model geometry projected onto different planes. Modifications were then made only where necessary, either to better constrain the boundaries of existing geological units or to define bodies that were not intersected by the initial cross-sections.

This approach proved particularly useful in the southern part of the study area, where a small granitic domain was identified. Rather than representing a distinct intrusive body, this domain corresponds to a zone of varying density within the southern granite. Initially, the entire granite was assigned a density of 2.60 g/cm³. However, this produced an excessively strong negative anomaly, resulting in the extensive blue region visible in the lower-left corner of the map (Fig. 21). To improve the fit, the granite was subdivided into three density domains. The eastern sector retained the original density of 2.60 g/cm³, while a narrow zone adjacent to the southern margin of the VPA pluton was assigned a density of 2.65 g/cm³. The remaining portion of the southern granite was assigned a density of 2.70 g/cm³.

This increase in density is interpreted as a consequence of mineralisation within the area (Fig. 22). For the same reason, the northeastern granitic body was also assigned a slightly higher density of 2.65 g/cm³, although the change in density was smaller than that applied to the southern granite.

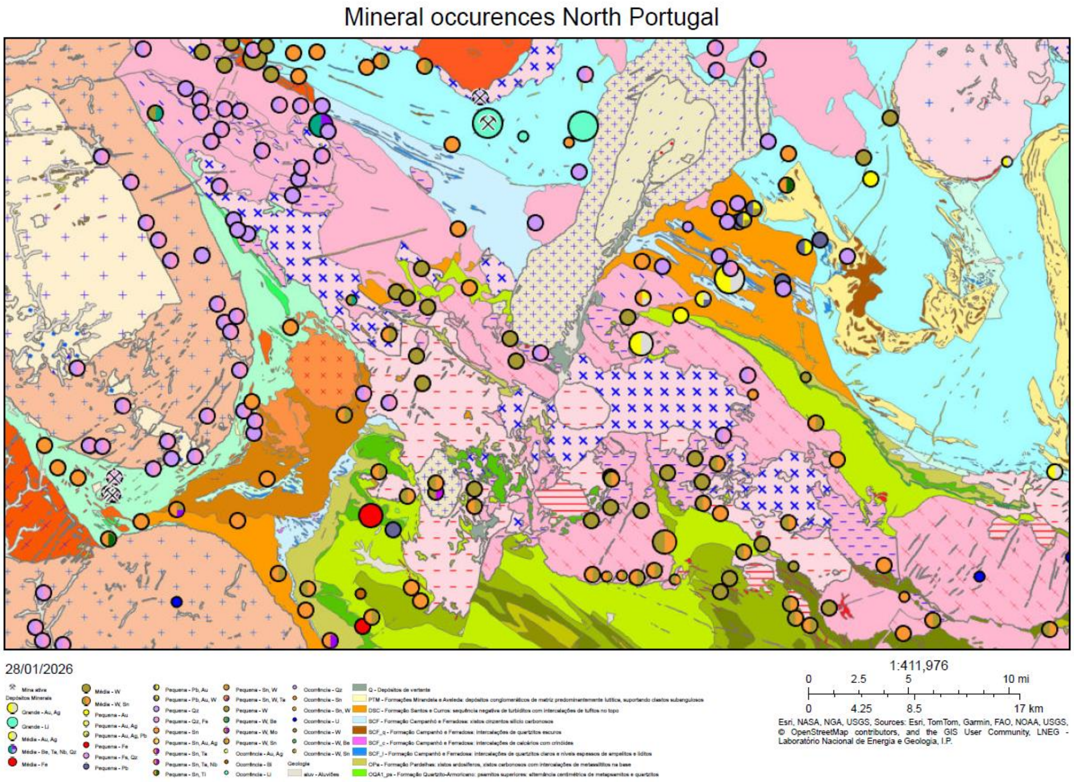

Figure 22 - Mineralization map south of the VPA study area

The surface topography map with geology units digitised is shown on Figure 23.

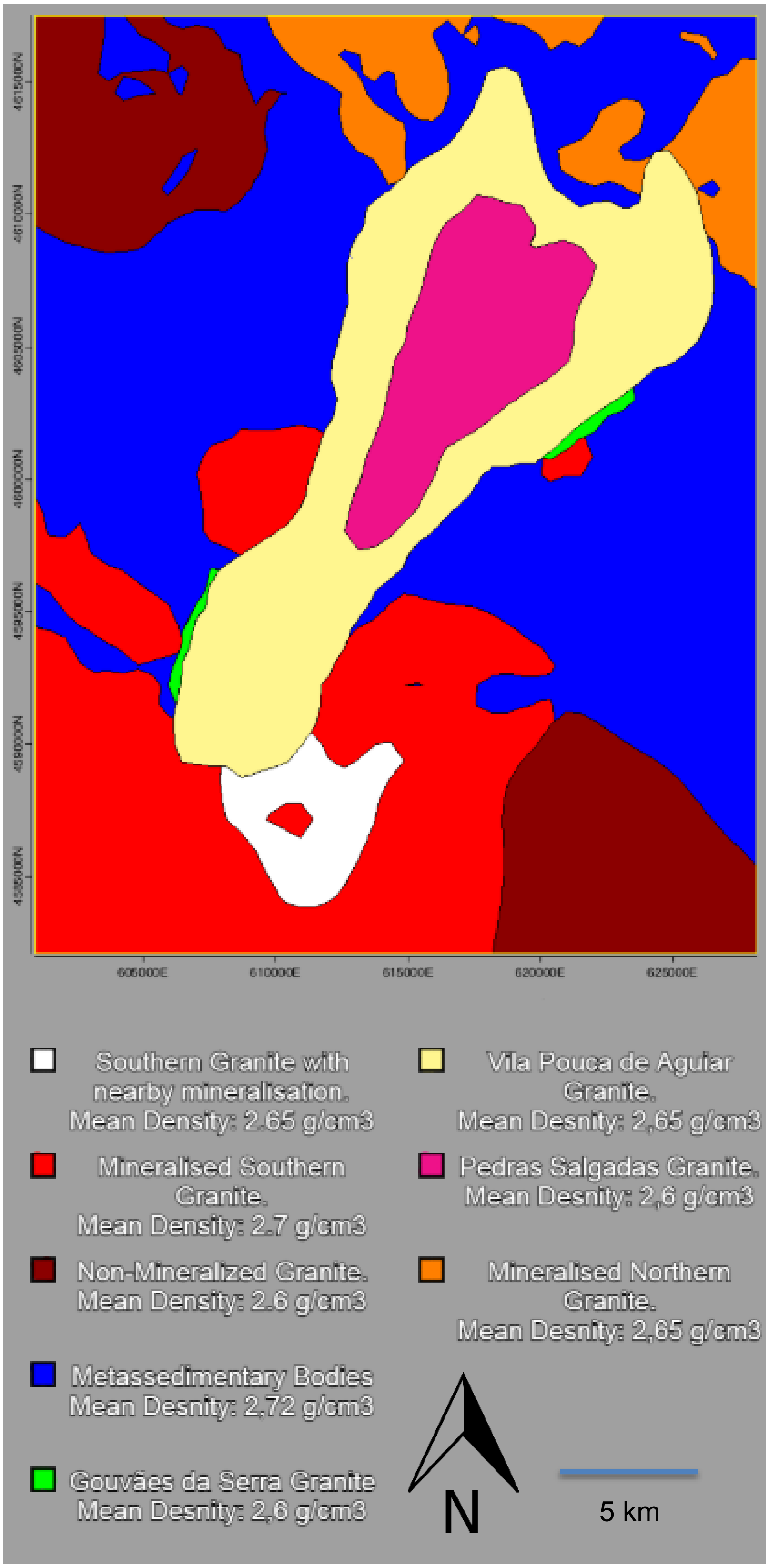

Figure 23 - Digitised geological units in the VPA study area.

After applying the changes previously mentioned, forward modelling produced a gravity response closely matching the observed residual anomaly, with the pluton clearly resolved and flanked by denser metasedimentary bodies (Fig. 24).

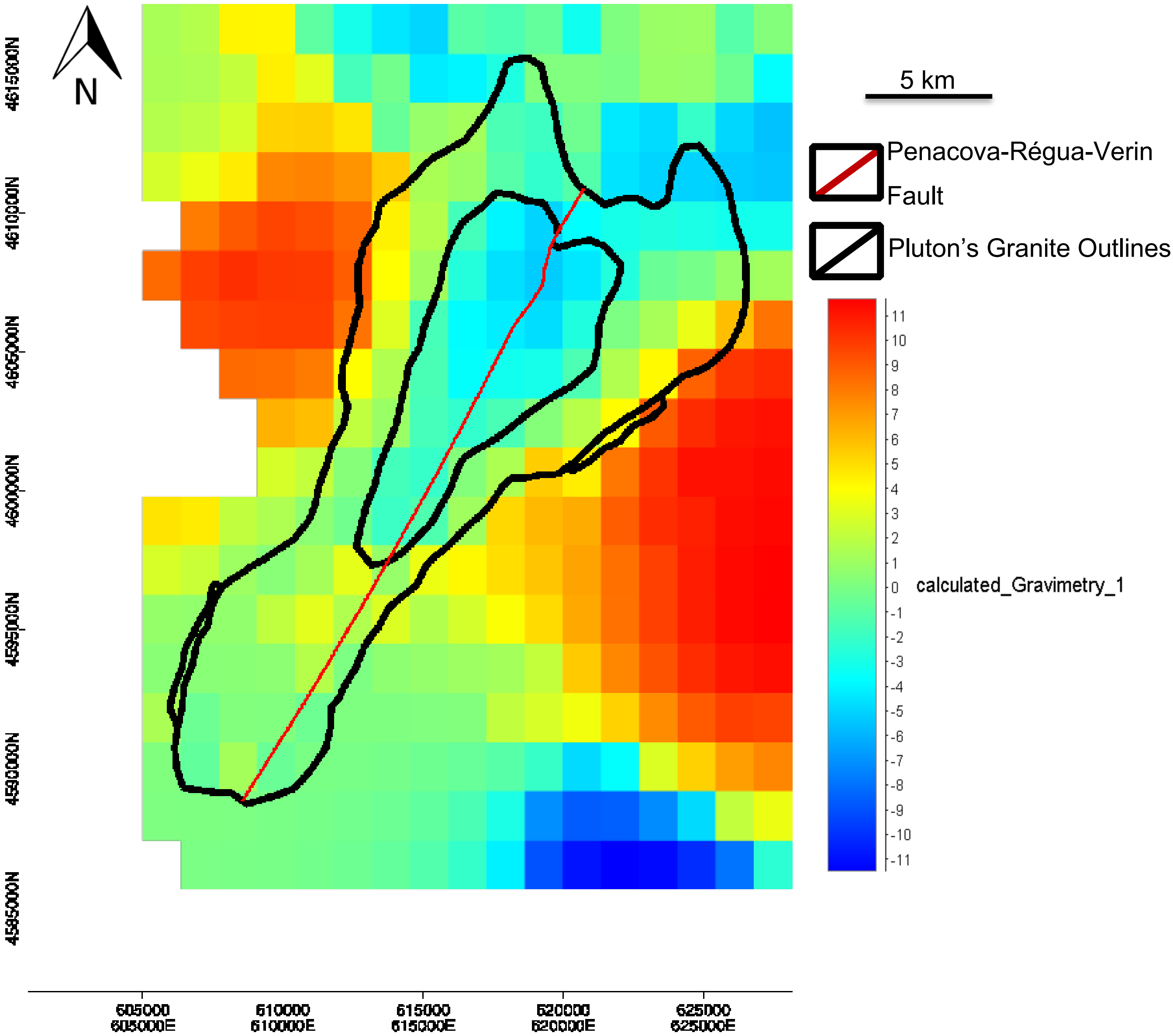

Figure 24 - Final Forwarding Result Before Inversion (dX: 1362.45; dY: 1768.35)

This model was then used as the input for gravity inversion. The inversion results suggested only minor additional adjustments, indicating that the model was already well constrained. After applying these changes, a final model was obtained (Fig. 25) whose computed residual gravity closely reproduces the observed anomaly.

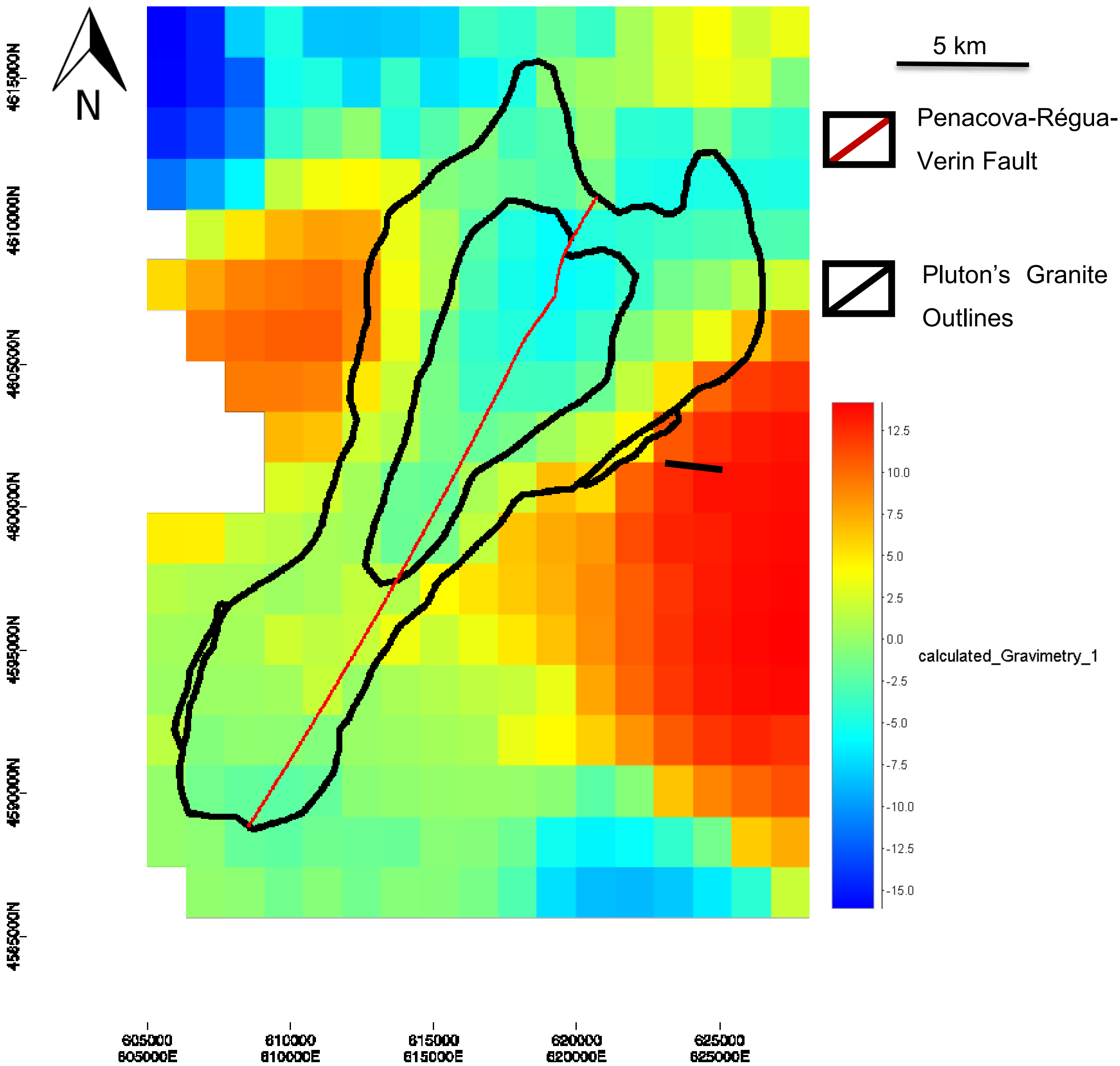

Figure 25 - Final calculated gravity anomaly after Inversion (dX: 1362.45; dY: 1768.35)

Figure 26 shows the final model, after the inversion.

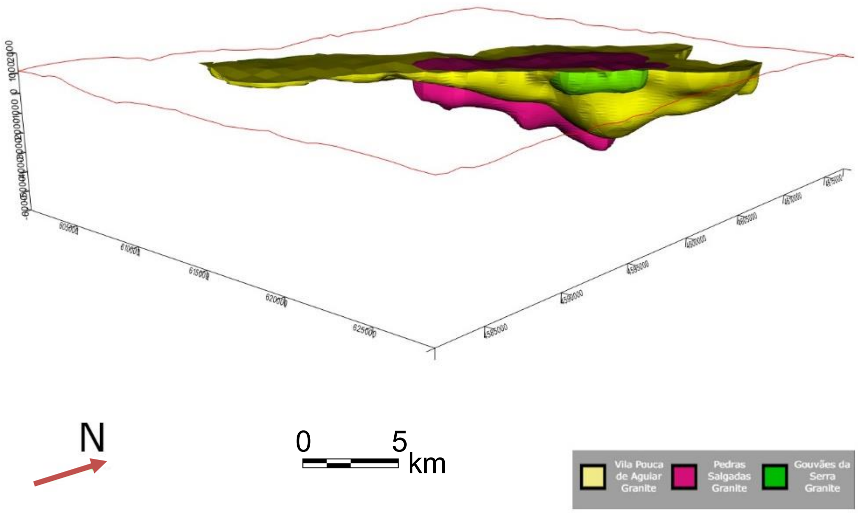

Figure 26 - VPAP's Final 3D Model

That was so by the inversion misfit (Fig. 27 and 28) displayed results that were both geophysically and geologically viable, as per described in methodology.

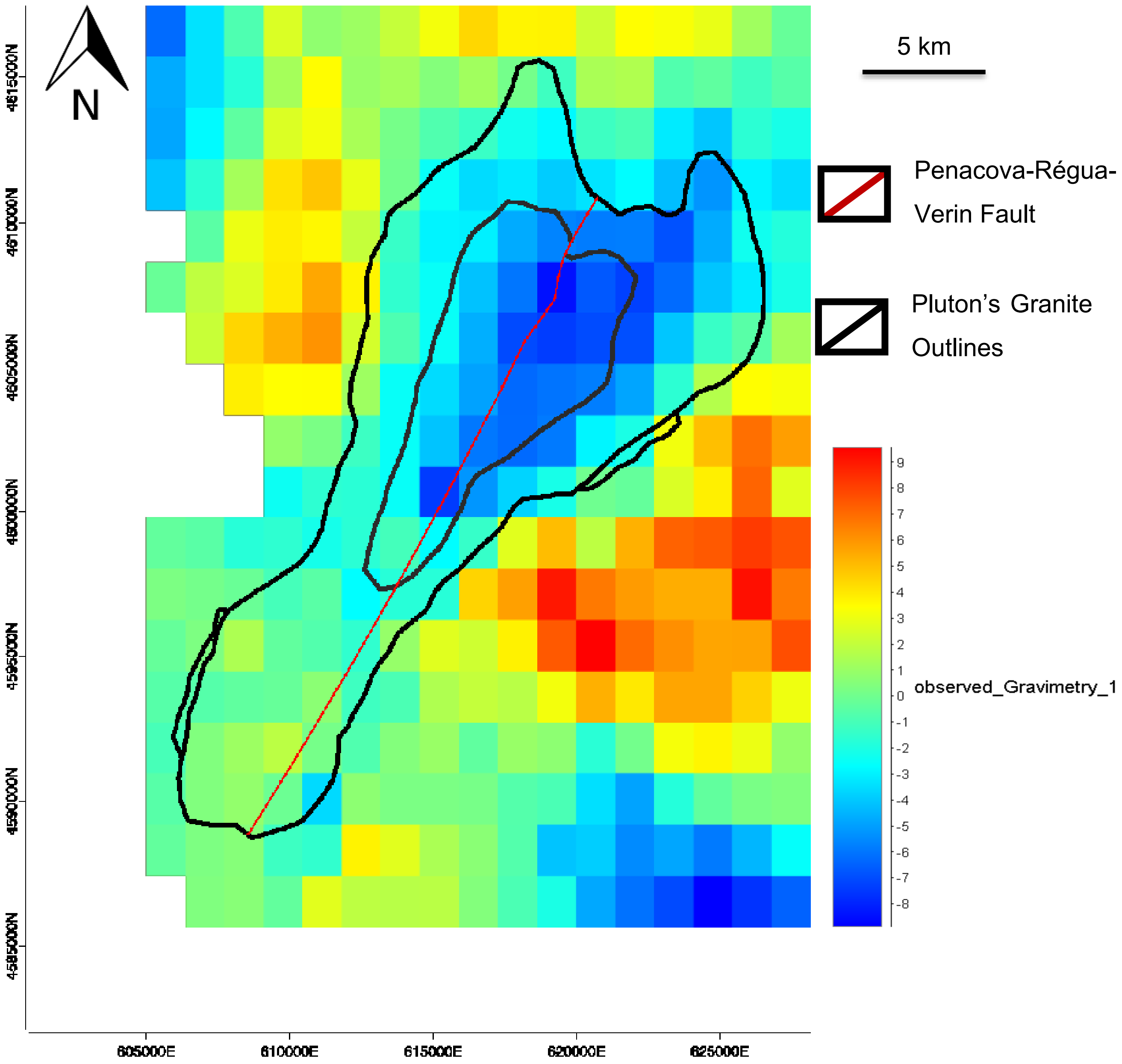

Figure 27 - Observed gravity anomaly of VPAP's study area (dX: 1362.45; dY: 1768.35)

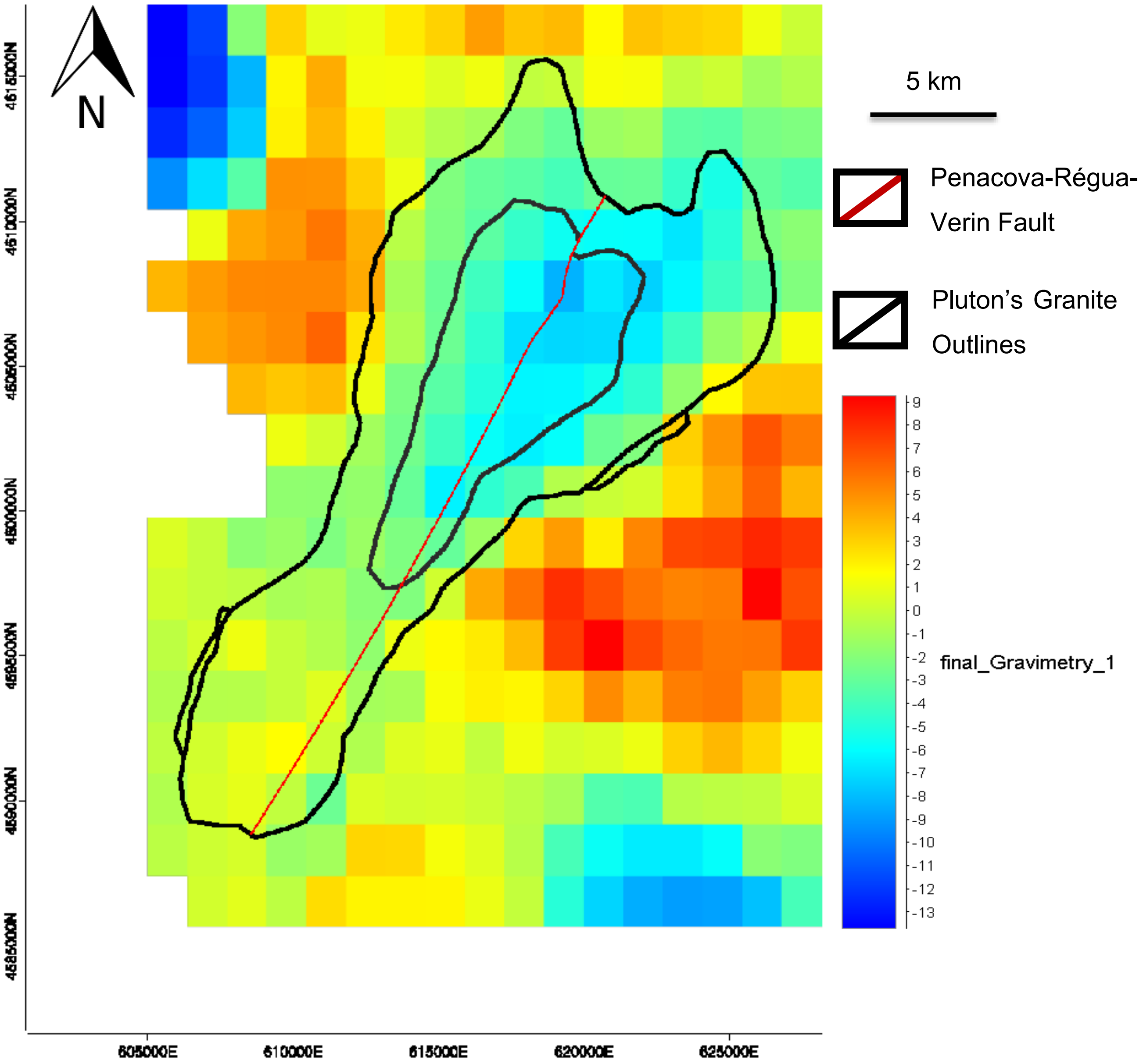

Figure 28 - Final Calculated Gravimetry of VPAP's study area (dX: 1362.45; dY: 1768.35)

4.3.2 Águas Frias

The Águas Frias proved the most difficult plutonic body to carry out a 3D model. The digitisation of the granite's cross-sections did not face many issues, with the exception of the nearby CSB, for the same reasons as mentioned in the 2D modelling section. From Oasis Montaj, the model was firstly modelled with only one deep root going to the pluton's core. After the inversion, the results displayed certain anomalies in the northern sector of the pluton that did not align with what was already modelled. These anomalies were interpreted as a secondary root (Fig.29).

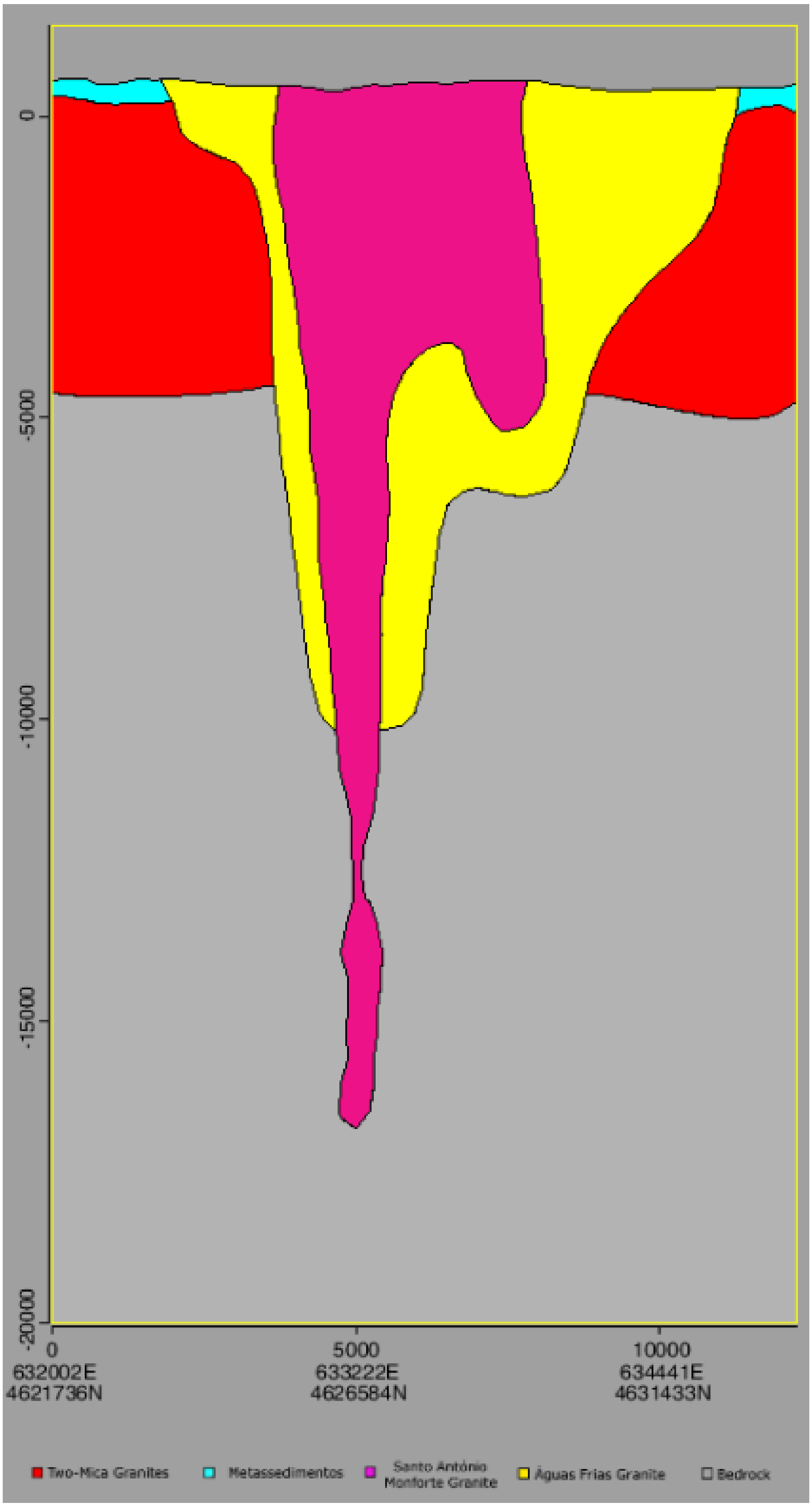

Figure 29 - AFP's Cross-Section #1 sporting a dual root system

Originally the second root was placed directly in the north of the pluton, but it was later moved to the western regions of it, to better fit the observed gravity map (Residual Gravity Map). To the same end of the VPAP model, three cross-sections were added to better constrain the model. SectionFix1 was delineated with a South-East to North-West direction to help define the sedimentary basin, but also the central portions of the pluton. SectionFix2 helps constrain the north of the model with a direction West to East. SectionFix3 helped constrain the sedimentary bodies following the Tâmega river and the CSB. The low-density sedimentary bodies proved challenging to model and were progressively reduced in volume until their gravimetric response was closer to the observed gravity, in the final model gravity maps (Fig. 30 & 31).

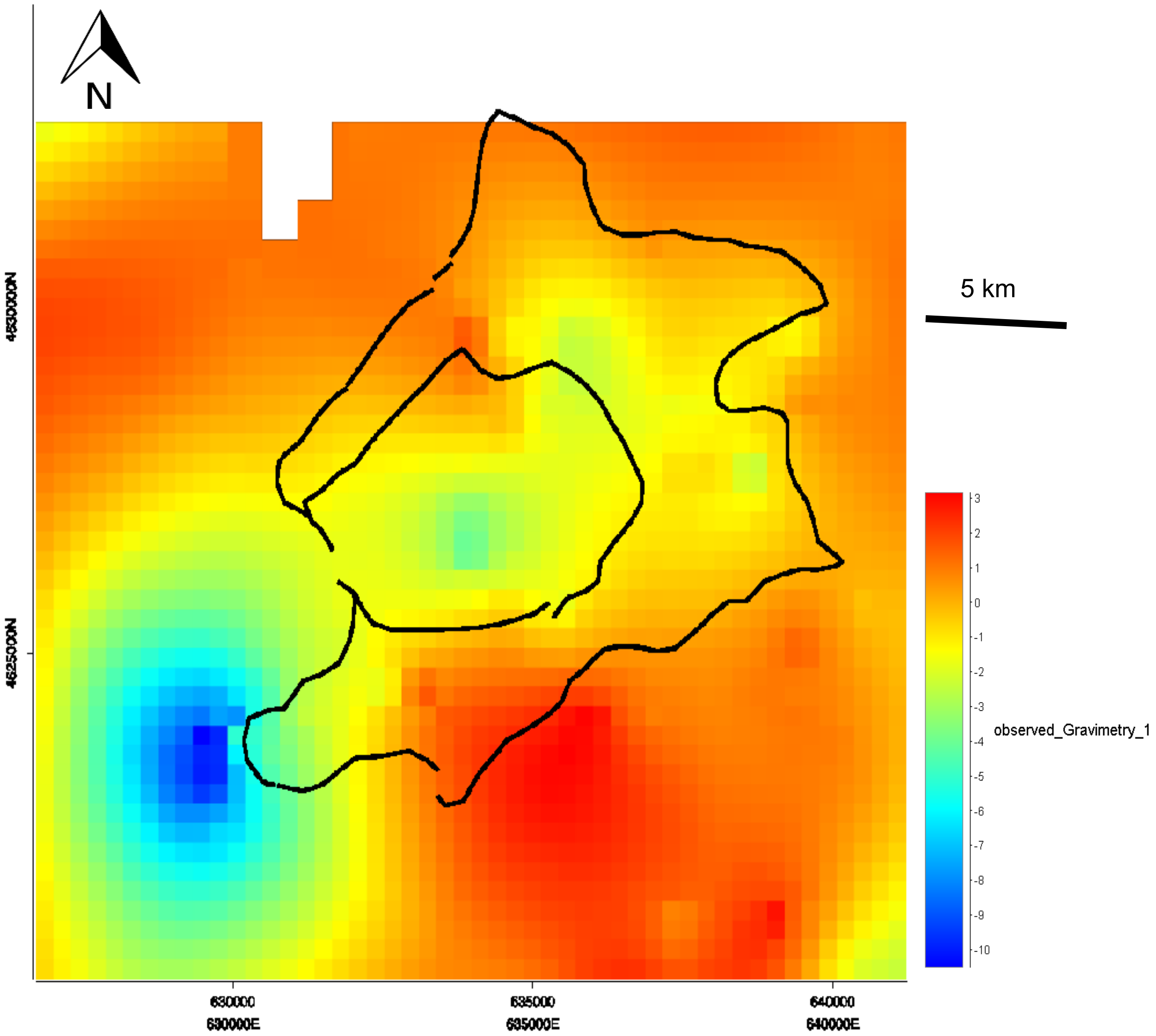

Figure 30 - Observed Gravimetry map of AFP's study area (dX: 290.24; dY: 280.82)

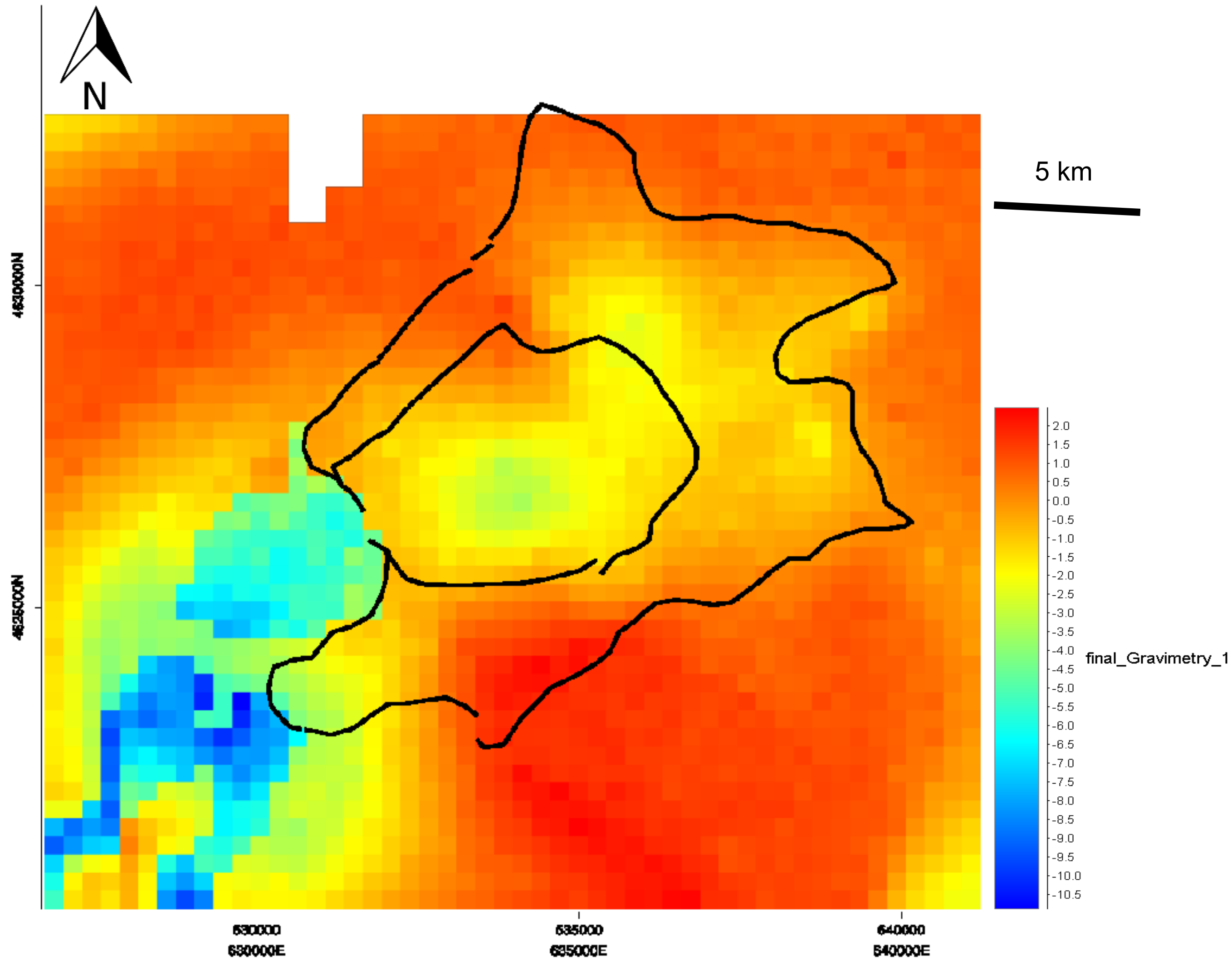

Figure 31 - Final Calculated Gravimetry of AFP's study area (dX: 290.24; dY: 280.82)

The final version of the model consists of a wedge shaped and zoned pluton composed of AFG and SAMG, with AFG reaching depths of 10 km while the SAMG goes to depths of 16 km. The pluton has two roots, one in the path of the PRVF and another, smaller, root coming from the north-western portion of the model (Fig. 32).

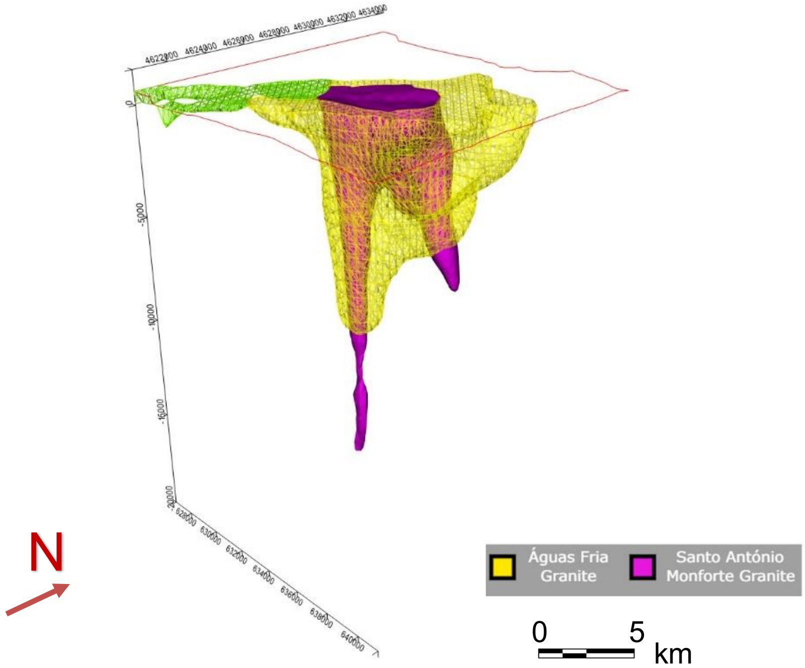

Figure 32 - AFP's Final 3D Model

4.3.3 La Maladeta

In la Maladeta, the various cross-sections were digitised into GeoModeller (Fig. 33), then forward gravity modelling was applied.

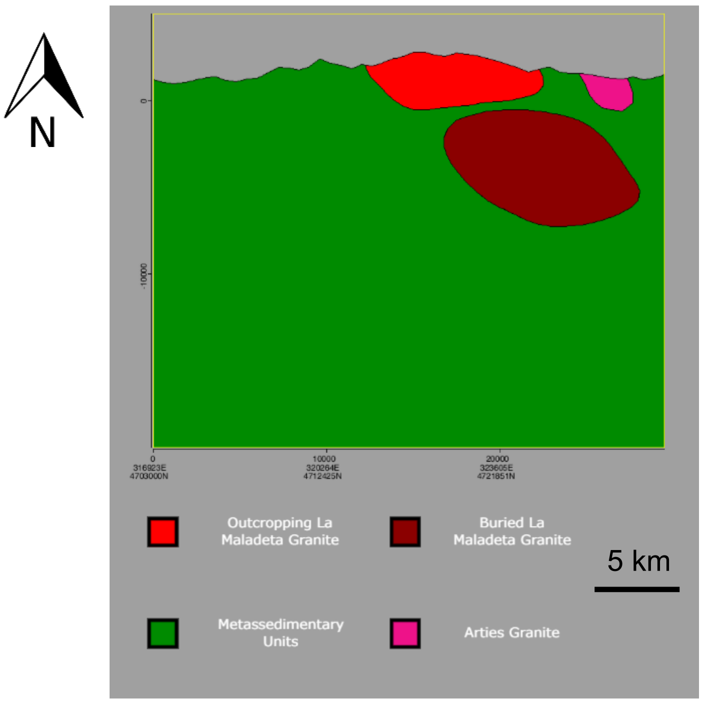

Figure 33 - LM's Cross-Section B-B'

During the digitisation of the cross-sections, metasedimentary units were reduced to a single layer with an average density value, with appropriate amounts of variation.

Early geophysical forwarding results displayed a lower density zone in the north, outside of the plutons reach, that would prove hard to work with. To remedy this an attempt was made to fix the gap by expanding surrounding granitic structures into the area. That proved to be geologically unfeasible due to the small size of those same structures. The size of the other structures was reverted to a more realistic one, and new changes were instead done on the LM pluton instead. Whereas before the LM Pluton division was not well defined, that was improved so it would now be much more clearly 2 different bodies, with the smaller body having a stronger tilt northward, expanding both further northwards and deeper. Inversion of these changes proved fortuitous. After a few changes and inversions, the results (Fig. 34 & 35) allowed to the creation of the final model (Fig. 36). It allows us to see that the LMP is a laccolithic shaped pluton, with a root set in the north, that lead to the creation of both granitic bodies, and that expanded southwards.

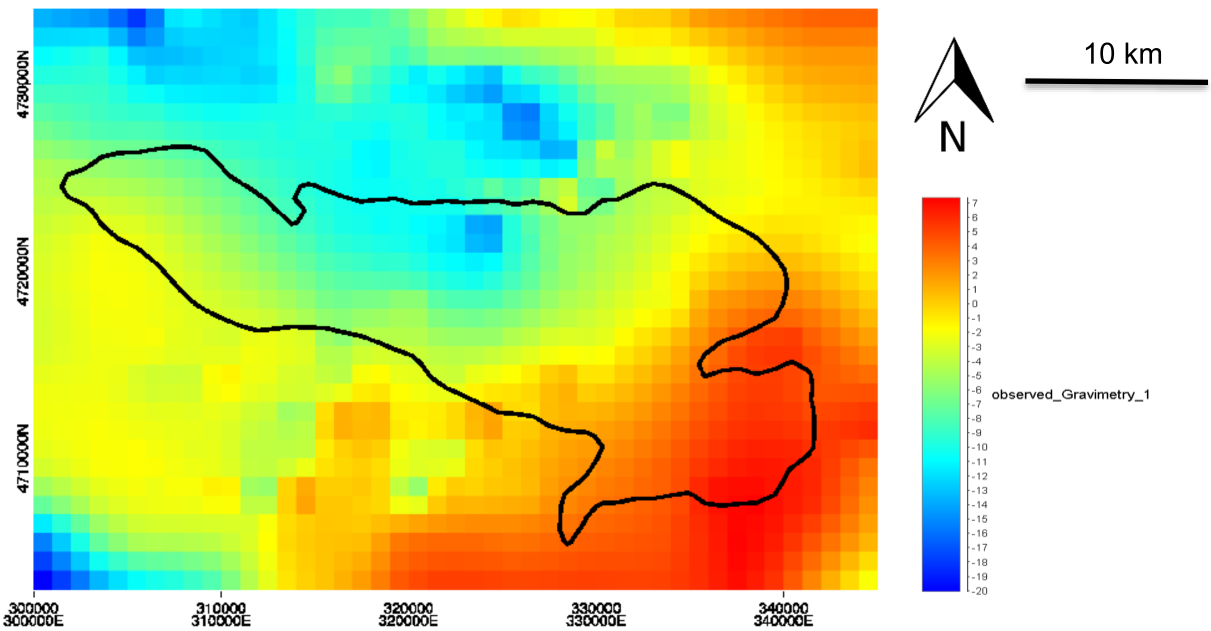

Figure 34 - Observed Gravimetry map of LM's study area (dX: 1000; dY: 1000)

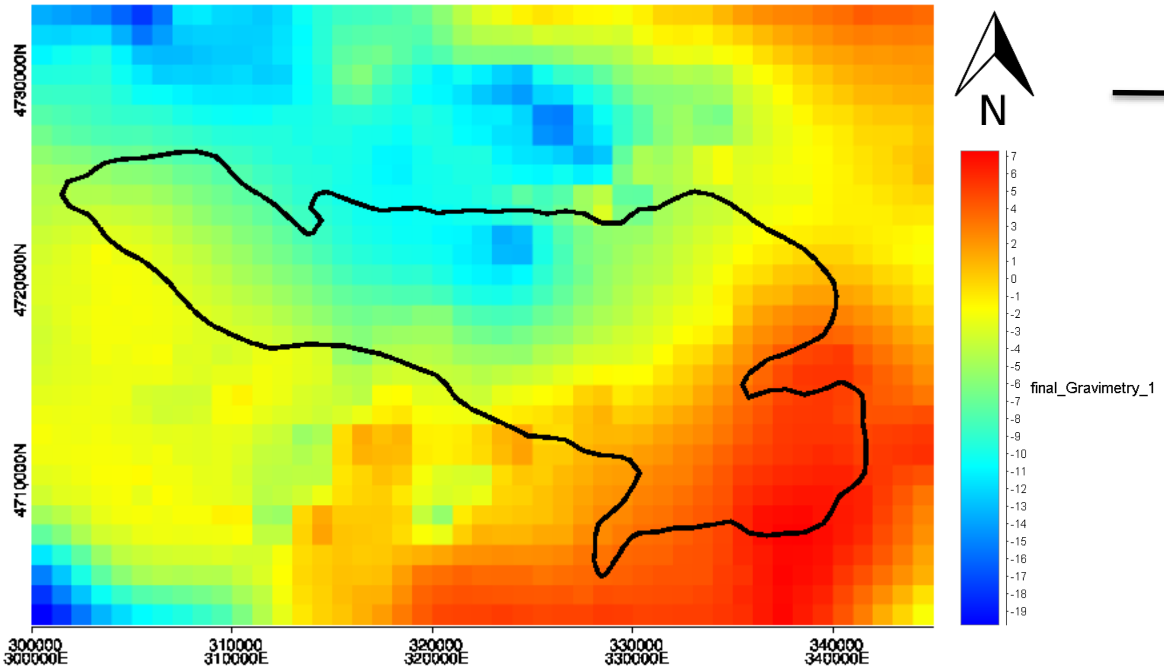

Figure 35 - Final Calculated Gravimetry map of LM's study area (dX: 1000; dY: 1000)

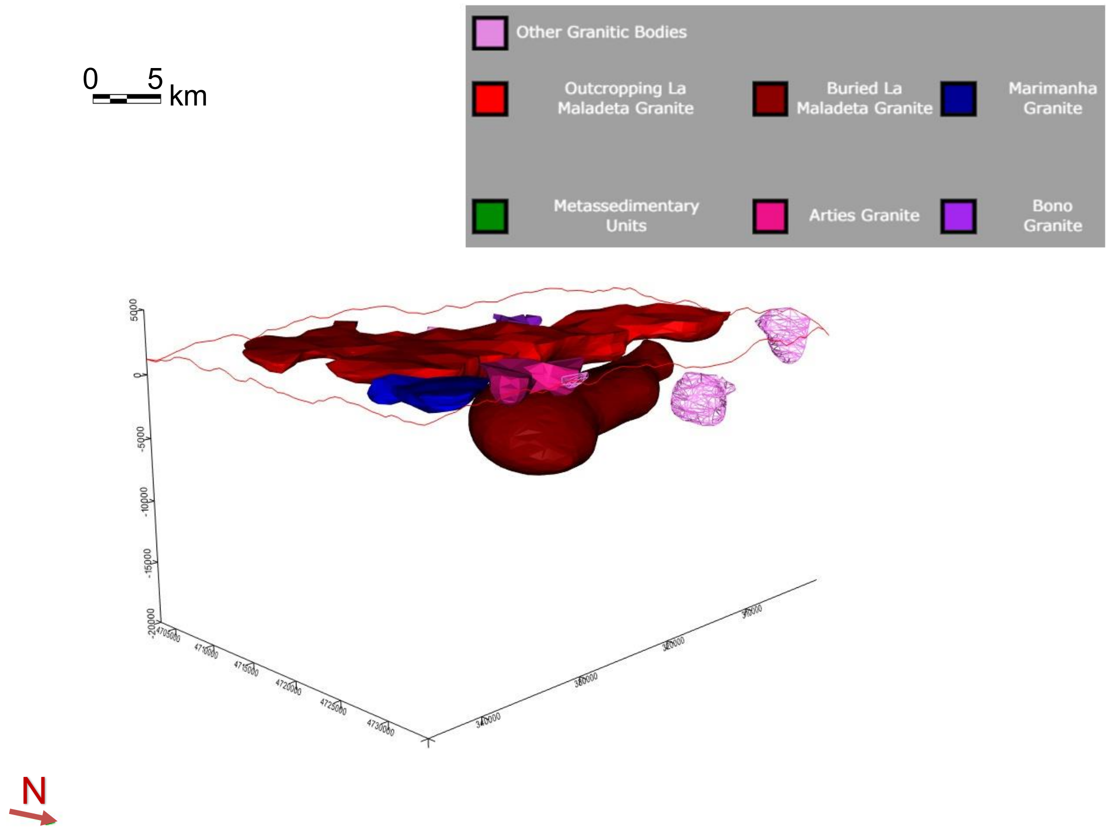

Figure 36 - LM's Final 3D Model

4.3.4 Andorra Mont-Louis

The AML model proved harder to finalize. After the digitisation of the cross-sections, the 3D model quickly approached a functional model, and so inversion began being undertaken much earlier than the others. Much like in the case of the LM, here the metasedimentary units were also simplified to a single layer with a density equal to the weighted average of all the layers combined, of 2.7 g/cm^3.

Also modelled in this part of the work were the gneissic bodies that cover a portion of the AML and the La Cerdanya Basin, due to it's very low density. The La Cerdanya basin was not modelled immediately, but that resulted in a clear disparity between the observed and computed density values (Fig. 37).

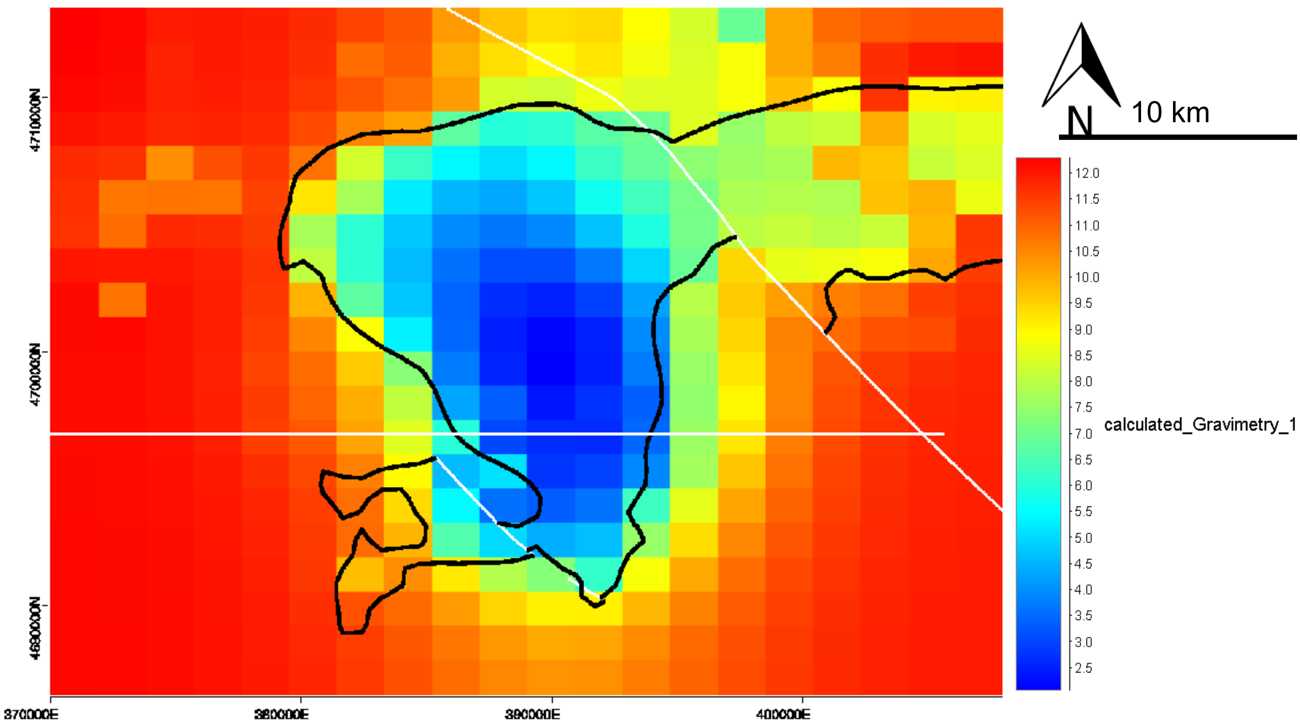

Figure 37 - Preliminary Results before the modelling of the La Cerdanya Basin (dX: 1000; dY: 1000)

Modelling the La Cerdanya improved the model (Fig. 38), better fitting the observed values.

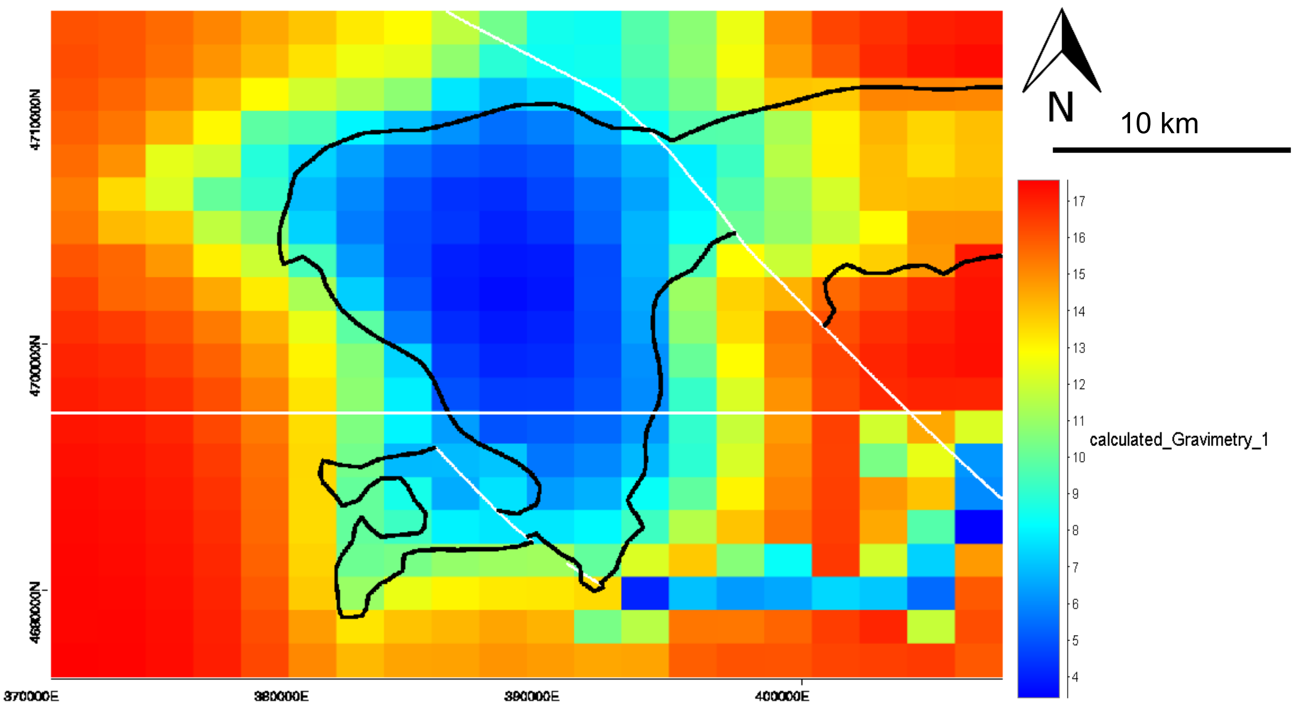

Figure 38 - Preliminary Results after the modelling of the La Cerdanya Basin (dX: 1000; dY: 1000)

Although improved, the model was not finished. In forwarding it was possible to see that the minimum mGal values of the model were still too much above the minimum values of the observed. While Inversions were helpful, the results many times defied the changes done to the model.

At first an approach of trying to follow the inversion suggested changes to better understand the problem was taken. This resulted in a model that was geophysically functional but was not geologically viable. The Bent root for the pluton and the large volume of the gneissic body made it unfeasible. Hence two new paths were taken. The first would be to straighten the root and attempt to tweak the density value and geometry and search of better inversion results.

The other path involved taking into account the complex nature of the AML body and model the leucogranite bodies that are part of the AML as their own geological unit with a lower density. In both cases the gneissic volume was drastically reduced to more realistic levels. Independent of changes done, keeping the model simplified with a straight root did not deliver geophysically acceptable results.

As so, instead, leucogranitic intrusions were taken into account as their own lithology with a lower density. This contributed greatly to a better model (Fig.39), finally delivering both geologically and geophysically acceptable results (Fig. 40 & 41).

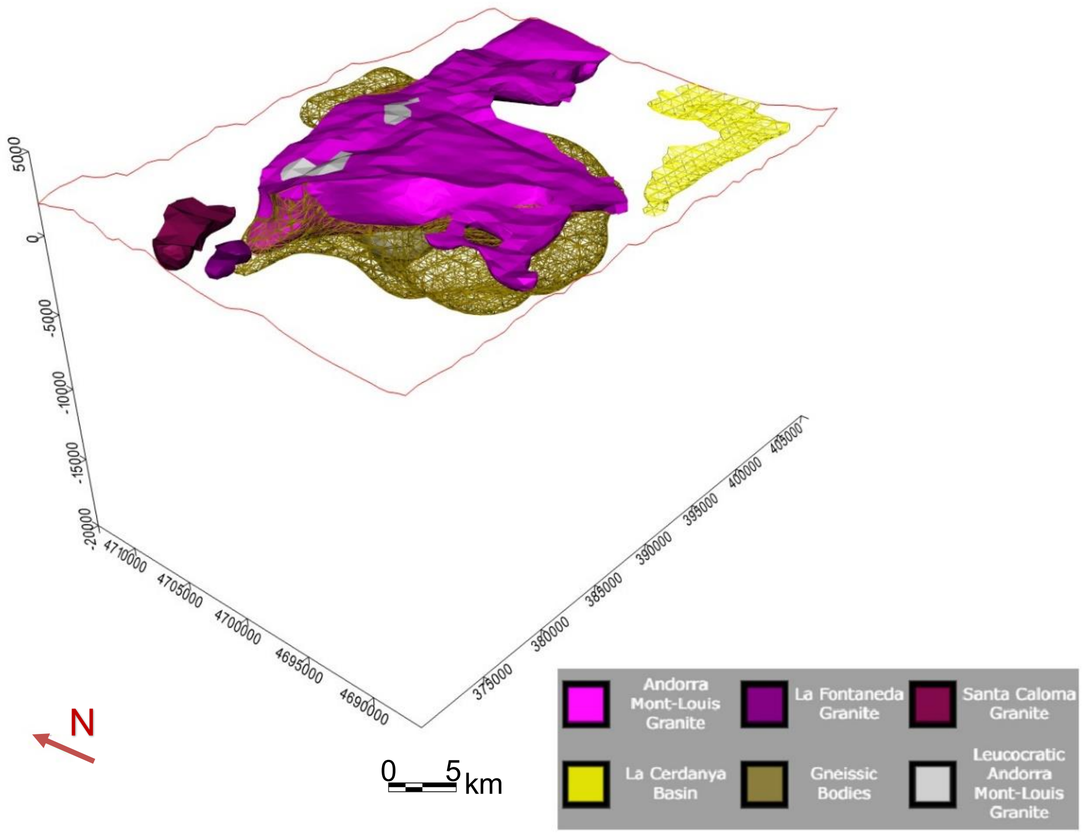

Figure 39 - AML's Final 3D Model

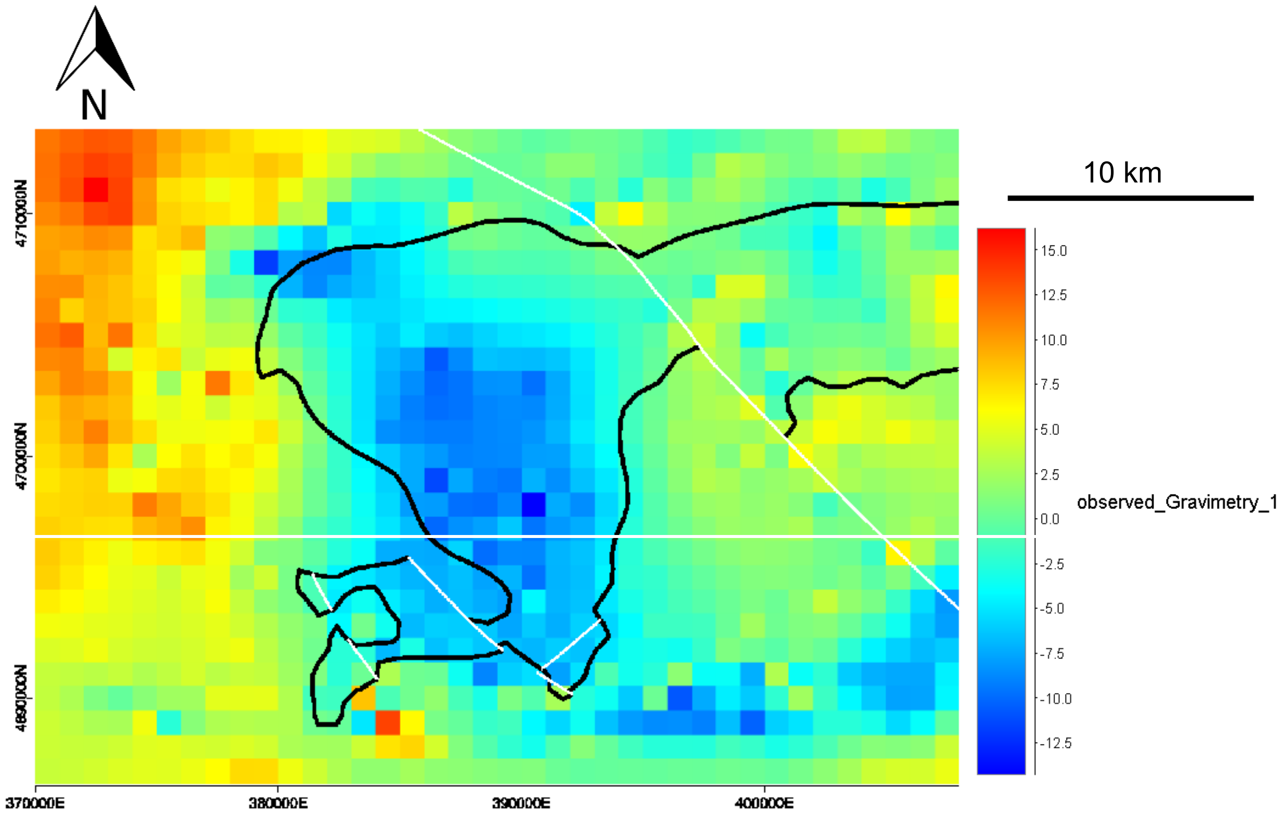

Figure 40 - Observed Gravimetry map of AML's study area (dX: 1000; dY: 1000)

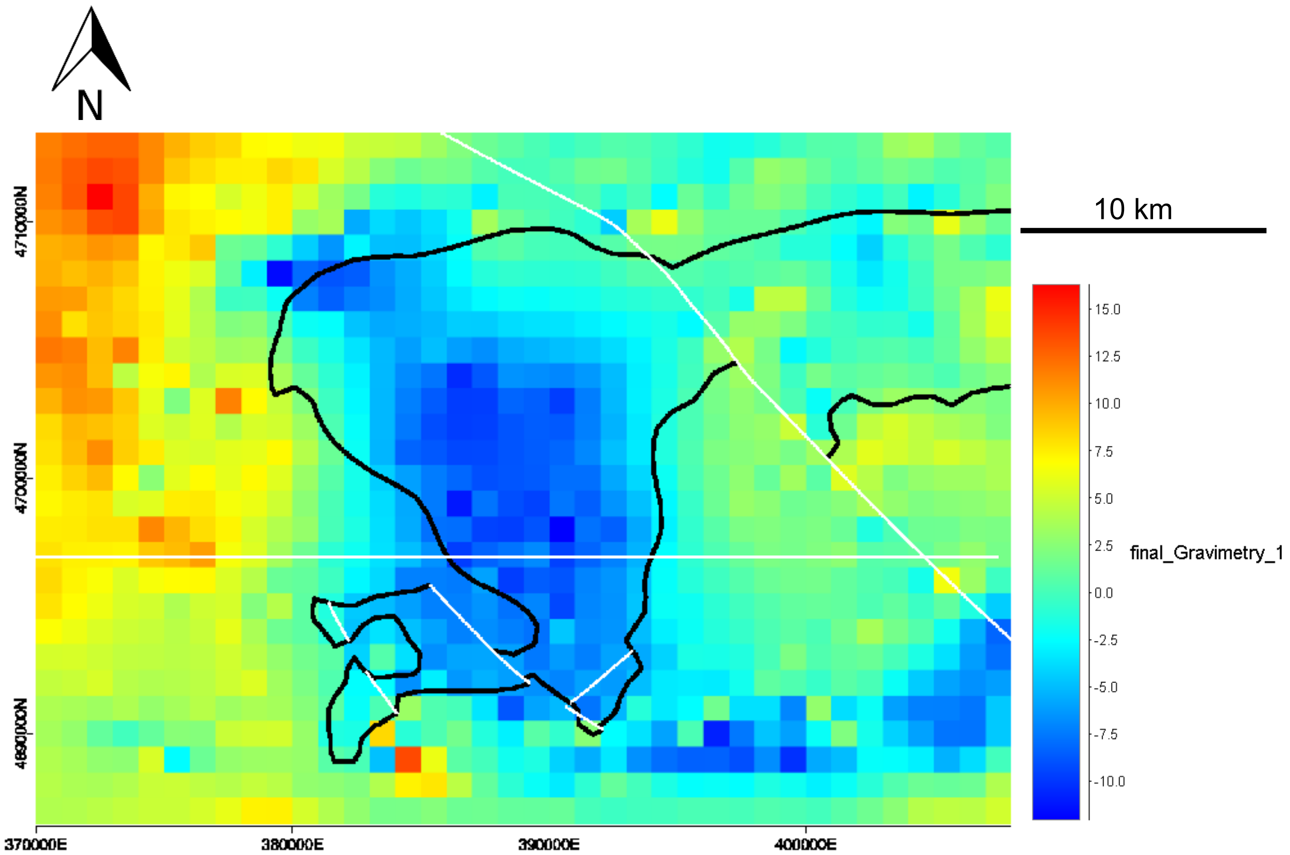

Figure 41 Final Calculated Gravimetry of AML's study area (dX: 1000; dY: 1000)

5 - Discussion

5.1 – VPAP

5.1.1 – Gravity Anomaly

The observed gravity anomaly map (Fig.42) for the VPAP helped evaluate an initial idea of the pluton's shape at depth.

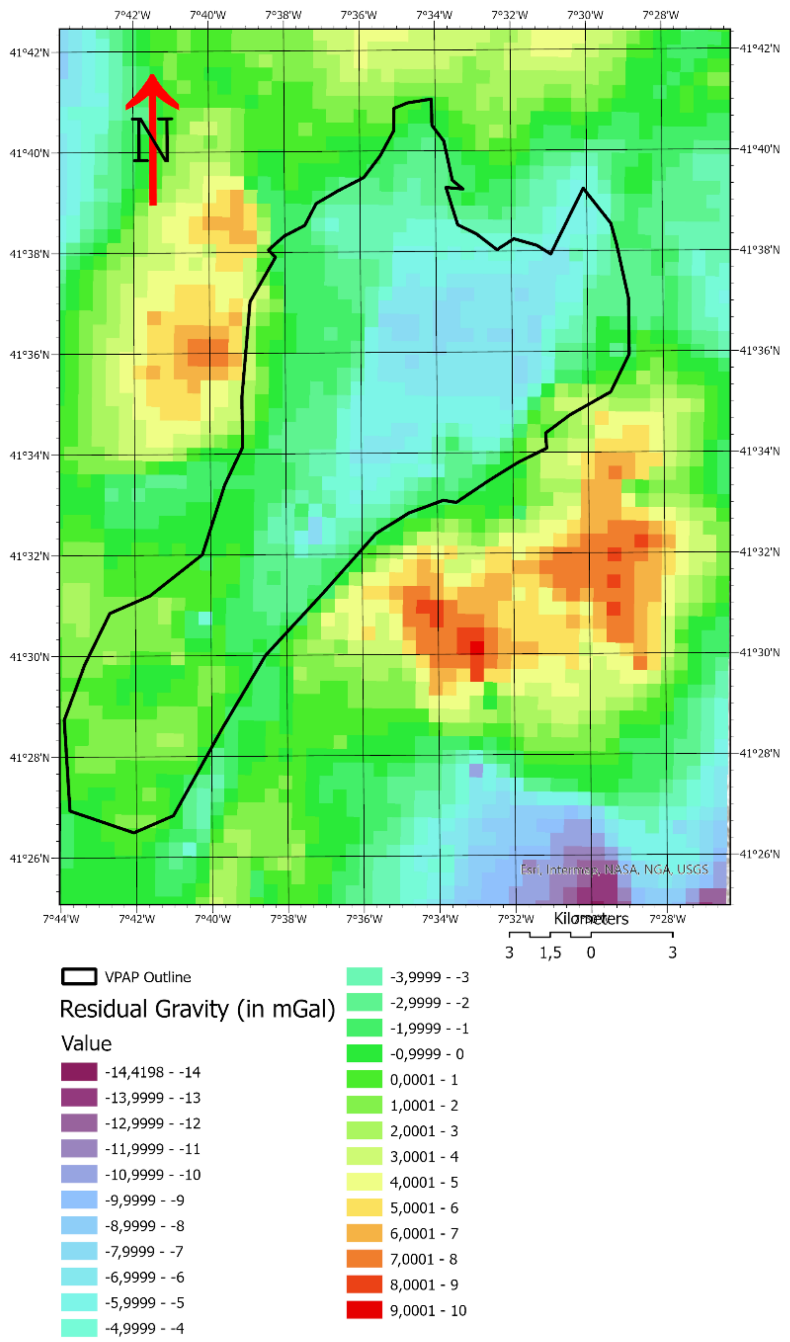

Figure 42 - Residual Anomaly Map of VPAP's study area.

The clear outline of the negative anomaly values approximately coincides with the outline of the outcrop. Based on the gravity pattern, we can observe a clear difference between the pluton density and the surrounding rocks in its central sector. Furthermore, the values progressively increase towards the plutons southern edge. That is explained by the theoretical existence of a metasedimentary rocks buried under the thin layer of VPAG, as they would help compensate the effect of the thin layer of VPAG covering them.

The most negative residual gravity values are concentrated near the central portion of the pluton, coinciding spatially with the trace of the Penacova-Régua-Verín Fault (PRVF) and its associated fault network. This structural zone is interpreted as the principal magma ascent pathway, where repeated fracturing facilitated magma transport and emplacement. The localization of the gravity minimum values in this area suggests that the pluton reaches its maximum thickness near this location in the PRVF, serving as yet another evidence of a root location in the area.

5.1.2 – 2D Model

With 2D modelling a geophysically constrained image of the plutons' geometry at depth was obtained. The first 2D Cross-Section were drawn by hand, based on the surface geology information. In them it was where the idea of metasedimentary bodies buried under the granite was first put forward. When digitised into Oasis Montaj, several adjustments were made to the cross-sections, especially for the depth of the pluton, the results of the modelling indicating that the depth was much shallower. The results of the modelling show a number of geologically plausible cross-sections. Here we see that the buried metasediments were gravimetrically necessary to obtain a model whose gravimetric response fitted the observed one.

In the Cross-section 2, as well in cross-sections 1 and 3, we can observe that the granite displays very little depth being laminar in shape. Cross-sections 4 and 5 display an increase in pluton depth with the appearance of the PSG. Cross-section 6 was plotted near the deepest point of the pluton and as so we see the biggest increase in depth, especially in the PSG portions, likely associated with the root of this magma pulse. Cross-Section seven displays a decrease in depth, after the possible magmatic root location. Lastly Cross-section 9 shows changes in depth of the pluton from north to south. We observe a pluton observe the borders of the pluton being thin and the core central portion of the structure being deeper.

It is important to indicate that the preliminary cross-sections allowed us to better visualise the existence of metasedimentary lithological units buried under the post-tectonic granites. This could cause negative gravity anomalies under the pluton associated with its low density. The likely explanation for this geometry is that during the variscan orogeny the syntectonic granite cut the metasediments from below, leaving a layer only on the surface.

Following this hypothesis, the results from the modelling indicate that the VPAG was emplaced, laterally truncating the metasedimentary units and effectively sealing them beneath the intrusion. As a result, a thin layer of metasediments remained preserved between the pre-existing granites and the VPA pluton.

Furthermore, the shape of the pluton was refined through the modelling. The edges resulted to be thinner than expected. 2D modelling also allowed for a better understanding of how depth changes happened along the pluton, with VPAG remaining mostly thin and shallow up to the core, where it gets deeper, in contrast to PSG which has a very steeply increases in depth, beneath the deepest portion of the plutonic body. In fact, the increase in depth of the PSG points out that the root of the pluton is likely to be where PSG achieves its greatest depth between cross-sections 5 and 6.

In Cross-section 9 we see that the pluton does not develop a thin layer to the north like it does to the south, that could be a clue of a directional magma chute. Possibly related to the hypothesis of the magma's origin being the same as the AFP's, giving the magma an origin point further north in the PRVF. This hypothesis will be discussed further in 5.6 section.

Two-dimensional models, once constrained by the gravity data, showed a robust picture of the plutons' geometry at depth. The initial cross-sections were drawn by hand from the available geological data. These preliminary cross-sections already incorporated the idea of metasedimentary bodies buried beneath the granite. When these sections were later digitised in Oasis Montaj, several adjustments were required, most notably to pluton depth, which, in many cases, had to be made considerably shallower than originally drawn. The result was a final set of cross-sections that were both consistent with the gravity data and geologically plausible. This process demonstrated that the buried metasediments were not only gravimetrically consistent, but in fact, necessary to adjust the observations.

Cross-section 2, along with cross-sections 1 and 3, shows very little depth and a broadly laminar geometry of the pluton. Cross-sections 4 and 5 record an increase in pluton depth coinciding with the appearance of the PSG. Cross-section 6, located near the deepest point of the pluton, shows the most pronounced increase in depth, particularly within the PSG, likely marking the root of this magma pulse. Cross-section 7 then shows a decrease in depth beyond the probable location of the magma conduit. Finally, cross-section 9 highlights the north–south variation in pluton depth, with the structure thinning markedly at its ends while deepening toward its central core.

These preliminary cross-sections were particularly valuable in revealing the presence of metasedimentary units buried beneath the post-tectonic granites. The most likely interpretation is that, during the Variscan orogeny, syntectonic granite replaced the metasediments from below, leaving only a thin remnant layer at the surface. The subsequent emplacement of the VPAG then laterally truncated these metasedimentary units, effectively sealing them beneath the intrusion. As a result, a thin layer of metasediments remains preserved between the pre-existing granites and the VPA pluton.

The 2D modelling also refined the overall shape of the pluton, showing its edges to be thinner than initially expected, and clarified how depth varies along its length. The VPAG remains largely thin and shallow except at its core, where it deepens, in marked contrast to the PSG, which increases in depth more steeply and constitutes the deepest portion of the plutonic body. This steep deepening of the PSG suggests that the root of the pluton lies where the PSG reaches its greatest depth, between cross-sections 5 and 6.

Notably, cross-section 9 shows that the pluton has different thickness to the north that it does to the south, a possible indication of a directional magma conduit. This observation may support the hypothesis that the magma shares a common origin with the AFP, sourced further north within the PRVF, a possibility explored in greater detail in Section 5.5.

5.1.3 – 3D Model

The final 3D model (Fig. 43) depicts the VPA pluton as a laccolithic intrusion with a pronounced root zone directly associated with the RVF (Fig. 44). The Vila Pouca de Aguiar Granite (VPAG) forms a thin sheet that thickens toward the pluton core, while the central PSG defines the main feeder structure responsible for magma ascent.

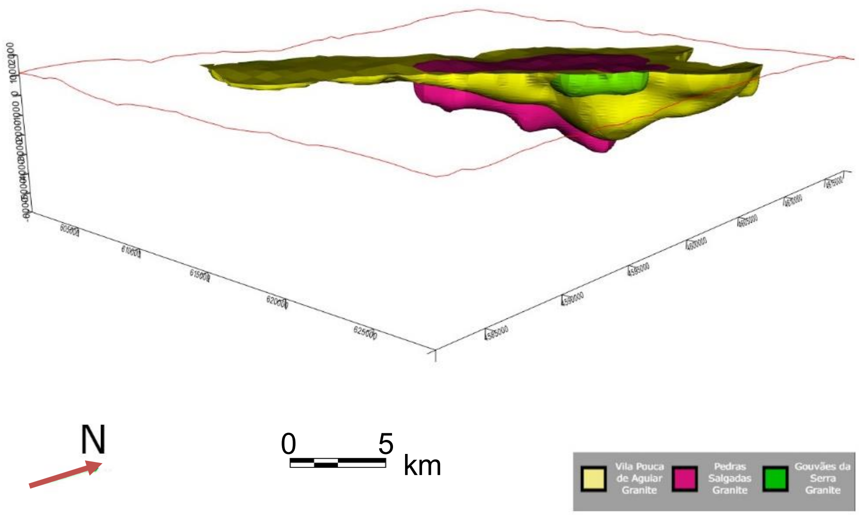

Figure 43 - Side view of the finished VPA model, with a visible thickening towards the north where the PSG granite is, and a very thin "tail" to the south, far from the core. View Direction: NW-SE

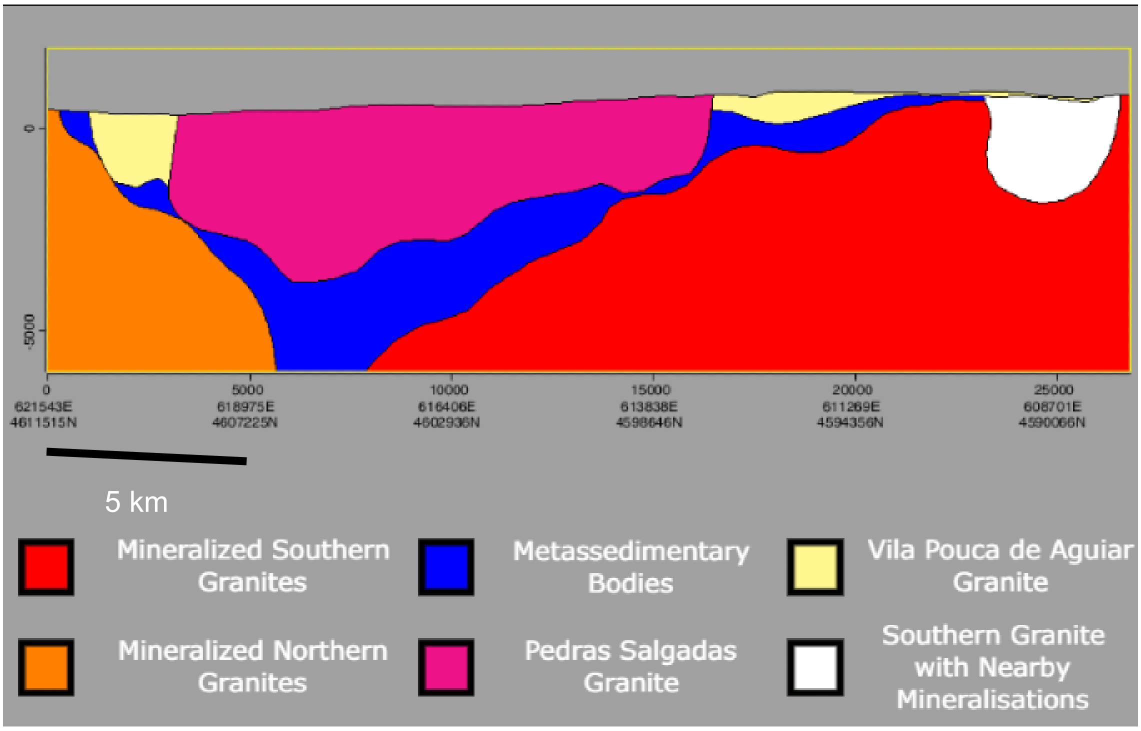

Figure 44 - VPAP's Cross-Section #9

The geometry of the model supports a structurally controlled emplacement, with the RVF acting as the primary magma pathway. Remnants of the GSG at the pluton margins suggest that earlier granitic units may have once partially enclosed the intrusion from above but were subsequently removed by erosion.

5.2 – AFP

5.2.1 – Gravity Anomaly

Unlike other plutons, in which the plutons' gravimetric signature is easily visible in the anomaly map due to their low-density values, AFP is much difficult to distinguish because is limited by a big Cenozoic sedimentary deposit, the CSB, which has, on average, a much lower density value of 1.4 g/cm3. Outside the sedimentary deposits, a few gravity minima are displayed in the residual anomaly map (Fig.45).

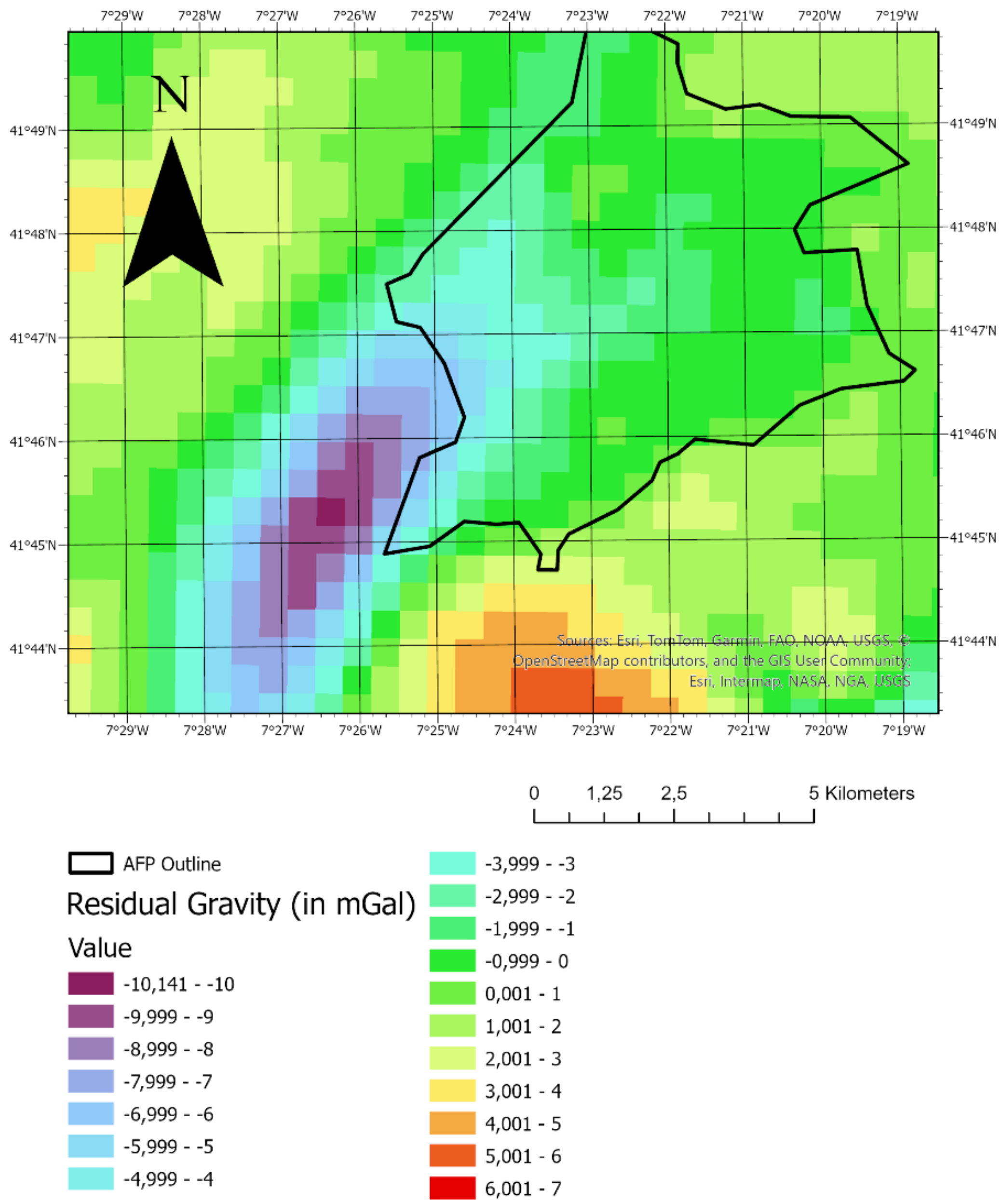

Figure 45 - Residual Gravity Maps of AFP's study area

These are located on what the geological map shows to be inside the bounds of the SAMG and seem to be the location of the deep roots of the AFP, where the SAMG extends in great depth creating this gravity signature.

This would point to the root's location. One deep root over the lower gravity values, located near the centre of the SAMG, and also on the part of the PRVF. Once again, we see that the PRVF can be interpreted as the main magma ascent pathway and as a facilitator of magma transport and emplacement.

5.2.2 – 2D Model

With the 2D modelling of the AFP, a significant increase in pluton depth was observed. In particular, a pronounced root developed beneath the area where multiple fault systems intersect the pluton, resulting in a substantial deepening of the intrusive body.

Two key observations emerged from the modelling process. First, the results confirmed that the SAMG is characterised by being part of a pronounced deep root, indicating a strong wedge shape. Second, the CSB proved to be a significant challenge for the modelling effort. Owing to its exceptionally low density, the CSB generates a strong gravity minimum that exerts a considerable influence on the surrounding profile. During the initial stages of 2D modelling, the pluton was represented with only a single root. As improving the understanding of how the system evolved, the cross-sections were revisited to assess the geophysical plausibility of a more complex geometry. Adjustments were made to the dimensions of the pluton in cross-section 3 to improve the fit between observed and calculated anomalies.

Cross-section 4 was initially discarded due to the difficulties to adjust the anomalies with a geologically sound geometry for the granite and the CSB. Once more geological and petrophysical information was incorporated to the modelling, and the observed gravity was adjusted with a geologically consistent model, solution had been identified, however, cross-section 4 was subsequently digitised and incorporated into the 3D model.

5.2.3 – 3D Model

The final 3D model reveals a rapid increase in pluton depth, particularly within the SAMG, which develops two distinct roots. The deeper root is located near the centre of the pluton and is interpreted to be controlled by the PRVF. A second, smaller root is associated with subtle gravity anomalies identified northeast of the pluton.

Accordingly, the final model depicts a zoned, wedge-shaped plutonic complex. The AFG forms the outer portion of the intrusion and extends to depths of approximately 10 km, whereas the SAMG continues to greater depths, reaching approximately 16 km. The secondary root is less developed, extending to depths of around 8 km. As in the 2D models, the influence of the PRVF appears to be a fundamental control on magma emplacement and pluton geometry. The relationship between the AFP and the PRVF may therefore be comparable to that previously proposed for the VPAP and the PRVF.

Ultimately, the misfits associated by the CSB could not be satisfactorily reconciled within the model. The calculated gravity anomaly over the CSB yielded results that were not considered geologically plausible. Owing to time constraints, it was not possible to obtain a solution that simultaneously accounted for the CSB while preserving the consistency of the remainder of the model. Nevertheless, because the primary objective of this study was the modelling of the AFP rather than the CSB, and because the resulting misfit did not significantly affect the areas occupied by the AFP, this discrepancy was considered acceptable for the purposes of this study and was excluded from subsequent interpretation.

5.3 – LM

5.3.1 – 2D Model

The 2D cross-sections of the LM were largely based on previously published models (e.g. Clariana et al., 2021, Soto et al., 2022). More recent magnetotelluric studies (Piña-Varas et al., 2023) indicate a two-body configuration, contrasting with the single-body interpretations proposed in earlier works. This revised interpretation fundamentally changes the conceptual model of the pluton. Rather than being interpreted as a single intrusive body with a pronounced northward-dipping root closely associated with the thrust system, the pluton is now understood as comprising two distinct but genetically related bodies (Fig.46). Although these bodies remain connected and likely derive from a common magmatic source, their geometry no longer supports the interpretation of a single rooted pluton.

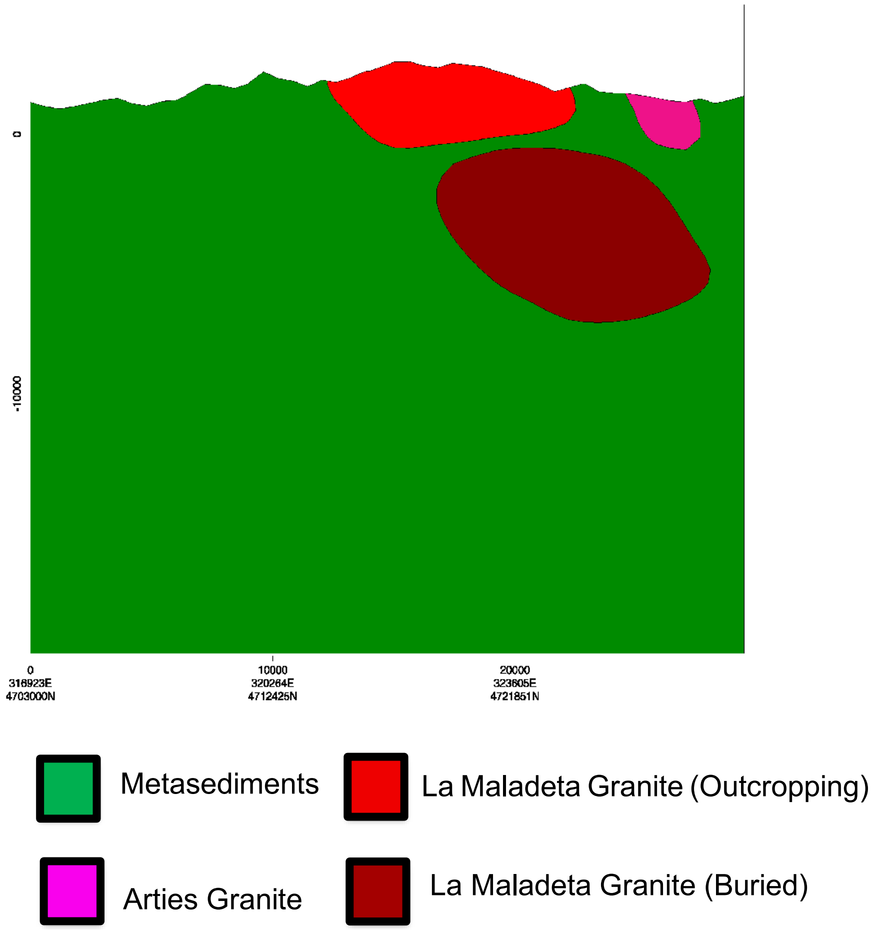

Figure 46 - La Maladeta cross-section B-B'

5.3.2 – 3D Model

The 3D model of LM refined the interpretation of the pluton as being composed of two distinct bodies. The main body is a long and relatively thin pluton. The second body is a smaller round shaped plutonic body with a strong tilt northward. This body is likely the reason behind the gravity signature of the north of the pluton. The origin of these two bodies is likely associated with two magmatic pulses (Piña-Varas et al., 2023).

5.4 – AML

5.4.1 – 3D model

For AML the 3D model displays a classic batholithic shape. The plutons root lies approximately at its center. It is thickest at its center and progressively thins towards its edges. In most of its central section, the pluton is surrounded by a gneiss related to the L'hospitalet gneiss that outcrops further north. The gneiss has slightly lower density and form a thin sheet that covers the bottom of most of the pluton. La Cerdanya basin, located to the SE of the granite, basin also presented modelling challenges, similar to those encountered in the AFP, but after constraining its geometry the associated gravity signature became manageable, and a geophysically consistent solution was obtained. The broader AML study area forms part of the Pyrenean Axial Zone, where Alpine deformation involved Paleozoic basement thrust sheets and the reactivation of inherited structures. However, the Andorra–Mont-Louis pluton should not be described as a body fractured into three parts as a direct result of Alpine fault reactivation. Instead, it is better interpreted as a composite late-Variscan pluton, whose internal subdivision mainly reflects its Variscan emplacement history (Maurel et al., 2004). Gravity-constrained modelling further indicates that the Andorra–Mont-Louis granite has a more batholithic geometry, locally associated with an underlying lower-density gneiss dome, rather than a simply tilted or fractured pluton (Soto et al., 2022).

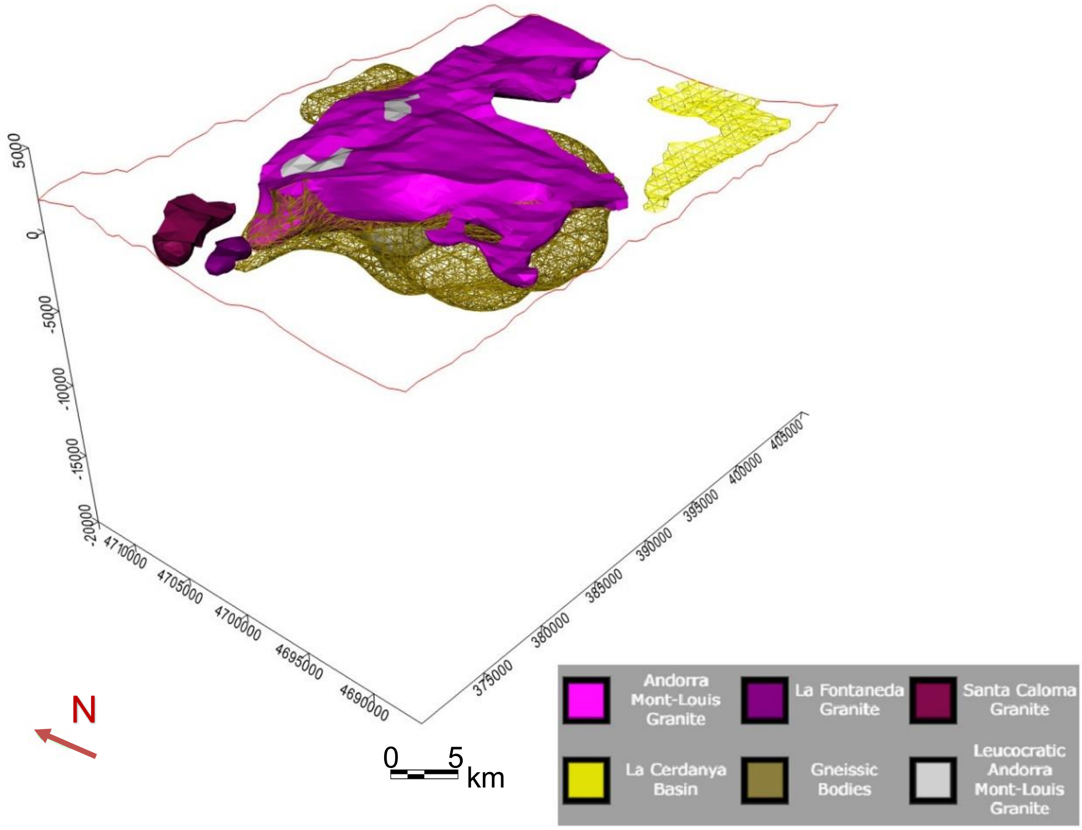

Figure 47 - Andorra Mont-Louis final 3D model

5.5 - Pluton Comparison

The final stage of this study involved comparing the granitic bodies of northern Portugal with those of the Pyrenees. As concluded from the modelling results, several notable similarities exist between these intrusions, particularly among the laccolithic Vila Pouca de Aguiar Pluton (VPAP), the La Maladeta Pluton (LMP), and the Andorra-Mont Louis Pluton (AMLP). These plutonic bodies share a common architecture characterised by one or more feeder zones or root structures from where the magma propagated upward and laterally to form intrusive bodies whose surface outcrops are considerably larger than their source regions.

Despite these similarities, important differences become apparent when considering the size, geometry, and spatial distribution of the root zones. The Portuguese plutons are generally smaller in size than their Pyrenean counterparts. Furthermore, the root zones of the Pyrenean plutons are typically offset from the centre of the intrusion, commonly occurring along their northern margins and expanding southwards where they are usually thinner. In contrast, the Portuguese plutons are characterised by centrally located roots from which the intrusive bodies expand radially outward.

A structure of regional significance is the PRVF, which appears to have exerted a fundamental control on magma emplacement within both the AFP and VPAP. In both cases, the geometry of the plutons and the location of their principal root zones suggest a strong structural influence exerted by this fault system. The similarities observed between the two plutons may therefore reflect a common emplacement mechanism governed by the PRVF. Given additional time and data, a logical continuation of this work would involve testing the hypothesis proposed by Martins et al. (2007) that the VPAP and AFP may be connected at depth. Three-dimensional gravity modelling of a unified subsurface structure could provide valuable insights into the extent of magmatic connectivity between these plutonic systems and further constrain the role of the PRVF in regional magma transport.

A further distinction concerns the influence of Alpine tectonics on the Pyrenean plutons. Alpine tectonism significantly affected their present-day position and outcrops. Regional uplift associated with the Alpine Orogeny contributed to their exhumation. Consequently, while the overall geometry of the Pyrenean plutons may have been preserved, they were subjected to uplift, tilting, and fault reactivation. Evidence for this fault reactivation is particularly apparent within the AMLP, where the thinner portions of the batholith are affected by prominent fracture systems, dividing the pluton into three parts as mentioned before.

5.5.1 - Comparison with previous research

The results from the present study broadly supports several interpretations proposed in previous geological and geophysical investigations while also providing new constraints on the subsurface geometry of the studied plutons through integrated gravity modelling.

For the Vila Pouca de Aguiar Pluton (VPAP), previous studies suggested a laccolithic geometry emplaced along the Penacova–Régua–Verín Fault (PRVF), with emplacement strongly controlled by pre-existing crustal structures and local host-rock anisotropies. The gravity-derived model obtained in this study supports these interpretations, revealing a centrally rooted intrusion with lateral expansion towards the margins. Furthermore, the model indicates the presence of low-density material beneath portions of the pluton, consistent with the hypothesis that metasedimentary units may remain preserved beneath the granitic body. These results reinforce previous interpretations regarding the structural control exerted by the PRVF while providing additional three-dimensional constraints on pluton geometry.

The Águas Frias Pluton (AFP) has previously been interpreted as a wedge-shaped intrusion associated with late-Variscan tectonic structures and spatially related to the Chaves Sedimentary Basin. The gravity model developed in this study is consistent with this interpretation, reproducing the asymmetric geometry proposed by earlier works. However, the present model highlights the importance of density contrasts associated with the sedimentary basin in controlling the observed gravity response, suggesting that the current geometry may result from the combined influence of magmatic emplacement processes and subsequent basin development.

For the La Maladeta Pluton (LMP), previous geological and geophysical studies proposed a complex emplacement history involving two magmatic pulses and significant structural control by major Pyrenean tectonic structures, as deduced from the magnetotelluric constraints (Piña-Varas et al., 2023). The present modelling results generally support these interpretations, reproducing a laccolithic geometry with a northern-rooted feeder zone. Although gravity data alone cannot uniquely constrain feeder geometries, the results are consistent with previously proposed emplacement mechanisms (Piña-Varas et al., 2023; Leblanc et al.,1994).

The Andorra Mont-Louis Pluton (AMLP) has been interpreted as a composite intrusion strongly affected by subsequent Alpine deformation. The present model agrees with this interpretation, showing an asymmetric geometry and a displaced root zone with a gneiss beneath the granite. Compared to the Portuguese plutons, the AMLP exhibits a greater degree of structural deformation, which is interpreted as reflecting the stronger tectonic overprint associated with Alpine compression. This observation supports previous studies (Ayala et al.,2020; Ayala et al. 2021; Clariana et al., 2021) suggesting that Alpine orogeny played a significant role in the present-day position and some geometric features of Pyrenean plutonic bodies.

Overall, the results obtained in this work are in agreement with previously published geological and geophysical interpretations. This work presents the first, gravity-constrained three-dimensional models of the plutons, providing a more detailed characterization of pluton geometries and root locations, allowing a direct comparison between the emplacement mechanisms of the plutons in different tectonic settings. The comparison suggests that inherited crustal structures and host-rock properties exert a major control on pluton architecture, while subsequent tectonic events may significantly modify their present-day geometry. These results complement existing models and contribute to a better understanding of the factors controlling granite emplacement in Variscan terranes and its subsequent deformations due to the Alpine orogeny.

Conclusion

This work was able to successfully investigate the 3D subsurface geometry of the Vila Pouca de Aguiar, Águas Frias, La Maladeta and Andorra Mont-Louis plutons, integrating gravity data, geological cartography, density data and 3D forward and inversion modelling. From 2D modelling of the residual gravity anomalies of cross-sections constrained by density data and geological interpretations, it has been possible to build up 3D models that are consistent with geophysical observations, petrophysical data and regional geological knowledge.

Forward gravity modelling has helped to create a model whose gravimetric response pattern was close to the observed one. Gravity inversion has been used to refine the models, ensuring a geologically consistent model while achieving a good fit between the computed and observed residual gravity anomalies.

For Vila Pouca de Aguiar, residual gravity associated with the pluton is characterized by a strong negative signature that closely traces the surface outcrop. The location of the most negative gravity values in the central sector of the pluton, in the intersection of the Penacova-Régua-Verín Fault or subsidiary faults, suggests that this major structure played a fundamental role in controlling magma ascent and emplacement. The gravity data therefore provide independent support for a structurally controlled emplacement model.

A marked increase in depth towards the central sector and progressive thinning towards the margins, consistent with laccolithic geometry, were deduced during the interpretation of gravity-constrained 2D cross-sections. It was assumed that magma accumulated laterally at shallow crustal level while remaining connected to a deeper feeder zone. The possible presence of buried metasedimentary units beneath parts of the pluton further highlights the complex interaction between successive intrusive phases and pre-existing lithologies during the Variscan orogeny.

The final 3D geological model reinforces these interpretations. The Pedras Salgadas granite forms a deeper-rooted core aligned with the Penacova-Régua-Verin Fault, while the Vila Pouca de Aguiar Granite forms a thinner sheet that thickens towards the pluton's centre. Variations in density within surrounding granitic bodies, interpreted as reflecting mineralization or compositional heterogeneity, were necessary to achieve an improved fit between observed and computed gravity anomalies.

In the AFP study area, it is possible to see that the CSB creates a strong gravimetric signature due to its low density. These density values interfere with results due to their extreme effect on gravity readings, altering the gravity signature of nearby structures like the AFP. The border between the CSB and the AFP is also delineated by the PRVF, once again displaying the importance of this major structure.

2D and 3D Modelling allowed for a visualisation of the plutons wedge shape, with deep roots, with one also closely associated with PRVF, where, once again, it has served as a controlling factor in magma ascent and emplacement. The roots steeply reach depths of up to Sixteen Kilometres for the SAMG and ten kilometres for the AFG. Although the pluton misfit was minimal, issues with the CSB gravity signature persisted.

In the Pyrenees, previously existing 2D cross-sections were slightly modified and used to create the 3D models.

In LM, some of the cross-sections were modified, according to the results of the previous magnetotelluric interpretation, changing the pluton into two bodies instead of one. The 3D model revealed the LM is composed by a laccolithic pluton that outcrops into where it is found today, and a second body buried under the main pluton, reaching 6km in depth. Both granites have a pronounced tilt to the north.

AML 3D modelling displayed a complex batholithic pluton. It has a central root that coincides with a leucocratic zone that causes a gravity minimum. The AML displays strong signs of fracturing related to the Alpine Orogeny event. The bottom of the pluton is underlined with a thin layer of gneiss, probably related to L'Hospitalet Gneiss. In the study area, at the southeastern part of the main pluton, the La Cerdanya Basin is characterized by strong low density gravity signature that does not seem to have affected the shape of the granite.

These plutons compare on many metrics. For example, both LM and VPAP are laccolithic plutons, and both AML and AFP have a sedimentary basin with a strong low density gravity signature on their borders.

The shared impact of the PRVF proved an important factor in magma emplacement and control for VPAP and AFP, relating the two plutons.

The impact of Alpine Orogeny also proved important for both pyrenean plutons, as both plutons experienced extreme uplift, and with AML showing a noticeable tilt due to its emplacement along a previous fault. Another result of Alpine Orogeny is the fracturing we see in these plutons. Multiple fractures we see cutting across the AML pluton may be the result of reactivated faults during the orogeny. This sets the pyrenean plutons apart from the Portuguese ones as the north Portuguese plutons did not experience the impacts of Alpine orogeny, remaining largely unaffected, with no noticeable changes to their shape and geometry.

These results present a robust and consistent interpretation of the plutons' geometry at depth, highlighting the importance of integrating integration of geological knowledge with gravity modelling and incorporating other geophysical constraints, like magnetotelluric data.

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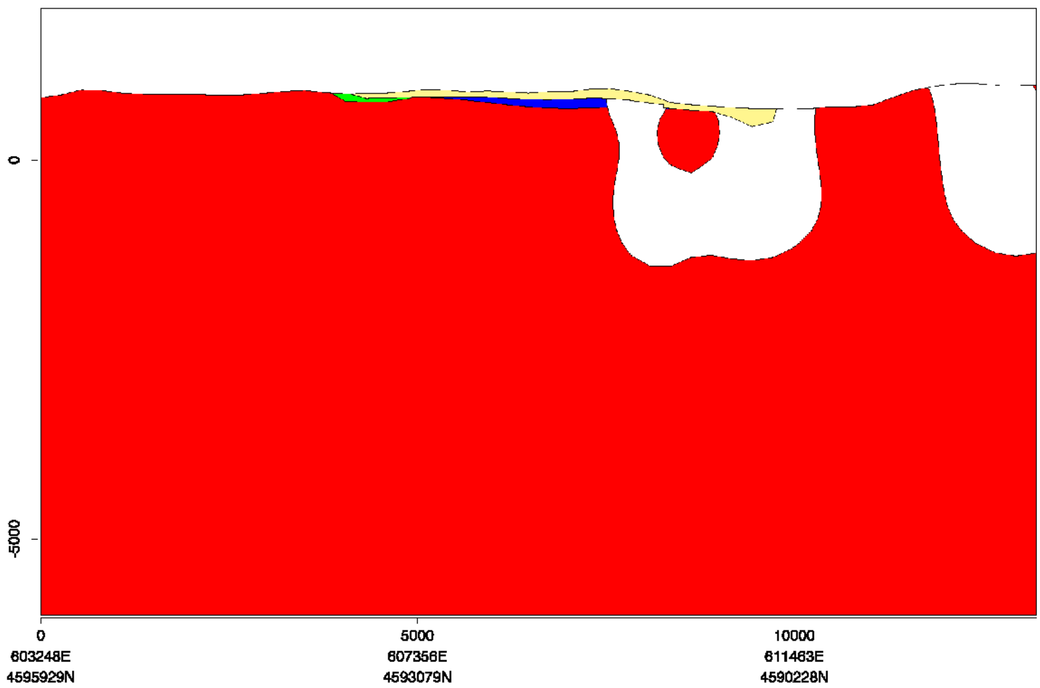
Attachment - Library of 2D Cross sections in Geomodeller

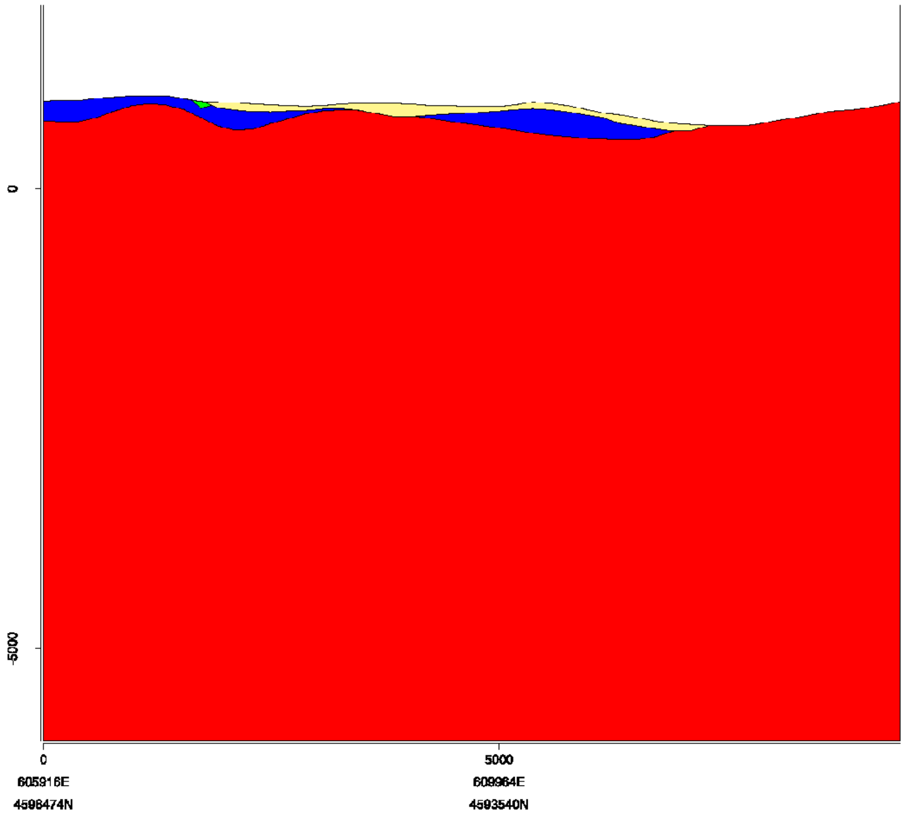
This attachment is a library of all digitised cross-sections into geomodeller. The colour schemes used correspond to the same units in their respective cross-sections shown before.

VPAP

1



2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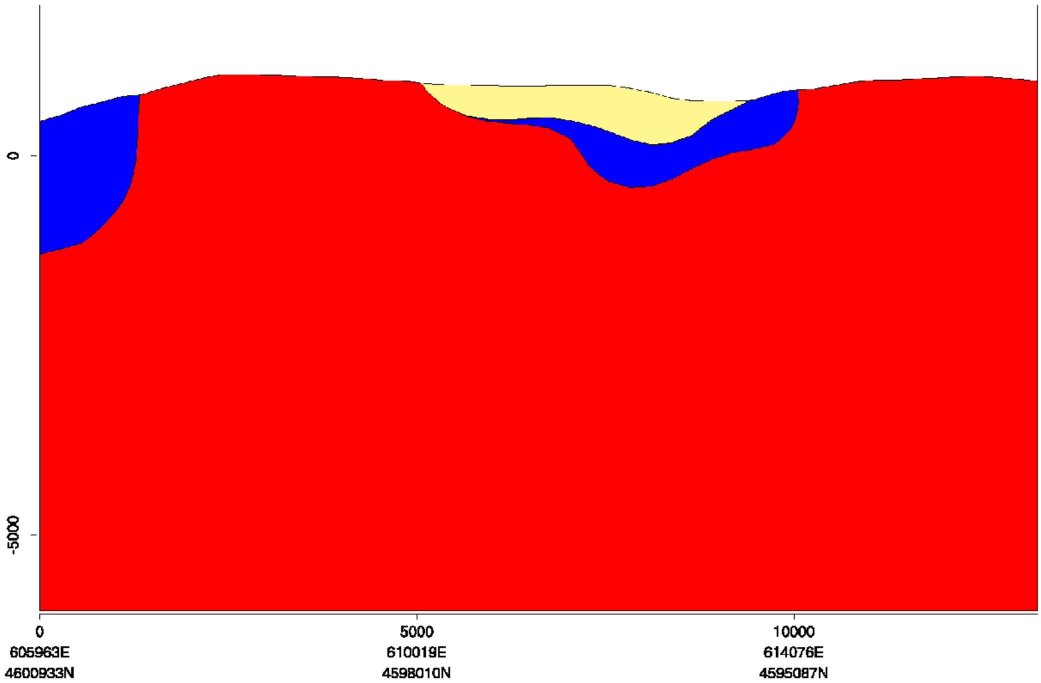
0
5000
605916E
4596474N
609964E
4593540N

3


0
-5000
0
5000
10000
605963E
4600933N
610019E
4598010N
614076E
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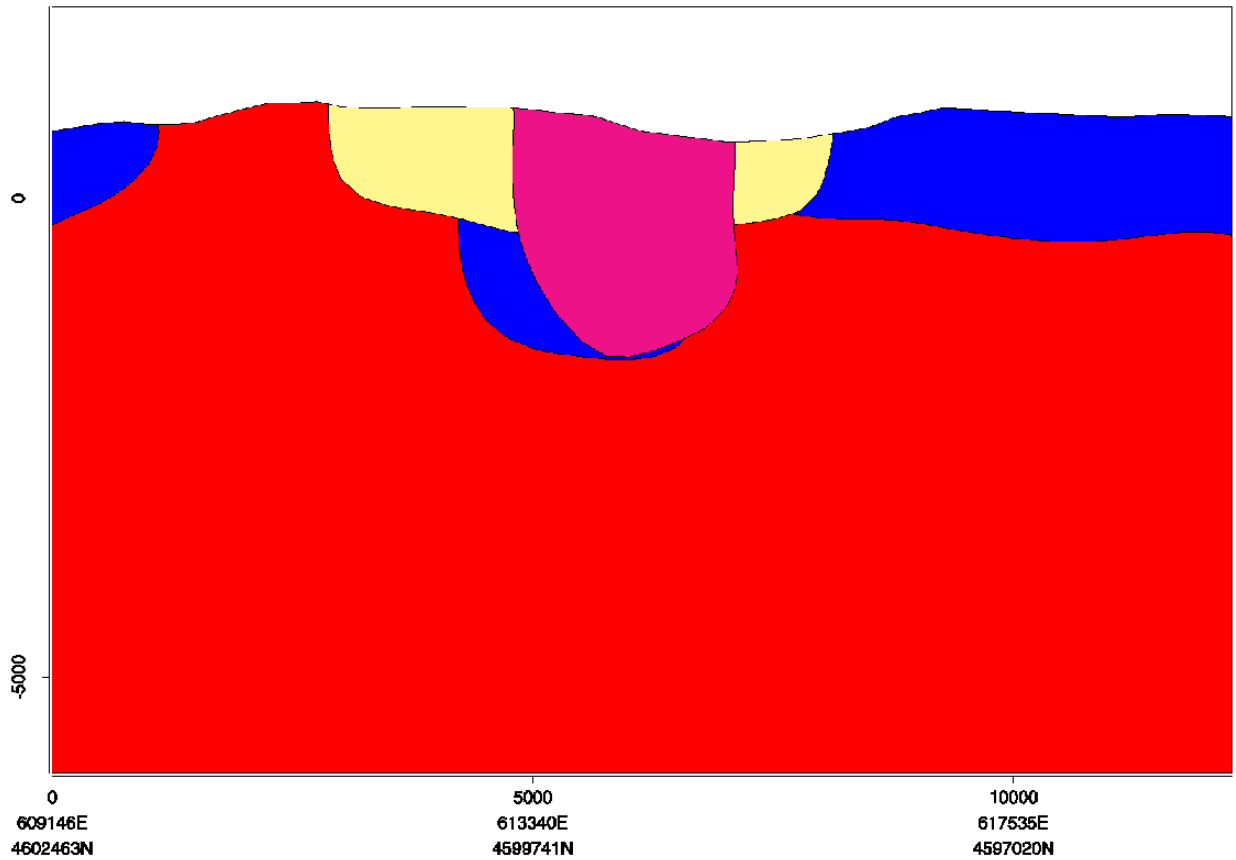
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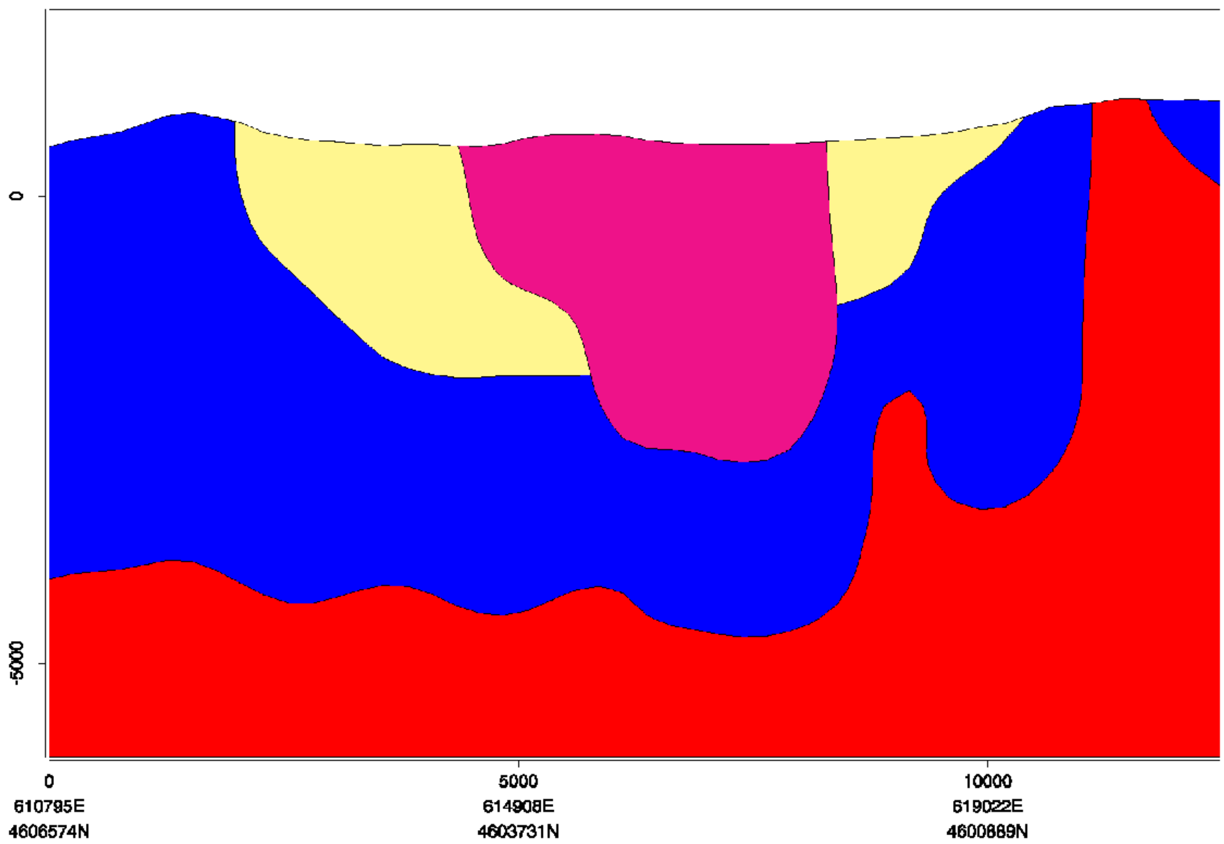
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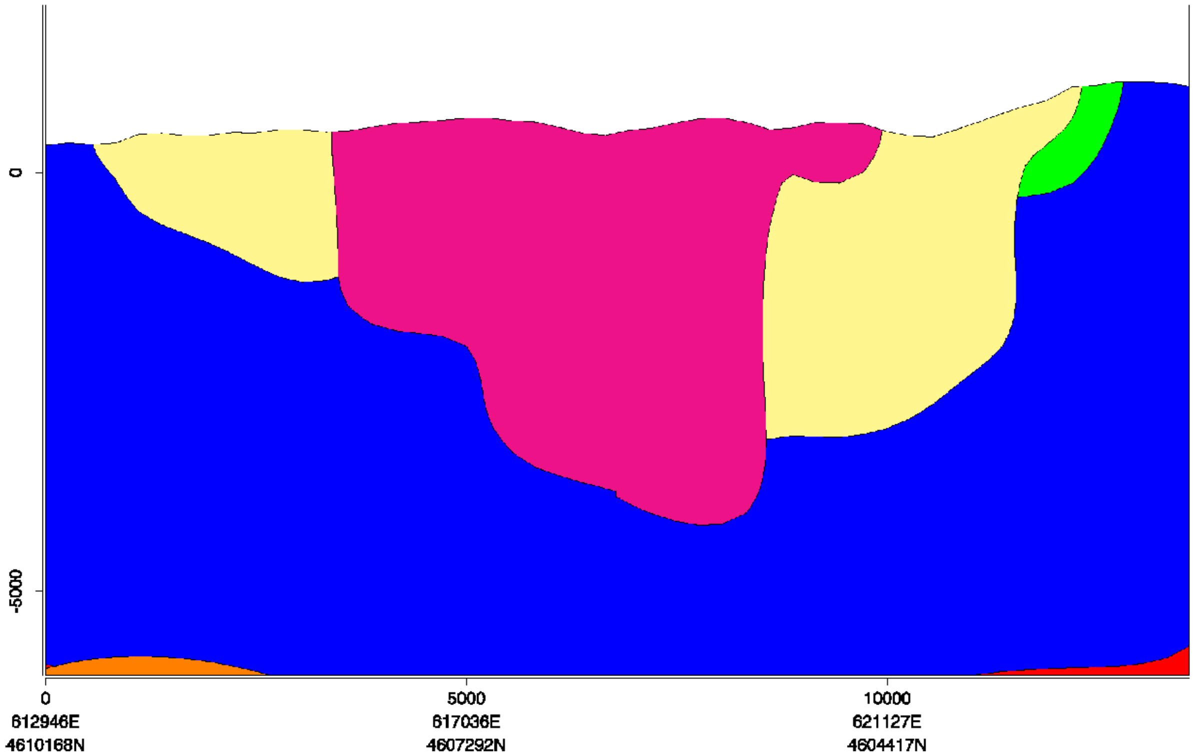
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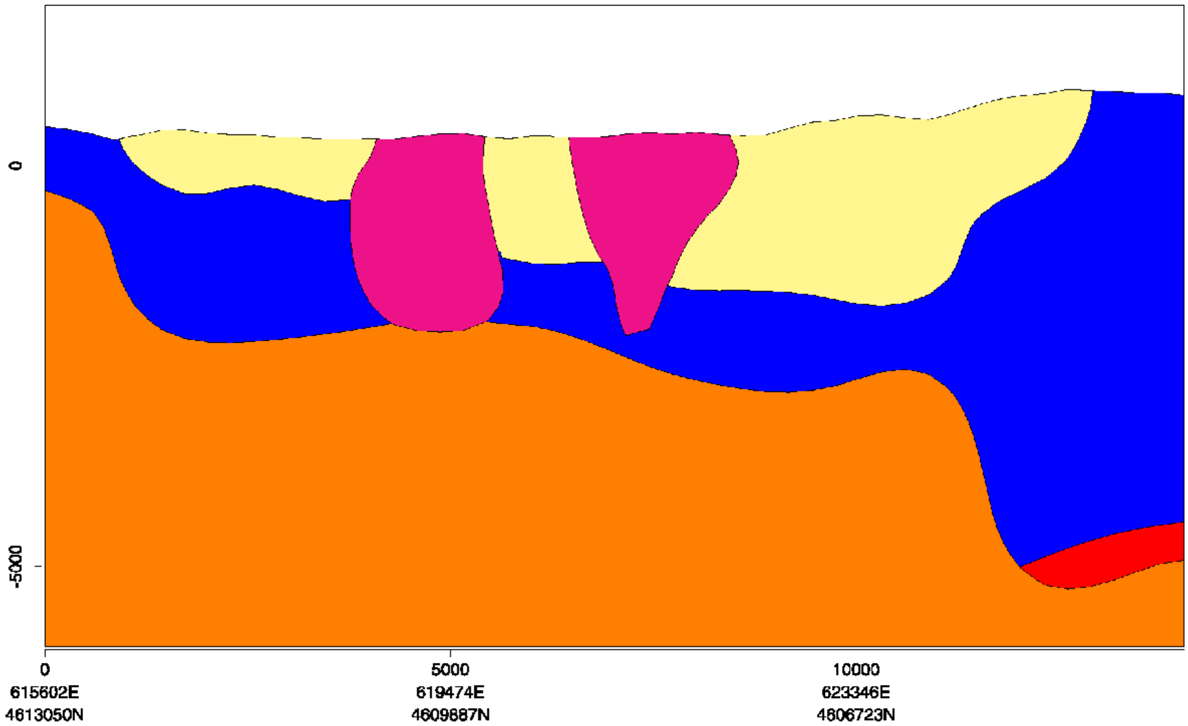
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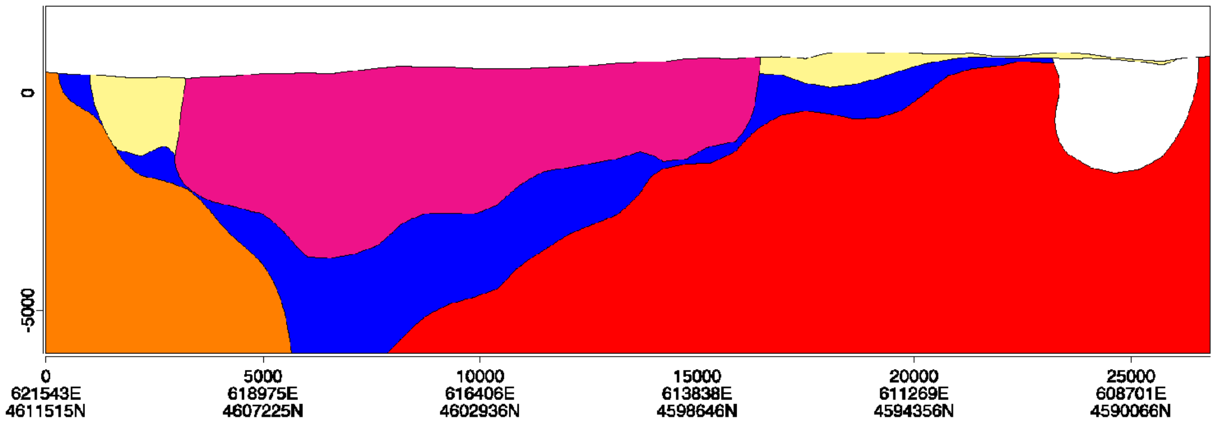
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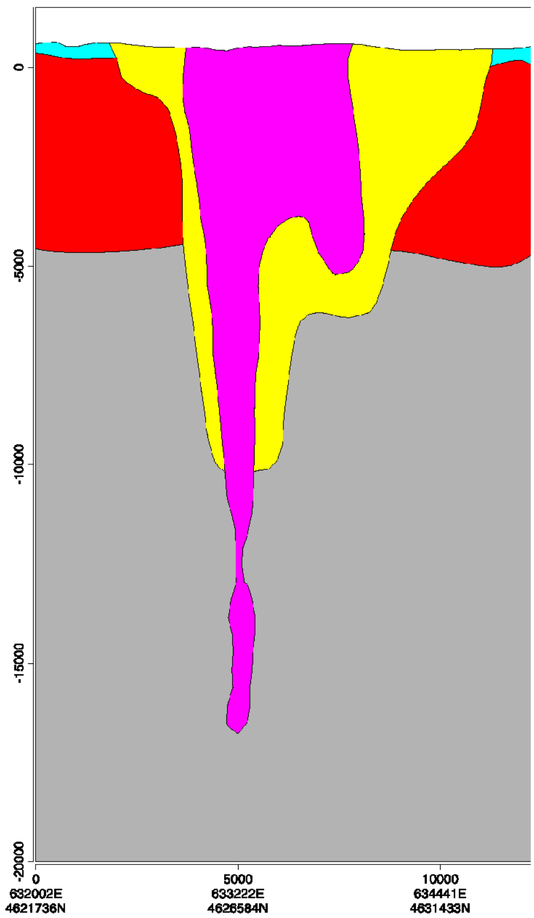
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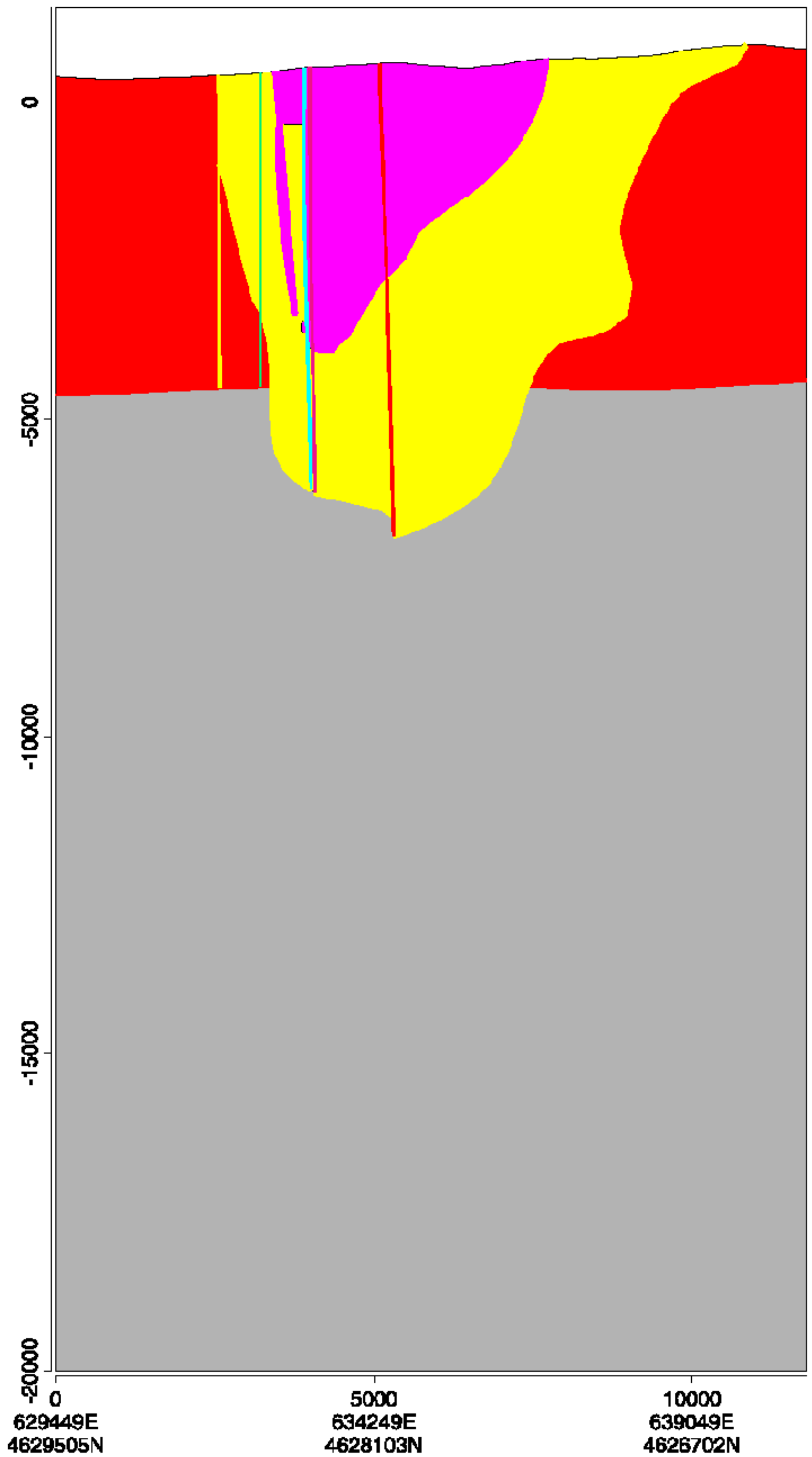
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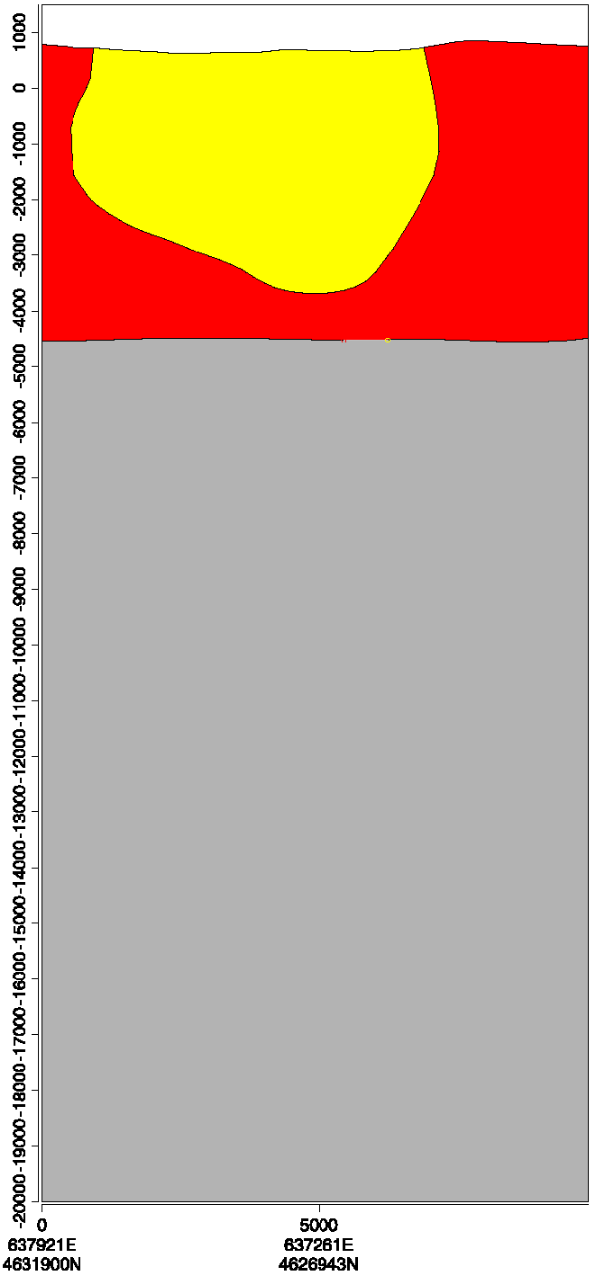
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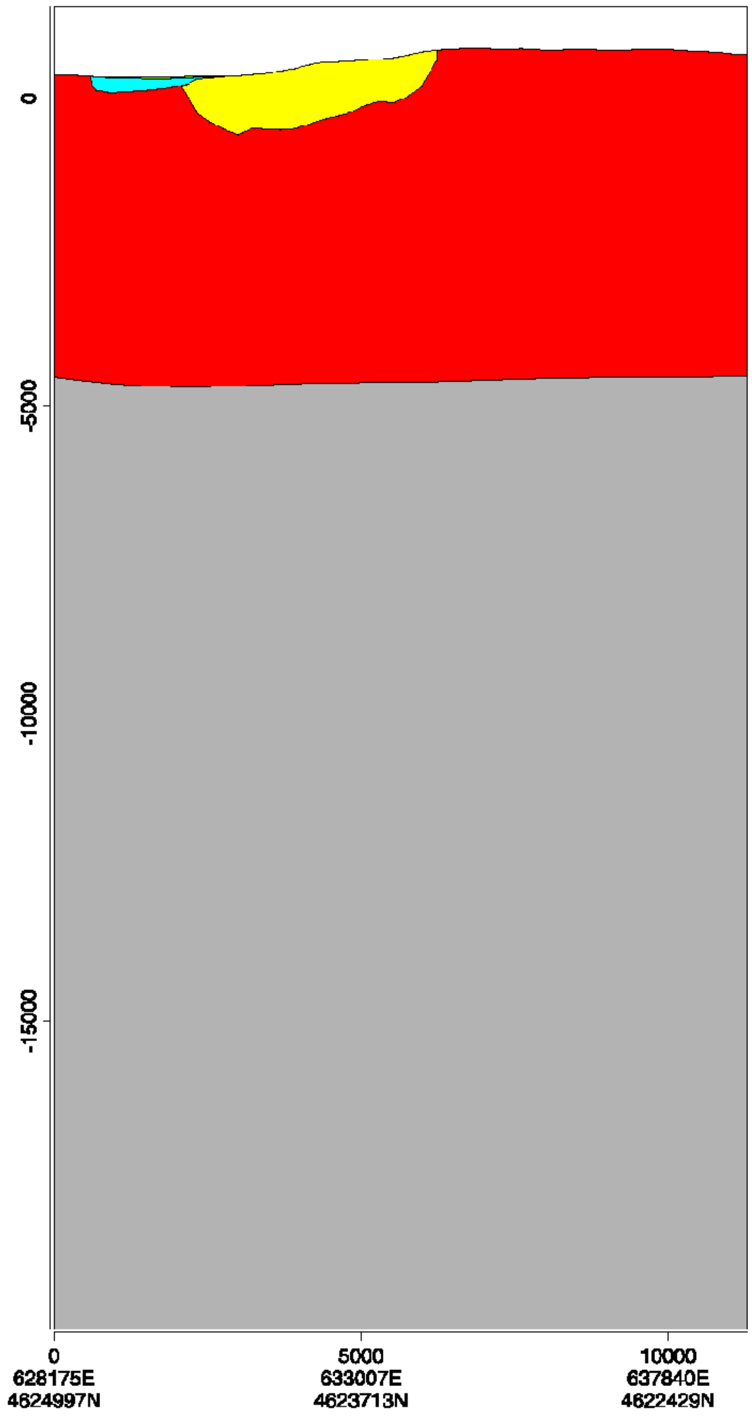
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LM

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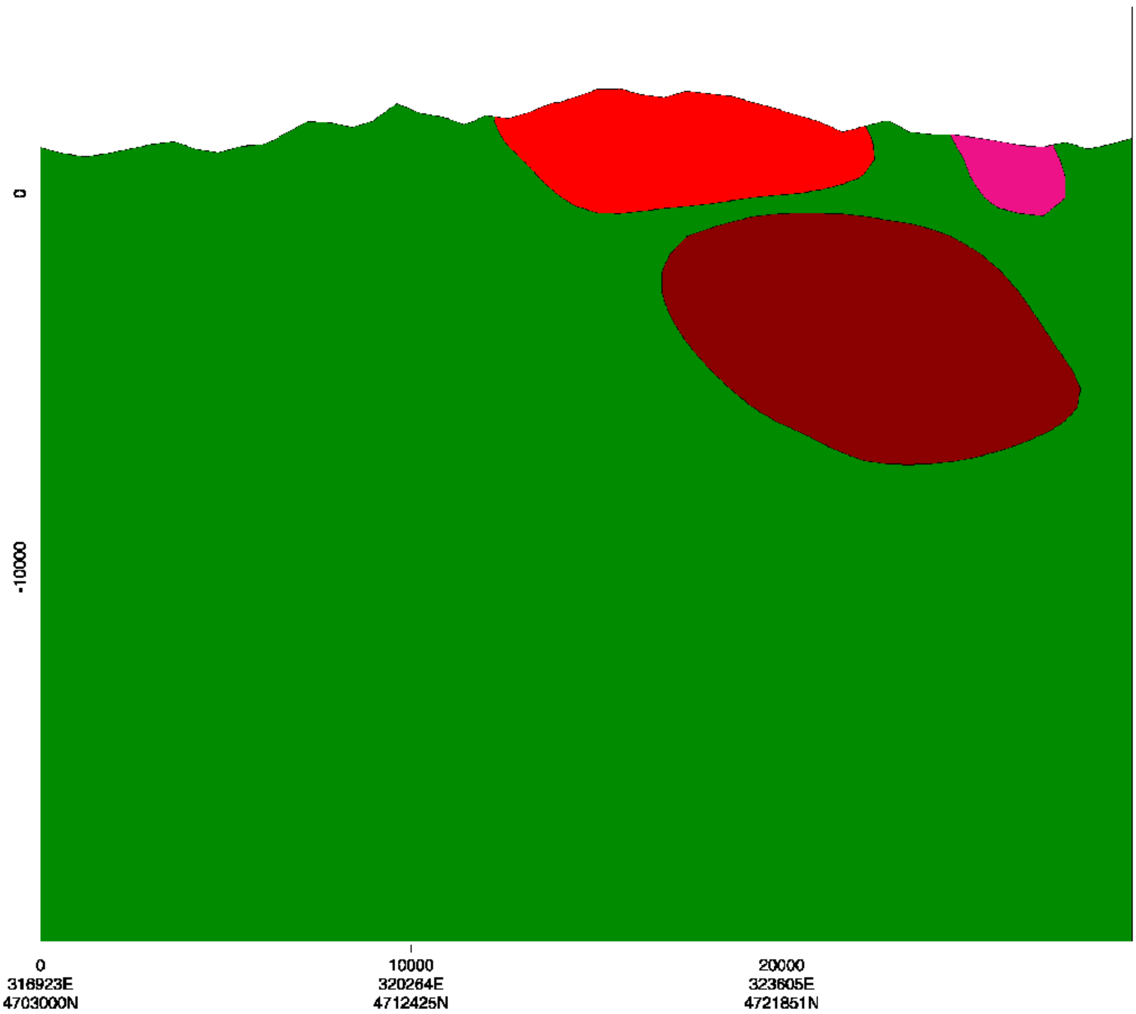
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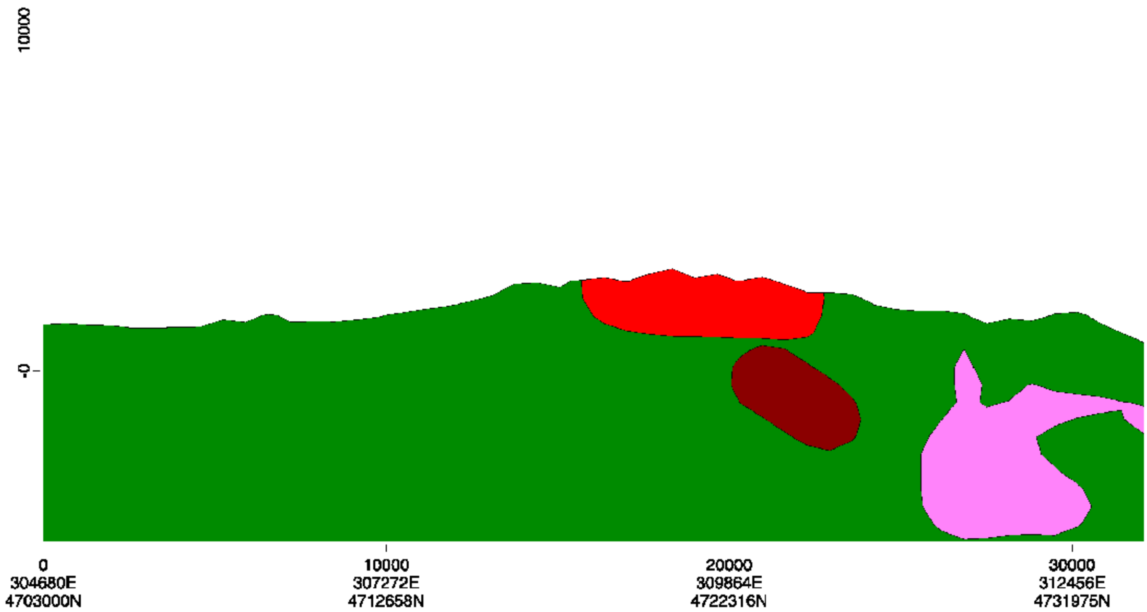
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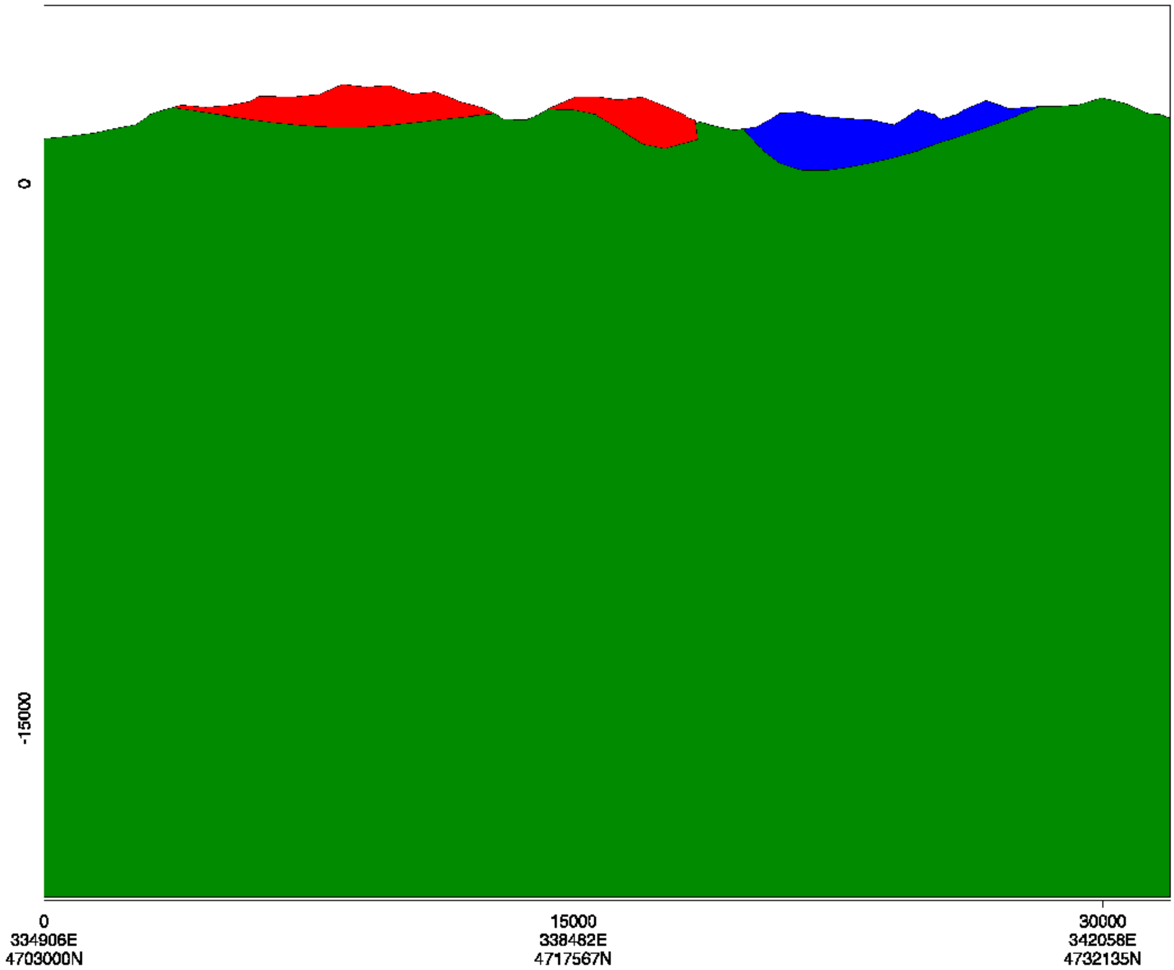
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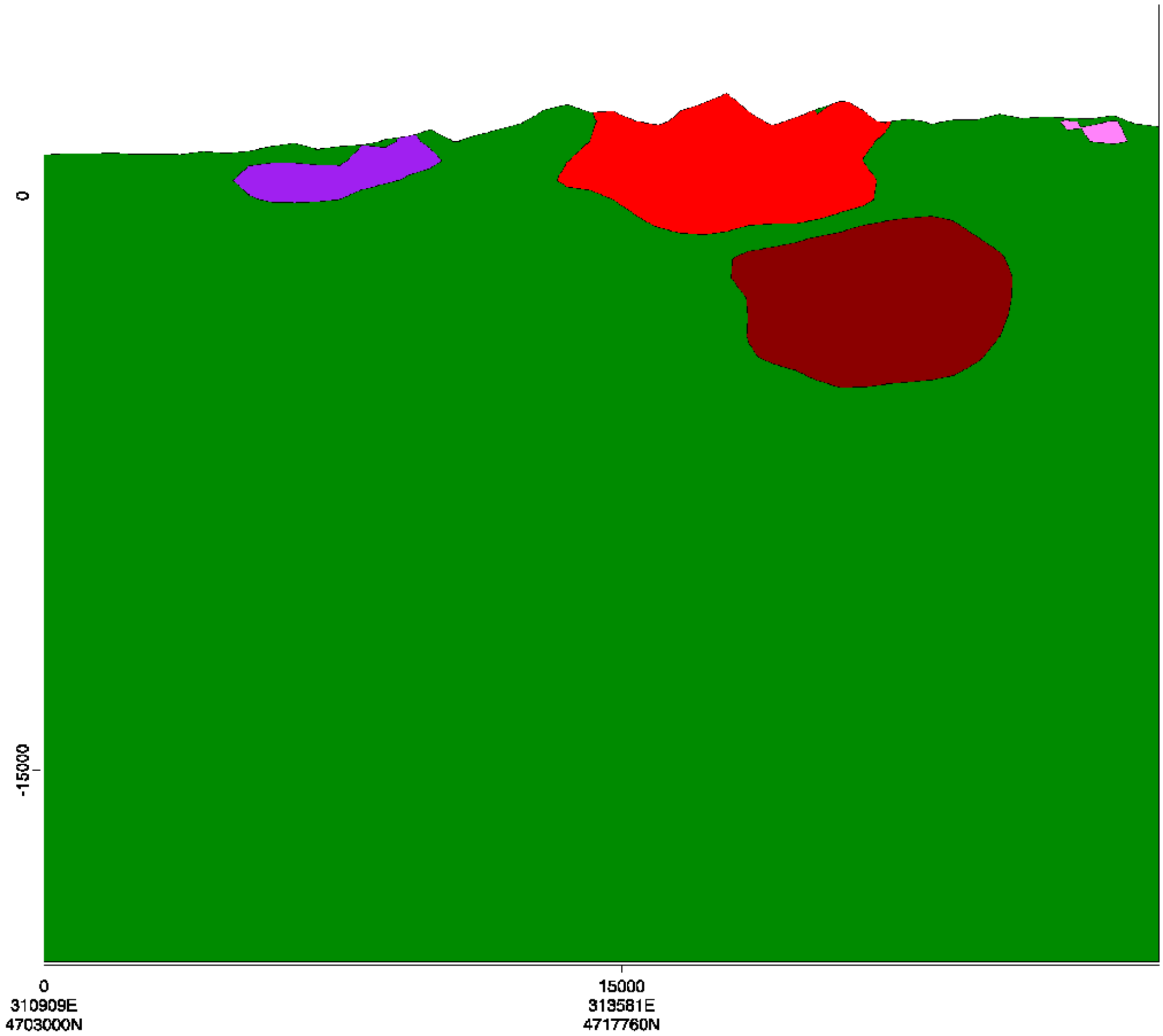

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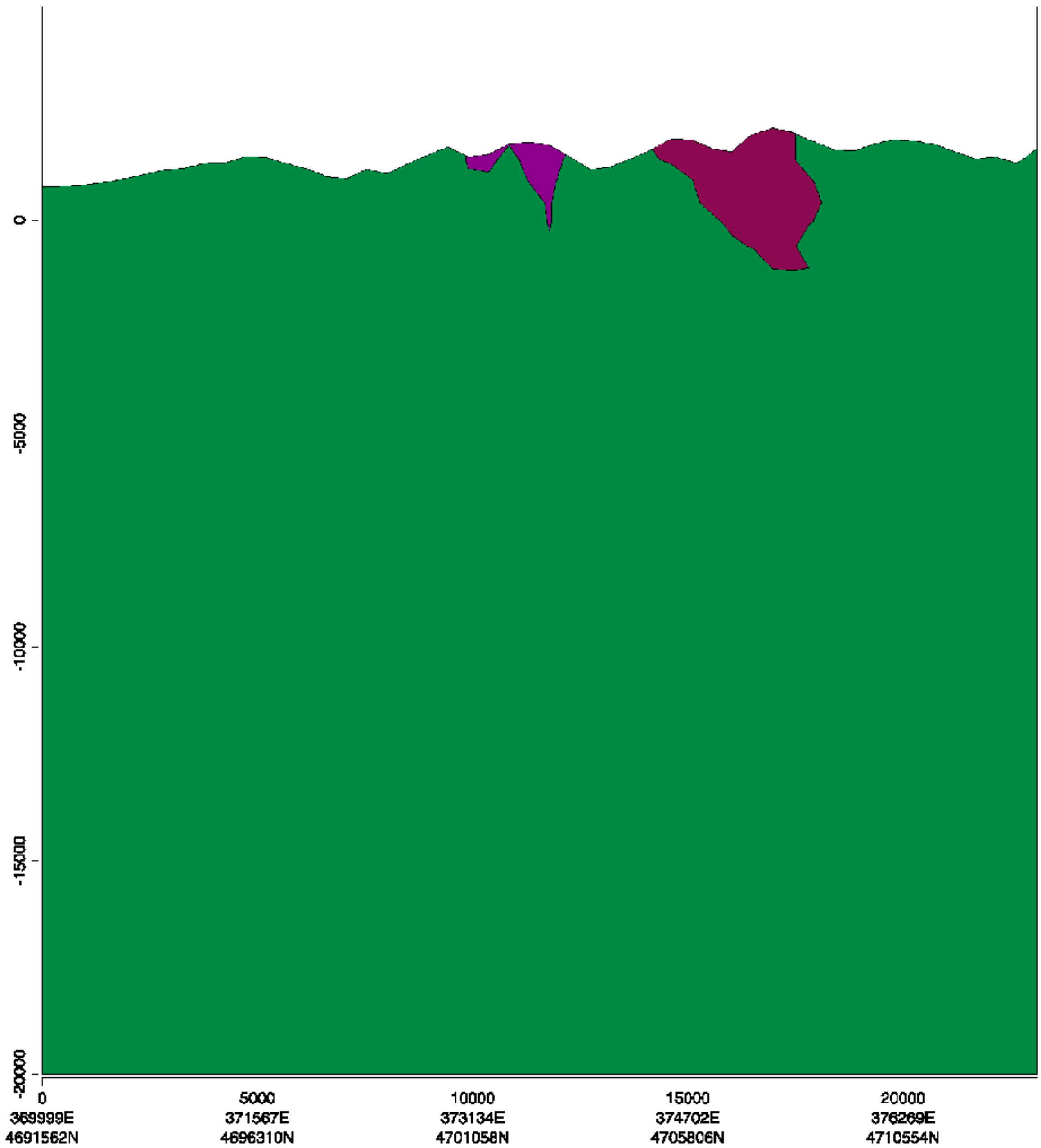
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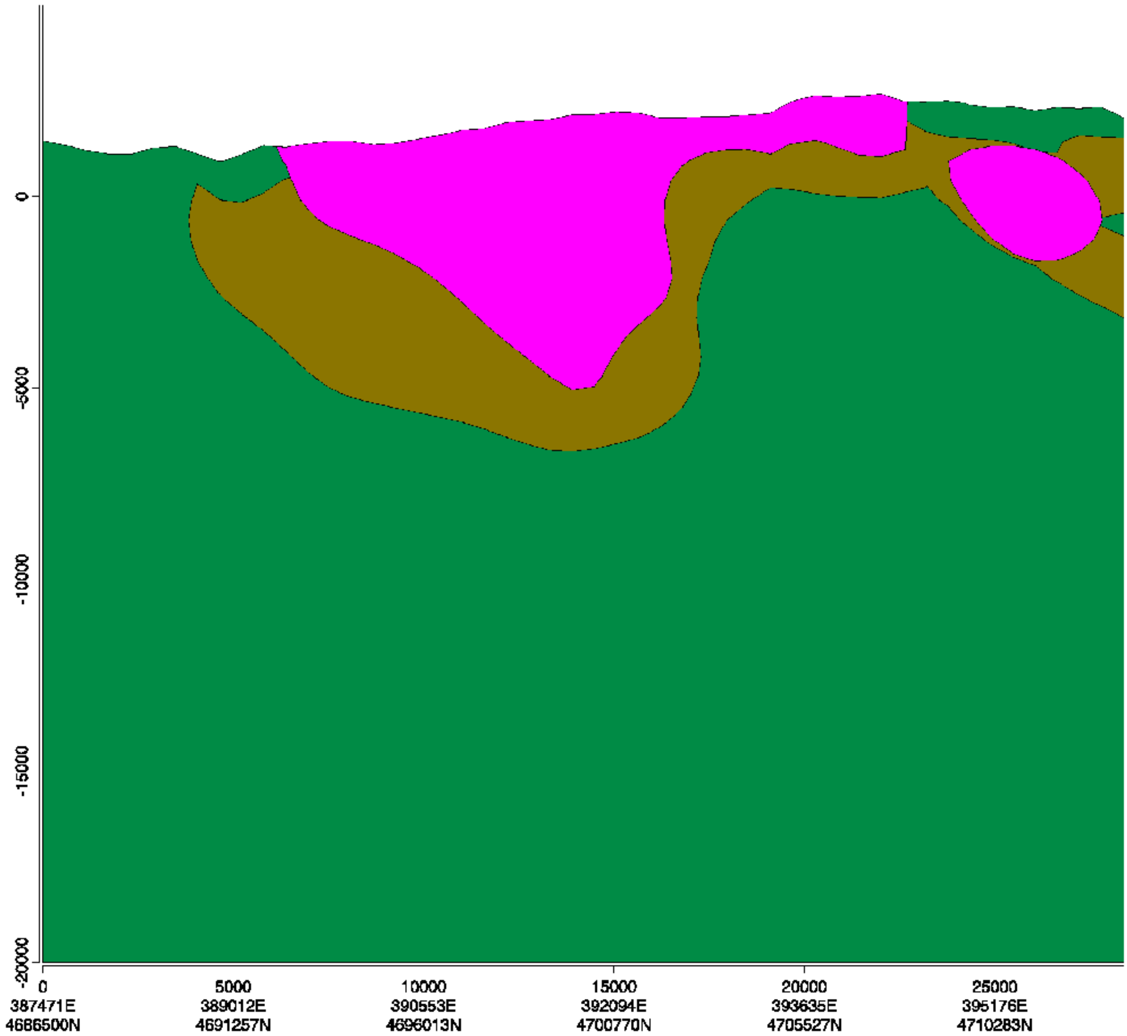
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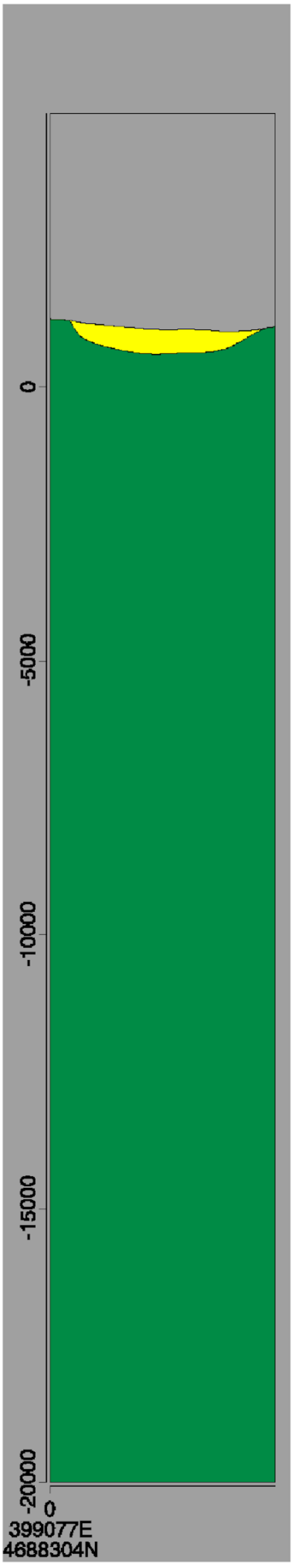
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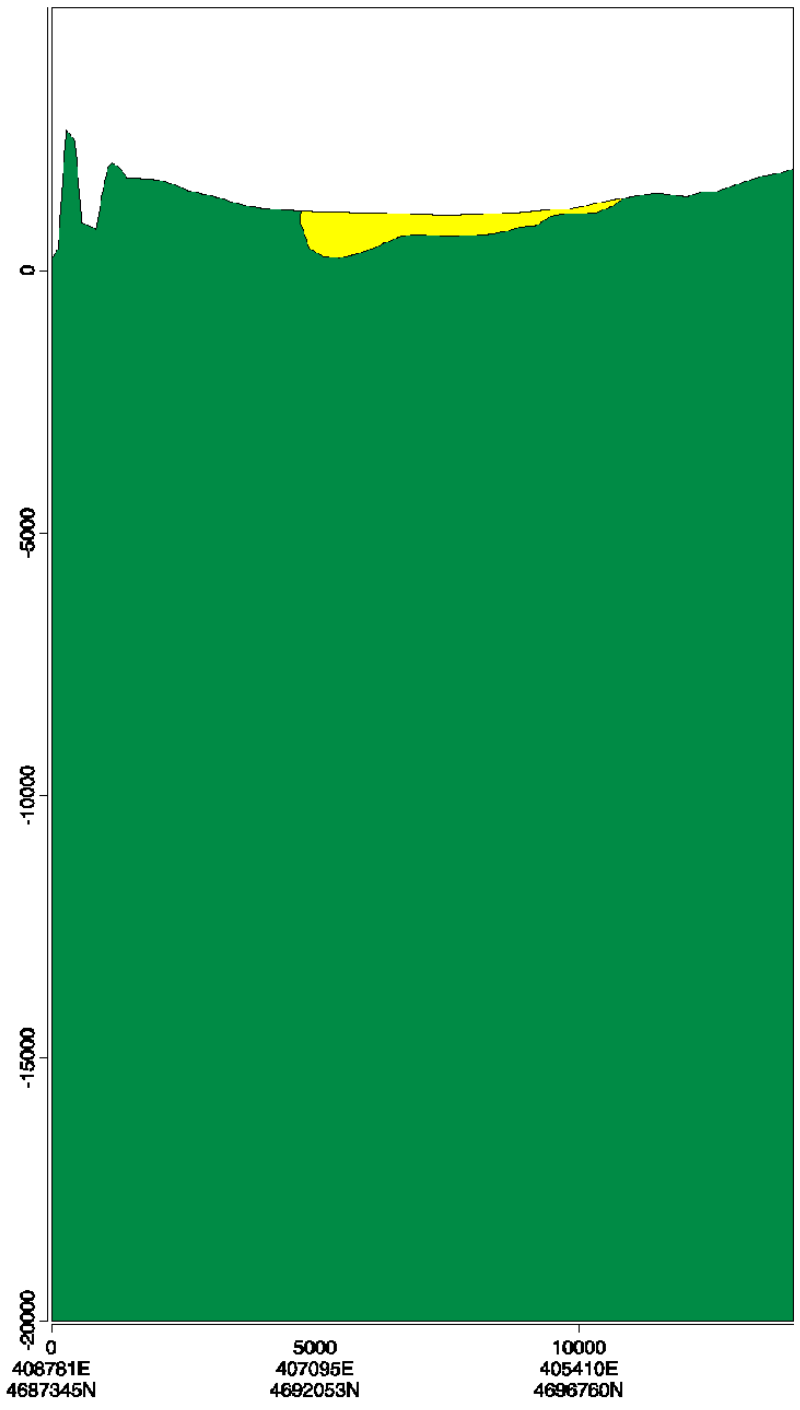

Attachment – Poster for ICT

Attachment – Abstract for AHPGG

Constraining the Geometry of Variscan Granite Plutons through 3D Geophysical Modelling: Examples from Portugal and the Pyrenees

Varzim, Diogo[1]; Cruz, Cláudia[1,2]; Soto, Ruth[3]; Clariana, Pilar[3]; Sant'Ovaia, Helena[1,2]; Ayala, Concepción[4];

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[(2)] Instituto de Ciências da Terra, Rua do Campo alegre, s/n 4169-007, Porto

[(3)] Instituto Geológico y Minero de España, ICME-CSIC, Unidad de Zaragoza, Zaragoza, Spain

[(4)] Geociencias Barcelona (GEO3BCN – CSIC), C/Lluís Solé i Sabarís s/n 08028, Barcelona, Spain

SUMMARY

This work presents the construction of four geological 3D models of granitic plutons in the Iberian Massif and the Central Pyrenees. The plutons are Vila Pouca de Aguiar (VPA) and Águas Frias (AF) in northwestern Portugal, and La Maladeta (LM) and Andorra-Mont-Louis (AML) in the Central Pyrenees. They share the same age (~300 million years), linked to the Variscan orogeny, and similar geological histories, except for the stronger Alpine deformation affecting the Pyrenean bodies. The aim is to compare their 3D geometry and assess how inherited Variscan structures and Alpine deformation influenced their present configuration.

Starting with 2D modelling, multiple cross-sections were drawn for the Portuguese granites using geological maps and literature. These were imported into Oasis Montaj and improved using GM-SYS, with gravity data constraining them. For the Pyrenean bodies, cross-sections were derived from previous studies and further improved in Oasis Montaj. The 2D sections were digitised into GeoModeller and integrated into a 3D model consistent with observed data and geophysical constraints using stochastic inversion.

The VPA and LM models are complete, whereas AML and AF are still in progress. The VPA pluton reveals a laccolithic geometry with a flat floor, thickening northward, with one root controlled by the Penacova-Régua-Verin Fault. The LM batholith consists of two bodies: a laccolith (1–4.5 km depth) and a buried northern body, thickening eastward and dipping northward. Preliminary AML results indicate two roots and buried granitic bodies and gneisses to the north. The AF pluton is expected to be wedge-shaped with a deep central root. Results will be compared to assess the effects of Alpine deformation on their final geometry.

Attachment – Abstract for CNG

XII Congresso Nacional de Geologia

Granite pluton geometries in the Iberian massif and Central Pyrenees: Vila Pouca de Aguiar, Águas Frias, La Maladeta and Andorra Mount-Louis case studies

Diogo Varzim [1]; Claudia Cruz [1,2]; Ruth Soto 3; Pilar Clariana [3]; Helena Sant'Ovaia [1,2]; Concepción Ayala [4]

[1] Departamento de Geociências, Ambiente e Ordenamento do Território, Faculdade de Ciências da Universidade do Porto, Rua do Campo Alegre, s/n, 4169-007, Porto;
[2] Instituto de Ciências da Terra, Rua do Campo alegre, s/n 4169-007, Porto;
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[4] Geociencias Barcelona (GEO3BCN – CSIC), C/Lluís Solé i Sabarís s/n 08028, Barcelona, Spain.

Resumo

During the post-tectonic stages of the Variscan Orogeny, several granitic bodies were emplaced across Europe. This work focuses on four plutons: Vila Pouca de Aguiar (VPA) and Águas Frias (AF), located in northern Portugal, and La Maladeta (LM) and Andorra-Mont-Louis (AML), in the Central Pyrenees [1,2]. The VPA and AF plutons belong to the Late Carboniferous granitic magmatism associated with NNE–SSW structures [4,2]. Both are leucocratic two-mica granites interpreted as crustal melts generated during Late-Variscan tectonic relaxation [1,4]. The LM and AML plutons occur in the Pyrenean Axial Zone, a Variscan basement exhumed during Alpine thrusting [3,5,6]. They are calc-alkaline to mildly peraluminous granites intruded into Paleozoic metasedimentary rocks and gneisses, presently exposed due to Pyrenean uplift and erosion [3,7]. Modelling was carried out using GM-SYS and GeoModeller, integrating geological, density, gravimetric, and magnetotelluric data. Cross sections were constructed from geological maps for Portugal and from Soto et al. [5] for the Pyrenees. GeoModeller's stochastic inversion approach was used to obtain models consistent with the geophysical constraints. VPA has been fully modelled while AF's is still ongoing. Results indicate a laccolithic geometry less than 1 km thick in the south, thickening northward, with roots associated with the Penacova–Régua–Verín Fault. The LM model suggests two bodies: a main laccolith extending from ~1 to ~4.5 km depth, and a secondary buried body thickening eastward to ~6.5 km and tilted northward. AML modelling reveals two distinct roots and additional buried granitic bodies to the north. Buried gneisses are also inferred beneath and around the pluton, although they only crop out farther north. The results highlight different geodynamic impacts on the plutons.

Referências

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[7] Piña-Varas, P. et al., 2023. High-resolution scan of the Pyrenean crustal structure combining magnetotelluric and gravity data. https//doi.org/10.1016/j.tecto.2023.230022

Agradecimentos

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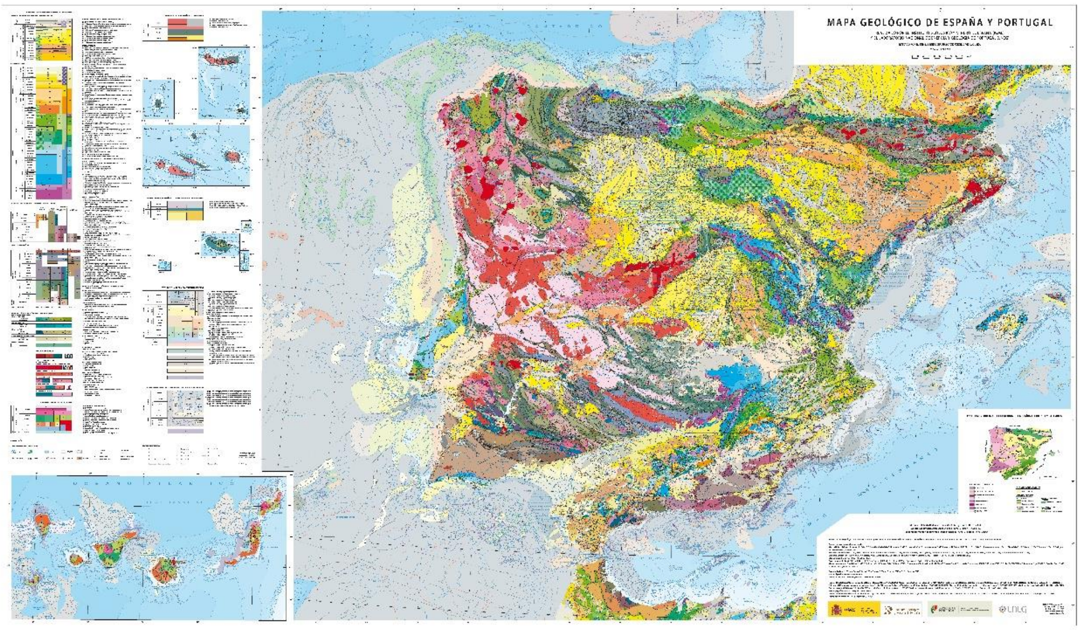
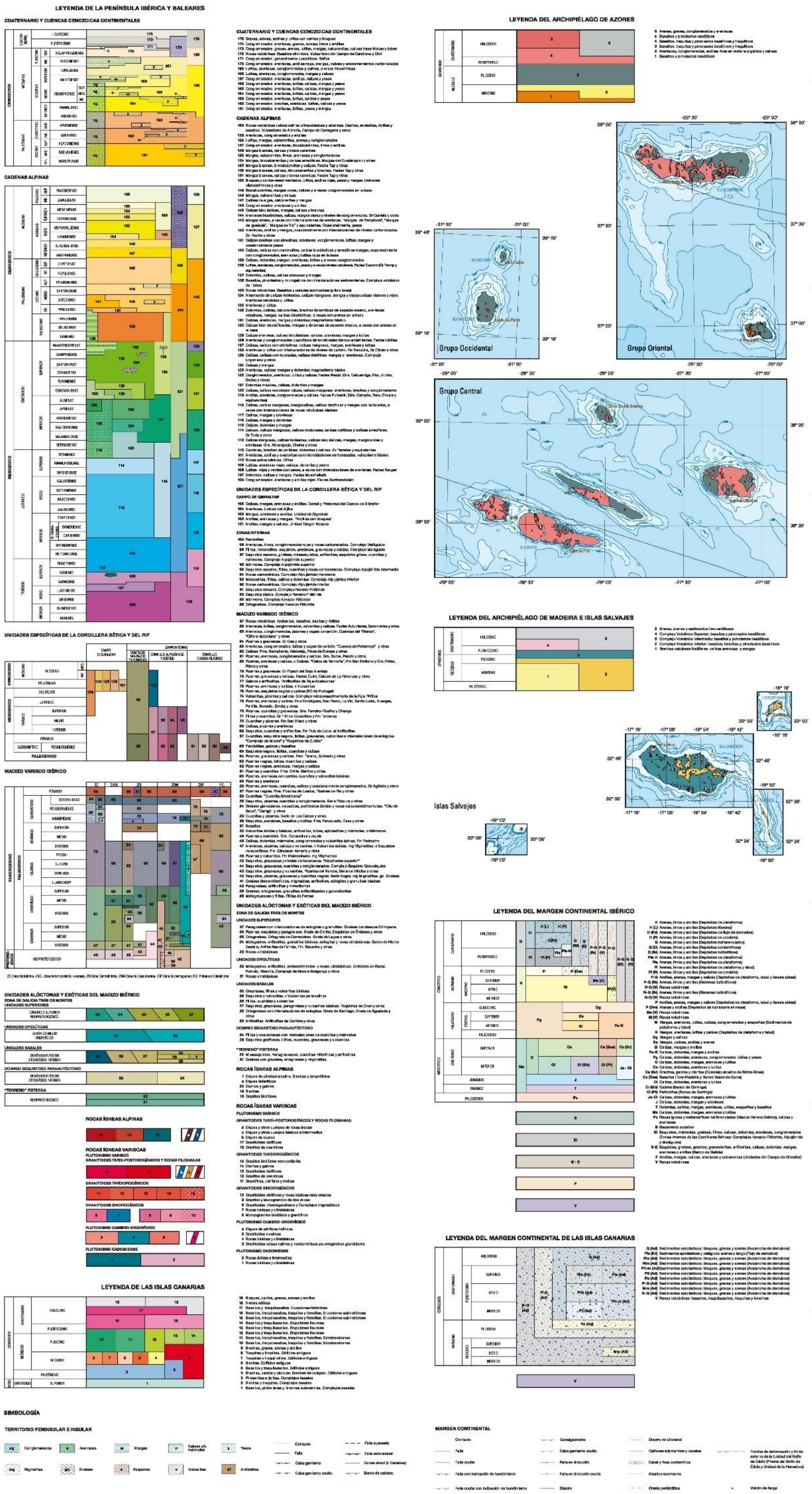
Attachment – Geologic Map of Iberia

The full uncropped and unedited geologic map of Iberia used in Fig.1. After it, just the key for ease of reading.




LEYENDA DE LA PENÍNSULA IBÉRICA Y BALEARES
CUATERNARIO Y CUENCAS CENOZOICAS CONTINENTALES
CADENAS ALPINAS
UNIDADES ESPECÍFICAS DE LA CORDILLERA BÉTICA Y DEL RIF
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ROCAS ÍGNEAS VARISCAS
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Grupo Oriental
Grupo Central
LEYENDA DEL ARCHIPIÉLAGO DE MADEIRA E ISLAS SALVAJES
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LEYENDA DEL MARGEN CONTINENTAL DE LAS ISLAS CANARIAS
SIMBOLOGÍA
TERRITORIO PENINSULAR E INSULAR
MARGEN CONTINENTAL

Attachment – Table of Densities