COMBINED USE OF LAND GRAVITY DATA AND 3D GEOLOGICAL MODEL TO IMAGE DEEP GEOLOGICAL BASIN: CASE OF REGION OF LA BROYE, SWITZERLAND

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Abstract- Over the last decade, in Switzerland, geothermal projects target deeper structures in hope to find potential geothermal resources to produce electricity. Among the deep geological features, deep Permo-carboniferous basins could host large geothermal reservoirs. The region of La Broye, in the western molasse plateau in Switzerland, was investigated to confirm the existence of such deep structures. The aim of the study is to bring new insight on the origin of the gravity variations in the region of La Broye. Reprocessing of previous gravity data set has improved the resolution of gravity decrease associated to the basin of la Basse-Broye that is made of moraine and post glacial deposits. Over 100 km^2, we surveyed 824 new gravity stations. Then, a 2 mGal gravity decrease long of 10km has been well defined, which is located over the molasse hills, between Neuchâtel Lake and the plain of Basse-Broye. A 2D sensitivity study using a 2D geological model from seismic atlas shows that observed gravity decrease over the hills cannot be associated to rock density variation from either shallow layer from post ice age period, or sedimentary layer from Mesozoic period. However, the 2D model was inconclusive for a deep structure source. The 3D forward gravity model computed using Swisstopo 3D geological model provide clear information that only a deep structure can generate the observed gravity decrease. Shape of this deep structure has been estimated through 3D forward gravity model, by doing a stripping of the gravity effect associated to each formation for geological layers from the Tertiary, Quaternary and Mesozoic periods. Finally, based on its location and extend, the source of the gravity variations over the hills can only be a deep Permo-carboniferous basin.

I. INTRODUCTION

The study area covers 100 km^2 oriented NE-SW, which is the NW part of Region of La Broye, in the western molasse plateau and covers both the plain of Basse-Broye and the hills north of it (red dashed line, Figure 1). The molasse plateau results of the Alps mountain belt uplift and erosion. The region of La Broye was strongly affected by the last major ice period, through deep erosion and deposit of moraine and post glacial deposit [Lapaire, 2000; Clavien, 2001]. In the eastern part of La Broye, the plain of Basse-Broye is a periglacial valley filled thick layers of quaternary deposit (>200 m thick) and underlain by a layer of moraine [Lapaire, 2000; Clavien, 2001]. Of tertiary ages, the molasse formations are mostly made of series of sandstone and clay. Recent gravity work suggested that the region of La Broye was possibly on the rim of a large Permo-carboniferous sediment structure, which further extend throughout the western molasse basin, but more information is required to properly define it. [Altwegg, 2015].

The aim of the study is: 1) to bring new insights on the gravity variations by re-processing old gravity data set, 2) by surveying new stations to improve the spatial resolution, 3) to investigate shape and depth of geological bodies that generate the main gravity variations.

II. FIELD SURVEY

1.1. Previous studies

The gravity survey of Switzerland exists since the 1970's. In the western Swiss Plateau, the previous studies used in this study are the gravity map of the Swiss plateau [Olivier, 1983], the gravity model of the region of Fétigny [Clavien, 2001], the gravity study of the morphology of the deep molasses in the Basse-Broye Valley [Lapaire, 2001] (Figure 2).

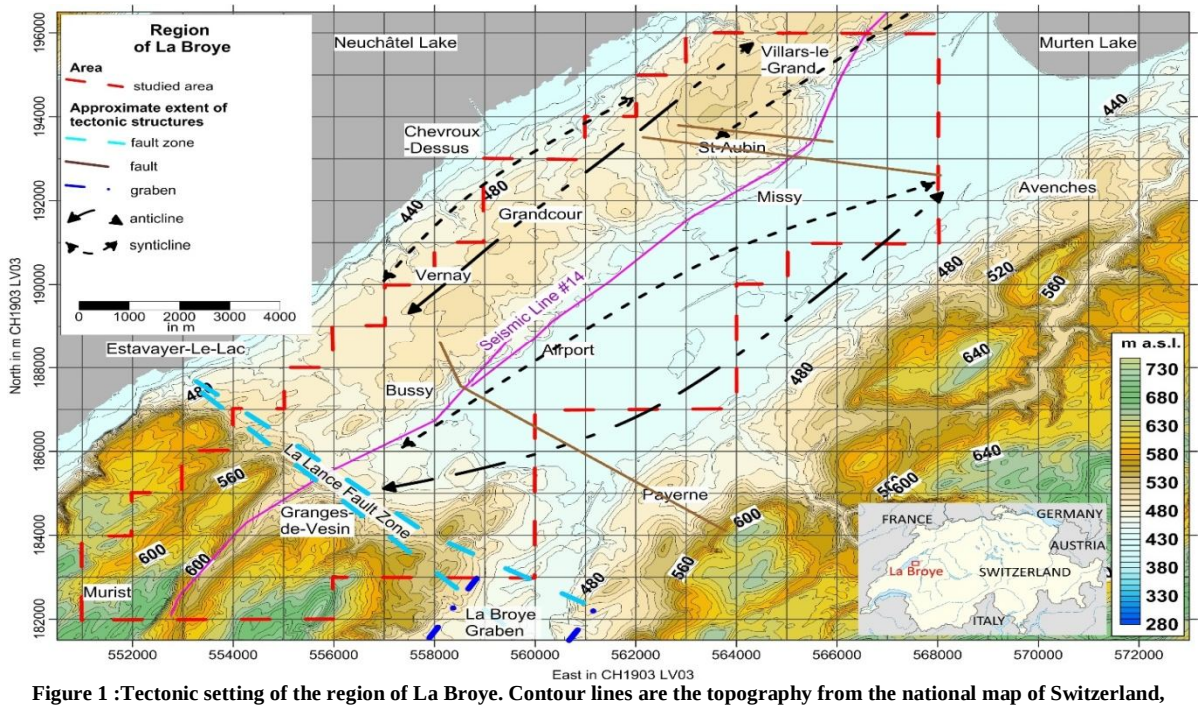


Figure 1 :Tectonic setting of the region of La Broye. Contour lines are the topography from the national map of Switzerland, 1:25'000 [Swisstopo, 2005]. Only the main tectonic features are shown in the figure and a complete description can be found in the work of Mosar et al. [2011] and Diem et al. [2012].

1.2. 2015 gravity survey

The gravity survey was carried out over 5 months over 100 km^2. Survey was conducted using a CG-5 gravimeter and geo referenced was done using a DGPS-Leica GS-15 with a real-time connection to the swipos network (swipos® in LV03 from Swisstopo). 824 new gravity stations were surveyed, which includes 70 locations also measured in previous studies. 220 stations were done with a sampled step of 100 m along the seismic line #14 (Figure 2).

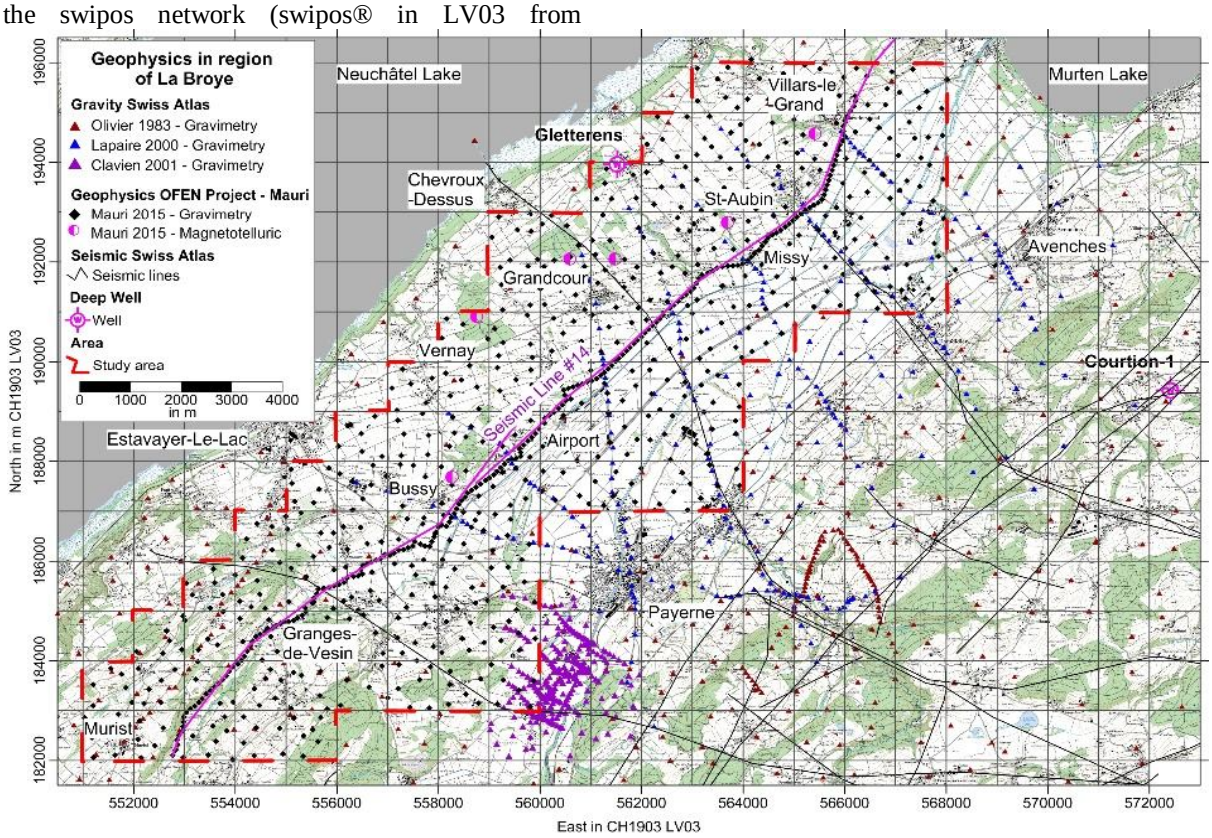


Figure 2 : Geophysical data set for the region of La Broye. Black dots indicate the location of gravity station surveyed in 2015 over 100 km^2(red dashed line, this study). Black lines are seismic profiles (Sommaruga et al., 2012). Other gravity data are from the work of Olivier [1983], Lapaire [2000] and Clavien [2001].

Other parts of the study area were covered by 4 to 6 gravity stations by square kilometre (604 stations). Additionally, to obtain a better assessment of the uncertainty, 9.57% of the total stations have been resurveyed over time. Mean standard deviation of gravity measurement is lower than 0.080 mGal for 87.5% of the stations and gravity variation over time is lower than 0.050 mGal for 92.5% of the re-surveyed stations.

III. RESULTS

To better merge the 4 data sets, all data have been corrected using the same method to obtain the Bouguer anomaly value. All data have been corrected of Earth Tide. Corrections were done using the software Corr-Topo [Altwegg, 2015], which include topographic correction, plateau correction, Earth curvature and g-theoretic calculation. The topographic correction use 3 sets of Digital Elevation Model (DEM): 1) a high resolution DEM with grid size of the 2m and a vertical uncertainty of 0.1m from the SwissALTI3D (Swisstopo, 2010) for the proximal zone (less than 200m away from the station), 2) used a DEM with grid size of the 25m and a vertical uncertainty < 2m (Swisstopo, 2005), for the average zone (from 200m to 20 Km), 3) a DEM with grid size of a 400m and a vertical uncertainty < 15m from SRTM data (RASTER GDEM METI and NASA, 2009) for the distant zone (from 20 Km to 167 Km). In addition, gravity effect of water volume from Neuchâtel lake (~13.98 km^3) and Murten lake (~0.55 km^3) were calculated using bathymetry data from previous studies [Liechti, 1994; Swisstopo, 2005; Reusch et al., 2015]. After merging all the data set, total uncertainty is of 0.140 mGal.

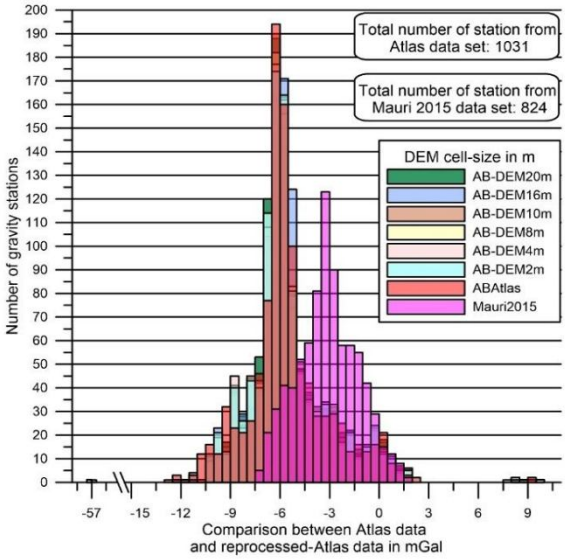


Figure 3 : Histogram presenting the variation of residual Bouguer values in region of La Broye. Red colour represents the Bouguer variations (named here ABAtlas) before re-processing that include data set from previous works of 1983 gravity Atlas [Olivier, 1983], M·Sc. work of Lapaire [2000] and M·Sc. wok of Clavien [2001]. Then data have been reprocessed using different cell-size DEM to investigate effect of DEM resolution. In purple is the data set collected in 2015 (this study named Mauri 2015), which has been corrected using the 2m DEM of Switzerland [Swisstopo, 2010].

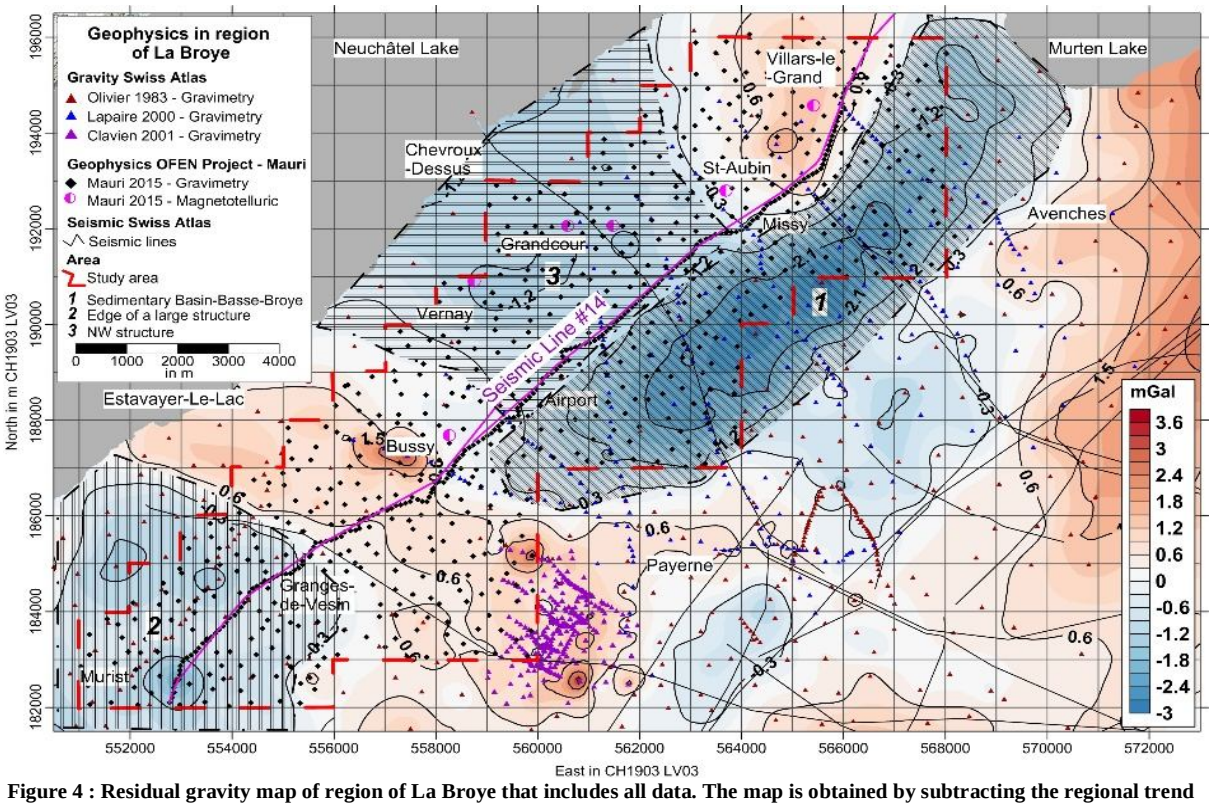


Figure 4 : Residual gravity map of region of La Broye that includes all data. The map is obtained by subtracting the regional trend to the Bouguer anomaly map for a density reference of 2.67 g·cm-3. See text for details. Contour line is of 0.300 mGal. The number highlight the delineation of the main gravity decreases.

In Switzerland, regional trend is associated to the roots of the Alps mountain belt, which decrease as one divided by the square distance from the Alps (Kahle et al., 1976; Klingelé, 2006; CREGE, 2012; Altwegg, 2015). Then, a traditional bilinear regression has been computed using all the Bouguer values from all gravity data (Figure 3). The residual gravity map is obtained by subtracting the computed bilinear regional trend to the Bouguer anomaly map (Figure 4).

Over the studied area of the region of La Broye, the residual gravity variations allow us to characterize 3 main gravity decreases: The new residual gravity map highlight 3 main gravity decreases (Figure 4): 1) Over the Basse-Broye, the plain is associated to an extended decrease of gravity (Anomaly 1, Figure 4). The work of Lapaire [2000] has shown that the gravity decrease is due to both glacial sediment and of deep moraine layer at the base of the paleo-valley. 2) In the SW corner of the studied area (Anomaly 2, Figure 4), the gravity decrease seems to correlate with the edge of an extended gravity decrease that extend further west, which is presented to be associated to a Permo-carboniferous sediment layers at depth [Altwegg, 2015]. In the northern part of the region of La Broye over the hills made of molasses (Anomaly 3, Figure 4), a clear gravity decrease is highlighted by the new land gravity data (2 mGal in amplitude and 10 km long).

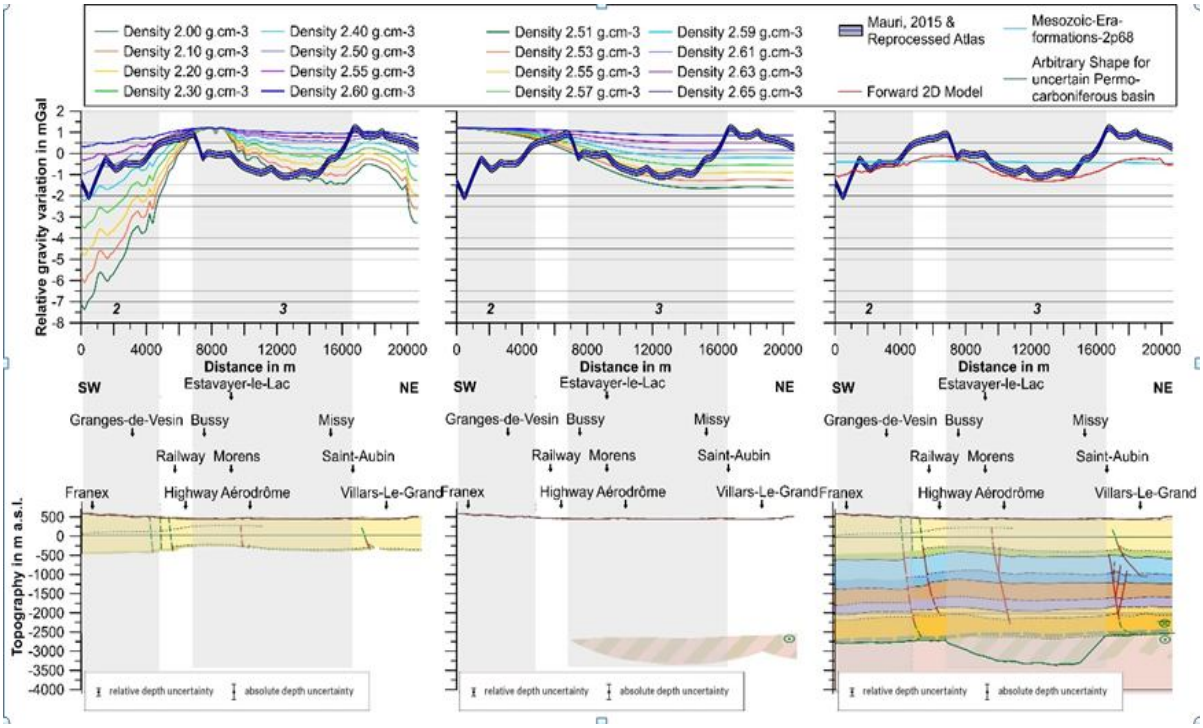
Table 1 : Density parameters used in 2D and 3D forward modeling. *Literature values [Wagner et al., 1999; Lapaire, 2000; Clavien, 2001; CREGE- GeoNE, 2012; Altwegg et al., 2013, 2015; Altwegg, 2015].

Formation	Density used in kg m^{-3}		
	Literature*	2D model	3D Model
Quaternary sediment	1800 - 2200	2540	2000
Tertiary molasse OMM	2200 - 2500	2540	2300
Tertiary molasse OSM	2200 - 2500	2540	2400
Cretaceous	2640 - 2690	2680	2500
Late Malm-Oxfordian	2650 - 2680	2680	2690
Early Malm	2570 - 2680	2680	2690
Dogger	2610 - 2680	2680	2680
Liassic	2120 - 2680	2680	2680
Late Triassic / Keuper	2530 - 2830	2680	2680
Early-middle Triassic / Muschelkalk	2450 - 2620	2680	2650
Uncertain Permo-carboniferous sediment	2450 - 2620	2570	2350
Crystalline rock	2600 - 2830	2670	2690

IV. DISCUSSION

1.1. 2D sensitivity study

Based on rock density variations found in the molasse plateau and Jura mountain in Switzerland (Table 1), and on the geological model from the Seismic Atlas of Switzerland Switzerland(ASS) [Sommaruga et al., 2012], we calculated the gravity effect of the main geological formation period. Over the area, the geometry of rock layers from the Mesozoic period (Muschelkalk to Cretaceous) is constant, which present a relative homogenous gravity effect over the study area (not shown here). The main gravity variation effect comes from the Quaternary and Tertiary formation. However, these shallow formations do not fit the observed gravity variation along the seismic line #14 (left plot, Figure 5). The 2D geological model from the ASS indicates the hypothetic shape of an uncertain Permo-carboniferous graben. Our results indicate that if such graben exist with such shape, then its gravity effect does not fit the observed gravity variation (middle plot, Figure 5).



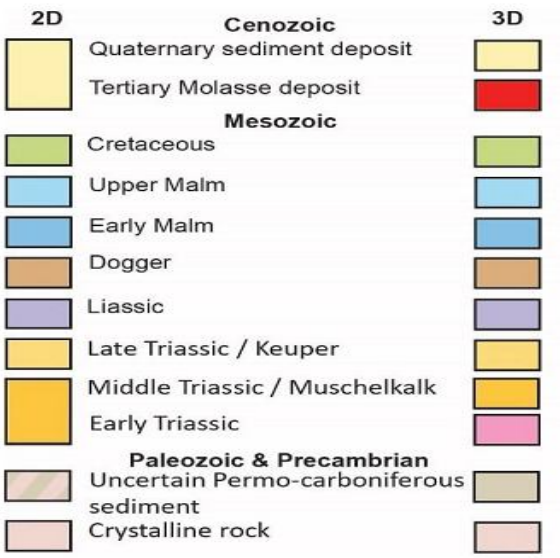


Figure 5:Gravity profile following the seismic line #14. Blue line with light grey uncertainty band: Reprocessed data set merged with the 2015-survey, with an estimated uncertainty of 0.140 mGal. Top Left: Gravity effect of the combined tertiary and quaternary layer for different density. Top Middle: Gravity effect of the hypothetic Permo-carboniferous graben, as suggested in the Seismic atlas. Top Right: Gravity effect of the entire geological pile. The green line represents the shape of the hypothetic Permo-carboniferous graben that best fits the observed gravity decrease. Cross-section and geological legend: Geological cross-section based on the interpretation of the Seismic line #14, as presented in the Seismic Atlas of Switzerland. Modified from Sommaruga et al., 2012. Bottom: Legend from the Seismic Atlas of Switzerland [Sommaruga et al., 2012].

The 2D geological model based only on the seismic line #14 cannot explain the gravity variation observed. There are several reasons: 1) the model is only in 2D and that geological source responsible for the gravity variation (anomaly #3, Figure 4) is not an infinite volume; 2) The geological model from the SSA can discriminate the quaternary sediment from the different types of tertiary molasse (yellow layer, left plot, Figure 5); 3)The seismic line #14 is located on the SE edge of the gravity anomaly and therefore the seismic line does not image properly the geology beneath the anomaly #3.

1.2. 3D forward model

To better model the gravity variations over the region of La Broye, we used the 3D geological model from Swisstopo (grid edge length of 250m; part of the Geomol project), which includes a detailed mapping of the Quaternary post-glacial sediments, as well as the all the formation of Mesozoic age (Figure 6Figure 6) [GeoMol Team, 2015; Baumberger & Allenbach, 2016]. Using 3D computation Ginger software [Altwegg et al., 2015], we were able to determine that neither the Quaternary-age formation, nor the Tertiary-age formation could reproduce the gravity anomaly #3. The only model that best fit the observed gravity is when we add a volume of rock at the interface between the Muschelkalk (based of the Mesozoic) and the crystalline basement (dark grey surface, Figure 6).

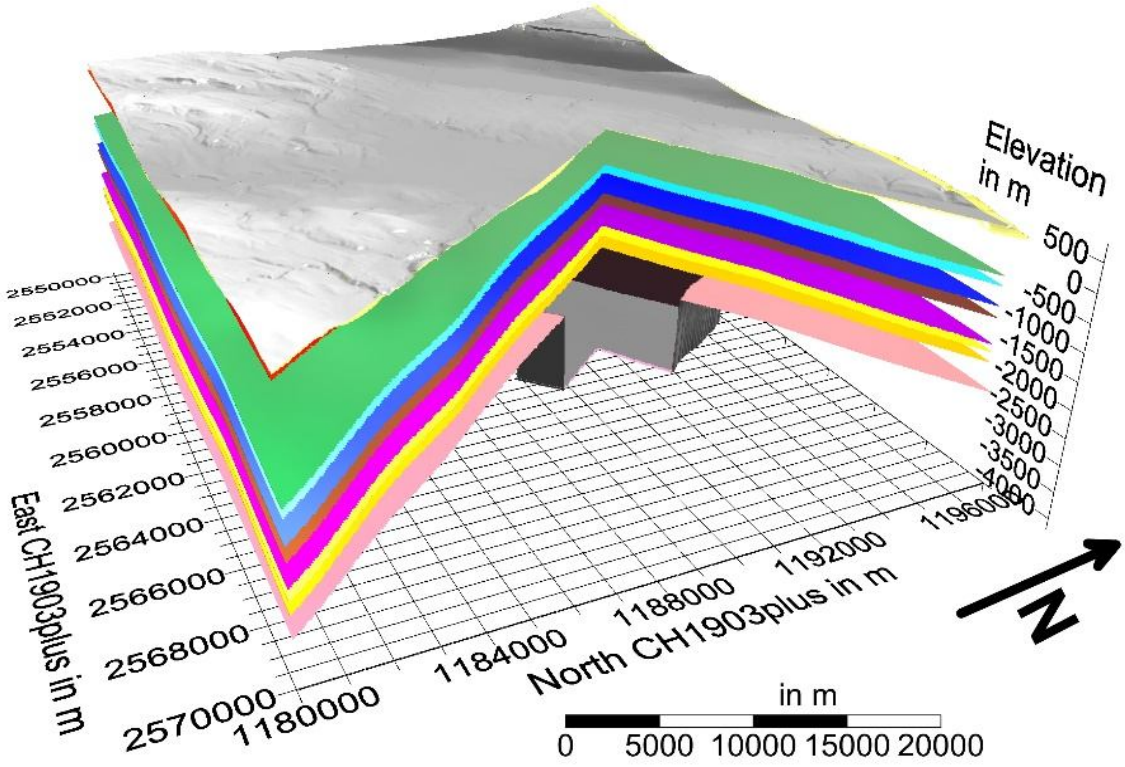


Figure 6 : Modified 3D geological model of Swisstopo for the region of La Broye. The original model includes a detailed mapping of quaternary and tertiary-age formation (legend, see right side of Figure 5). The model has been modified by adding a geometric shape (grey structures) at the bottom of the 3D model. The shape of the structure is based on 3D forward model that best represent the observed gravity decrease.

The best fit between the residual gravity data and the gravity effect of the model show that misfit over anomaly #3 is within the uncertainty of the gravity data (Figure 7). Based on the depth this deep structure (from 2.5 km to 3.5 km), and because it is at the bottom of the Mesozoic-age formations, it is likely that the model structure represents a deep Permo-carboniferous basin (Figure 6). The deep basin is about 5 km by 5 km and about 1 km deep (Figure 6).

Analyses of the misfit indicates that the 3D model reproduces well (Figure 7): 1) the gravity effect of the geological layers from Top Quaternary to bottom of Mesozoic deposits; 2) the gravity decrease of anomalies #1 and #3. In addition, a visible trend (oriented NW-SE) on the misfit is explained by the deepening and thickening of the molasse toward the Alps, which has been partially overcorrected by the regional trend.

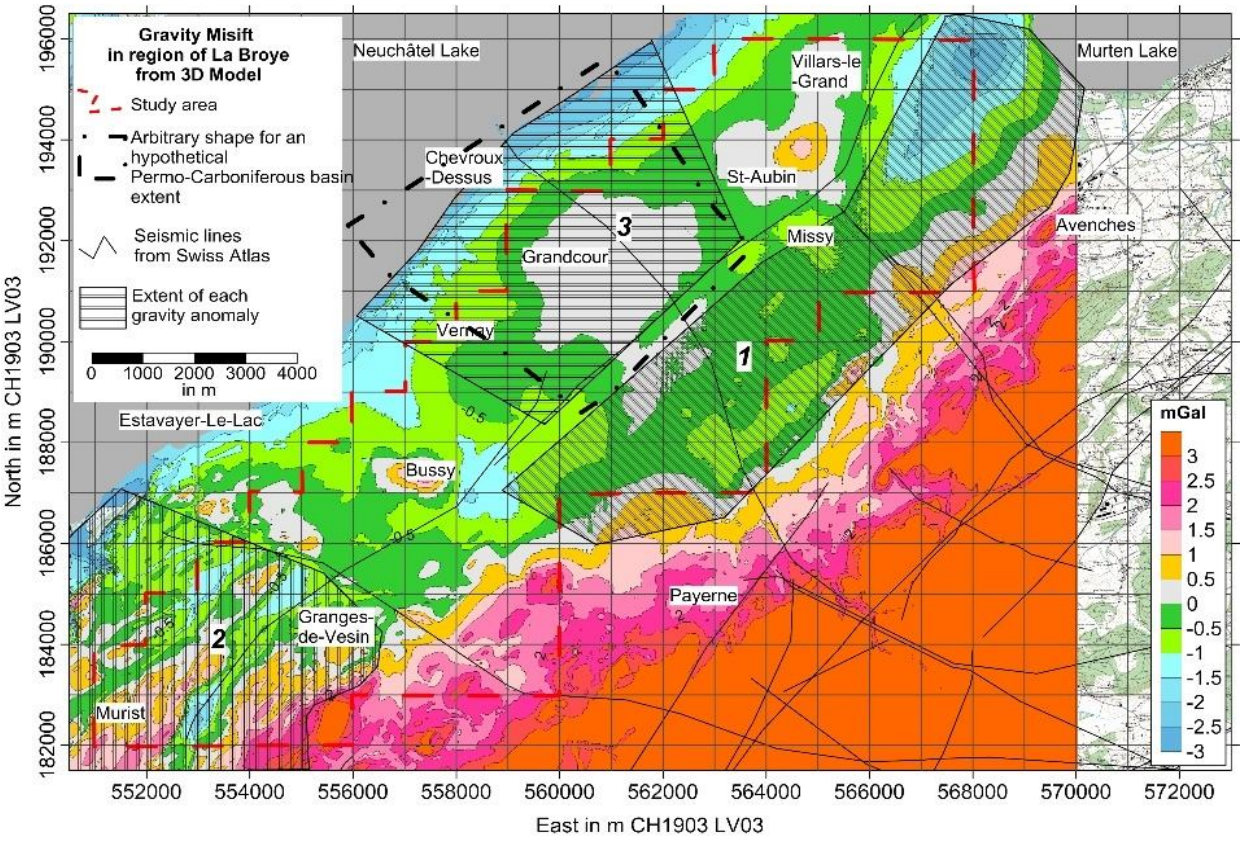


Figure 7 : Misfit between the observed gravity (Residual Bouguer data) and the computed gravity responses from the 3D geological model. The shaded areas represent the extend of each gravity decrease observed. The dashed black line is the extend of the deep basin-structure that allow to best fit the gravity decrease.

CONCLUSION

Reprocessing of existent gravity data sets and a new gravity survey has allowed us to well define the existence of a gravity anomaly of 10 km wide and 2 mGal amplitude (anomaly #3). This anomaly is not associated to either the gravity decrease of the plain of Basse-La Broye (anomaly #1), or to the regional gravity decrease beneath the western part of the western molasse basin (anomaly #2).

The 2D sensitivity study was inconclusive, due to the lack of constraints on the geometry of the geological formation. Use of the 3D geological model of Swisstopo, which includes detailed mapping of the shallower geological layers, has allowed to support the hypothesis that only a deep geological structure could be explain anomaly #3 and that this structure is likely a deep Permo-carboniferous structure. In addition, with the use of 3D forward computation, we obtained geometric constrain on this deep Permo-carboniferous basin.

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