# Gravimetric Survey to Detect Geological Structures Involved in Thermal Water Circulation in the Italian Western Alps

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## ABSTRACT

Two thermal sites are located in the south-western Alps at Bagni di Vinadio and Terme di Valdieri in the Argentera Massif which is is the southernmost of the External Crystalline Massifs of the Western Alps, right at the border between Italy and France. The Argentera massif provides an ideal site to investigate the potential of gravity measurements since the thermal anomalies reveal surface manifestations such as hot springs showing temperatures up to 72˚C and reservoir temperatures estimated to be 130°C for the waters of Vinadio and 110°C for the ones at Valdieri. The geology and structural setting, however, is very complex and can be extrapolated to the subsurface only by structural investigations. In addition to the structural data that are already available from previous studies, a geochemical campaign has been lately carried out in 2009, in order to understand the circulation system also in comparison with previous geochemical studies in the region.

In this study, we will present the interpretation of a gravity campaign that was carried out during summer 2010. One of the main goal is to investigate the geological structures at depth to identify any natural gravity anomaly and figure out if could be related to the circulation of hot waters or to the presence of a geothermal reservoir at depth.

## Introduction and Description of the Study Area

In Italy, only a few geothermal exploration projects were developed outside of Tuscany even though the northern part of Italy shows interesting geological settings where low to medium enthalpy geothermal resource could be exploited. The southern part of Piedmont and in particular the Argentera Massif in the Alps at the border between Italy and France, presents a high concentration of hydrothermal circulations related to fault systems in the Western Alps. Favorable conditions for geothermal investigations of thermal waters are found at Bagni di Vinadio and Terme di Valdieri. In fact the Argentera Massif has been studied in the past on the geological and geochemical point of view by several authors but any geophysical survey was ever carried out to investigate the development of the structures controlling the thermal waters circulation. To figure out this point new geochemical investigations were carried out (Guglielmetti, 2010) and passive geophysical methods such as gravity were chosen. Gravity is a potential field method and thus subjected to the rule of non-uniqueness of interpretation but is widely used in geothermal exploration with excellent results.In this paper we will presents the results of a gravity survey that was carried out during the summer 2010 in the Italian side of the Argentera Massif where the highest concentration of thermal springs are located at Bagni di Vinadio and Terme di Valdieri.

On the geological point of view, the Argentera Massif, the southernmost of the external crystalline massifs of the Alps. It is a pop-up structure cropping out owing both to its uplift and to the erosion of the Mesozoic sedimentary succession (Perello, 2001). It can be divided into two main complexes (Fig.1): the Malinvern Argentera Complex, mainly constituted by migmatitic gneisses and located on the italian side, and the Tinée Complex, mainly formed by anatectic gneisses. In particular the studied thermal springs are entirely located within the Malinvern Argentera Complex, which rocks, mainly constituted of quartz, K-feldspar,

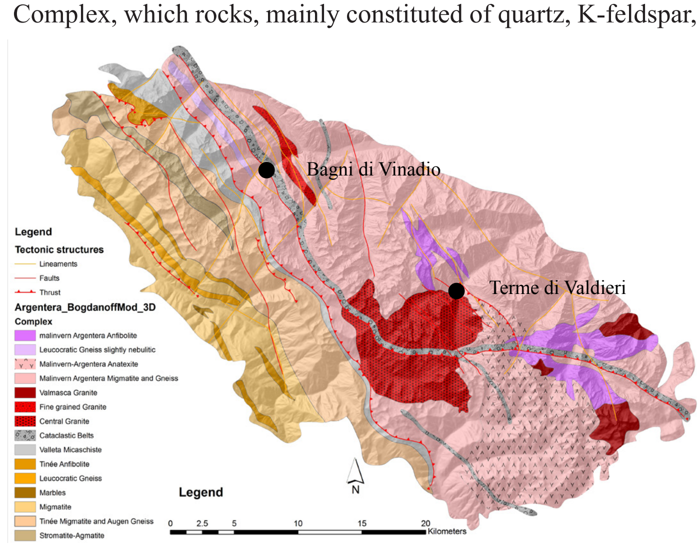


**Figure 1.** Geological sketch of the Argentera Massif (from Bogdanoff, Ribolini, Musumeci, mod).

plagioclase, biotite, are highly milonitized and, as a result, the reservoir rock contains numerous micro-fractures (Michard, 1989). The structural setting of the Argentera Massif is the result brittle reactivation of pre-Alpine and early-Alpine ductile shear zones. A main NW-SE shear zone, the Valletta Shear Zone, crosscuts the massif dividing the two complexes and runs parallel to the corridor of the Bersezio Fault, a wide zone of fracturing and pervasive cataclasites composed by several faults trending 150° and consisting of fractured protholith rocks, fault breccias, cataclasites and gouges. In the central part of the massif, the Bersezio Fault connects to the Fremamorta Shear Zone, a E-W oriented milonitic corridor with a reverse sense of shear.

At Bagni di Vinadio, thermal springs discharge at 1320 m.a.s.l. through intensely fractured aplitic dykes located at the margins of the Bersezio Fault. The Terme di Valdieri springs discharge at 1425 m.a.s.l. in one of the most elevated sector of the Argentera Massif. This area is pervasively cut off by NE-SW strike-slip faults with right-lateral slip components and by subsidiary left lateral ENE-SWS striking faults. In particular the springs emerge through the damaged zone of the Lorusa Fault a 7km-long NW-SE strike slip fault that cuts through migmatitic gneisses in association with the Cougne Fault that is more developed within granites.

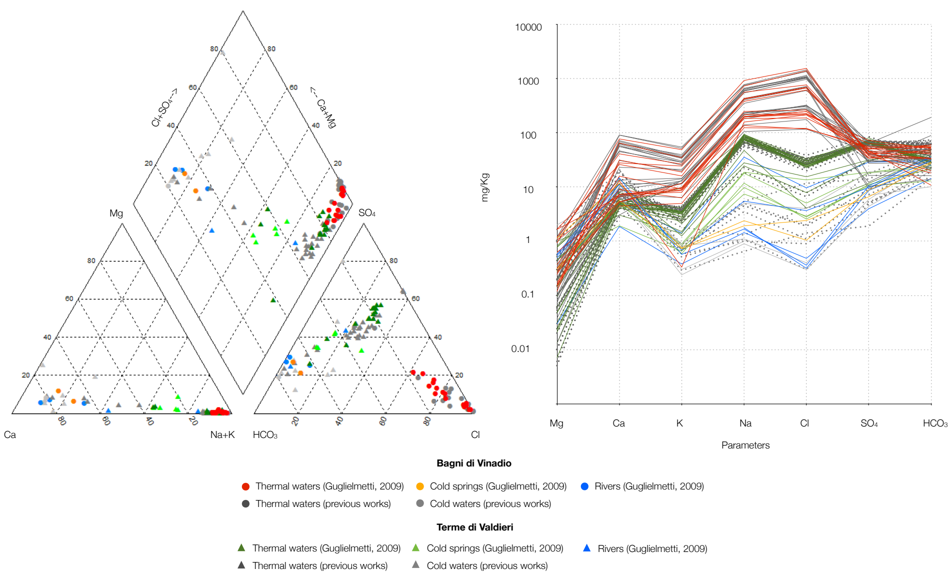


**Figure 2.** Piper and Schoeller plots showing the main chemical compositions of the waters at Bagni di Vinadio and Terme di Valdieri and the distinction between thermal and subthermal waters at Vinadio whereas at Valdieri this does not occur.

In 2009 two campaigns were carried out to sample both thermal and cold waters. All the samples were analyzed by means of ion chromatography for the major ions, by means of Inductive Coupled Plasma Spectrometry (ICP) for trace elements, heavy metals, Si and water stable isotopes and tritium were analyzed as well. These two sites present waters with different chemical compositions even though they are located in the same lithological setting (crystalline rocks of the Argentera Massif) and only 17 km apart. The thermal springs are concentrated within two small areas surrounded by high relief massifs. The maximum discharge temperature reaches 72°C and water have been analyzed both chemically and isotopically ($^{18}O$, $^{2}H$, $^{3}H$) to decipher the origin of the fluids in relation to natural pathways inferred from geological and geophysical prospection.

At both sites deep waters have a meteoric origins and infiltrate between 1800 and 2000 m a.s.l as inferred from the stable isotopes of oxygen and hydrogen. At Valdieri a mixing process occurs between cold and hot springs both showing a $NaSO_4$ composition that is typical of water circulation within the crystalline massifs of the Alps. However at Vinadio it is evident a mixing process between a deep saline (TDS up to 3000 mg/Kg and $Cl^-$ concentration up to 1500mg/Kg) NaCl end member and a shallow and cold $NaSO_4$ end-member (Fig. 2). The origin of the Chloride is anomalous for waters circulating in a crystalline massif but can be related to the dissolution of halite, as supported also by the Cl/Br ratio, trapped at depth in particular along the main fault zones (Michard, 1989) and could also partially derive from fluid inclusions and dissolution of plagioclase (Perello, 2001). Geothermometers and Saturation indexes were used to estimate the reservoir temperature at both sites to be 130°C at Bagni di Vinadio and 110°C at Terme di Valdieri (Tab.1).

## Gravimetric Data Acquisition

During the summer 2010 a gravity survey was carried out in the Italian side of the Argentera Massif. Previously collected data on the Western Alps were available from the International Gravimetric Bureau IGB but are not dense enough and homogeneously distributed. In fact of the total 61available points just five are located in the study area (the italian side of the massif). However these data were useful to correct the regional trend of the Bouger Anomaly. A much more detailed campaign was planned to to increase the number of measures to be able to detect the gravity anomalies related to density distribution variation at depth related to variation of permeability, fracturation and to the possible presence of water circulating within the main discontinuities. 384 measures were collected along roads and trails every 250 meters using a Scintrex CG-5 Autograv gravimeter that assures a reading resolution of 1 microGal. During the data acquisition the main problems were related to the topography of the region: high peaks up to 3297 m a.s.l. (Mount Argentera) and narrow valleys prevented to cover the area with a regular grid of measures. Gravity data were then collected along 11 profiles perpendicular, as much as possible, to the main geological structures to be able to detect the gravity anomalies that are supposed to be strictly controlled by the fault and the cataclastic belts widely spread all over the area. 2

**Table 1.** Resuming table of the main chemical and physical paramenters of thermal waters of the study areas.

| Thermal Area | T max(°C) | Q (kg/sec) | TDS max (mg/kg) | pH | Type | Reservoir T (°C) | Tritium (T.U.) |
|---|---|---|---|---|---|---|---|
| Bagni di Vinadio | 72 | 2 | 2700 | 9.1 | Na - Cl - $SO_4$ | 130 | 0.6 |
| Terme di Valdieri | 65 | 3 | 300 | 9.5 | Na - $SO_4$ | 110 | 1.6 |

Differential GPS (DGPS) AshTech ProMark 2 were used to collect the XYZ position of each measure (Fig. 3). The first GPS was placed as a base station, collecting its position each 5 seconds for about 12 hours per day, in correspondence of the gravity station located in the middle of the gravity profile that was supposed to be covered during the day. This way it was possible to measure the gravity values at the base station 3 times a day (morning, noon and at the end of the day) to correct the instrumental drift of the gravimeter. The second gps was used as a rover station to collect the position of the gravity stations. This way the maximal distance between the two gps was about 4km, assuring high precision of the rover positions. The position of the daily gps base station was then corrected during post-processing using a permanent reference base station located in Cuneo, about 30km far away from the study area. After post-processing gps the 97% of the gps position showed an precision for the Z lower that 0.15m.

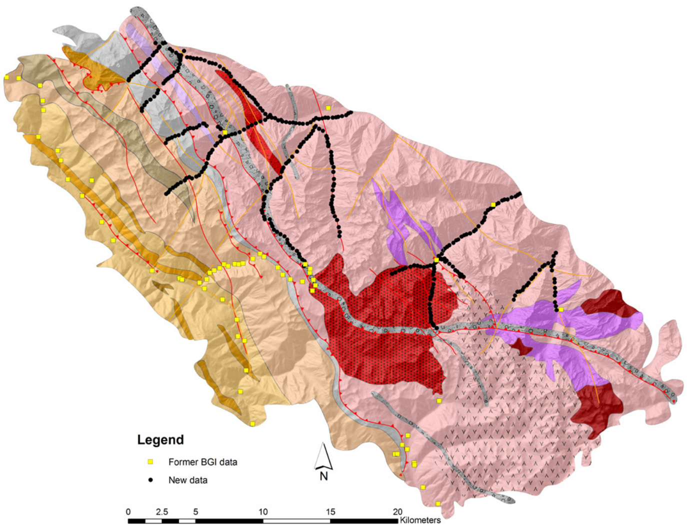


**Figure 3.** Distribution of gravity station of BGI and collected and presented in this paper.

## Calculation of the Bouger Anomaly

The raw gravity measures were automatically corrected by the gravimeter for Earth tides, then the instrumental drift was also corrected and the resulting data were elaborate using a new code (Abdelfettah, 2009) that takes into account the standard correction as follows:

**Bouger Anomaly (AB) =** $\mathbf{g}_{\text{meas}}$- $\mathbf{g}_{\text{th}}$ - ($\mathbf{\Delta g}_{\text{free air}}$ + $\mathbf{\Delta g}_{\text{plateau}}$ - $\mathbf{\Delta g}_{\text{topo}}$)

where:

$\mathbf{g}_{\text{th}}$= 978031.846 · (1 + 0.00527889sin2ϕ + 0.000023462sin4ϕ) (mGal)

$\mathbf{\Delta g}_{\text{free air}}$= 0.3086 · h (mGal)

$\mathbf{\Delta g}_{\text{plateau}}$ - $\mathbf{\Delta g}_{\text{topo}}$ are combined and calculated by the code using a DEM

where h and ϕ are the elevation and the latitude of the station.

The free air correction is manly affected by the precision of the elevation of the station but using a DGPS the inaccuracy was limited down to 0.03 mGal. The topographic correction is critical to obtain reliable results especially in complex area. To achieve a topographic correction with high accuracy a new algorithm was developed which uses a Digital Elevation Model (DEM). The main interesting aspect for the employed topography correction is the high accuracy results are obtained because the earth topography is well reproduced using high accuracy DEM and there is not any approximation calculated on the gravity effect. Moreover, with this approach we compute the plateau effect and the topography effect in the once time. The objective is to redeploy the DEM to the prism and assign a density value for each one. The gravity effect for each prism is computed according to each gravity station. The gravity effect is computed using the exact formula for a prism which has 3D extension and far from the gravity measurement point by a known distance (e.g. Blackely 1995). Taking x1, x2, y1, y2, z1 and z2 the 3D extension of a typical prism distant from the gravity station by R. The gravity effect $g_P$ for this prism is computed by:

$$g_P = G\delta \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \mu_{ijk} \left[ z_k \arctan \frac{x_i y_j}{z_k R_{ijk}} - x_i \log\left(R_{ijk} + y_j\right) - y_j \log\left(R_{ijk} + x_i\right) \right]$$

where:

$$\mu_{ijk} = (-1)^i (-1)^j (-1)^k$$

and G is the gravitational constant and δ is the density assigned for this prism.

Finally, the total gravity effect g at the gravity measurement point is computed by summing the gravity effect $g_P$ for all prisms. A first correction was calculated using the NASA 30m DEM but to increase the anomaly accuracy, we opted for the 10m DEM of the Argentera area (Ribolini, 2008). The regional Bouger anomaly was then filtered for wavelengths at 20km to come out with a the residual Bouger anomaly map (Fig. 4). This map shows the measure stations and the calculated anomaly with a buffer of 250m around each station as we considered not reliable coming out with a map interpolating profiles somewhere too far away from each other. The Bouger Anomaly varies between -11.145 and 13.144 being lower in the north-western part of the study area and increasing towards south-east. The lower values are located in the two

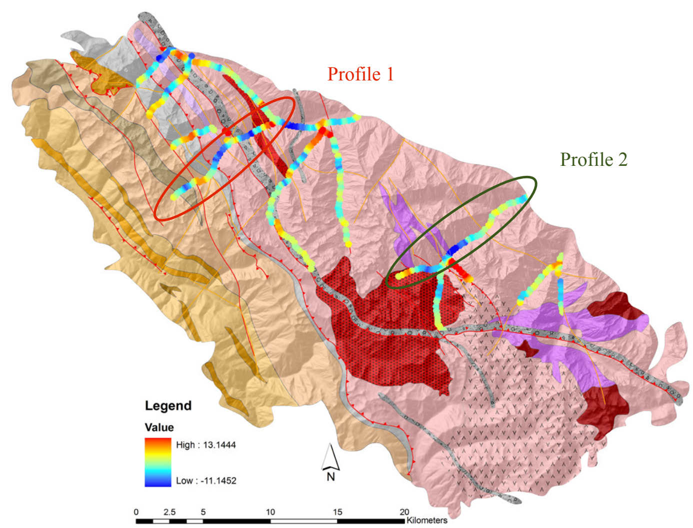


**Figure 4.** Residual Bouger Anomaly map superposed to the main geological features.

thermal areas. In particular at Bagni di Vinadio it is well show a negative anomaly in the proximities of the thermal springs that then develop towards the Stura Valley at east; a negative anomaly but more localized can be found at Terme di Valdieri as well. These two negative areas can be related to zones of intense and pervasive fracturation that can favor the up-flow of deep thermal waters.

## Data Analysis

The residual Bouger anomaly values were analyzed to identify possible relations between the density anomalies and the circulation of hot waters. For each profile 2D forward and inversion models were calculated and compared to the results from field data. In particular we will focus on two profiles that were chosen because are located in the areas of higher interest in the proximities of the thermal sites (Fig. 5).

Both profiles show that the thermal springs are located in areas of lower density. Thermal springs in the Alps are usually located in areas of high fracturation and therefore lower density. A small increment in density anomaly might be related to the presence of waters in the fractures which fills the empty spaces. Hot waters circulate within the fractured zones and when reach reach the fault core zone which is characterized by the intersection of several sets of fractures, they found a preferential way towards the surface. In the study areas the spring location also corresponds to the intersection between the fault zone with the bottom of the valley, and tend to form groups of springs that are localized in small areas (usually 100x100m).

The support this hypothesis this work started with the creation of a 3D geological model of the Argentera Massif using 3D Geomodeller software by Intrepid Geophysics that allows both to design 3D models and to carry out geophysical forward and inversion modeling. We must point out that all the available geological information derived from geological (Malaroda 1979, Bogdanoff 1989) and structural maps (Musumeci 2002, Baietto 2006, Ribolini 2008) but any information from borehole or geophysics is available to decipher the structures at depth. Once the model was created, density values (obtained by measures on collected samples) were attributed to each formation and a first forward model was calculated on the entire Massif.

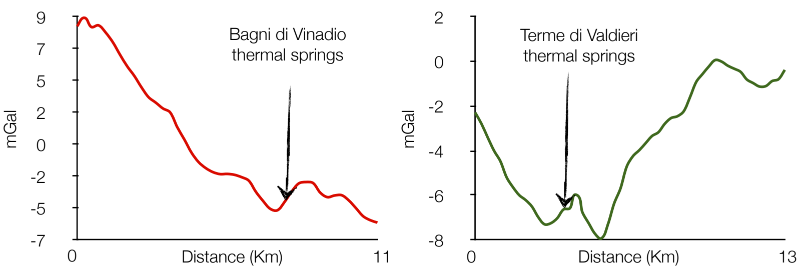


**Figure 5.** Selected profiles in the proximities of the hot springs areas of Bagni di Vinadio (red plot) and Terme di Valdieri (green plot).

Direct modeling was calculated using native codes of 3D Geomodeller and showed that the modeled geology could fit with the general trend of the calculated residual Bouger anomaly from field data. To study more in details the area of interest, forward models were calculated on the two selected profile to compare the model response the the Bouger Anomaly calculated from collected data. Also in this case we can compare the two profiles if considering the main anomalies, therefore the 3D geological models respects very well, at the scale of the Massif, the gravity trend of the area. However it doesn't describe with enough accuracy the detailed distribution of the masses at depth. For this reason we carried out 2D inversion modeling along the two selected profiles using a compact gravimetric inversion code.

## Gravimetric Inversion Models

To invert the gravimetric data along single profiles a 2D constrained compact gravimetric inversion is adopted. We used as starting point an existing software (Stocco et al., 2009) which performs the 2D compact magnetic inversion and which has been developed from the original approach by Last and Kubik (1983); the code has been however opportunely modified by appropriate equations to account for the gravimetric anomaly even if the code structure has been maintained.

A gravimetric body can be defined to be 2D when its strike length in the direction perpendicular to the profile is at least 10 times its width (Telford et al.,1990). Following (Bhattacharyya, 1964) the domain beneath the gravimetric profile can be splitted in $M$ rectangular prisms orthogonal to the profile direction, being $d_j$ the unknown relative density of the j[th] prism. Using the formula reported in literature (Telford et al.,1990) we are then able to calculate at each of the $N$ measuring points along the gravimetric profile the value $g_i$ of the Bouger anomaly due to the gravity fields of all the prisms:

$$g_i = \sum_{j=1}^{M} K_{i,j} d_i \qquad (1)$$

where $K_{i,j}$ is a geometrical function relating the size and the distance of the prism $j$ from the measurement point $i$. Eq. 1 can also be written in matrix form as:

$$g = K \times d \qquad (2)$$

being **g** a column vector with $N$ rows, **K** a kernel matrix $N \cdot M$ and **d** a column vector with $M$ rows.

The principle of the compact inversion used involves minimizing the area of the Source body (maximize its compactness). As most of the cases, we deal with slightly underdetermined problems, therefore we need to solve the inversion problem using the weighted–damped least-squares method. The results of the inversions along two example profiles are reported in figure 6. Relative density values are reported in contour maps accounting also for the topography of the profiles (bottoms of figure 6.). As it can be observed a very good fitting with experimental data is obtained by means of the adopted procedure for both profiles (tops of figure 6).

## Conclusions

It has been shown in the past that gravity method is appropriate to investigate thermal waters circulation paths and thus geothermal reservoirs at depth. Applying this method in an Alpine context with very complex topography and geological structures, involves

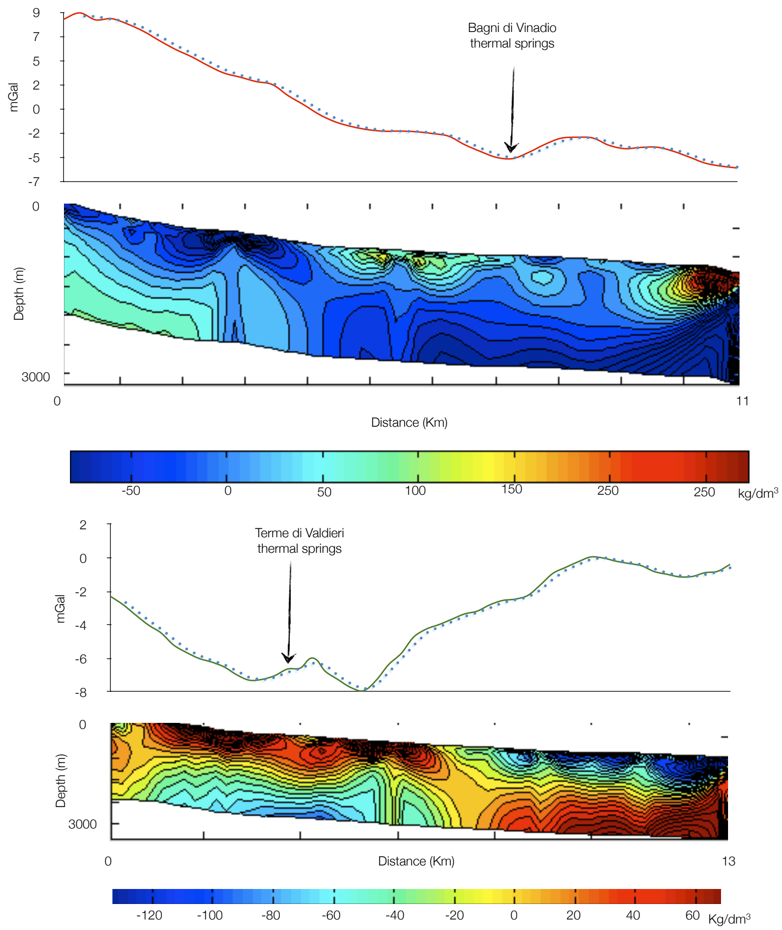


**Figure 6.** 2D inversion models on the two selected profiles at Bagni di Vinadio (left) and Terme di Valdieri (right). On the upper part of the plots the residual Bouger anomaly (red line) is superposed to the model calculated by the code showing the good fitting. The lower part shows the computed cross section up to 2000m depth and it is superposed to the main geological features that have been modeled in 3D. Also in this case there is a good fitting between the two models.

several problems both in data acquisition, as it is not possible to collect data following grid, and in data elaboration. In particular for gravity data it is crucial to reach high quality both on the field measures and for digital data such as high definition DEM that are not always available at the desired quality. Using the available data the main result of the forward modeling is the good correspondence between the 3D geological model and Bouger anomaly computed from field data. Two profiles were selected because close to the thermal areas and the general trend of the 3D model and the collected show and encouraging fit in particular for the areas surrounding the hot springs. However further studies are suggested to collect gravity data on the French side of the Argentera Massif increasing the density of the stations that are already available from the IGB and gravity results could benefit from magnetotelluric measurements that could be carried out in some selected areas to highlight the resistivity anomalies at depth and compare them to the density distribution variations showed by gravity. Moreover a geomechanical study should be carried out to better understand the fracturation conditions of the cataclastic belts and fault zones to come out with more detailed 3D models that could be a useful tool to simulate thermal waters circulation and identify the presence of geothermal reservoirs that could be exploited for heat production and even power generation.

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