Application of the gravity method to constrain geological structures of geothermal interest in the Geneva Basin

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ABSTRACT

This study focuses on the processing and analysis of public data from the gravity Atlas of Switzerland to evaluate the possibility to use gravity as a standard subsurface investigation tool in the Geneva Canton to constrain the main geological features of geothermal interest. The Geothermie 2020 program developed by Services Industriels de Genève (SIG) and the Geneva Canton, aims at exploring the subsurface to tap geothermal resources for heat production and storage, and power production. Therefore, shallow aquifers, as well as deep targets need to be investigated to identify potential areas of interests where detailed geophysical surveys and drilling of exploration wells can be carried out. We identified 4 main formations that are both geothermal relevant and show significant density variations which can be constrained by the gravity method: shallow quaternary deposit, Tertiary Molassic sediments, Mesozoic carbonates and deeper crystalline basement with embedded Permo-Carbonifer troughs.

The processing workflow focuses on the calculation of the Complete Bouguer Anomaly (CBA), from which a regional trend is removed to produce a residual gravity anomaly to enhance the signal from geological structures of interest, followed by the calculation of gravity gradiometry. Finally, Butterworth bandpass filters at increasing bandwidth were employed to produce a set residual anomalies associated to gravity anomaly sources located at increasing depth.

The results, which are interpreted according to the available geological data, show the potential of the gravity method in delineating both shallow geological features and deeper structures related to the Mesozoic sequence and to the Permo-Carbonifer sediments filling the troughs that locally cut the crystalline basement.

1. INTRODUCTION

The identification and characterization of potential targets prior drilling is crucial to define potential geothermal targets. 2D seismic has proved to be the most effective method to image the Mesozoic formations in the Greater Geneva Basin GGB (Clerc et al., 2015; Moscariello, 2018), but showed some limits in delineating shallow Quaternary deposits, and was not designed to illuminate deep structures (>4000 m) and thus cannot provide accurate spatial information about the deep sedimentary units deep Permo-Carboniferous grabens.

In the framework of a continued desire to improve the understanding of the subsurface in the GGB, the use of existing and newly acquired gravity data has been considered. Despite being a well-established geophysical investigation technique, this was never been considered as a tool to support geothermal exploration in the Geneva area.

Therefore, this study aims at evaluating the added value of existing gravity data analysis as a subsurface investigation tool to outline better the basin configuration and identify density variations within the geothermal horizon targets.

In this paper, we aim at:

1. Processing the existing gravity data across the GGB using a pseudo-tomography approach

2. Delineating gravity anomalies associated with the main geological features of the study region

3. Interpreting the observed anomalies in a geothermal perspective according to the current geological knowledge of the GGB

2. GEOLOGIC SETTING

The Greater Geneva Basin (GGB) covers an area of about 2000 km^2 extending from the town of Nyon to the NE, down to Vuache Mountain to the SW and it is limited by the Jura Haute-Chaine to the NW and by the subalpine nappes towards SE.

The GGB is the westernmost part of the North Alpine Foreland Basin that extend from the Savoy region in France to Linz in Austria (Kuhlemann and Kempf, 2002). Four major lithological units are recorded at depth (Kempf and Pfiffner, 2004; Kuhlemann and Kempf, 2002; Mazurek et al., 2006): the crystalline basement including the Permo-Carboniferous troughs, its sedimentary cover composed respectively of Mesozoic, Tertiary and Quaternary sediments. The GGB (Figure 1).

The tectonic evolution of the GGB is associated with the alpine compressional phase that caused the decoupling of the sedimentary succession from the basement by a detachment surface occurring on the Triassic evaporites (Guellec et al., 1990; Sommaruga, 1999; Affolter, 2004; Arn et al., 2005). Additionally, inherited basement reliefs and normal faults bounding Permo-Carboniferous troughs might have played a role in the nucleation of the Mesozoic north-westward thrusts observed in the SE sector of the Geneva Basin and Bornes Plateau (Gorin et al., 1993; Signer and Gorin, 1995).

In response to the alpine compression, the Mesozoic and Cenozoic sedimentary cover of the GGB underwent some shortening locally coupled to a rotational motion. This shortening was absorbed through the structuration of the fold and thrust reliefs of the Jura arc mountains during the late Miocene and Early Pliocene (Meyer, 2000; Affolter, 2004) and by the coeval formation of accommodation of strike-slip faults. The most relevant surface evidence of such structures is the NW-SE Vuache fault (Charollais et al., 2013b), which crosscuts the entire basin and bounds the western side of the study area.

In the GGB, apart from the regional Vuache fault, series of smaller-scale NW-SE striking left-lateral wrench faults affect the southwestern part of the Geneva area. Unlike the Vuache fault, no obvious connections between these structures and the Jura Mountain can be drawn across the study area (Rusillon, 2018; Brentini 2018) as suggested in previous interpretations (Signer and Gorin, 1995; Paolacci, 2013). Towards the northeast of the basin, the structural configuration is dominated by E-W striking faults. NW-SE and E-W strike slip faults occur as series of subvertical individual faults often affecting most of the Mesozoic sequence, down to the Triassic decollement surface, with associated smaller-scale sets of conjugates. Upward extension through the Cenozoic interval of the most important faults often appears as flower structures. This shallow subsurface expression is consistent with fault geometries observed in Tertiary Molasse outcrops (Charollais et al., 2007).

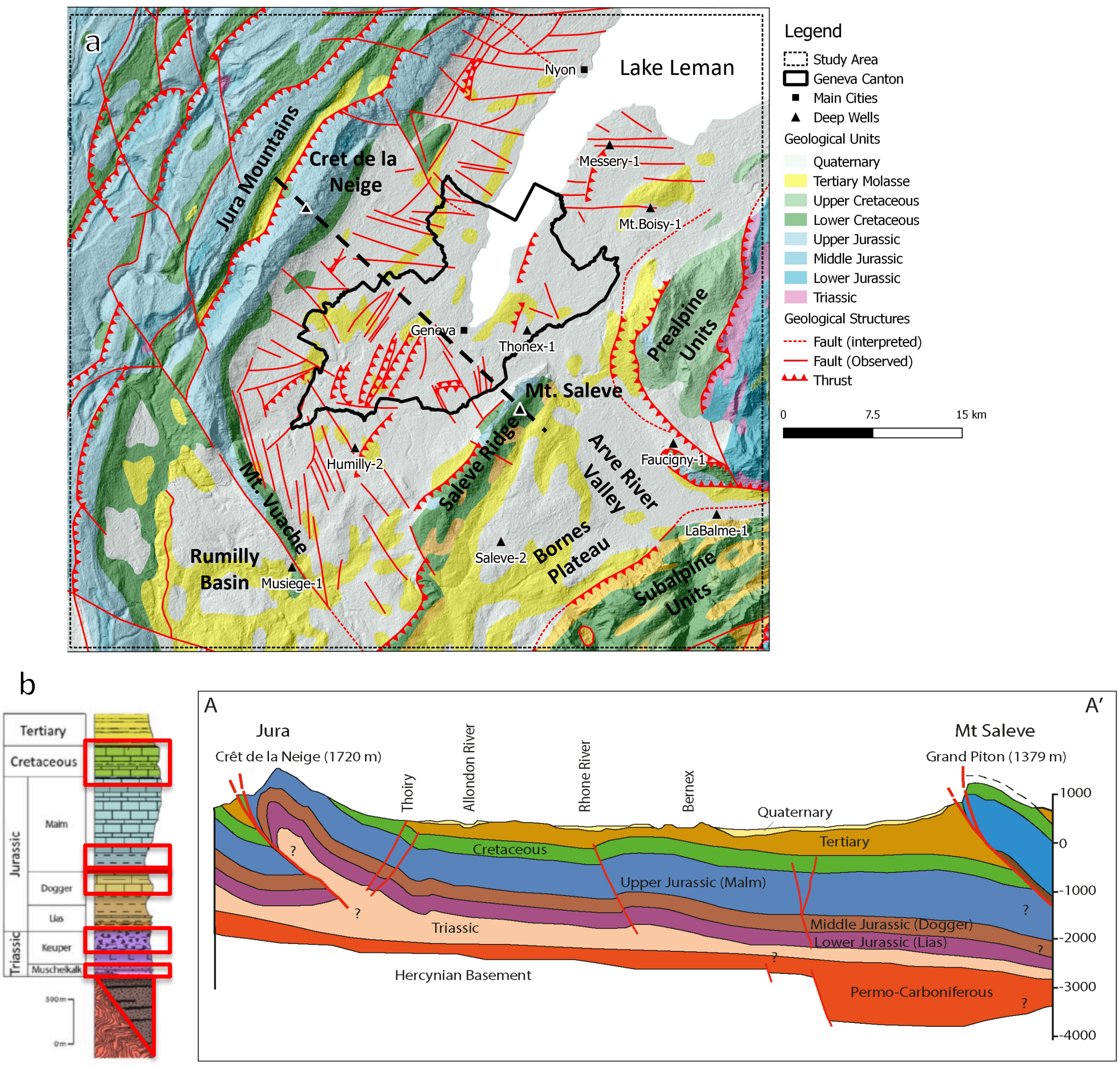

Figure 1 - a) Geological map over the Geneva Basin with indication of the main deep wells (structural interpretation mod. from Clerc, in prep); B) Cross section cutting though the GGB (mod. from Moscariello, 2018) indicating the main potential geothermal reservoirs on the stratigraphic pile (red polygons)

3. GRAVITY DATA IN THE STUDY AREA

Gravity method is a standard geophysical subsurface exploration technique, which applications in different geological settings are largely documented in literature (Allis, 2000; Guglielmetti, 2013; Reynolds, 1996; Telford, 2010; Uwiduhaye, 2018; 1990, Wilkinson 2017). The main source of data for the study area is the gravimetric Atlas of Switzerland (Olivier et al. 2010) with an average station density of 0.3 station/km^2. In addition, more data for the surrounding French areas are available from the International Gravimetric Bureau BGI at a less dense station distribution (average 15 station/100km^2) (Figure 2).

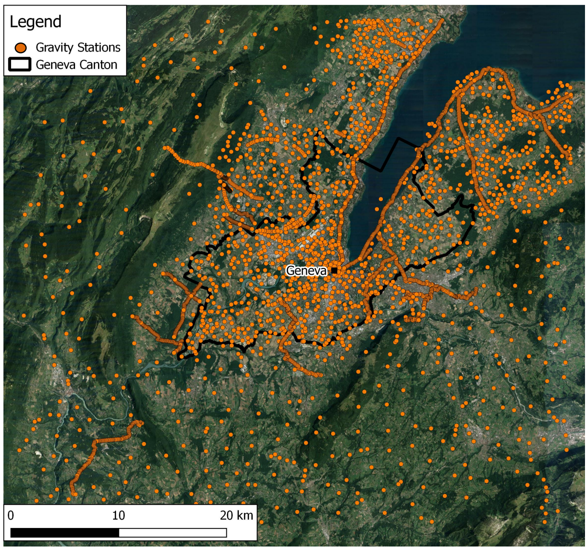

Figure 2 - Gravity stations from the Gravity Atlas of Switzerland and the Bureau Integrnational de gravimetrie BGI over the GGB

On a regional scale across the whole Molasse Plateau Kahle et al. (1976) and Klingelé (2006) showed a clear gravity regional NW-SE oriented trend of the Molasse basin, controlled by the deepening of the crust towards the Alpine front (Figure 3). Klingelé & Schwendener (1984) provided constraints for the depth, geometry and density of one of the major P.C. though in N-E Switzerland. In particular, they highlighted that the negative anomaly associated with this can be explained by a 100 kg/m^3 density reduction of the Permo-Carboniferous sediments with respect to the surrounding crystalline rocks. Abdelfettah et al (2014) reported that density variations up to 580 kg/m^3 have been observed in several wells in NE Switzerland for the Permo-Carboniferous sediments, which density was reported to be highly variable, ranging between 2210 and 2620 kg/m^3 (Matter et al. 1987), whereas a variation between 2430 and 2740 kg/m^3 is observed for the crystalline basement. For the GGB area, the Permo-Carboniferous measured density in the Faucigny-1 well varies between 2620 and 2660 kg/m^3 whereas in the Humilly-2 well the grain density ranges between 2678 and 2786 kg/m^3 whereas the bulk density is recorded in the 2678-2768 kg/m^3 range indicating low porosity values between 0.3% and 1.6% (Rusillon, 2018).

Gravity data were collected in the Geneva area and surrounding regions for hydrocarbon-resources exploration, and research studies. Gravity survey carried out across the whole Geneva canton covering the area with 3 stations per km^2 (Poldini, 1963), showed the sequence of SW-NE oriented negative and positive anomalies, crossing the study area. The formers are associated with the glacial valley filled with quaternary deposits. The latter were interpreted as morphological features of the transgressive contact Molasse. Vertical gravity gradient was used to infer density variations in the quaternary filling (Montadon et al. 2000) while lateral and vertical heterogeneities of Quaternary to Cretaceous sedimentary layers were refined combining gravity and inverted velocities from well data to density lateral variations models (Carrier et al. 2017).

Gravity studies for geothermal prospection in Switzerland (Altwegg et al. 2015) were implemented to estimate density variations in the subsurface associated with Quaternary deposits and deep Permo-Carboniferous thoughts using 3D seismic as geometrical constrain for gravity stripping processing. A similar approach was applied by combining gravity data, 3D litho-constrained forward modelling, and stripping processing to define density variations in the subsurface (Mauri et al. 2015). Furthermore mapped Permo-Carboniferous troughs in northern Switzerland using sequential Butterworth filtering were used to identify the gravity anomaly wavelengths associated with the different geologic units (Abdelfettah et al. 2014).

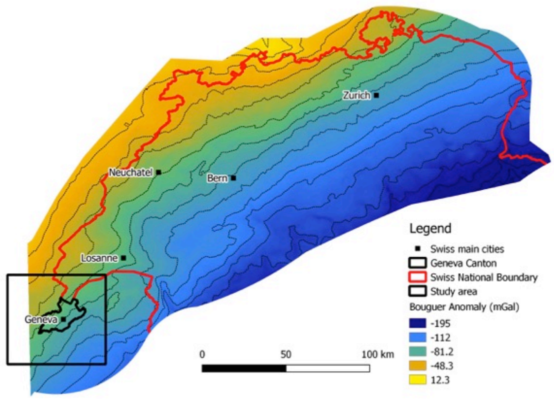

Figure 3 - Gravity stations from the Gravity Atlas of Switzerland and the Bureau Integrnational de gravimetrie BGI over the GGB

4. PROCESSING OF GRAVITY DATA

The processing and analysis of the existing gravity data across the GGB aimed at constraining the gravity signature of the main geological features, namely the Quaternary deposits, the Tertiary sediments, the Mesozoic carbonate sequence and the Permo-Carboniferous troughs affecting the crystalline basement. Therefore, the processing was carried out aiming at producing a set of residual gravity anomaly, representative of the geological structures of interest at different depth ranges. The processing has been carried out using the software Geosoft Oasis Montaj version

9.4 (2018), which provides a whole set tools for 2D and 3D processing.

The processing followed the sequence (Figure 4):

- Combination of the data from the Gravimetric Atlas of Switzerland and the Bureau International de Gravimetrie, and quality control.

- Calculation of the Latitude, Free Air, and Bouguer anomalies as well as the Terrain corrections to produce a Complete Bouguer Anomaly (CBA). The CBA was calculated using a reference density of 2670 kg/m^3, which was constrained by using the Parasnis (1952) and Nettleton (1939) methods. For the terrain correction the ASTER Global Digital Elevation Model V002 (GDEM), having a 30m horizontal resolution, was used. The full resolution DEM was used for the inner correction at a distance of 1 km from each station and it was automatically de-sampled for the outer correction over a distance of 167 km.

- Application of the gravity gradiometry techniques to delineate density contrasts associated with anomaly shallow subsurface source structures. Derivatives help in interpreting gravity data because they isolate contacts, being associated with abrupt density variations. In this study, both the vertical and the horizontal derivatives have been analyzed.

- Filtering of the CBA by applying the pseudo-tomography approach (Abdelfettah et al., 2014), assuming a direct link between wavelength of the gravity anomaly and depth of the geological structure originating it. This is particularly the case of the Geneva Basin which geological structures can be simplified as a “layer-cake” model with subparallel units gently dipping towards SE. In a first instance, filtering was applied to the CBA anomaly to remove the regional trend, hence removing the effect of deep and regional (lithospheric) masses, and to emphasize the effect of the shallow structures of interest. This produced a residual gravity anomaly. Secondly, bandpass Butterworth filtering (Butterworth, 1930) was applied in the frequency domain using the Geosoft Oasis Montaj software through the selection of the long and short cut-off wavelengths, keeping a degree of filter function fixed as 8 as per default.

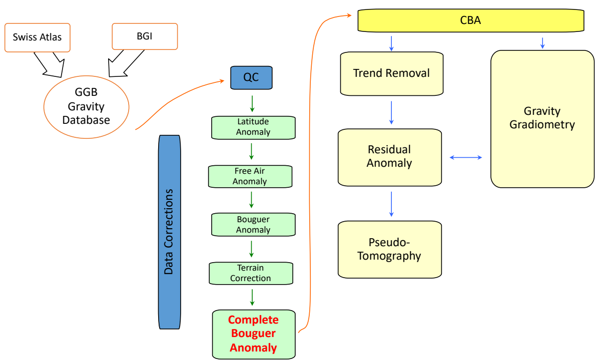

Figure 4 – Processing workflow applied in this study

4. RESULTS

4.1 Gravity anomalies

The Free Air Anomaly (FAA) show values between -67 mGal and 99 mGal and the anomaly distribution is strongly correlated to the elevation of the gravity stations, hence the local topography, which, in the case of the Geneva basin is controlled by the tectonic activity, allowing the main lithological and density contrast, specifically Cenozoic/Mesozoic, to be exposed (Figure 5). Therefore, positive values of the FAA correspond to the main topographic heights such as the Jura and Vuache Mountains, and the Saleve Ridge where the Cretaceous and Jurassic limestones are exposed. Two areas showing intermediate values between -5 and +15 mGals are located at the Bornes Plateau and at Mt. de Sion hills situated between the termination of the Mt. Vuache and Saleve Ridge. In both areas, Quaternary and Tertiary sediments are exposed. Low anomaly values are associated the Rumilly Basin at the Western border of the study area, to the Geneva area, with values ranging between -20 and -50mGal, and to the Arve Valley on the SE of the area where the lower values (-67 mGal) are observed.

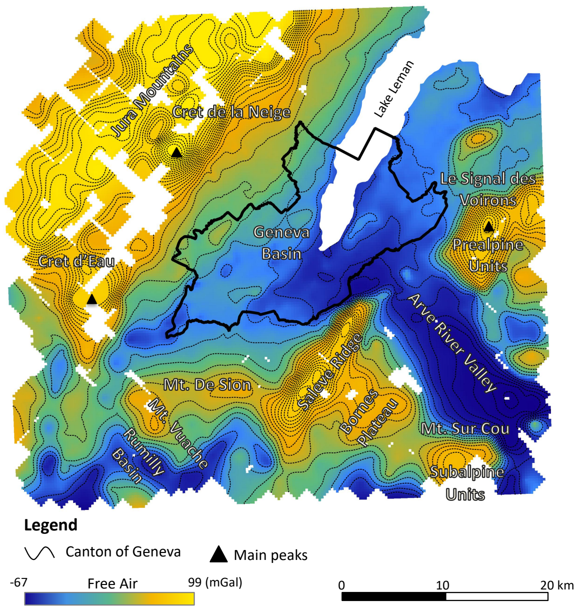

Figure 5 – Free Air Anomaly (FAA) over the study area

The Bouguer Anomaly (BA), shows a NW-SE oriented linear, ranging from -42.7 mGal to -133 mGal. However, some local disturbances with respect to the regional trend can be observed, in particular associated with local topographic highs. This effect has been removed by applying the Terrain Correction to produce the Complete Bouguer Anomaly (CBA). CBA ranges between -105 mGal and -32 mgal and is characterised by a NW-SE linear trend, which is coherent with the gravity regional trend in the whole Molasse Plateau and with the regional deepening of the lithosphere towards the Alps (Figure 6).

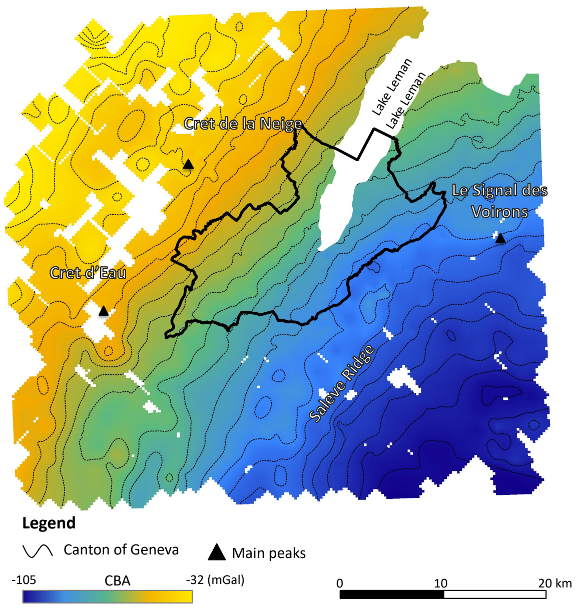

Figure 6 – Complete Bouguer Anomaly (CBA) over the study area

As the deepest geological features targeted by this study (i.e Permo-Carboniferous troughs) are located approximately located at 3.5-5 km in depth, the linear trend was removed from the CBA in order to produce a residual gravity anomaly, which highlights the shallower gravity structures (Figure 5).

The residual anomaly ranges between -6 mGal and 4.5 mGal and four main negative anomalies can be observed (Figure 7):

- Anomaly A is located in the Geneva Basin, ranges between -6 mGal and -1.5 mGal, shows an about 20 km SW-NE oriented elongated shape and overlays the Humilly-2 and Thônex-1 wells. The anomaly mainly corresponds to the thickness variations within the Cenozoic units. The thickness of the Tertiary Molasse increases in the NW-SE direction, towards the Salève front, and from the SW to the NE as observed in the two wells. In the Thônex-2 well, 73 m of Quaternary deposits and 1258 m of Molasse sediments were drilled before entering the Lower Cretaceous limestones, whereas 67 meters of Quaternary deposits and only 372 m of Molasse sediments were encountered in the Humilly-2 well. In addition, the presence of a 3-5 km wide Permo-Carboniferous trough extending along the Salève front has been recognised in 2D seismic data (Gorin et al., 1993; Paolacci, 2012; Moscariello, 2016) whose infill sediments were encountered at bottom of the the Humilly-2 well (Brentini, 2018).

- Anomaly B is located in the Jura Mountains, where the Cretaceous and Jurassic limestones are the only exposed lithologies. The anomaly has a rather circular shape of about 10 km in diameter and ranges between -5 mGal and -1 mGal. Small outcrops of Triassic limestones and anhydrites are exposed in the surroundings region (Brentini, 2018), and presumably extends at shallow depth below the Cretaceous and Jurassic limestones as indicated by seismic data in the area (Gorin et al., 1993; Paolacci, 2012). Triassic lithologies are known to have a lower density (2620 kg/m3) compared to the surrounding Cretaceous and Jurassic limestone (2680 kg/m3), which can contribute to the observed negative anomaly..

- Anomaly C is located on the Rumilly Basin and ranges between -3 mGal and -0.5 mGal being the smallest negative anomaly among the four observed. The main formations cropping out are the Quaternary and Tertiary sediments and their total thickness is estimated to be 500 m. The closest well (Musiege-1), located a few kilometres towards the south, in the proximity of the Vuache Fault, encountered 150 m of Molasse sediments above the Lower Cretaceous limestones (Paolacci 2012; Moscariello et al., 2014)..

- Anomaly D is located in the Bornes Plateau and expands to the Arve River Valley. It's a large anomaly extending for more than 20 km in the SW-NE direction and about 10 km from NW to SE. The range of the anomaly is in between -6 mGal and -1 mGal. Two wells are located at the two extremities of the anomaly. The Salève-2 well on the SW drilled 1750 m of Tertiary Molasse sediments after 25 m of Quaternary deposits; the Faucigny well, the deepest of the region, drilled 1576 m of the Tertiary Molasse, but only after 1339 m of Quaternary deposits and Prealpine carbonate units. This well also penetrated 359 m of Permo-Carboniferous sediments filling a basin (Paolacci, 2012; Brentini, 2018).

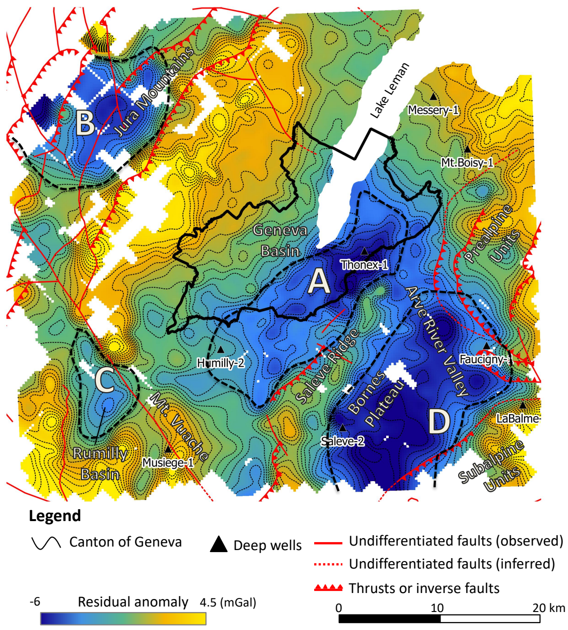

Figure 7 – Residual Anomaly over the study area, resulting after removing the linear trend from the CBA

4.2 – Gravity gradiometry

First vertical derivative (FVD) has been computed and interpreted in combination to the pseudo-tomography results, to constrain the geometries and the wavelengths of the anomalies generated by the shallower geological structures, such as the thickness of the Quaternary sediments (Figure 8). Particular attention has been directed on the Geneva area where the highest gravity station density and other subsurface data (seismic and wells) are available. This allows a more consistent constrain of the gravity anomaly and a better understanding of the correlation between gravity data and subsurface geological features (i.e. vertical and lateral density changes). The FVD enhances the main density contrasts observed in the residual anomaly. The main four negative anomalies are constrained and reveal the effect of the shallower lithologies such as the Cenozoic stratigraphic units for the anomalies in Zones C and D. With respect to Zone B anomaly, the FVD suggests that its source is at rather shallow depth within the Mesozoic units, located in the Jura mountains. In the Geneva area, a rather linear SW-NE trending local negative anomalies alternates to parallel elongated positive anomalies. Additional positive anomalies are observed at the front of the Jura Mountains which is bounded towards NE by a N-S trending positive anomaly and to the SW by the NW-SE trending positive anomaly associate with the Vuache Fault. The Saleve ridge is marked by a positive anomaly, as well as the Eastern Border of the area where the Pre-Alpine and Sub-Alpine Units are exposed.

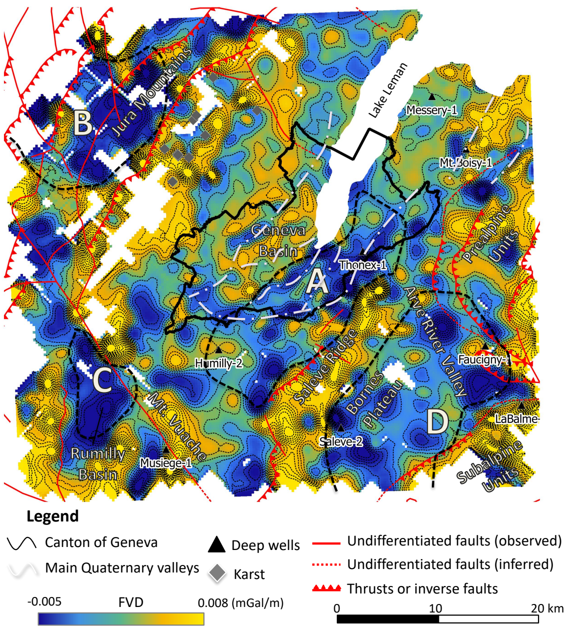

Figure 8 – First Vertical Derivative over the study area

The horizontal gradient (HG) has been used to enhance the edges of the main anomaly sources (**Errore. L'origine riferimento non è stata trovata.**). This resulted in highlighting the edges of the four main negative anomalies, marked by positive linear features. An analysis of the strike of the main lineaments of the HG shows three main trends as follows: EW, NW-SE and SW-NE (Figure 9). The same trends are observed for the geological structures. However, some differences are observed as the HG analysis accounted for all the lineaments, associated with both geological structures and morphologic features, whereas the analysis done on the geological data accounted for the fault and thrust structures only. The Anomaly A anomaly is well constrained on its Northern and Southern borders by SW-NE positive lineaments. Anomaly B anomaly is bounded at its S-E edge by SW-NE trending positive, whereas the N-E and S-W edges are limited by NW-SE trending positive anomalies. Anomaly C anomaly is limited to the North by the Vuache Fault to the West by N-S oriented contacts, and to the South by a SW-NE structure, perpendicular to the Vuache fault. Anomaly D anomaly is fully surrounded by positive anomaly features, which align to the Salève to the N-W, to the Pre-Alpine and South-Alpine fronts on the East and on the South respectively. In the Geneva area, clear evidence of the Quaternary sediment is observed in the HG maps, which enhances the alternation of linear SW-NE trending positive and negative anomaly structures across the whole area of the Canton of Geneva.

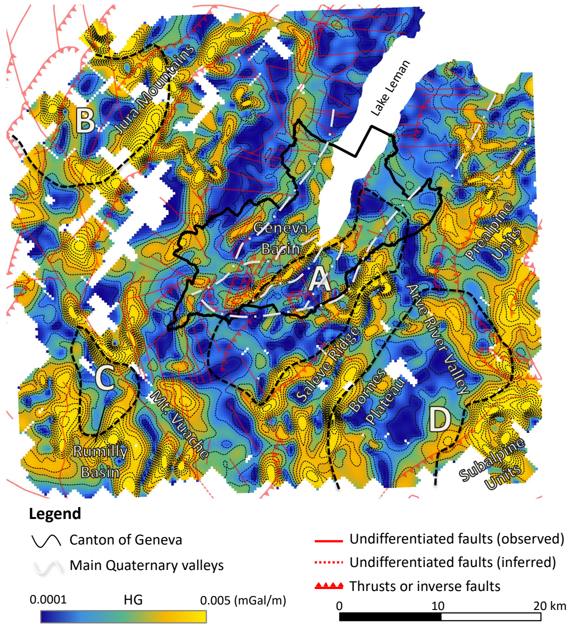

Figure 9 – Horizontal gradient over the study area

4.3 Pseudo-tomography

The pseudo-tomography method has been used to detail the contribution of the geological structures to the gravity anomaly signal at different depth. This method was first applied keeping fixed to 1 km the short cut-off wavelength and gradually increasing the longer cut-off wavelength. All the signal having wavelength shorter that 1km has been considered as noise. Then the process was inverted by keeping fixed to 60 km the long cut-off wavelength and moving towards shorter wavelengths until 1 km. This processing aimed at constraining the contribution of both the Quaternary fillings and the deep source of anomaly. Finally, the remaining wavelengths were analysed to enhance the contrast between Tertiary sediments and Mesozoic sequence.

The results show the different residual anomalies at increasing gravity signal bandwidth. The 1-5 km anomaly, as for the vertical derivatives, has to be analysed in particular in the Geneva area and correlations with the thickness of the Quaternary deposits are observed, whereas in the rest of the area only scattered anomalies are observed due to the insufficient gravity station density (Figure 10).

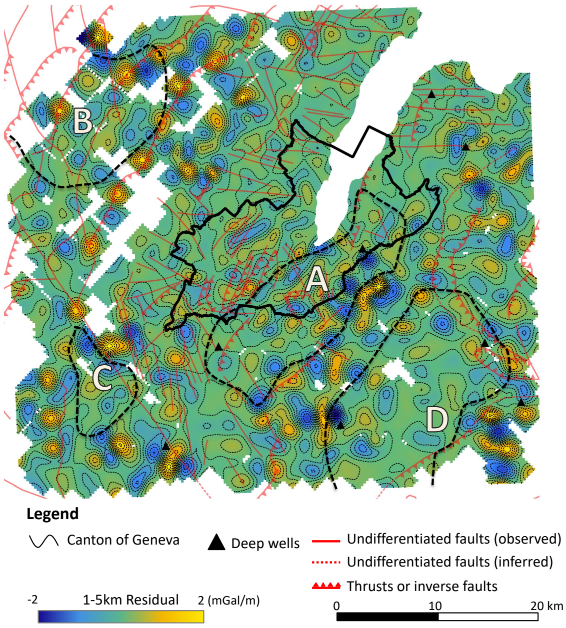

Figure 10 – 1-5km bandwidth residual anomaly over the study area

The 5-17.5 km residual anomaly (Figure 11) shows correlations mostly with the Tertiary Molasse sediment pile. The strong effect of the Tertiary sediments in defining negative gravity anomalies, such as anomaly C, is supported by the Musiège-1, Thônex-1 and Salève-2 wells where the top of this formation is located at rather shallow depth. Interestingly the Humilly-2 and Faucigny-2 wells correspond to positive anomalies where carbonate units are known to be located at shallow depth.

The main features are:

- The Hu-2 well which lies on a local positive anomaly, which represents the anticline structures which was targets by the well as it was interpreted as a hydrocarbon trap.
- The negative anomaly at the Th-1 wells associated with the thick Cenozoic pile drilled by the well.
- The positive anomalies associated with the Jura front, Vuache fault and the Saleve ridge.
- Anomalies B and C are well constrained.
- The positive anomaly at the centre of the Geneva Canton.
- The two negative anomalies north of the Geneva Canton.
- Anomaly D is composed by two negative anomalies separated by a NW-SE lineament running from the Saleve ridge to the Sub-Alpine units.

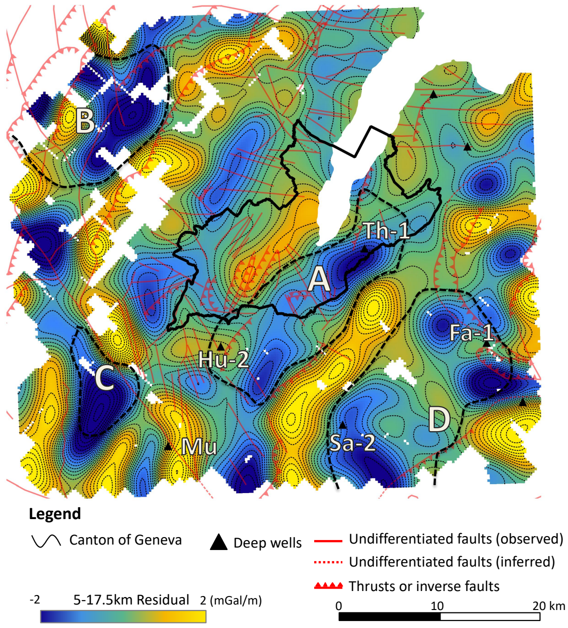

Figure 11 – 5-17.5km bandwidth residual anomaly over the study area

The residual 17.5-20 km (Figure 12) shows an abrupt change in anomalies distribution. In particular the positive anomalies of Vuache and at the centre of the Geneva Canton positive anomaly, are no longer constrained. Also, the negative anomaly associated with the thick Molasse succession in the Thônex-1 well, is not defined and is overprinted by a larger anomaly which centres on the Hu-2 well. Anomaly D appears as a unique large body at whose eastern boundary is located the Faucigny-2 well. The Salève ridge and the Jura are still preserved, the latter being limited towards SW by the Vuache fault.

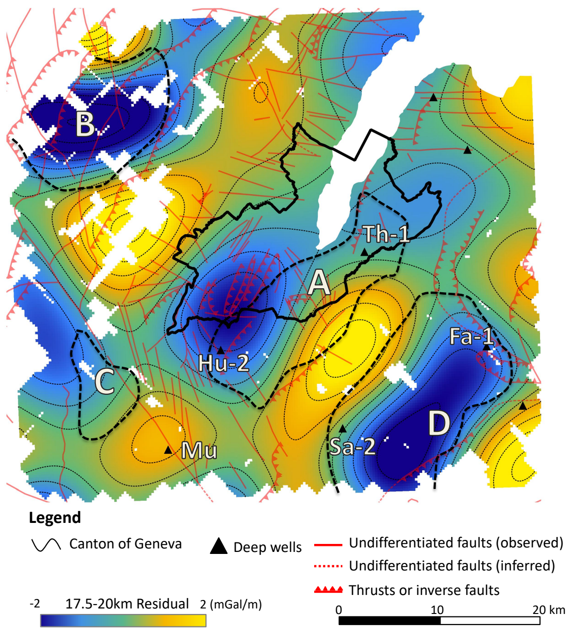

Figure 12 – 17.5-20km bandwidth residual anomaly over the study area

The 20-25km residual anomaly shows very sharply the alternation of SW-NE trending positive and negative anomalies. Negative anomalies are associated with anomalies A, B, C, and D whereas positive anomalies are coupled to the roots of the Jura chain and the Saleve ridge (Figure 13).

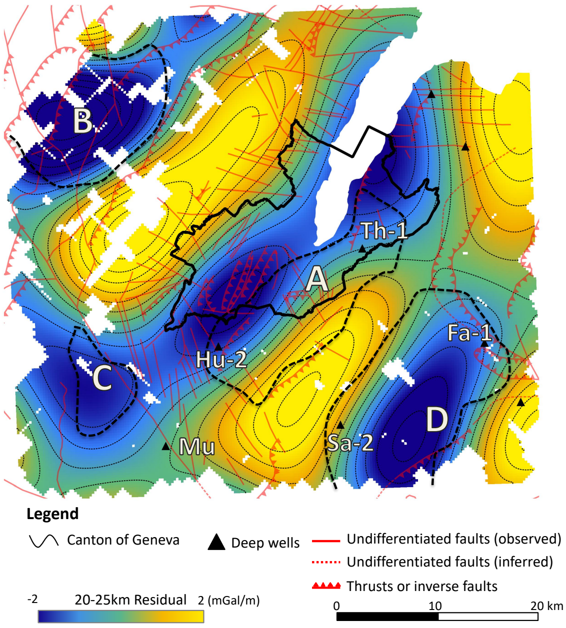

Figure 13 – 20-25km bandwidth residual anomaly over the study area

The 25-40 km residual shows wide anomalies in continuity with those observed on the 20-25 km residual. Anomalies B, C are characterized by wide negative anomalies and anomalies A and D overlap possibly due to deep Permo-Carboniferous sediments. However, the negative anomaly in correspondence of the Humilly-2 well is no longer constrained indicating that it is limited within the 20-25 km bandwidth. Among positive anomalies only the one corresponding at the surface to the Jura is still observed (Figure 14).

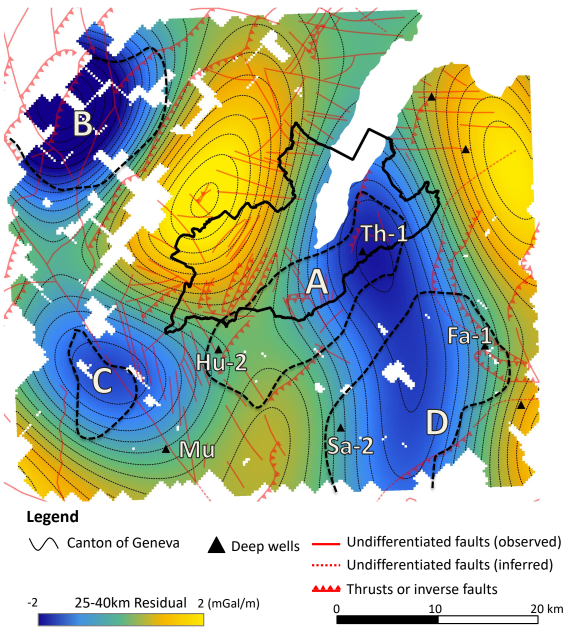

Figure 14 – 25-40km bandwidth residual anomaly over the study area

6. CONCLUSIONS

The results of this study based on the computation of residual gravity anomaly maps generated from existing data has shown encouraging results to constrain geological structures of interest for geothermal development.

The residual anomaly produced by removing the regional trend from the CBA reveals four main zones with negative anomalies. Zone A, C and D, located on the main sedimentary structures, have a double source composed mainly by the Molasse sediments and partially by a deeper source located between the base of the Mesozoic and the top basement where low density evaporitic lithologies and Permo-Carboniferous sediments are observed in the deepest wells of the region. Zone B anomaly, located in the Jura Mountains, has a rather shallow source most probably some thick evaporitc level in the Triassic units, which locally crop out in the surrounding area. Positive anomalies are associated with the Mesozoic limestone that crop out in the whole region and are deeply rooted at the level of the Triassic units.

The FVD shows correlation with the position and lateral extent of the Quaternary deposits in the Geneva area which fills Würmian glacial valleys. Some correlation between local negative anomalies and karst features in the Jura mountains area observed but the scattered distribution of gravity station impose to study more in detail such correlation, possibly by collecting new data in the future.

The HG helped in enhancing the lateral density contrast. In the Geneva Canton the HG provided good correlation with the geometry of the glacial fills, in agreement with FVD and with the short wavelength residual anomalies computed via the bandpass filtering. HG also helped to limit the lateral extent of the four main negative anomalies. Additionally, the HD highlighted three main trends of gravity lineaments which are coherent with the main trend of the main geologic structures of the study area such as the thrusts systems of the Saleve ridge and Jura mountain and the Vuache fault.

The pseudo-tomography approach has proven to be useful to imaging gravity anomalies at different scales such as small anomalies associated with shallow geological features such as the Quaternary sediments filling glacial valleys, larger anomalies within the Molasse-Mesozoic sequences, and even larger negative anomalies responding to density variations at larger depth at the transition between the Mesozoic base and the top crystalline basement, where low density lithologies are observed in the Triassic units and filling the Permo-Carboniferous troughs. All these geological features are important in a geothermal perspective.

The results are encouraging and can be further improved by 2D and 3D gravity modelling, joint interpretation with other geophysical data and by the acquisition of new data at higher resolution, to enhance the resolution of the shallower units.

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