Cadernos Lab. Xeolóxico de Laxe
Coruña. 2005. Vol. 30, pp. 87-98

ISSN: 0213-4497

Gravimetric anomaly modelling of the post-tectonic granite pluton of Águas Frias – Chaves (Northern Portugal)

Modelação da Anomalia Gravimétrica do maciço granítico pós-tectónico de Águas Frias – Chaves (Norte de Portugal)

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Abstract

The aim of this study was to establish the three-dimensional shape of Águas Frias (AF) pluton using the interpretation of the gravity data and the modelling of the obtained residual anomaly. The relationship between the granites from AF pluton and Vila Pouca de Aguiar laccolith, which is located SSW from the former, is also discussed, in order to understand its emplacement mechanisms. AF pluton is a thick and deeply rooted body and its main volume is located under the outcrop of the two-mica granite. The AF granite was fed through a deep conduit located at the centre of the pluton, and then the biotitic granite and the two-mica granite are two different facies, which probably had the same feed zone. VPA and AF plutons, similar in mineralogical, chronological and magnetic features, are joined together in depth and were fed through feeding zones located within the NNE-SSW Penacova-Régua -Verin Fault (PRVF).
The shapes from the two granite plutons are quite different: VPA pluton is laccolithic and AF pluton belongs to the wedge-floored pluton type. Gravity data also suggest that AF pluton is more rooted than VPA pluton. We consider that this difference can be related to the great depth of PRVF in the sector of Chaves.

Key words: granite, post-tectonic, gravimetric, and modelling.

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INTRODUCTION

Actually, granite bodies are studied through structural studies for their potential in recording events related to their emplacement. These structural studies can be achieved by accurate measurements of granite petrofabrics, using classical or Anisotropy of Magnetic Susceptibility (AMS) techniques (BORRADAILE & HENRY, 1997; BOUCHEZ, 1997, 2000). However, extrapolation at depth of surface structures is not straightforward, so gravity data inversion is now currently combined with structural studies (VIGNERESSE, 1988, 1990; AMEGLIO *et al.* 1997). Amongst the geophysical tools applied to granite bodies, gravimetry measurements are best suited to investigate the shape of plutons at depth (VIGNERESSE, 1990), because two kinds of data can be obtained:

- profiles (2 dimensional information)
- volume (3 dimensional information)

Through the inversion of gravity data, which is particularly sensitive to density contrasts, the shape at depth of the pluton, and depth of its floor, may be obtained with good confidence. The understanding of the 3 dimensional shapes of the granite bodies and of their floor's depth can be used to find the feeder zones of the plutons. Combining this information with structural patterns allows us to achieve a model for the pluton emplacement according to the tectonic context.

The combination of surface geological observations, mapping of AMS and gravimetric surveys is now widely used in the study of Variscan granites from Centro Iberian Zone (AUDRAIN *et al.*, 1989; AMICE, 1990; ARANGUREN, 1994; MOREIRA & RIBEIRO, 1994; YENES *et al.*, 1995; SANT'OVAIA *et al.*, 2000).

The present study deals with the characterization of 3 dimensional shape of the Águas Frias (AF) pluton, using the interpretation of the gravity data and the modelling of the residual anomaly obtained. The relationship between the granites from AF pluton and Vila Pouca de Aguiar (VPA), located SSW from the former, is also discussed in order to understand the emplacement mechanisms.

GEOLOGICAL SETTING

The Variscan orogeny was a major event in the tectonic evolution of Western Europe, characterised by a subduction-obduction-collision belt with a stacking of large-scale thrust nappes, between 390 Ma and 320 Ma (DIAS & RIBEIRO, 1994). In the northwestern part of the Iberian Peninsula, three main phases of deformation (D_1, D_2 and D_3) were found and the last one was intra-Westphalian in age (NORONHA *et al.*, 1979). A late brittle phase (post-D3), Late Carboniferous to Permian in age, is characterised by a set of conjugate strike slip faults (NNW-dextral and NNE-sinistral), pointing to a late-Variscan main compression around N-S (RIBEIRO, 1974; ARTHAUD & MATTE, 1975). Radiometric ages suggest a continuous magmatic activity from the Upper Devonian to the Upper Carboniferous or Permian in Northern Portugal. Based on several geological, petrographical and geochemical studies, these granites are divided into two main groups: the two-micas granites, dominantly syn-D3, and the biotite granites mainly late to post-D_3 and post-D_3 (FERREIRA *et al.*, 1987).

The AF granite pluton (figure 1), considered as post-tectonic (post-D3), occurs as a small body occupying an area of 30 km^2, located near the city of Chaves. This pluton is located in the "Galiza Média Trás-os-Montes Zone", a geotectonic zone of the Variscan Iberian Orogen (fig. 1) and crosscuts two-mica syntectonic granites and also a Upper Ordovician to Lower Devonian metasedimentary sequence characterised by N120° trending folds with sub horizontal axes and sub vertical axial planar foliation S_3 (RIBEIRO, 1988). It is composed by non-deformed porphyritic granite, which is biotite-rich, coarse-medium grained, with K-feldspar megacrysts and occasionally plagioclase. Petrographic observations indicated the presence of quartz, K-feldspar (orthoclase and microcline), zoned plagioclase and biotite as the only ferromagnesian mineral. As accessory minerals, these rocks present frequently apatite, zircon, allanite, sphene, some muscovite and rare cordierite (SANT'OVAIA *et al.*, 2003). This granite is designated in 1/50 000

Geological Map (sheet 6B-Chaves 1974) as "granito de Águas Frias e Santo Estevão" and as a "calcalkaline monzogranite" (TEIXEIRA et al., 1974). In 1/200,000 geological Map, sheet 2 ("Carta Geológica de Portugal", 2000), it is considered as post-tectonic porphyritic coarse-medium biotite granite. In the centre of AF granite pluton occurs as a small outcrop of a two-mica medium-grained granite.

In the field, these rocks appear as almost isotropic and no evidence of magmatic fabric nor deformation fabric is present.

In southwestern prolongation of AF pluton, there are alluvium deposits, which fill the Chaves graben.

The AF pluton is spatially associated with Penacova-Régua-Verin fault (PRVF). This fault, still tectonically active (CABRAL & RIBEIRO, 1993), belongs to the NNE-trending brittle system crosscutting the whole of Northern Portugal. This accident was nucleated on D_3 and reactivated later as a sinistral strike-slip fault with transtensional component.

GRAVITY DATA ACQUISITION

The raw gravity data and Bouguer anomaly values of the region of Vila Pouca de Aguiar-Chaves, previously reported in MOREIRA *et al.*, (1992), are interpreted and modelled in the present study. Gravity measurements were performed over 3649 closely spaced stations homogeneously distributed within an area of 379 km^2, situated between the meridians 620 and 641 km and the parallels 4615 and 4632 km of the U.T.M. Kilometric System (fig. 2). The gravity surveying coverage was extended over the AF pluton and its nearby surroundings.

The raw gravity data were obtained with a gravimeter Lacoste & Romberg, G model, with a precision of ± 0.01 mGal and with temperature and pressure compensations.

Elevations were determined using a precise (± 1 m) baro-altimeter that was calibrated several times a day.

BOUGUER ANOMALY

The treatment of raw gravity data comprises several stages:
- gravimetric corrections
- substraction of the regional effect
- modelling (inversion techniques)

In a gravity surveying, several effects are produced by sources, which are not of direct geological interest for the purpose of this study. Once these effects are removed by correcting the raw data to a datum (topography, elevation, latitude) and also from the tidal and instrumentation variations, the Bouguer anomaly values are determined. With these values, a grid can be computed and a Bouguer anomaly map is drawn. The combination of the isovalue contour line gradient of the Bouguer anomaly map and geological knowledge yields a first interpretation for the geometry of the granite body.

Our raw gravity data were corrected for the intrinsic constant of the apparatus and tidal effects and also for the usual topography, latitude and elevation corrections. The Bouguer correction was performed assuming a density of 2.70.

The resulting Bouguer anomaly was interpolated by kriging along 1 km-sided grid, using the application Surfer (Version 6, Golden Software Inc.). Using this grid, a map of isovalues contour lines of the Bouguer anomaly was obtained (fig. 3).

The Bouguer anomaly map shows that the AF pluton appears as a depression with anomalies ranging from –55 to –61 mGal. The pluton is well outlined by the -55 mGal contour line with a gradient inward to the pluton. A region of pronounced minima (<63 mGal) is present at the southwestern border of the pluton, which corresponds to the alluvium deposits from Chaves graben.

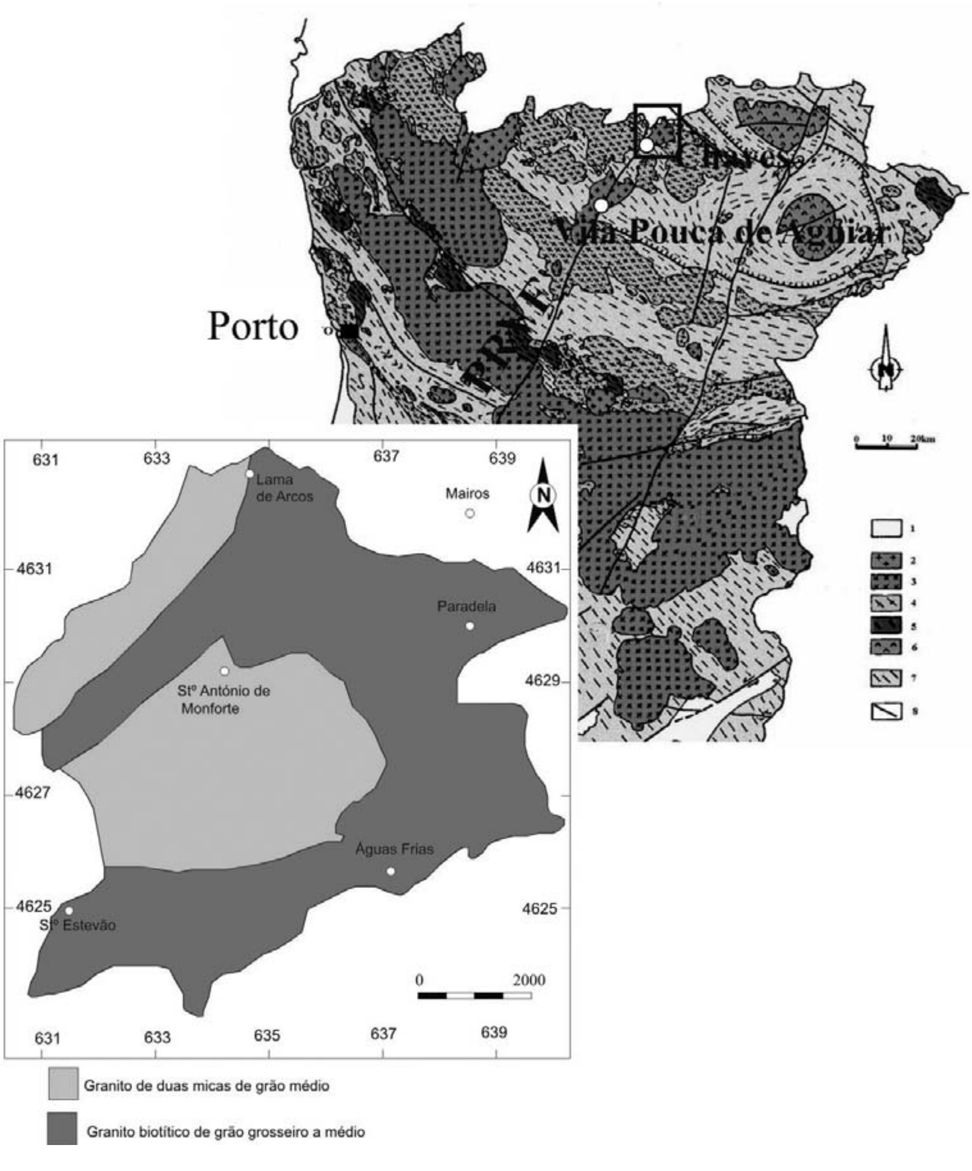

Figure1: Geological sketch map of the Águas Frias (AF) pluton and its country rocks. Geographical coordinates: UTM kilometric System.
Legend: 1- Post Paleozoic; 2-5 Hercynian Granitoids: 2-Post-tectonic biotite granites; 3- Late-tectonic biotite granites; 4- Syn-tectonic two-mica granites; 5- Syn-tectonic biotite granites; 6-Ultrabasic complexes; 7- Cambrian to Carboniferous metasedimentary rocks; 8-Faults (Ferreira et al. 1987, modified). PRVF – Penacova Régua Verin Fault.

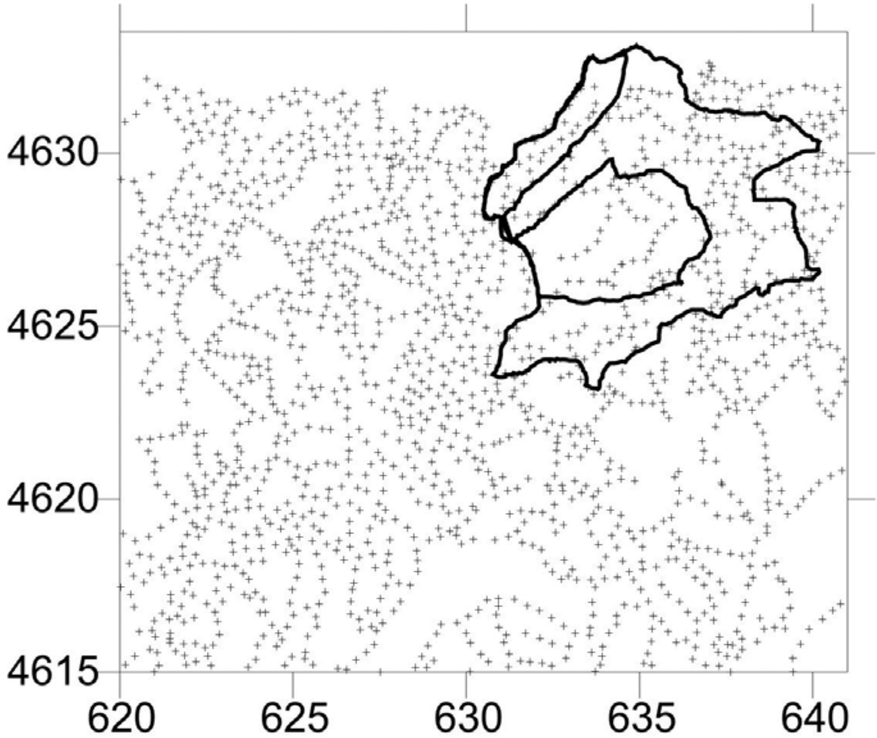

Figure 2: Gravimetric stations map of the AF pluton and surrounding areas. (Sketch map of the pluton in black).

EXTRACTING THE ANOMALY CAUSED BY THE AGUAS FRIAS PLUTON

Before any local interpretations are undertaken, the regional field effect must be subtracted from the Bouguer anomaly, in order to determine the residual anomaly that represents the local field associated with the granite.

The residual anomaly is calculated from the Bouguer anomaly map and determined by eliminating the regional effects induced by far-located bodies or by deep-seated sources. Several techniques, manual or digital, using frequency filters, subtracting polynomial or hand-drawn surfaces obtained after filtering on profiles, or gridded averages, have been improved to define the regional field (VIGNERESSE, 1990). This step is probably the most ambiguous part of the work. In fact, the separation of the local field from the regional field depends on what is considered to be the local field.

In the present study, the residual anomaly was calculated from the Bouguer anomaly map by subtracting the regional gravity trend, which was modelled by a polynomial adjustment. Polynomial methods consist in finding a surface which mathematical definition is a polynomial from linear to second or third degree and its function is given by $f(x,y)=a_0+a_1x+a_2y+a_3x^2+a_4xy+a_5y^2+\ldots$ This surface establishes a level which is a regional trend surface.

When the regional anomaly, modelled by that polynomial adjustment, is removed the residual anomaly map isolated the effect of the granite pluton. According to previous works (VIGNERESSE, 1990), the convenient residual anomaly map is obtained when the zero contour level of this map

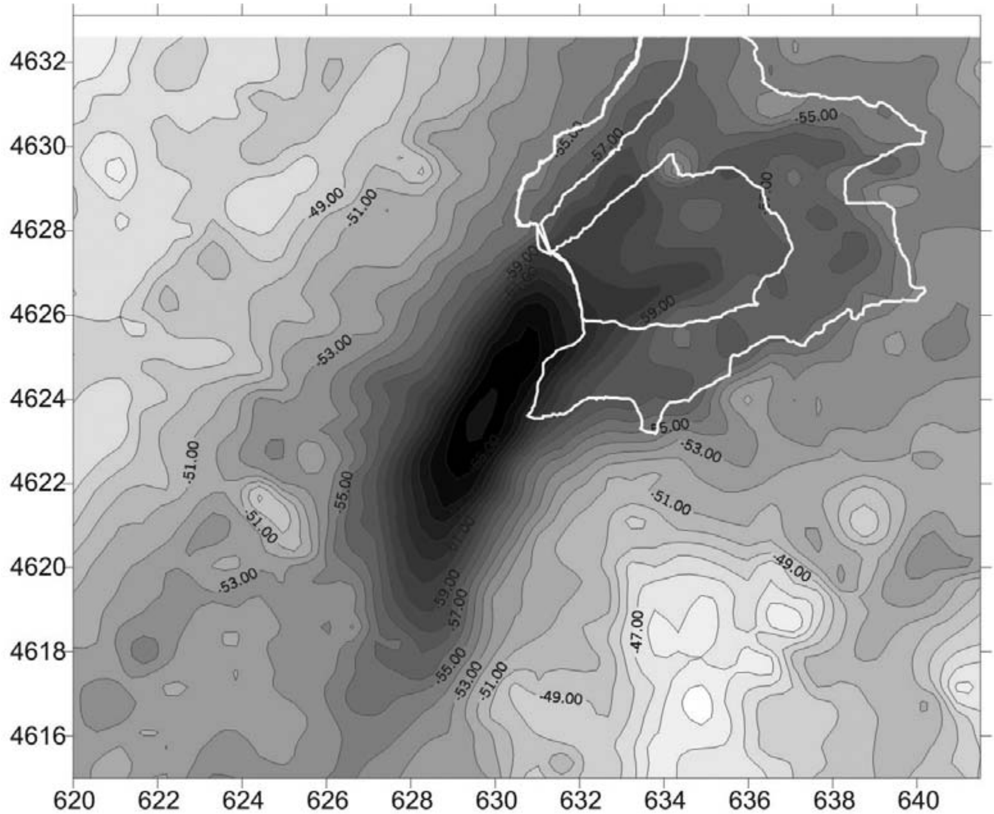

Figure 3: Bouguer gravity anomaly map of the AF pluton and surrounding areas (in mGal). (Sketch map of the pluton in white).

outlines the contour of the granite body.

In this study, a polynomial adjustment: f(x,y)= -54,5+(-1/10)X+(-1/9)Y and X=(x-635) and Y=(y-4630), was used. After the regional field has been subtracted from the Bouguer anomaly, the residual anomaly map for AF pluton (fig. 4) is determined. This map yields a negative signature for the studied pluton of about 0 to – 6 mGal in amplitude, and a positive anomaly at the east and west of the area, that can be correlated with metasediments. The residual anomaly map satisfactorily isolates the effect of the studied pluton, except at its southwestern part, where the zero contour level doesn't close. In this sector there is a separation between the zero contour level, elongated parallel to the graben and with a NNE-SSW trending outward the studied area limits. The negative anomaly of AF pluton is related to a lower density of the granite than that of the surrounding country-rocks. In the graben, we have also a strong negative residual anomaly (–12 mGal) due to the lower density of the alluvium deposits.

THREE-DIMENSIONAL SHAPE

Three main techniques have been evaluated (VIGNERESSE, 1990) in order to process the residual anomaly in terms of the pluton's shape and/or depth of the pluton's floor: the direct modelling, indirect processing of the measured anomaly and the inverse technique. With the inverse technique, model parameters are computed directly from measurements and the shape and the deep of the source body can be determined.

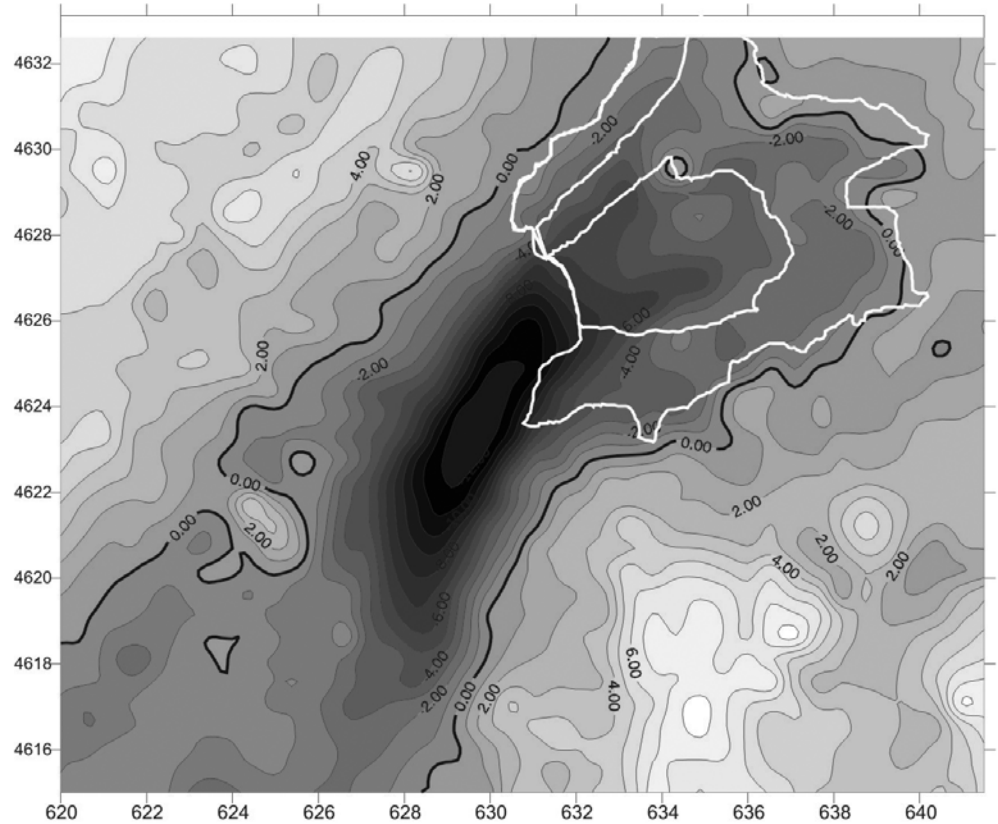

Figure 4: Residual gravity anomaly map of the AF pluton and surrounding areas (in mGal). (Sketch map of the pluton in white).

The residual anomaly was inverted using an iterative procedure. Among the several possible inversion methods, our modelling was performed using three-dimensional iterative procedure (CORDELL & HENDERSON, 1968), adapted to small-scale gravimetric investigations by (VIGNERESSE, 1990; AMEGLIO *et al.*, 1997).

The iterative procedure comprises three steps: (i) definition of an initial model based on the measured residual field; (ii) computation of the gravimetric effect of that model and (iii) modification of the model, until the measured and the calculated anomalies become alike. The second and the third steps consist of successive iterations until the convenient adjustment.

In these methods the area under study is sliced into elementary vertical prisms, each one having a constant density. Provided gravity measurements are distributed on a regular grid map, and then the thickness of the prism centred at each mesh point is computed. The resulting anomaly is then calculated from the 3-D structure defined by all prisms, and the differences between the computed anomaly and the measured one, are used to slightly modify the depth of each point of measurement.

In the present study, a map of surface densities for the granite body and surrounding rocks has been incorporated into the computation in order to better constrain the nominal densities of the prisms. The density contrast between the granite body from AF and the surrounding rocks was Dd=-0.07. In the sector where alluvium formations occurred, a density contrast of Dd=-0.7 was first used, to be sure that the effect produced by the low density of the alluviums was removed. Then a density contrast of Dd=-0.07 for the granite located under the alluvium was used. These density contrasts are in agreement with those obtained in our laboratory for the granite (d=2.70) and for the metasedimentary country-rocks (d=2.77). For the alluvium formations, densities weren't measured, but the contrast leads us to a density of 2.0 for those formations which is acceptable for this kind of material.

Gravity modelling of the AF pluton's floor (fig. 5) discloses that its floor presents depth values which reach 12 km. In the central zone, under the outcrop of the two-mica granite, there is the main volume of the pluton, with floor depths reaching 16 km. In this zone it is located a deep conduit which can be assumed as a feeding root. At the south limit, the pluton floor seems to extent in SSW direction under the cover rocks with shallow depth values.

DISCUSSION

The modelling of the residual gravity gives to AF pluton the shape of a thick and deeply rooted body. The main volume of the pluton is located under the outcrop of the two-mica granite. The AF granite seems to be fed through a deep conduit located at the centre of the pluton and then, the biotite granite and the two-mica granite are two different facies, which probably had the same feed zone. Chronological relations between biotite and two mica granite facies are not yet established.

The zero contour level doesn't close but extends in a SSW direction outward the studied area. On the treatment of residual anomaly of VPA pluton (see location at fig. 1), the same problem was experienced and a connection of the two plutons in depth was proposed (SANT'OVAIA *et al.*, 2000). We consider that this connection of the two granite bodies is possible and due to the presence of feeding zones along the PRVF.

Assuming this connection on depth, a similitude between the two plutons must be considered. Petrographic studies have shown similar mineralogical compositions for the granites of both plutons. They correspond to biotite-rich granites but we must emphasize the presence of cordierite in AF granite. Preliminary AMS studies of AF granite corroborated these results (SANT'OVAIA *et al.*, 2003). In AF biotite granite magnetic susceptibility has an average value of 9.2 x10^{-5} SI, typical from paramagnetic granites and related to the iron content from biotites. The anisotropy magnitudes are quite low, 1.7% in average, and confirm the non-deformed character of AF granite confirming its classification as post-tectonic.

However, the shapes from the two granite plutons are quite different: VPA pluton is laccolithic in overall shape (figure 6), less than 1 km in thickness on 60% of its thickness area; while AF pluton has a greater thickness (» 10 km) and belongs to the wedge-floored pluton type (AMEGLIO *et al.*, 1997).

Gravity data also suggest that AF pluton is more rooted than VPA pluton. This difference can be related to the depth of PRVF in the sector of Chaves. PRVF is a preferential location for several water springs. Pedras Salgadas, Vidago and Chaves are examples from water springs aligned within that fault, between Vila Pouca de Aguiar and Chaves. In the city of Chaves, spring thermal water can reach temperatures of 68°C in the summer. However, springs in Pedras Salgadas and Vidago, which are located at SSW from Chaves, water temperatures are respectively 17°C and 16°C (NORONHA, 2001). We assume that a deeper circulation in this sector of PRVF can explain the hotter water from Chaves spring. This is consistent with a deeper root from AF pluton than for VPA pluton.

Finally, we propose that AF pluton can be the result of the infilling of a dilatant volume within PRVF. Transcurrent movements during the latter phases of Variscan orogeny could achieve local dilatancy.

CONCLUSIONS

AF pluton is a thick and deeply rooted body and its main volume is located under two-mica granite. The AF granite was fed through a deep conduit located at the centre of the pluton. VPA and AF plutons, similar in mineralogical, chronological and magnetic features, are joined together in depth and both had feeder zones located within the PRVF.

The shapes from the two granite plutons are quite different: VPA pluton is laccolithic ad AF pluton belongs to the wedge-floored pluton type.

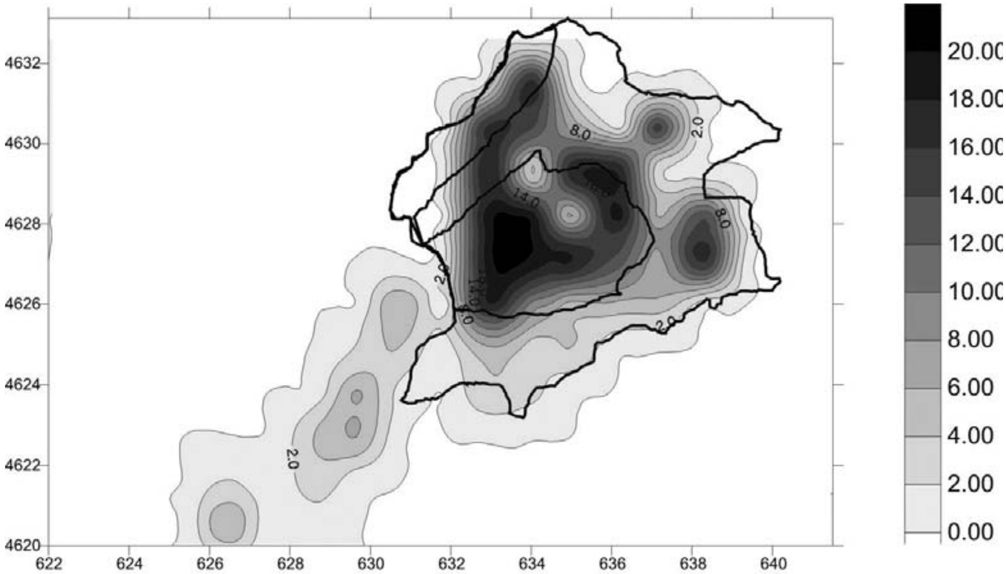

Figure 5: Three dimensional shape of the AF pluton. Depth contours (in km) of the pluton floor obtained after data inversion. (Sketch map of the pluton in black).

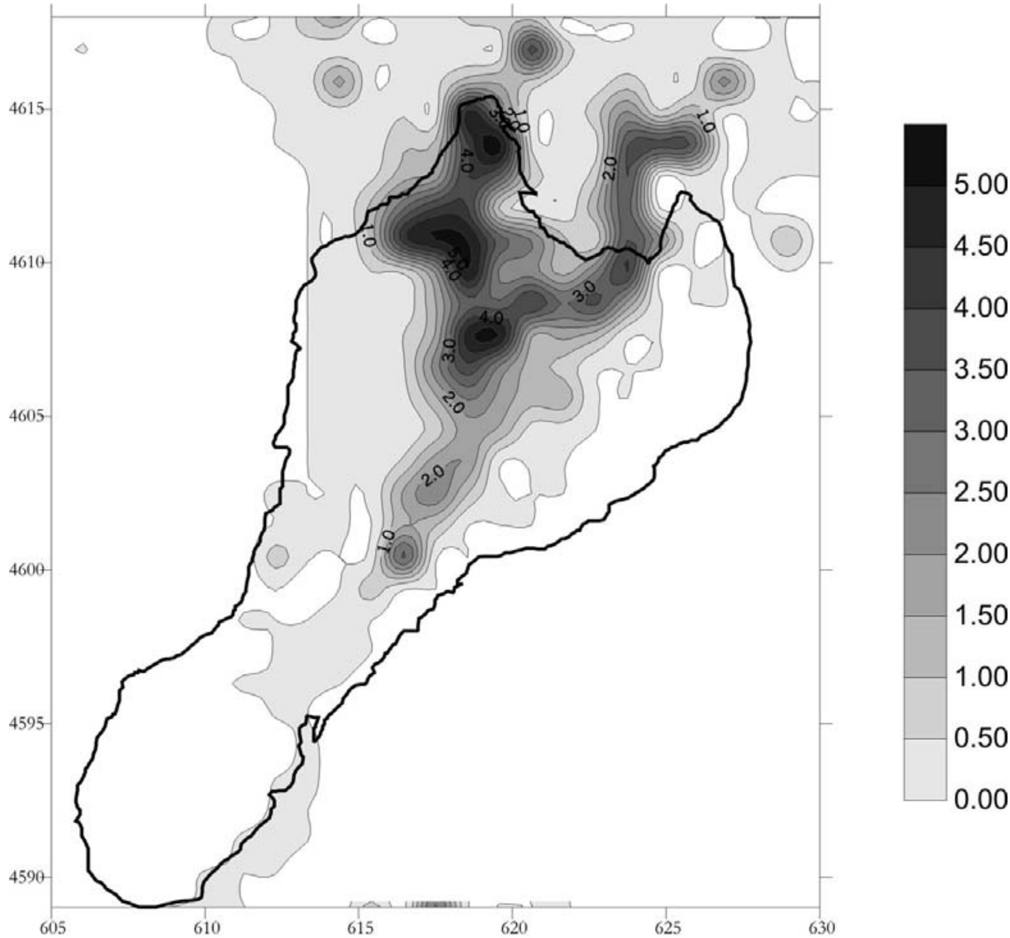

Figure 6: Three dimensional shape of the VPA pluton. Depth contours (in km) of the pluton floor obtained after data inversion. (Sketch map of the pluton in black).

Gravity data also suggest that AF pluton is more rooted than VPA pluton. We consider that this difference can be related to the great depth of PRVF in the sector of Chaves.

ACKNOWLEDGEMENTS

This work is integrated in activity of GIMEF "Centro de Geologia da Universidade do Porto", and received financial support of "LITHOSTRU-MODEL PROJECT" (POCTI/CTA/40813/2001). Available regional gravity data were kindly supplied by Professor Mendes Victor (Geophysical Institute, Lisbon).

Recibido:8/6/2005
Aceptado:10/8/2005

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