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Investigating and assessing the joint use of Magneto-Telluric and Gravity survey for deep geothermal reservoir in the western Molassic Basin

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Investigating and assessing the joint use of Magneto-Telluric and Gravity survey for deep geothermal reservoir in the western Molassic Basin.

Final Report

Guillaume Mauri, Laurent Marguet, Gunnar Jansen, Stephen A. Miller

Contract: SI/501188-01

Final Report 15-01

Report for:
Swiss Federal Office of Energy - SFOE

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Final Report 15-01: Investigating and assessing the joint use of Magneto-Telluric and Gravity survey for deep geothermal reservoir in the western Molassic Basin.

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Overview

INTRODUCTION

For a period of 5 months, from January 2015 to May 2015, the project is assessing the joint use of Magneto-Telluric and Gravity methods in a small part of the Western Swiss Molasse Basin, which is supposed to be above the edge of a deep Permo-Carboniferous Graben (Figure 1).

The study is localized over an area of ~100 square km (Figure 1), which is delimited by Payerne on east side, Granges-prés-Marnand in the South, Avenche in the North, and Estavayer-le-Lac in the west (See Figure 1). This area is mostly cover by the crops and has a very low population density. The presence of the aerodrome of Payerne is likely to generate some noise, but it would also be the opportunity to see the impact of air traffic on nearby MT stations.

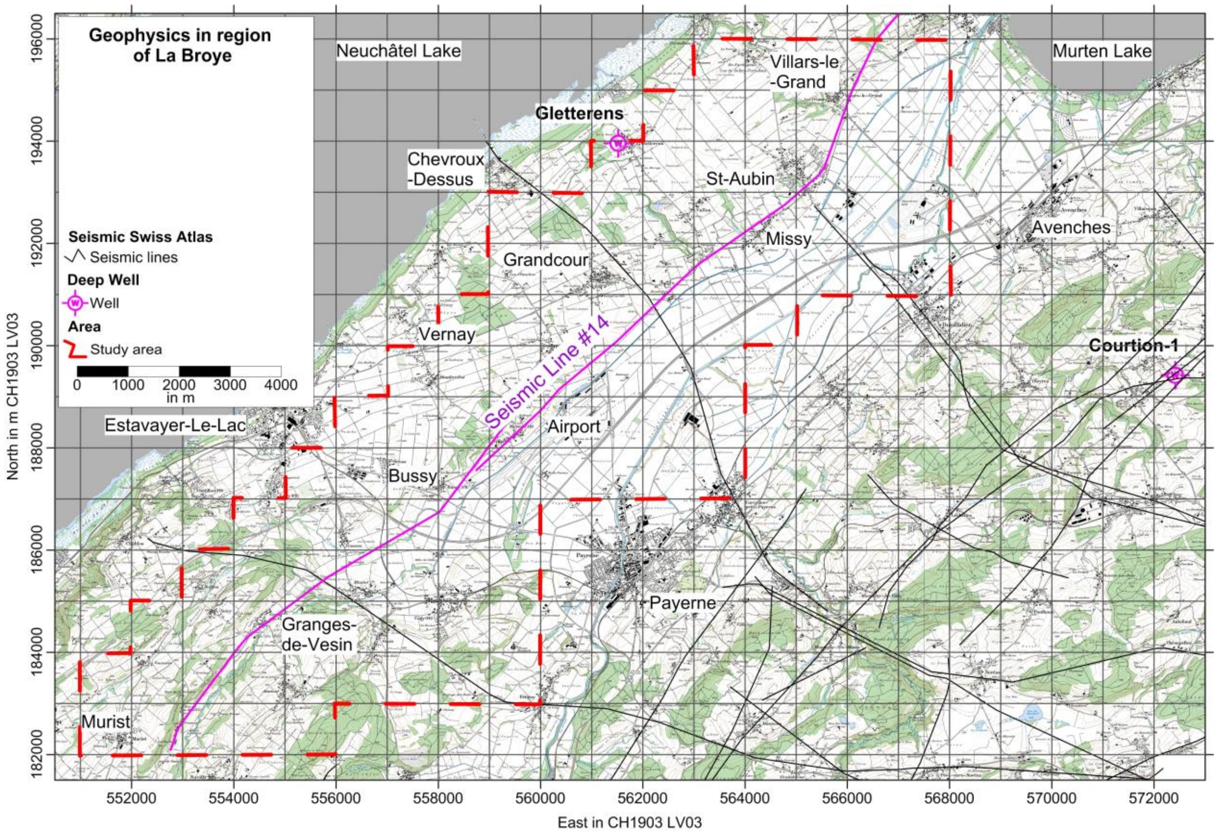

Figure 1: Region of La Broye. Red dashed line represents the extent of the investigated area, which is of 100 square kilometres. Black lines are seismic profiles (Sommaruga et al., 2012). The seismic line #14, from the Seismic Atlas, crosses the area from NE to SW (Sommaruga et al., 2012).

GRAVITY INVESTIGATION

The aim of the gravity study is to bring new insight on the gravity variations in the region of La Broye. Recent gravity work on the western Molasse plateau suggested that the region of La Broye was possibly on the rim of a large Permo-carboniferous sediment structure, but more information is required to properly define it (Figure 2) (Altwegg, 2015).

In winter-spring 2015, a gravity survey has been conducted to collect 824 gravity stations over the 100 square kilometres and more than 70 stations from previous study have been surveyed.

In the winter and spring of 2015, 100 km^2 were surveyed using a CG-5 gravimeter in the La Broye region to increase the measurement spatial density of gravity variations (Figure 2). A total of 824 new gravity stations were surveyed, which includes 70 locations also measured in previous studies. The data set surveyed in 2015 is organised as follows:

- one profile, 22-km long and 100m sampling step (220 stations), and following the seismic line #14.

- a spatial survey with 4 to 6 gravity stations by square kilometer (604 stations).

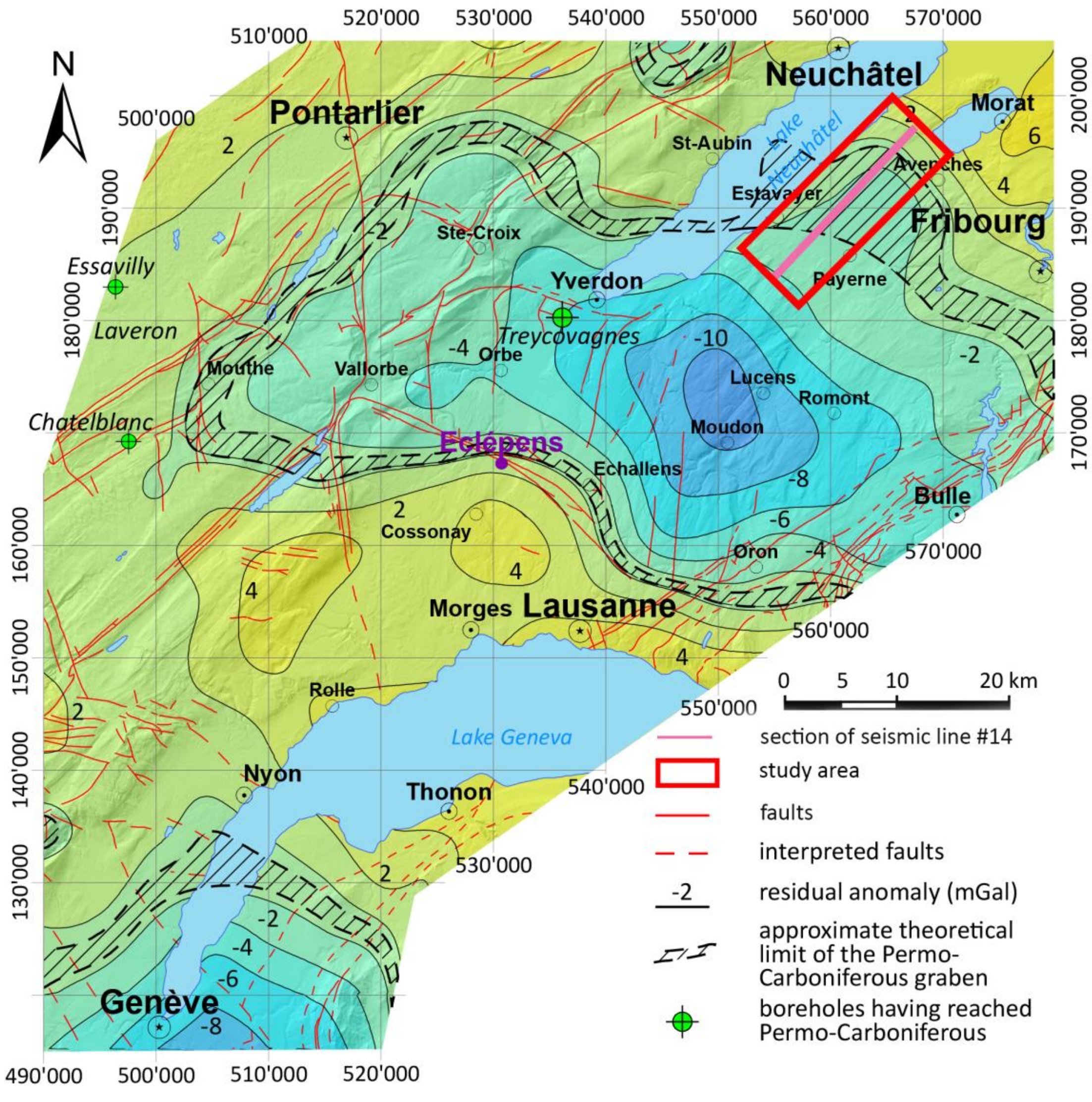

Figure 2: Residual gravity map over a part of the west molasses basin based on data of the Swiss Atlas of Switzerland as presented in the work of Altwegg (2015). Illustration modified from (Altwegg, PhD Thesis 2015). The blue colour over the land indicates relative decrease of gravity associated to possible Permo-carboniferous sediment basin.

In addition to the gravity survey, this study used available data from previous studies in the region:

- The gravity data sets from the 1983-gravity atlas (Klingele & Olivier, 1980; Olivier, 1983),

- The data from two M·Sc. work of the University of Lausanne were used to complement the study (Lapaire, 2000; Clavien, 2001).

Previous studies regroup 1031 stations, which were scattered over an area of 30 km by 31 km.

To reduce uncertainty when merging data sets, and to reduce uncertainty on each gravity data set, all data sets from previous surveys were re-processed using the Corr-Topo software (Altwegg, 2015) and the 2m digital elevation model from Swisstopo (Swisstopo, 2010).

Using the Bouguer values from all gravity data set, a regional gravity trend was calculated through a bilinear regression. Then subtracting the calculated regional trend from the new Bouguer anomaly map, it was possible to obtain a residual gravity map for the region of La Broye.

Additionally, in order to remove gravity variations due to the surrounding Lakes of Neuchâtel and Morat, the gravity effect of each lake was calculated using both high resolution bathymetry data from the work of Reusch et al. (2015) and bathymetry data from the 1:25000 map from Swisstopo (Swisstopo, 2005; Swisstopo & SITN, 2010).

Two sensitivity studies were performed to assess the potential gravity effects of potential underground structures on measured gravity variation. The sensitivity study was performed using the GINGER software (Altwegg et al., 2015). All the gravity stations from 2015 survey are far enough from buried structures to avoid any significant effect.

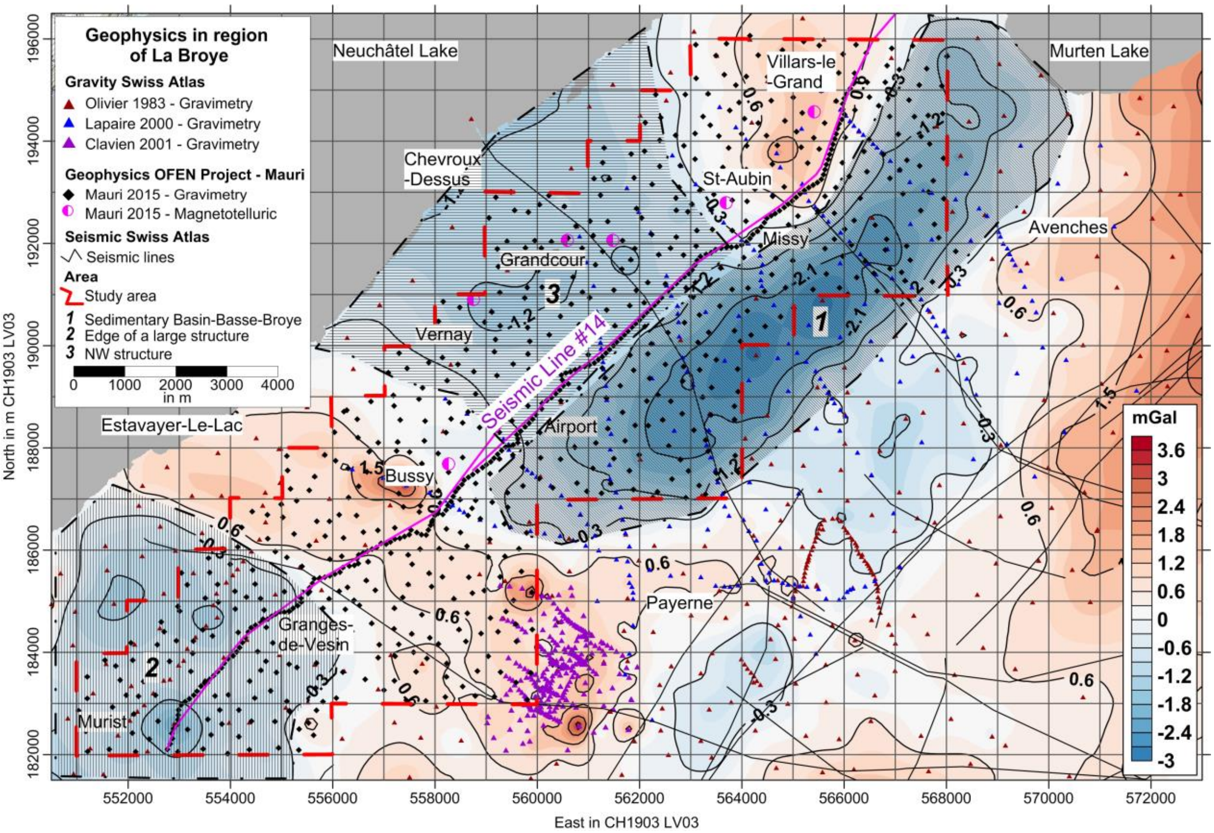

Figure 3 : Residual gravity map of the region of La Broye obtained by subtracting the regional trend to the Bouguer anomaly map for a density reference of 2.67 g·cm^{-3}.

A sensitivity study was also performed using a 2D approach to assess the gravity effects of a) the geological formation of either Tertiary or Quaternary ages and b) the possibility of a hypothetical deep formation of Permo-carboniferous sediment beneath the profile following the seismic line #14. The 2D structure of geological formation is based on the geological interpretation of Seismic line #14, such as presented in the Seismic Atlas (Sommaruga et al., 2012).

The new gravity map obtained from this study presents two distinct decreases of gravity in the region of La Broye (Figure 3).

- The first gravity decrease is a little further west (over Bussy and the airport), with a wavelength of about 6 Km and 1 mGal in amplitude. This anomaly could likely be explained by change happening with both quaternary and tertiary sediment. Indeed, in the work of Lapaire (2000), the gravity anomaly is defined to be only due to a contrast of density between the bed rock made of molasses (2.5 $g \cdot cm^{-3}$ and the thick deposit in the valley 2.0-2.2 $g \cdot cm^{-3}$), which is made of moraines and quaternary glacial sediments.
- The second anomaly is located in the southern part (South of Bussy), and appears to be the edge of the large extended gravity decrease present between the lakes of Neuchâtel and of Geneva. Indeed, the decrease of gravity is of about 3.5mGal. With only the edge part of this anomaly on the studied area, this study could not characterize the sources of this gravity decrease.

For the shallowest and the deepest sediment layers of the model, two sensitivity studies have been perform to investigate the effect of density variations on the gravity changes along the gravity profile (following seismic line #14, Figure 3). The shallowest model layer regroups quaternary and tertiary formations, while the deepest sedimentary model layer represents a hypothetical Permo-carboniferous layer. On the 2D investigation, the forward modelling is able to partially reproduce the measured gravity anomalies. Along the profile, located between Bussy and Missy (anomaly #3, Figure 3), the main gravity decrease can either be due to the shallowest layer or the deepest layer. The 2D model, with its current resolution, cannot distinguish between the two layers that cause the gravity decrease. However, based on consideration on behaviour of gravity field and on geological properties, it is more realistic to consider that the large gravity decrease is only due to the lithology variation within the shallowest layers. Such interpretation is following the results from the work on the Plaine of La Broye (anomaly #1, Figure 3), which shows that the strong decrease of gravity is only due to a thick low density post glacial deposit (Lapaire, 2000).

MAGNETOTELLURIC INVESTIGATION

The aim of the magnetotelluric study is to assess if it is possible to record magnetotelluric data, which are not too noisy to be useful in urbanized environment, such as in Switzerland. To do so the magnetotelluric survey has been conduct in spring 2015 in the region of La Broye. In the case, where the collected magnetotelluric data are good enough to obtain reliable 2D inversion, the results should then be added to the gravimetry investigation to improve the understanding of the deep geological structure.

In spring 2015, a magnetotelluric campaign has been conducted in the region of La Broye to assess if modern magnetotelluric equipment could help to overcome the noise generate by the human activity.

2 MT stations (ADU #58, #59) from the University of Neuchâtel have been used for the survey, which include 6 sites of measurement across the NE part of region of La Broye.

The recorded data set for each site is consequent and include between 5 to 10 days of recording. While this large amount of data was impossible to process at once, because the need in computational power was too high in comparison of what was available at the time of the study, the process of the data has been done by range of frequency. Doing so, it has been possible to qualitatively compare the noise effect on each range of frequencies.

Processing data by range of frequency has clearly showed that recording magnetotelluric data using the analogue low pass filter at the frequency of 4Hz was useful to reduce noise level on the recorded data.

Two tests of 512Hz survey (stations 3a and 4) have been conducted with the remote station located in the Vosges Mountain, which has been done in collaboration with the IPG Strasbourg. Unfortunately, the difference in calibration setting between the remote station and the stations in La Broye is for now an obstacle to process the MT data using the reference station.

The noise level on the data is significant near the known dead band frequency and adapted computational tools are required, which imply the necessity of developing new programming code that would allow for both filtering and combine different type of processing in order to reduce noise effect on the data set.

2D inverse modelling has been done in order to attempt to assess the impact on the noise on the inversion. Results of the inversion show clearly that the current data set, with the current noise level, cannot provide a reliable model.

Future work on magnetotelluric data should focus on:

- 1) Developing appropriate computation tools to efficiently reduce and remove noise from recorded data in order to extract the magnetotelluric signal from the deep structure.

- 2) Developing a computing tool that allows the process between the Metronix magnetotelluric stations (used in the study) and the reference station in the Vosges Mountain.

- 3) Increasing the number of magnetotelluric stations along a profiles, likely 1 station by kilometres, in order to better constrain lateral variation in conductivity at depth.

Acknowledgment

This work was done with the support of institution and people across Switzerland.

The project is financed by the Office Federal of Energy. We are very grateful to Gunter Siddiqi for supporting this project since its beginning.

We are thankful to Prof. Hunkeler and Prof. Benoit Valley (CHYN-UNINE) for their support.

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We are thankful to Prof. Olivier (Université de Lausanne, Institut des sciences de la Terre) and Mr. Marti (Swisstopo) for letting us uses the data set of previous gravity studies.

We are grateful to Reusch (ETHZ) & Prof. Strasser (ETHZ) for letting me use the High resolution bathymetry data of Neuchâtel and Morat lakes.

We are thankful to the Département du développement territorial et de l'environnement de Neuchâtel (SITN) for letting me use the topographic map of 1/25000, as well as the bathymetry map of Neuchâtel lake.

We are grateful to Dr. Sailhac (Institut de Physique du Globe de Strasbourg- IPGS, France) for letting me have access to the remote station in the Vosges Mountain.

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

Chapter I. Gravity Investigation of the Region of La Broye

1. Aims of the Study

The aim of the gravity study is to bring new insight on the gravity variations in the region of La Broye. Recent gravity work on the western Molassic plateau suggested that the region of La Broye was possibly on the rim of a large Permo-carboniferous sediment structure, but more information is required to properly define it (Figure 4) (Altwegg, 2015).

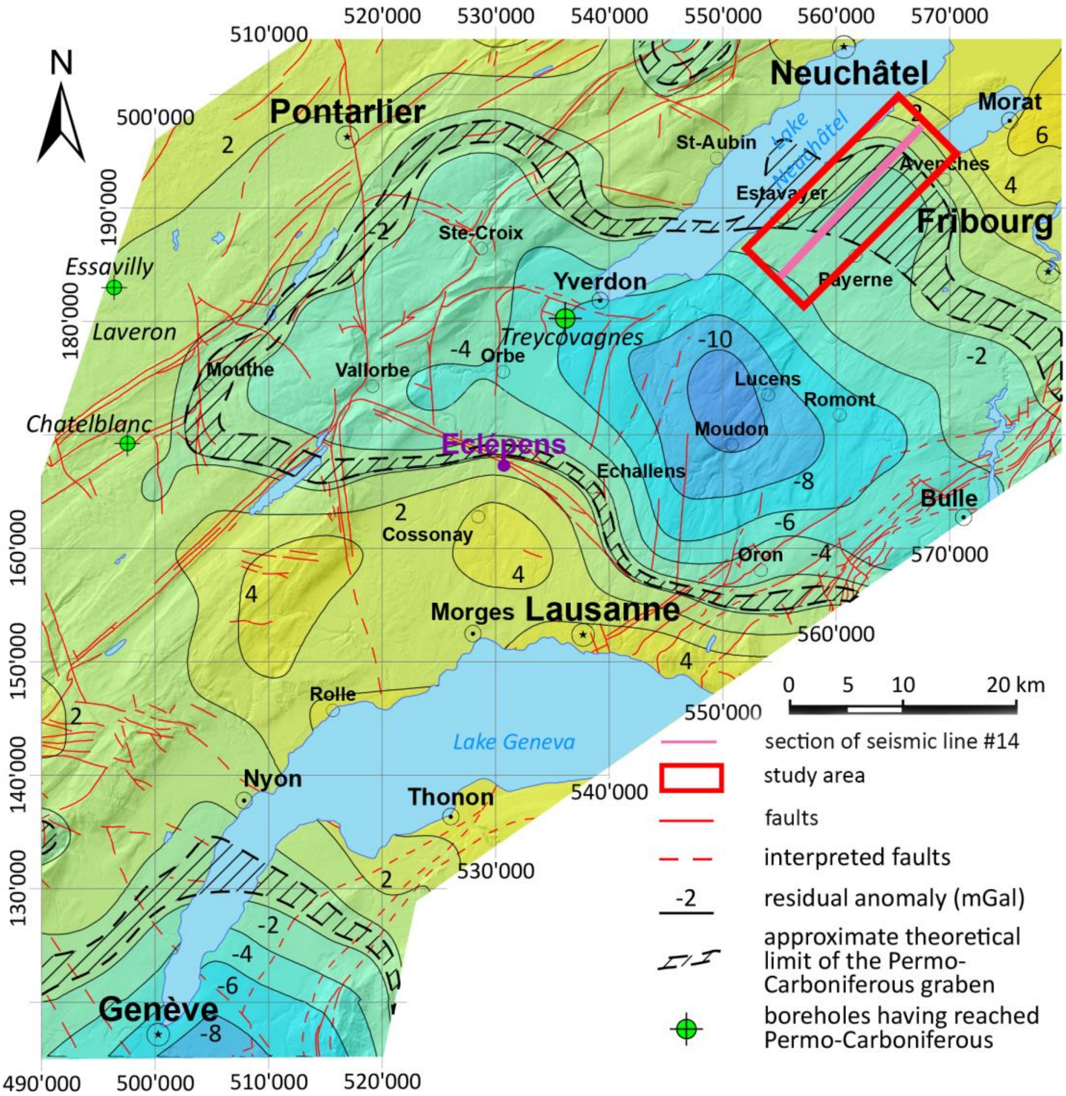


Figure 4: Residual gravity map over a part of the west molasses basin based on data of the Swiss Atlas of Switzerland as presented in the work of Altwegg (2015). Illustration modified from (Altwegg, PhD Thesis 2015). The blue colour over the land indicates relative decrease of gravity associated to possible Permo-carboniferous sediment basin. Image modified from the work of Altwegg (2015).

2. Brief geographical and geological setting

The studied area is located in the western molasses plateau in the region of La Broye (Figure 5), south-east of Neuchâtel Lake and south-west of Morat Lake. Neuchâtel Lake delineates the western border, while the cities of Avenches and Payerne are a few kilometres away from the eastern border of the area. The studied area covers 100 km^2, a band 3-5 km wide and about 22 km long from the NE corner near Morat Lake to the village of Murist in the SW corner.

As presented in previous work in the region (Lapaire, 2000; Clavien, 2001), the region of La Broye has been strongly affected by the last major ice period, through deep erosion and deposit of moraine and post glacial deposit. The eastern part of the area is made of the Basse-Broye, which is a periglacial valley filled thick layers of quaternary deposit (>200 m thick) and underlayed by a layer of moraine (Lapaire, 2000; Clavien, 2001). The Molasses formation forming of tertiary ages, are mostly made of series of sandstone and clay.

A detailed description of the geological formation making the molasses series and the quaternary sediment can be found in the master work of Lapaire (2000) and Clavien (2001) from the university of Lausanne and the references within.

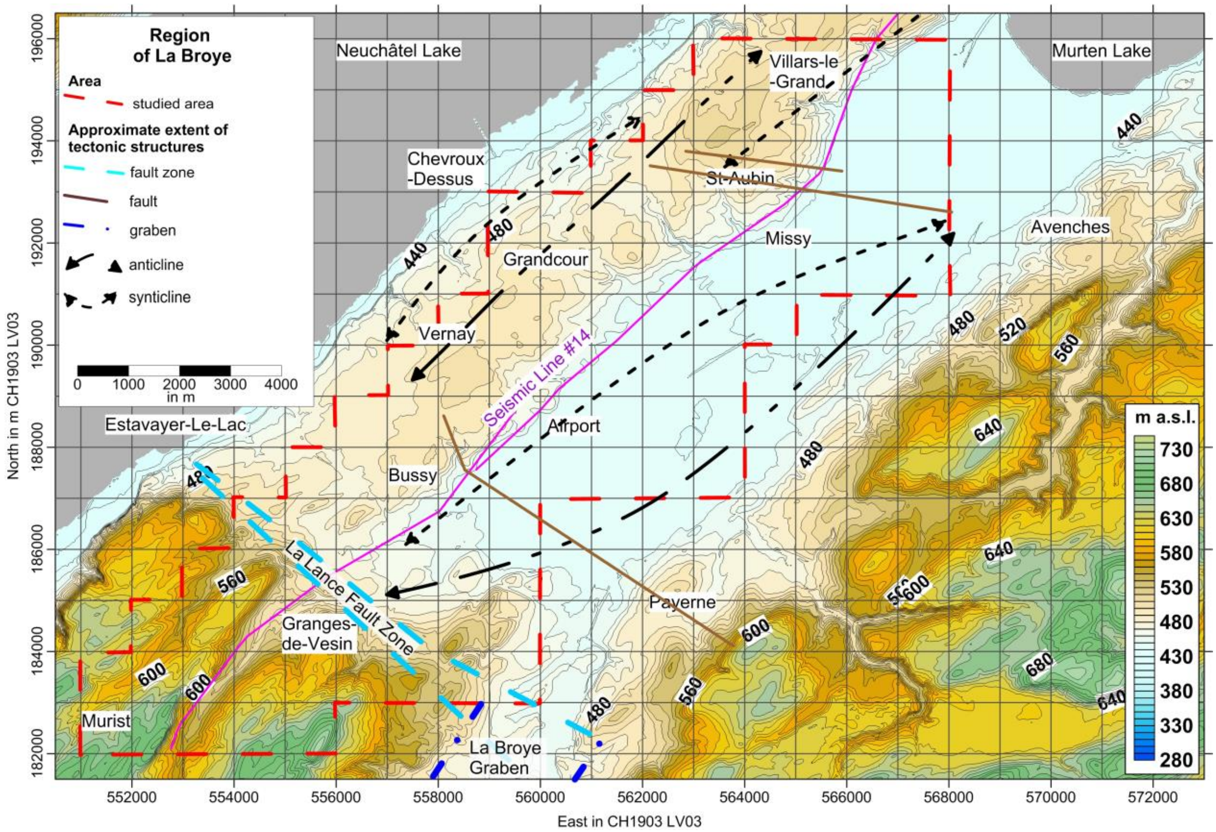


Figure 5 : Topography map of the region of La Broye represented with the national map of Switzerland, 1:25'00.(Swisstopo, 2005).Only the main tectonic features are showed in the figure and a complete description can be found in the work of Mosar et al. (2011) and Diem et al. (2012).

The geological stratigraphy of limestone and marl formations forming the formation of the Mesozoic Era are tilting toward the Alps (Vuataz et al., 2005; Gangnant, R. 2012; Schill et al., 2012).

From a tectonic point of view, further south, the region of La Broye is affected by the La Broye Graben, which will be a few kilometres away from the SE corner of the studied area (Diem et al., 2012). The change in the landscape between the villages of Bussy (Fr.) and Granges-de-Vesin is the surface expression of La Lance Fault Zone (Figure 5), which is oriented (NW-SE) (Ibele, 2011; Diem et al., 2012, and reference within).

Tectonic structures are also present further east near Courtion, where a compressional regime is present (Diem et al., 2012) and in the south part of the studied area with La Lance fault zone and the La Broye graben. (Diem et al., 2012). Figure 5 presents a very simplified presentation of the Lance Fault zone direction and of the position of La Broye Graben.

A more detailed presentation of the faults and tectonic structures can be found in the work of Mosar et al. (2011) and Diem et al. (2012).

3. Gravity Survey

3.1 Brief introduction of gravity method

Brief historical introduction

Gravitational force is one of the fundamental forces and it describes the attraction between objects from particle size (e.g., atoms) to celestial bodies (e.g., planets). Discovered in ancient Greece, it was only in the 17th century, with Sir Isaac Newton, that the first mathematical law of the Universal law of gravitation was described. At the end of the 17th century, the first measurement of Earth gravity was done by Pierre Bouguer and its co-worker, during an expedition in Peru where they used a pendulum. In the 19th century, Le Baron Roland von Eötvös (1890) developed the first relative gravimeter (Bod et al., 1991).

Since the 1930's, modern gravimeters, which are more stable and more accurate, have been developed to reach a wide panel of equipment from light portable land gravimeter (e.g., CG-5 gravimeter use in this study) to satellite based gravimeter (e.g., GOCE satellite). Today, there is about 30 different types of gravimeters and 20 different designs of gravimeters that exist.

A complete description of gravimetry equipment will not be described here, however, it is interesting to notice that in Switzerland, since the 1970's, gravity studies have investigated how to use a wide range of gravimeter, such as satellite based data (Wyss et al., 1993) and more commonly land gravity survey (Klingele, 1972, Klingele et al., 1980, Olivier et al., 2010). Swisstopo used both relative and absolute gravimeters to monitor the gravity network of Switzerland. To date, as far as my knowledge goes, no gravity measurements have been done on any of the lake in Switzerland.

In gravity investigation, while the international unit system for gravitation force is the $m \cdot s^{-2}$, the unit commonly used in both industry and literature is the mGal and sometime the µGal. In the present study, all the gravity variations are presented in mGal. As well, the unit use in the Swiss Atlas of gravimetry is the mGal (Olivier et al., 2010).

Unit system used in this report:

Earth gravity value in average is ~9.81 $m \cdot s^{-2}$ or ~981000 mGal

1 mGal = 10^{-5} $m \cdot s^{-2}$

1 µGal = 10^{-8} $m \cdot s^{-2}$

BRIEF INTRODUCTION TO GRAVITY DATA PROCESSING

This section only refers to relative gravity measurement and cannot be considered for absolute gravity measurements.

Before the 1970's, and until the beginning of the 21st century the traditional way to both handle and process gravity data to characterise local gravity variation were to use the Hammer terrain correction method (Reynolds, 2011). This method allowed for approximating the surrounding topography variation by dividing the surrounding area in sectors of different size, however, doing such approximation was time consuming and was generating significant uncertainty, making very difficult to characterize relative small gravity variation (less than 0.5 mGal).

Since the 1970's, with the development of computational programs, the automation of terrain correction allowed to reduce gravity uncertainty (often equal or above 0.5 mGal) and reduce the time of data processing. However, it was still difficult to properly characterise relatively small gravity variation.

In the 197's, the relief of the Swiss Romandy was digitalized in the work of Olivier (1971). Since the 1990's, the industrial development of satellite-based topography measurement, which are commonly called Digital Elevation Model (DEM), over large surface have contributed to better correct gravity effect of surrounding landscape. Unfortunately, until about 2005, the DEM had generally a cell-size of 25m, which was not enough to properly corrected surrounding topographic effect outside topographic plain. It is only since the 2010 about, that a high resolution DEM was made available. In Switzerland the 2m-DEM SwissALTI3D from Swisstopo is commercialized since 2010 (Swisstopo, 2010).

Until approximately 2005, the computational power of personal computer was still the main limitation to process gravity data using DEM, because commercial computers (e.g., workstations and laptops) were not capable to handle huge volume of data associated with the accuracy of digital elevation model.

Since then, computers and programs have evolved and are now capable to handle the necessary data. At the University of Neuchâtel, the recent works of Altwegg have made available new computational tools for both data processing and gravity forward model calculation (Altwegg, 2015).

BRIEF INTRODUCTION OF HISTORICAL GRAVITY STUDIES IN SWITZERLAND

In Switzerland, since the 1970's, a lot of work has been done to build a reliable base on how to process, compute and correct gravity data. A complete overview will not be presented here, because it will go too far outside the scope of this study. However, I believe it is necessary to state that this study would not have been possible without the work from past studies. One of the first steps toward a national gravity map was done in the work of Klingele (1972), with a study of western part of Switzerland. Later on, a description of a computation program to process gravity data was done in the work of Olivier (1974), and followed by others studies, such as on the region of Geneva Lake (Work of Alain Donze, published in Buchli et al., 1976). In 1980, the Bouguer anomaly map of Switzerland was published (Klingele et al., 1980), as well as the gravity map of the Swiss plateau (Olivier, 1983). More recently, the Swiss Atlas of gravity was released in 2010 (Olivier et al., 2010), which is the reference model in Switzerland. At Swisstopo, the Swisstopo, group of geodetic developments and contracts is in charge all the gravity network and of the gravity data base of Switzerland.

Since 2010, with the first chair of geothermics at the University of Neuchâtel, gravity studies have been done in the framework of geothermal exploration. Within this scope, contribution in gravity surveys have been made through different projects (i.e., GeoNE, St-Gallen, Eclepens project)(CREGE, 2012; Altwegg et al., 2015; Altwegg, 2015), as well as computation development, which has brought new tools to process gravity data and to calculate gravity effect of 3D models. The present work used some of these tools, with Ginger (Altwegg et al., 2015) and Corr-topo (Altwegg, 2015).

Since the 1970's, many studies have been done in Switzerland and it is outside the scope of this study to make a complete. For the present project in region of La Broye, in the western Swiss Plateau, the following past studies have been used:

- gravity map of the Swiss plateau (Olivier, 1983)
- Gravity model of the region of Fétigny (Clavien, 2001)
- Gravity study of the morphology of the deep molasses in the Basse-Broye Valley (Lapaire, 2001)

3.2 Winter and spring 2015 survey

The gravity survey was carried out in winter and spring of 2015, in the La Broye region to increase the measurement spatial density of gravity variations. A total of 100 km^2 were surveyed using a CG-5 gravimeter (Figure 6). Each station has been geo referenced using a DGPS-Leica GS-15 with a real time connection to the swipos network (swipos® in LV03 from Swisstopo).

Figure 6: Gravity survey in La Broye region. Left: in winter 2015 with the CG-5 and the DGPS Leica GS-15. Right: Gravity survey along the road, with the warning sign deployed.

The gravity survey has been done using two references stations. The first reference station is located at the University of Neuchâtel at the Uni Mail and the second station is located next to the temple at Villars-Le-Grands, which is in the northern part of the studied area.

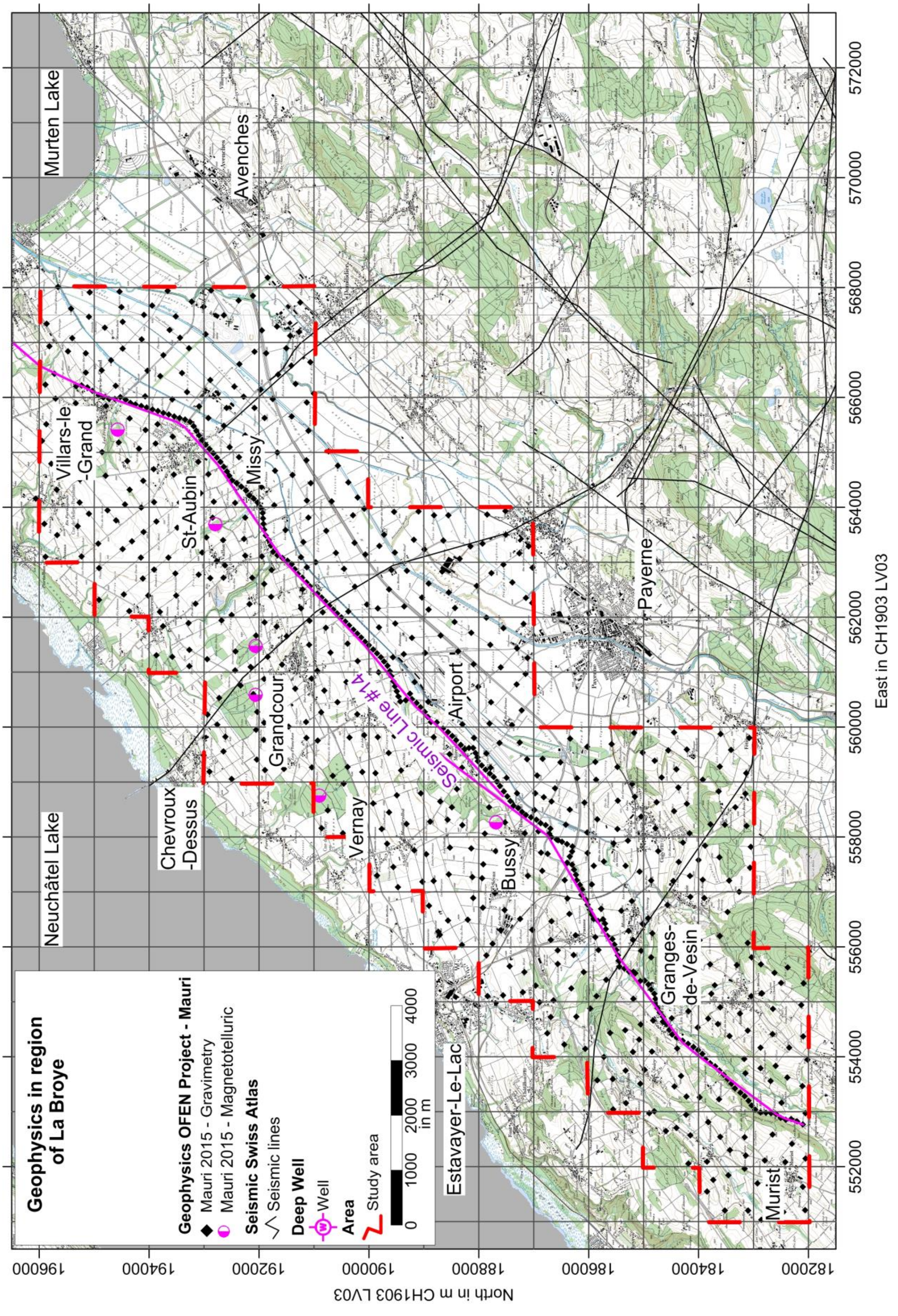
A total of 824 new gravity stations were surveyed (Figure 7) and which includes 70 locations also measured in previous studies. The data set surveyed in 2015 is organised as follows:

- One profile, 22-km long and 100m sampling step (220 stations), and following the seismic line #14.

- A spatial survey with 4 to 6 gravity stations by square kilometre (604 stations).

Additionally, 9.57% of the total stations have been resurveyed over time to obtain a better assess the uncertainty. The standard deviation of gravity measurement on each station is lower than 0.080 mGal for 87.5% of the stations (Figure 8). While resurveying a station, a gravity variation over time is lower than 0.050 mGal for 92.5% of the re-surveyed stations (Figure 9).

Figure 7 : Region of La Broye. Black dots indicate the location of gravity station surveyed in 2015 (this study). Pink circles represent the location of magnetotelluric sites measured in 2015 (This study Red dashed line represents the extent of the investigated area, which is of 100 km^2. Black lines are seismic profiles (Sommaruga et al., 2012). The seismic line #14, from the Seismic Atlas, crosses the area from NE to SW (Sommaruga et al., 2012).


Geophysics in region of La Broye
Geophysics OFEN Project - Mauri
Mauri 2015 - Gravimetry
Mauri 2015 - Magnetotelluric
Seismic Swiss Atlas
Seismic lines
Deep Well
Well
Area
Study area
0 1000 2000 3000 4000
in m
Murten Lake
Neuchâtel Lake
Avenches
Villars-le-Grand
St-Aubin
Missy
Chevroux-Dessus
Grandcour
Airport
Seismic Line #14
Payerne
Vernay
Bussy
Estavayer-Le-Lac
Granges-de-Vesin
Murist
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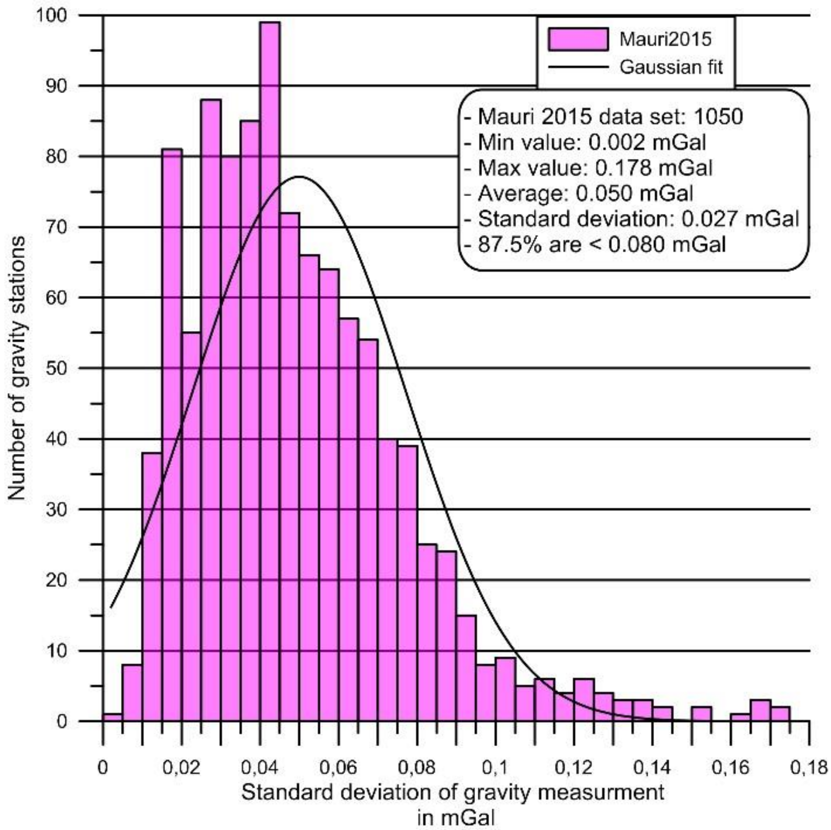


Figure 8: Absolute standard deviation of measured-G when surveying each station. 87.5 % of the data have an uncertainty lower than 0.080 mGal.

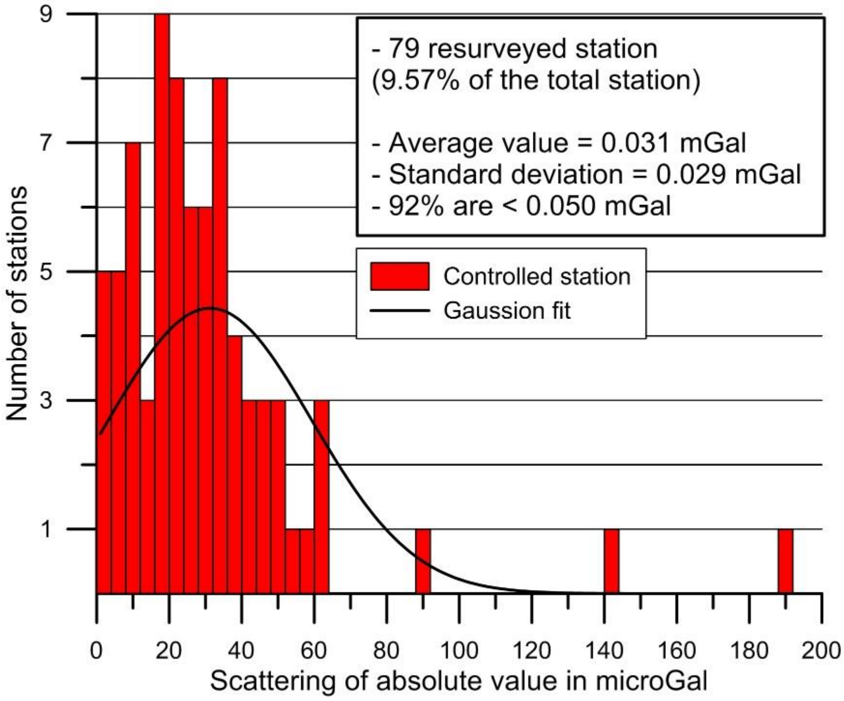


Figure 9: Absolute variation of measured-G over time when resurveying a station. 92% of the resurveyed station present a gravity variation lowers than 0.050 mGal.

4. Gravity corrections

Overview of the parameters taken in consideration

Gravity variation depends on the following parameters:

a) Technical control on the gravimeter stability, which is done by using the reference station method to correct drift of the device, as well as, control of the drift while during a continuous recording in a relative confined environment.

b) Elevation of the station, because gravity decrease with increasing distance from the earth's centre.

Points a) and b) are done during the survey and calculated through a statistical approach taking in consideration all the gravity measurements.

c) Earth Tide, which is the effect of the Sun and the Moon on the earth surface. The correction is directly calculated and corrected by the CG-5 gravimeter during the survey.

d) Latitude effect is due to the fact that earth is not a sphere. The gravitational force is stronger at the pole and weaker at the equator. This is correction is called the theoretical value of g at a given latitude.

e) Topography variation surrounding the location of the station. Near the station a high resolution DEM is needed to properly reduce the uncertainty on the correction, while at distance further than a few kilometres away a coarse model of the topography is sufficient. It is commonly accepted that topography correction should reach at least 167 km away from the station, in order to correction any gravity variation due to topography variation.

Points d) and e) are calculated during the processing of the gravity data in order to obtain the Bouguer anomaly values.

f) Change in the lithosphere thickness, such as the Alps root. Outside the Alps, like it is the case in this study, the gravity effect of the change in lithosphere thickness can be estimated through the calculation of a bilinear regression of the Bouguer values of the station over a much larger area than the investigated survey. See next section about the survey for more details.

g) Lake volume, because large volume of water (density approximately 1.0 $g \cdot cm^{-3}$) could have a significant effect locally. This can be done during or after calculating the Bouguer anomaly values. In the present study the effect of lake is calculated during the calculation of the Bouguer anomaly value through a comparison between processing done with topography without bathymetry and tomography that includes bathymetry data.

h) Large underground human building (e.g., building basement, tunnels). This is done through sensitive study to determine if it is necessary to apply any correction to the gravity stations.

i) Effect that are not relevant for spatial survey, but which are for continuous gravity survey: atmospheric temperature, tilt deformation of the ground, atmospheric pressure. This is required only for a continuous measurement over several days. For the present study, this point can be skipped, because, gravity survey of each station does not exceed 1 hour and atmospheric changes can be considered as negligible.

j) Change in density or volume of rock layers is the final aspect of the gravity study. It is commonly done on either 2D or 3D profiles. In the present study a 2D model has been done along the Seismic line #14, using the geology presented in in the Seismic Atlas (Sommaruga et al., 2012).

4.1 From survey to Bouguer anomaly map

The Bouguer corrections, which include topographic correction, plateau correction, Earth curvature and g-theoretic calculation, are done using the software Corr-Topo (Altwegg, 2015).

Three sets of Digital Elevation Model (DEM) where used for the processing:

a) For the proximal zone (less than 200m away from the station), the processing used a high resolution DEM with grid size of the 2m and a vertical uncertainty of 0.1m from the SwissALTI3D (Swisstopo, 2010).

b) For the average zone (from 200m to 20 Km), the processing used a DEM with grid size of the 25m and a vertical uncertainty < 2m (Swisstopo, 2005).

c) For the distant zone (from 20 Km to 167 Km), the processing used a DEM with grid size of a 400m and a vertical uncertainty < 15m. This DEM is made from SRTM data (RASTER GDEM METI and NASA, 2009). For more information see the work of Altwegg (2015).

For the present study, the uncertainty for the collected data range from 0.095 mGal to 0.138 mGal, detail of the uncertainties can be found on Table 1. Therefore, we consider that all collected data in 2015 have an uncertainty of 0.140 mGal.

Table 1 : Uncertainty on gravity data measured in 2015.

Type of correction	**uncertainty in mGal**
Measured data (including drift): 87,5%	0,080
Controlled station: 92%	0,050
Earth Tide	0,004
GPS uncertainty (1 cm)	0,003
Lake effect	<0,002
Bouguer correction (Plateau + Topo) + Theoretic g value (1984 WGS) *from Altwegg (2015)	0,003-0,100
Total uncertainty	0,095-0,138

4.2 Sensitivity study of underground human made structures

The region of La Broye, for the 100 km^2-area investigated in the present study, is relatively low populated. Therefore, only a few points are at less than 10m from building, which do not present presents a significant fraction and does not require any corrections.

However, near by the airport, either near the highway tunnels, it is necessary to estimate if the manmade underground structures require correcting the gravity data, which are less than 200m away.

To do so, a sensitivity study has been done to estimate the gravity effect of tunnels and of an underground hangar.

GRAVITY EFFECT OF UNDERGROUND HANGAR

For the Hangar, we do not have the plan of such military structures however, it is reasonable to use an approximate square shape. The choice has been done to consider a square shape of different length (100mx100m and 200mx200m, as well as height of 10m and 20m). The results are resumed on Figure 10.

In example, at a distance of 50m, for a Hangar of 200x200mx20m, the gravity effect of this underground hangar would be less than 0.040 mGal. In comparison, 0.040 mGal is 3-4 times smaller than the uncertainty and 10-50 times smaller than the main gravity variations in the region of La Broye.

Based on the result, it is reasonable to consider that any gravity survey, which is at more than 50m from the underground hangar, does not require any correction.

GRAVITY EFFECT OF TUNNELS

The sensitivity study for the tunnels has been done similarly than for the hangar. Highway tunnels are generally made of 2 tubes, in the region of La Broye.

Two configurations are possible based on the federal regulation (Groupe de travail de l'OFROU, 2002). For the highway, the tunnels are made of two separate tubes:

1 tube made of 2 lanes with side: 7.75m+2.0m = 9.75m

1 tube made of 2 lanes with emergency and side: 10.75m+2.0m = 12.75m

Therefore, a tunnel would be between 19.50m and 25.50m wide.

For the model parameters, as the grid cell-size is of 20m, the choice has been done to consider the following parameters.

Each tube is 20m wide and calculations were done for a height of 10m and 20m.

Doing so, by over estimating the width of the tunnels, we can get the upper limit of what would happen in terms of gravity variations due to a tunnel.

For a tunnels made of 2 tubes, each long of 600m, wide of 20m and tall of 10m, the calculated gravity effect is <0.031 mGal at 40m away.

The results are synthetized on Figure 11 and show that gravity effect from tunnels can be neglected, because all stations are always at more than 10m away from them, except one station, which is at 75m.

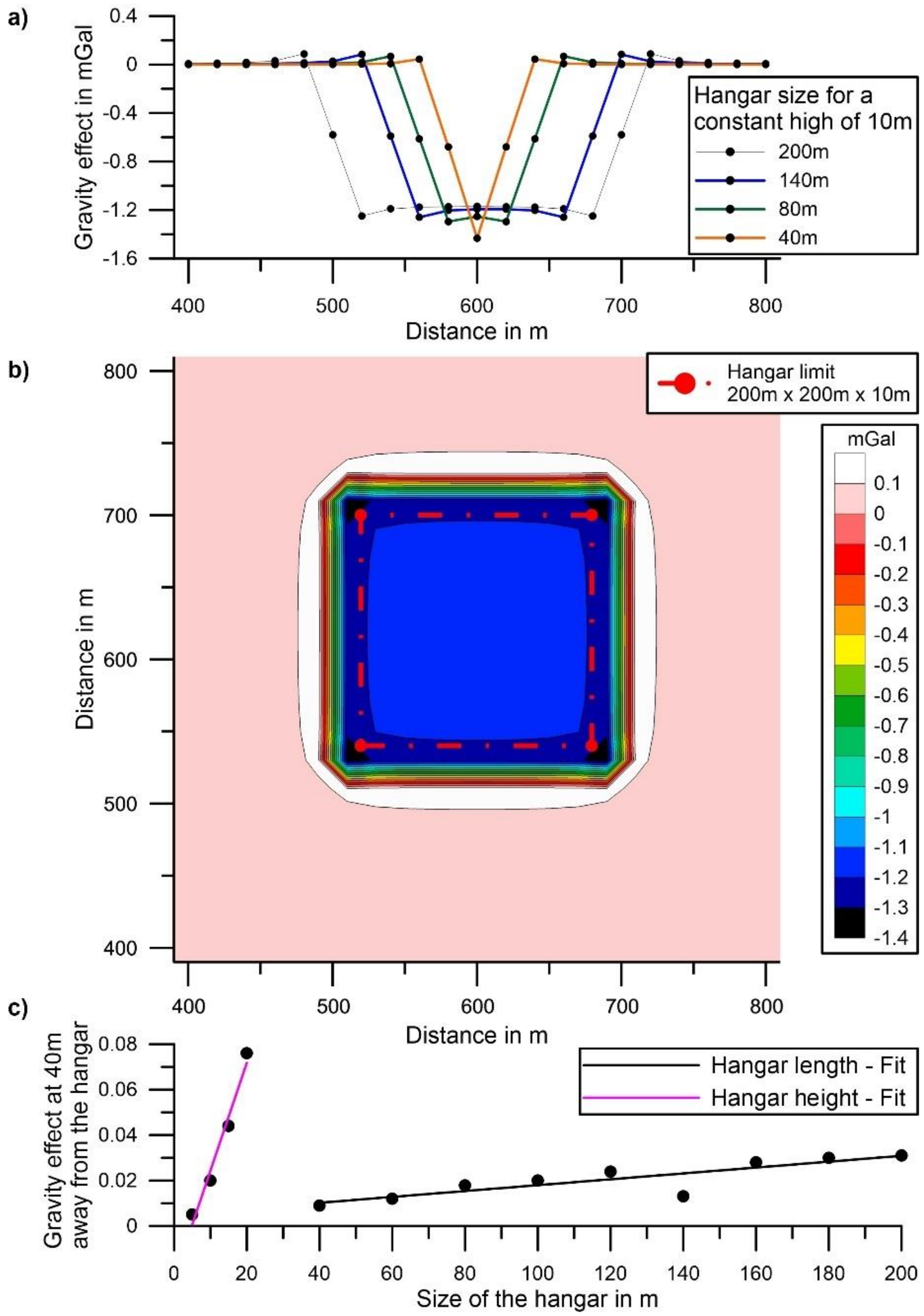


Figure 10 : Gravity effect of an underground Hangar as a function of its length and height. a) Gravity profile across the hangar for different length and for a constant height of 10m. b) 2D view of the gravity effect of a hangar of 200m x 200m x 10m. c) Gravity effect as function of the size. Purple line is function of the height. Black line is function of the length.

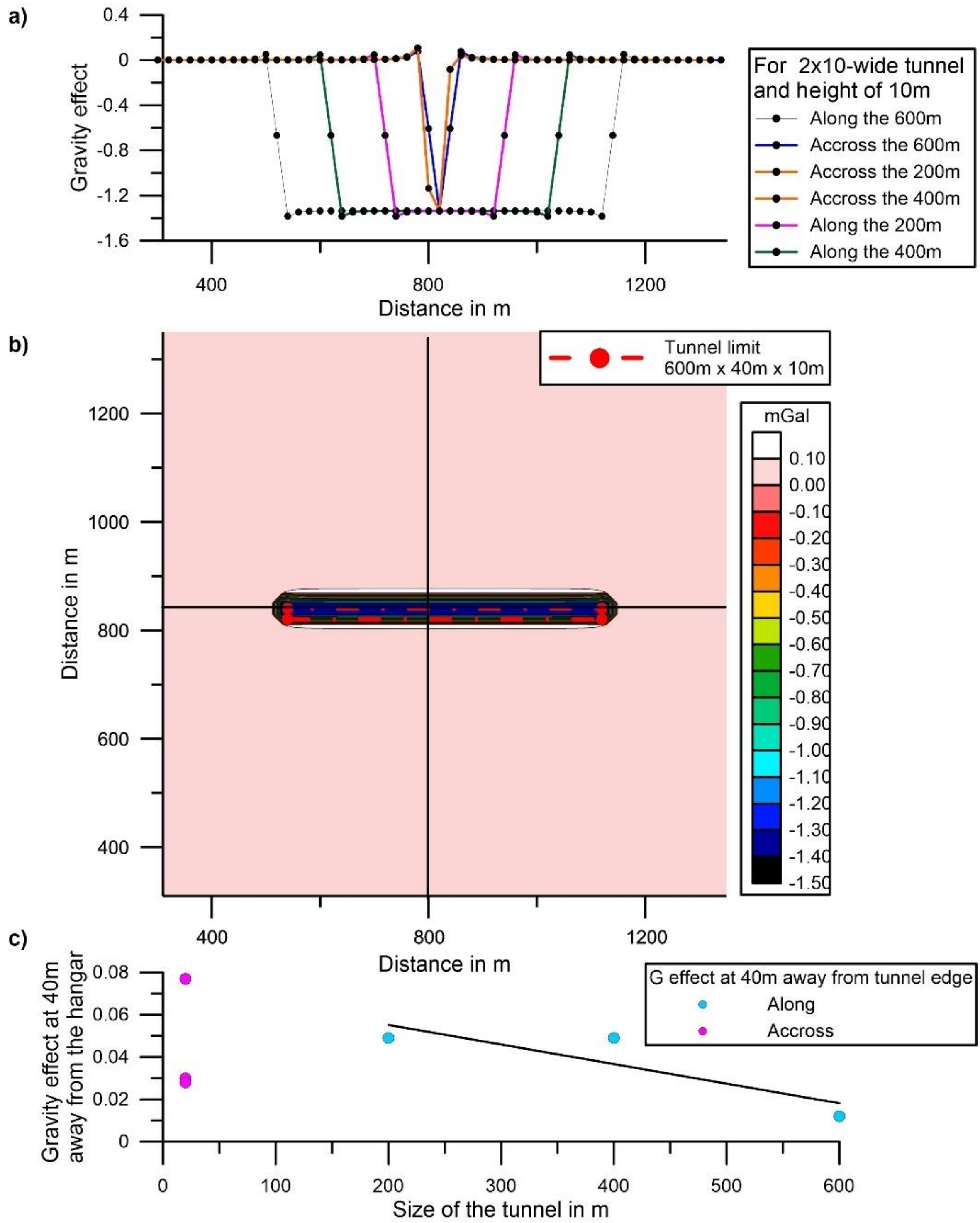


Figure 11 : Gravity effect of a highway tunnel as a function of its length and height. a) Gravity profile across the tunnel for different length and for a constant height of 10m. b) 2D view of the gravity effect of a hangar of 600m x 40m x 10m. c) Gravity effect as function of the size. Purple dotes are function of the height. Black line is function of the length.

5. Merging data set from previous gravity studies

5.1 Overview of previous study

The present study used three data sets from past studies.

- Gravity map of the Swiss plateau (Olivier, 1983)
- Gravity model of the region of Fétigny (Clavien, 2001)
- Gravity study of the morphology of the deep molasses in the Basse-Broye Valley (Lapaire, 2001)

The recent Atlas of Gravity data based (Olivier et al., 2010) includes more than 45000 gravity stations across Switzerland, which contains the above mentioned data set. It is possible that the Atlas gravity data based contain more data for the studied area, however, it was not possible to obtain the authorization from the Swiss Geophysical Commission to use it.

Therefore, the three data set presented above have been lend for this study by Prof. Olivier, to which we are grateful for the help and support.

The gravity data set for the Swiss Plateau (Olivier, 1983) cover an area of 31 km by 30 km, centred on the region of La Broye. The data set include 417 gravity stations. The uncertainty, on the gravity data is estimated to be of 0.080 mGal on the Swiss plateau (Lapaire, 2000). However, in the publication of the gravity Atlas of 2010 (Olivier et al., 2010), the uncertainty ranges between 0.200 to 0.300 mGal. Therefore, in order to be on the safe side, the uncertainty will be considered to be 0.300 mGal.

The M·Sc. works of Lapaire (2000) is an investigation of the deep molasses formation located at about 300m below the topography surface in the periglacial valley of Basse-Broye region and based on gravity inversion. The data set includes 7 gravity profiles, which are oriented NW-SE and regroups 251 gravity stations (atlas data base code 250) over an area of about 64 km^2 (if we consider each square kilometres that contain at least one station). In this work, the uncertainty, on the gravity data is estimated to be of 0.084 mGal.

The M·Sc. works of Clavien (2001) investigates the upper part of the molasses deposit in the transition zone between La Broye Moyenne and La Basse-Broye in the region of Fétigny (Fribourg). The data set regroups 362 stations (atlas data base code 253) which are covering an area of 36 km^2. In this work, the uncertainty, on the gravity data is estimated to be of 0.087 mGal.

In total, the three previous data sets regroup a total of 1031 stations, which are not scattered homogeneously over the region of 31 km by 30 km.

5.2 Difference in calculating uncertainty

As presented above, the uncertainties on gravity correction of the work of Lapaire (2000) and Clavien (2001) is lower (respectively 0.084 mGal and 0.087 mGal), than the value obtain for the 2015-survey (from 0.095 to 0.138).

It is important to notice that is mostly due to the difference in calculating the standard deviations for the measured station.

Indeed, there are two main differences:

1) In previous study, no difference is made between the standard deviation between the standard deviation obtained when measured one station and standard deviation obtained while –surveying a same station.
2) In previous work, the standard deviation is calculated on the relative variation, while the 2015-survey the standard deviation is calculated on the absolute variation. This results in a difference of several tens of µGal.

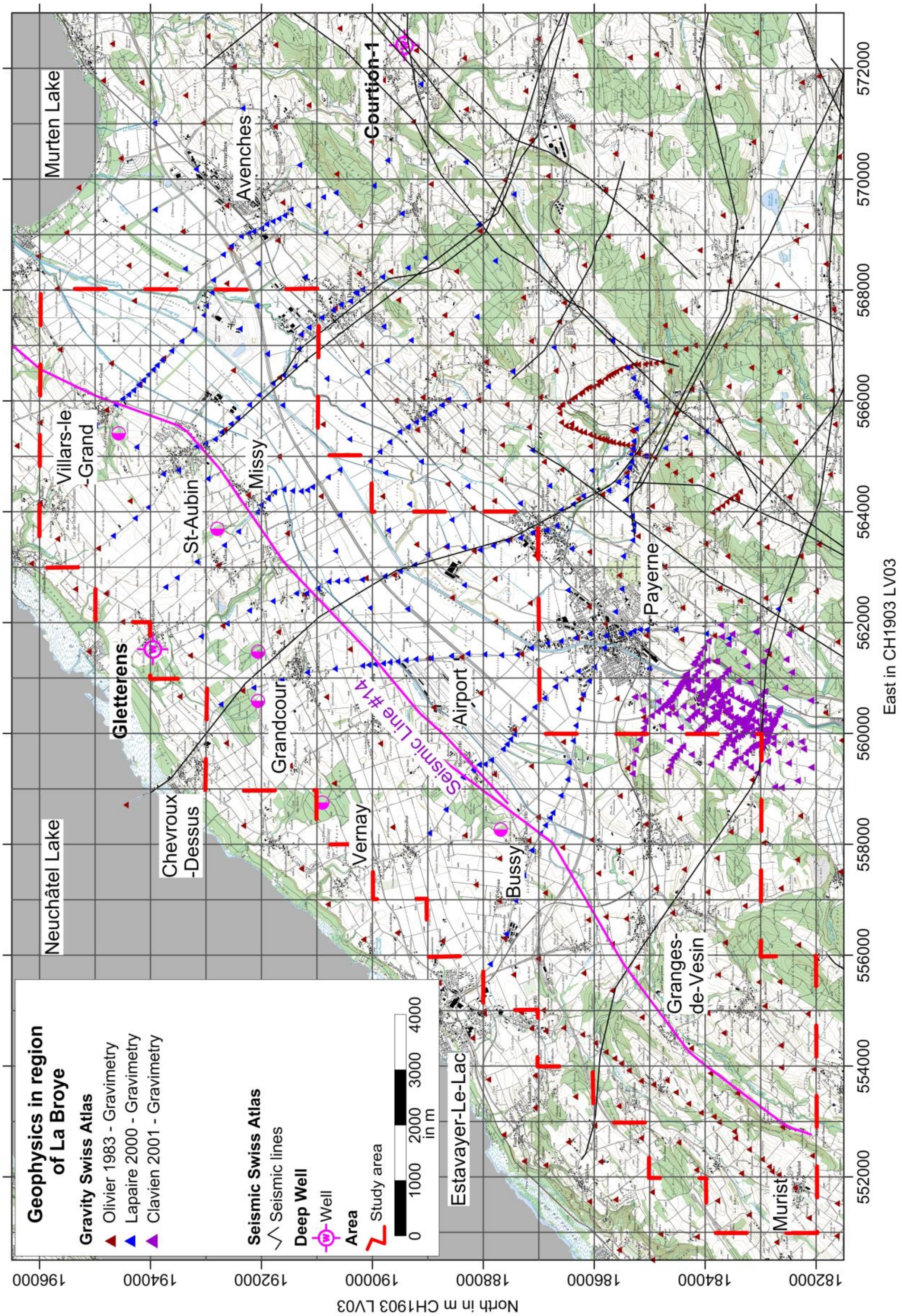
As example, in the work of Clavien (2001), the standard deviation range from -0.130 mGal to +0.080 mGal, while in the 2015-survey, the standard deviation is calculated in absolute value (from 0.000 mGal to +0.170 mGal). The results based on the method would necessary not be the same.

Regarding the data set from the Swiss Plateau data base (Olivier, 1983), it is more difficult to assess its uncertainty in the data, because of the difference found in the literature, which range from 0.080 mGal (Lapaire, 2000, Clavien 2001) and 0.200-0.300 mGal in the Gravity Atlas of Switzerland (Olivier et al., 2010). Therefore the upper limit of 0.300 mGal will be considered as safe uncertainty value, even if it is likely overestimated.

If we consider the absolute range of variations for the standard deviation, it is reasonable to assume that the 2015-survey is equivalent to the previous works.

After reprocessing the data set from the previous study, the uncertainty on the data is estimated to be similar to the 2015-survey, which has an uncertainty of 0.14 mGal.

Figure 12: Region of La Broye. Brown, blue, purple triangles represent respectively gravity data from 1983-gravity Atlas (Olivier, 1983), M·Sc. work of Lapaire (2000, UNIL) and M·Sc. wok of Clavien (2001, UNIL). Black dots indicate the location of gravity station surveyed in 2015 (this study). Pink circles represent the location of magnetotelluric sites measured in 2015 (This study). Red dashed lines represents the extent of the investigated area, which is of 100 square kilometres. Black lines are seismic profiles (Sommaruga et al., 2012). The seismic line #14, from the Seismic Atlas, crosses the area from NE to SW (Sommaruga et al., 2012).


Geophysics in region of La Broye
Gravity Swiss Atlas
Olivier 1983 - Gravimetry
Lapaire 2000 - Gravimetry
Clavien 2001 - Gravimetry
Seismic Swiss Atlas
Seismic lines
Deep Well
Well
Area
Study area
0 1000 2000 3000 4000
in m
Neuchâtel Lake
Murten Lake
Estavayer-Le-Lac
Chevroux -Dessus
Gletterens
Grandcour
Vernay
Bussy
Airport
St-Aubin
Missy
Villars-le -Grand
Avenches
Courtion-1
Payerne
Granges- de-Vesin
Murist
Seismic Line #14
East in CH1903 LV03
North in m CH1903 LV03
552000
554000
556000
558000
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562000
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570000
572000
182000
184000
186000
188000
190000
192000
194000
196000

5.3 Re-processing of previous study

The M·Sc. works of Lapaire (2000) and Clavien (2001) use the principle of the disk of Hammer, which divide the surround terrain is vertical prism. The proximal ring zone goes from 1m to 20m and is divided into 4 sectors.

Then, using the principle of Hammer disk (Hammer, 1936) these studies have used the 50m cells size DEM grid (Modèle Numérique d'Altitude de Swisstopo, see Lapaire, 2000; Clavien, 2001) to do the terrain correction from 20m to 167 km. Similarly the external rings are their outer rim at 52.5m, 2615m and 21950m. However, as presented in these two works, the terrain correction cannot be done for a greater distance due to Earth curvature (Lapaire, 2000; Clavien, 2001).

In the 2015-Survey, a different approach was use for the terrain correction, where the hammer disk is not used anymore, and where it is replaced by the use of three different digital elevation models. The high resolution digital elevation model (2m cell size DEM) replaces the proximal zone from the station to 200m away. A brief description is presented in section 3.1 "From survey to Bouguer anomaly map". A complete description of the software Corr-Topo used for the terrain correction can be found in the work of Altwegg (2015).

The difference in calculation generates additional uncertainty on the computed Bouguer Anomaly of each gravity station, when merging the all the data sets together.

Therefore, the choice has been made to re-process all the data set to reduce the uncertainties on the terrain correction.

Additionally, in order to get a feeling on the quality of the re-processing of the data set, the choice has been made to re-process each data set using different grid-size DEM. Indeed, the re-processing will change to a certain extent the final Bouguer value of each station, however, the distribution should be similar in term of gravity variation range and distribution range. To represent the distribution, all the data have been represented into a histogram, which will give visually a statistical view of the re-processing results (Figure 13).

Then, the re-processed data sets with each grid-size DEM have been compared to the data before reprocessing (Figure 14). The similarities in range and in the Gaussian distribution indicate that the re-processing went well and that the general trend should be relatively similar.

The shift in range of the 2015-survey (Mauri2015, Figure 14) in comparison to the previous study is coherent, because, the extent of the covered surface is not the same. The data set regrouping all the previous studies (Olivier, 1983; Lapaire, 2000; Clavien, 2001) include 1031 stations scattered over an area of about 930 km^2, while the 2015 survey regroup 824 stations over an area of 100 km^2. The fact that the Bouguer values from 2015 survey are completely include within the range of the re-processed data sets is a good indicator that the merging of the data is coherent and accurate.

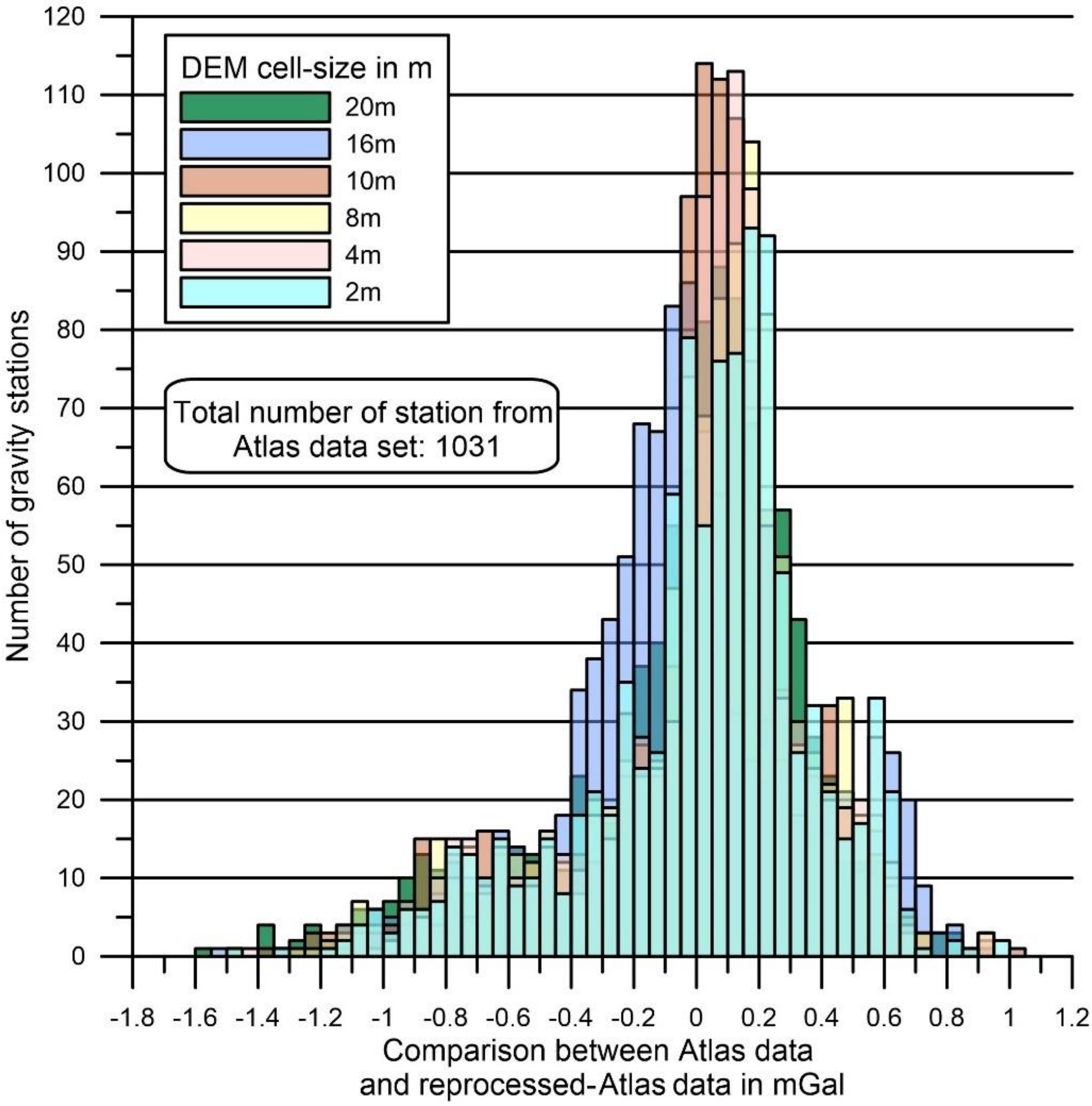


Figure 13: Histogram presenting the variation of the Bouguer values in the region of La Broye for the reprocessed data of previous studies with different cell-size DEM. The Bouguer variations regroup the data set from previous work of 1983-gravity Atlas (Olivier, 1983), M·Sc. work of Lapaire (2000, UNIL) and M·Sc. wok of Clavien (2001, UNIL).

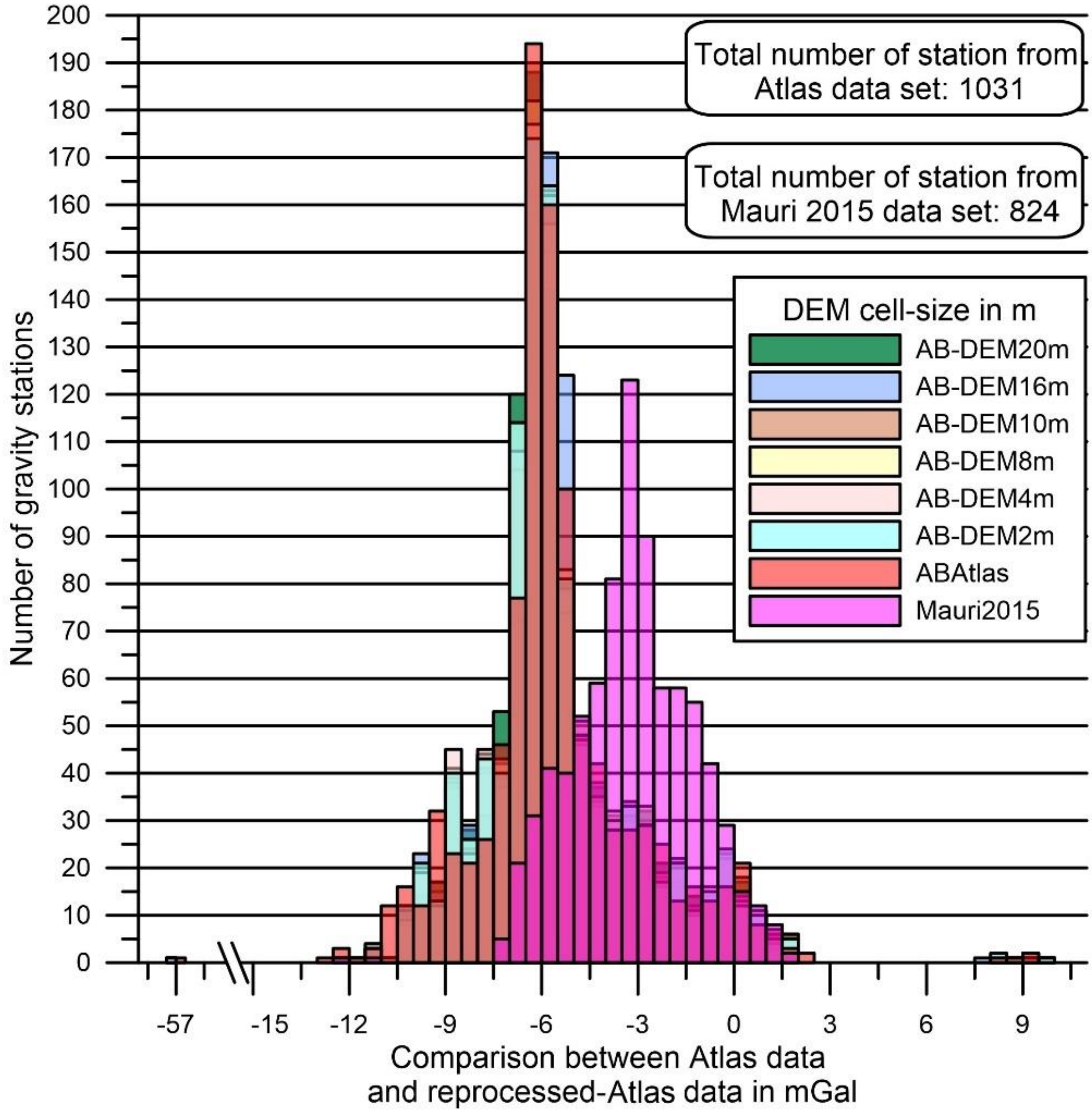


Figure 14 : Histogram presenting the variation of the Bouguer values in the region of La Broye for the reprocessed data of previous studies with different cell-size DEM. Red colour represents the Bouguer variations (named here ABAtlas) before re-processing, which regroup the data set from previous work of 1983-gravity Atlas (Olivier, 1983), M·Sc. work of Lapaire (2000, UNIL) and M·Sc. wok of Clavien (2001, UNIL). In purple is the data set collected in 2015 (This study).

5.4 Correcting gravity lake effect

Volumes of the Lake of Neuchâtel and Morat are respectively of ~13.98 km^3 and ~0.55 km^3 (Liechti, 1994), which make them a significant mass of water that is likely to have a gravity effect on nearby gravity stations. The gravity effect of the lakes decreases within the increase of the distance between the station and the shoreline. Based on previous gravity study on Neuchatel shoreline (GeoNE project, CREGE, 2010), the gravity of Neuchâtel lake is negligible after a few kilometres in land.

In order to be constant in the work flow, the choice has been done to calculate the gravity effect of both lakes on each station for each data set (Figure 15).

Thanks to the help of A. Reusch (ETH Zurich) and Prof. Strausser (ETH Zurich), it has been possible to use their high resolution bathymetry data sets (at a grid cell size of 25m) for each lake (Reusch et al., 2015). As the high resolution data set does not cover the entire surface of each lake, contour lines from the 1:25000 topographic map from Swisstopo (Swisstopo & SITN, 2010.) have been added to interpolate a bathymetry grid of each lake using ARC-GIS software.

First a 3D interpolated model have been generated using 3D Geomodeller over a 50m-cell grid, but too many artefacts where present to obtain a reliable model. Therefore, the building of a full 3D model has been cancelled and the choice has been done to use a different approach.

This second approach, which is used in this study, is to calculate twice the terrain correction using 2 different types of DEM. The first set of DEM does not include any bathymetry data and the lake surfaces are flat using the average elevation value of each lake. The second set of DEM includes the bathymetry data of each lake. The difference between each set of DEM corresponds to the volume of the lake. A similar approach was used in GeoNE project (CREGE, 2012) to calculate the gravity effect of the Neuchâtel Lake on the gravity data collected on the north shore of the lake.

Then, by subtracting the gravity terrain effect of DEM without bathymetry by the gravity effect obtained using the set of DEM with bathymetry, the result is the gravity effect of both lake at $2.67 g \cdot cm^{-3}$, which is the density of reference for terrain correction. Finally, by divided the gravity effect by $2.67 g \cdot cm^{-3}$, the results is then the gravity effects of both lake for a density of $2.67 g \cdot cm^{-3}$for each gravity station.

As expected the gravity decreases, with the distance from the lakes. The strongest effect is near Neuchâtel lake (-0.190 mGal). In comparison near the shore line of Morat lake, the gravity effect is only between -0.010 mGal and +0.010 mGal (Figure 15).

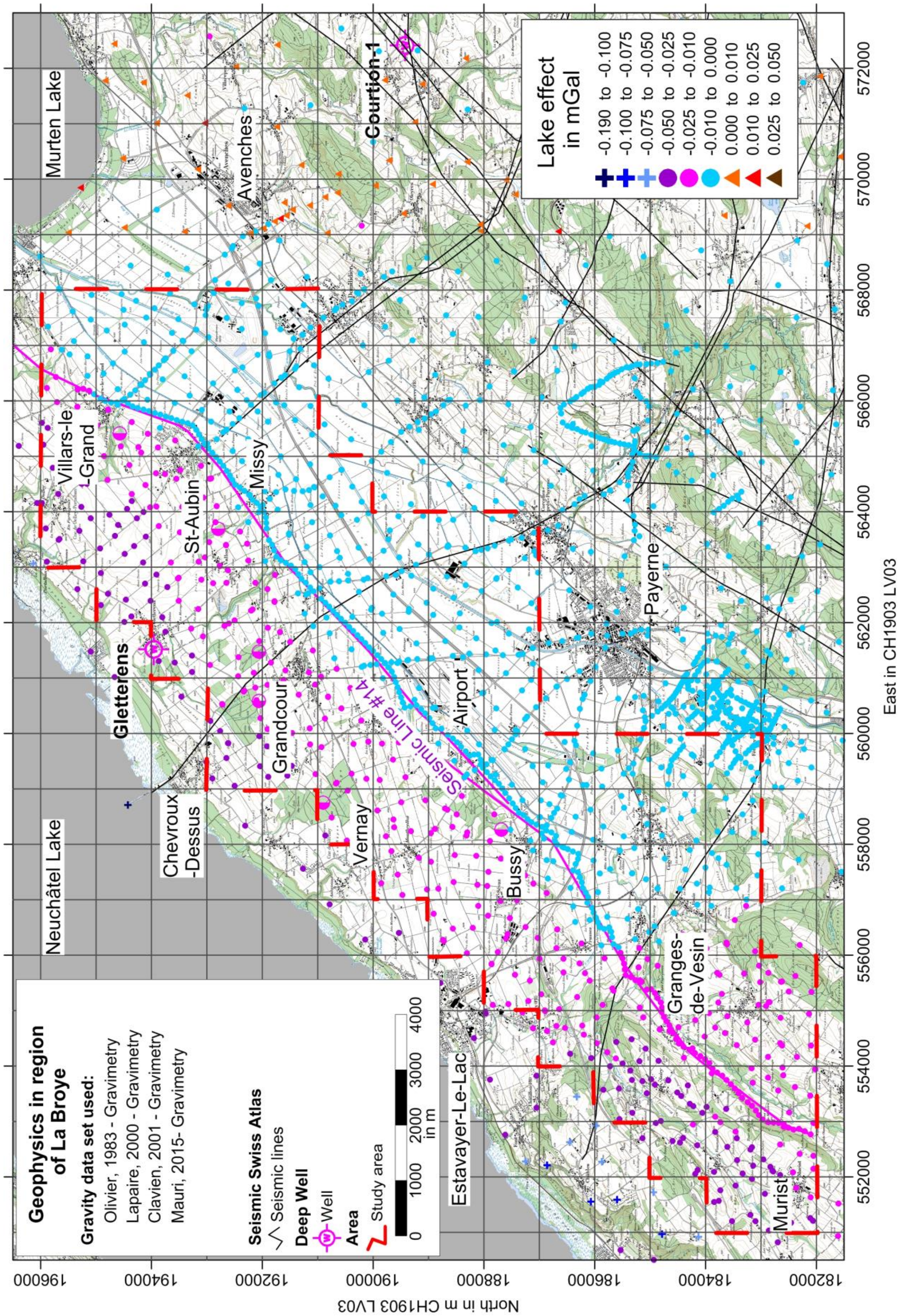


Figure 15: Gravity effect of both lakes Neuchâtel and Morat using all the gravity data sets.

6. From Bouguer Anomaly to Residual gravity map

Bouguer Anomaly Map

The Bouguer anomaly map has been computed using all the merged data sets (Olivier, 1983; lapaire, 2000; Clavien, 2001; 2015-survey) and based on the following kriging parameters in Surfer Software (Golden Software Inc., 2010).

For each grid node, the radius search is 3000 m, the ring search is divided into 6 sectors. The maximum number of data points use in all sectors is 150 points, while the minimum number of data points used in one sector is of 12 points. Additionally, the grid node is left empty, if at least 2 sectors are empty.

The computed grid covers the extent of 31 km by 30 km, with a 100m-grid size (Figure 16) and is characterized by the regional trend pattern from the thickening of the lithosphere due to the Alps.

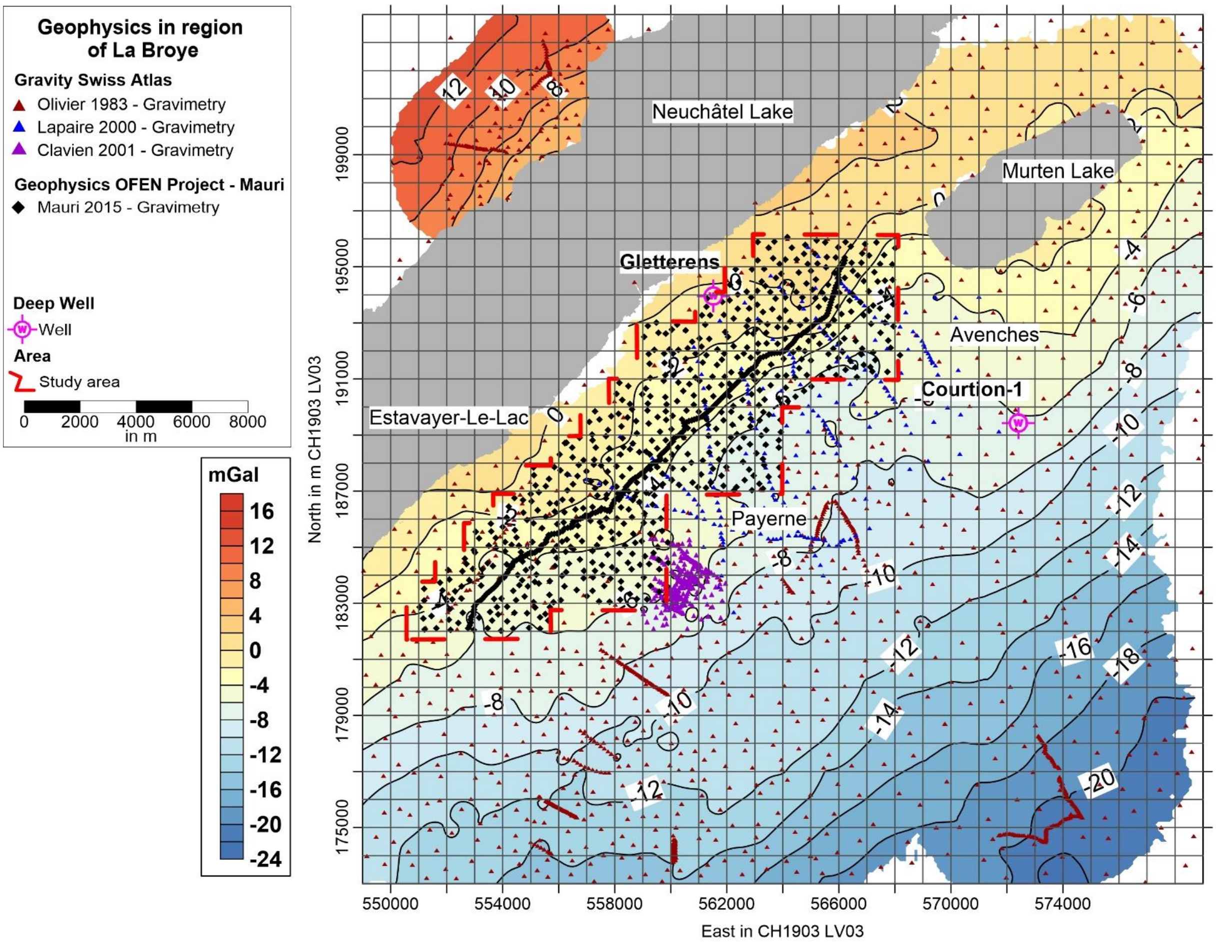


Figure 16: Bouguer anomaly map for a reference density of 2.67 g·cm^{-3}, using all gravity data sets. Kriging parameters: radius search of 3 km, 6 sectors of calculations, maximum number of data points used in all sector is 150 values and minimum number of data points used in one sector is 12. Grid node is blank if more than 2 sectors if empty. The lake surfaces are in grey colour.

Bilinear regional trend

In order to remove the regional trend, a traditional bilinear regression has been computed used all the Bouguer values from all gravity data sets (Figure 17). Indeed, the trend toward the Alps is well known (Kahle et al., 1976; Klingelé, 2006; CREGE, 2012; Altwegg, 2015) and outside the Alps a basic bilinear regression is good enough, because the gravity effect of the Alps (roots and mountains) decrease as one divide by the square distance from the Alps.

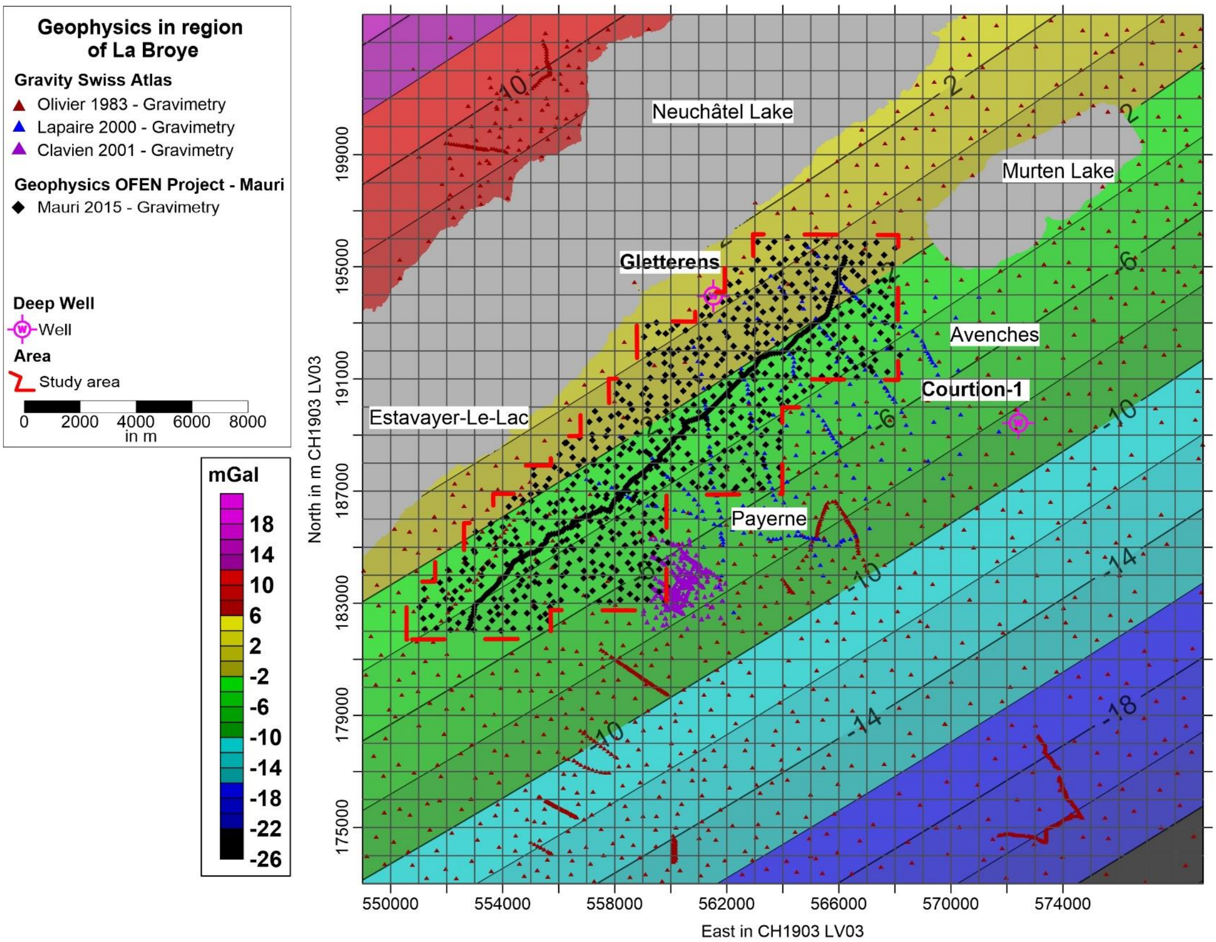


Figure 17: A regional gravity trend has been calculated from the Bouguer values from all gravity data through a bilinear regression.

Residual gravity map

The residual gravity map is obtained by subtracting the computed bilinear regional trend to the Bouguer anomaly map (Figure 18). Over the studied area of region of La Broye, the residual gravity variations allow us to characterize 2 main gravity decreases:

1) A decrease of gravity extent over the plain of La Broye and a part of the hills toward Neuchâtel Lake.
2) A decrease of gravity located in the south-west corner of the studied area and extent toward the south.

Across the studied area, the 824 gravity stations from the 2015-survey constrain well the spatial extent of gravity variation, which allows us to be confident in the characterisation of the anomalies.

In the south-west (Figure 18), some strong increases of gravity are of small extent (about or less than 1 km^2) and are often based on 2 to 5 gravity stations. The origin of such strong gravity increase (from about 0.6 mGal to about 1.5 mGal) cannot be easily explained, however, the following hypotheses are feasible:

- A local change in either the lithology thickness or in the density of the quaternary deposit.
- Artefact due to either error when merging the data or man-made effect due to modern construction between the 2000-survey (Clavien, 2001) and the 2015-survey. That is more likely near of Fétigny (Fr) area, because the gravity increases are punctual.

The choice has been made to not remove these small artefacts to avoid making new ones.

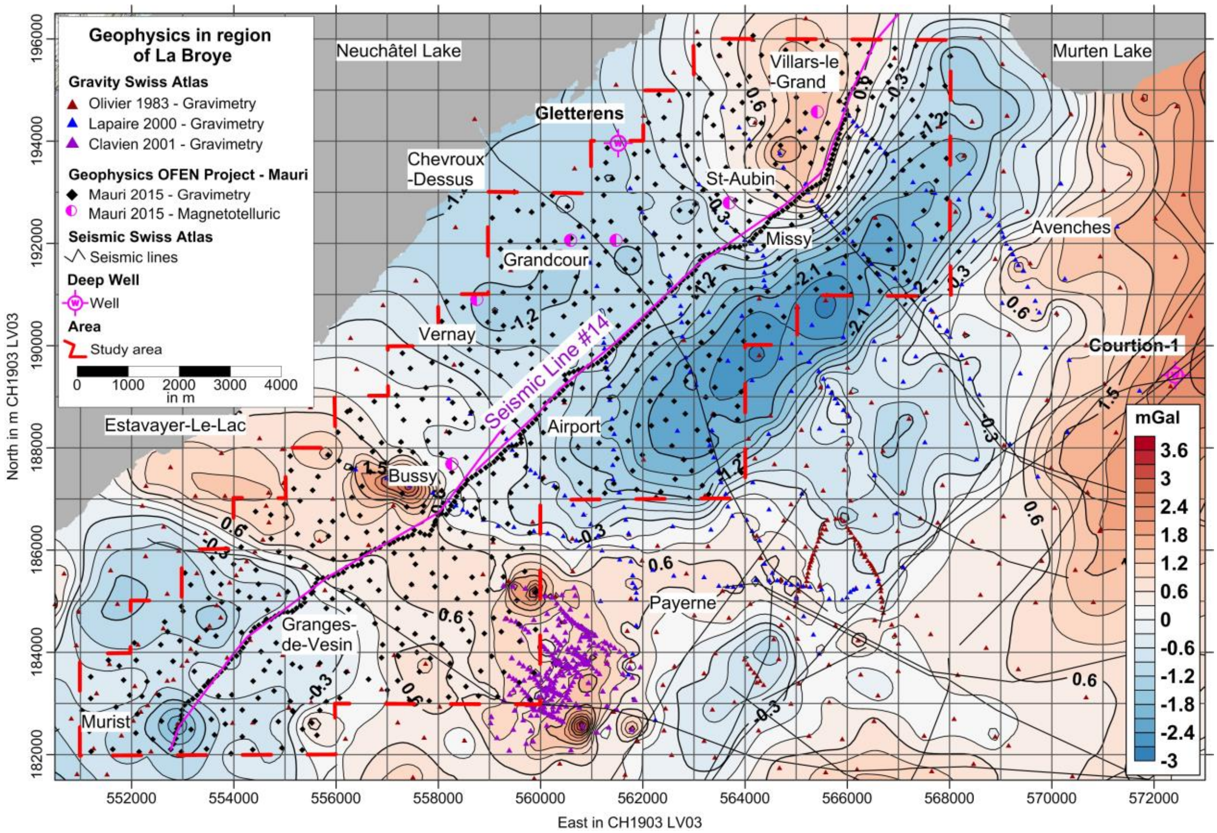


Figure 18: Residual gravity map of the region of La Broye obtained by subtracting the regional trend to the Bouguer anomaly map for a density reference of 2.67 g·cm^{-3}. Contour line is of 0.300 mGal.

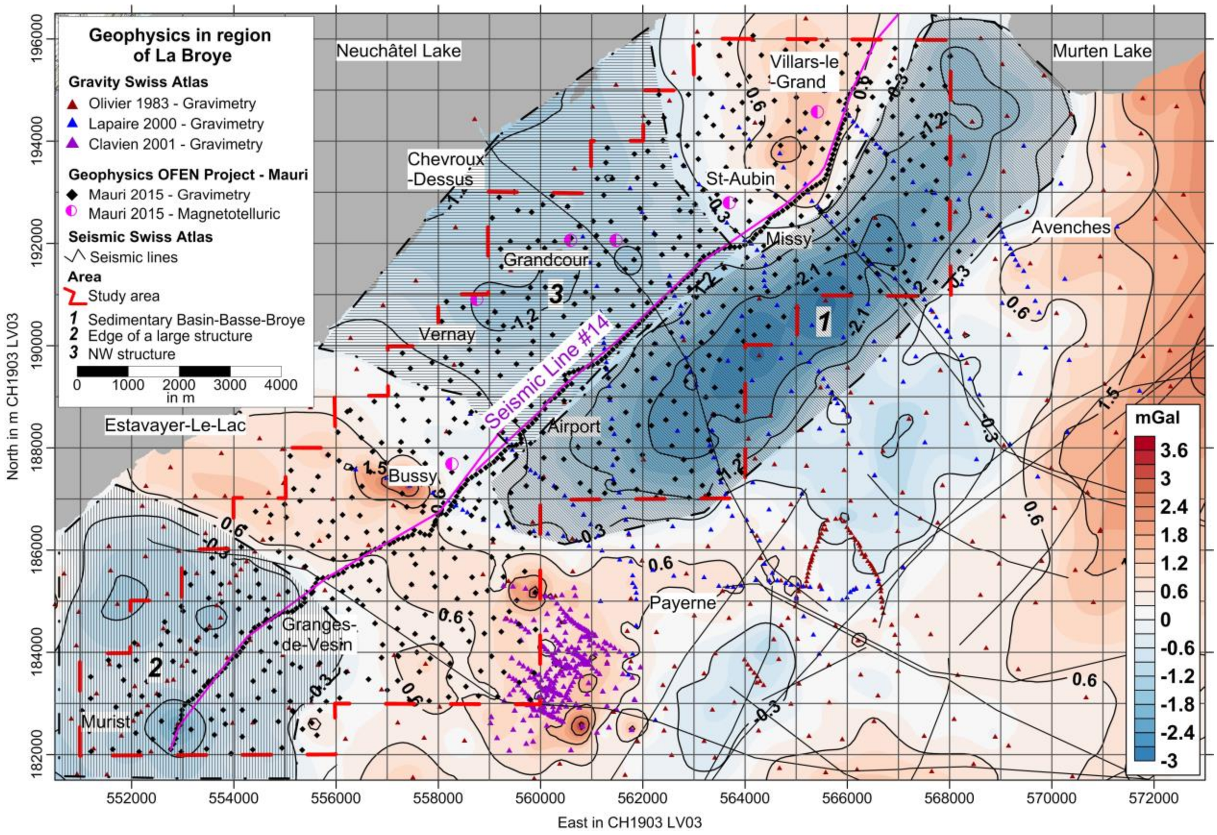


Figure 19 : Residual gravity map of the region of La Broye with the delineation of the different gravity decrease areas. Based on the Bouguer anomaly map for a density reference of 2.67 g·cm^{-3}.

7. 2D sensitivity study along Seismic line #14

7.1 Overview of geological structure associated to seismic line #14

The investigated region of La Broye is crossed by the seismic line #14 (Sommaruga et al., 2012). As presented in the Seismic Atlas of Switzerland, seismic line #14 passes nearby the villages or airport (Figure 20). From NE to SW: Villars-le-Grand, St-Aubin (Fr.), Missy, the airport, Bussy, Granges-de-Vesin and Murist. Within the studied area, the seismic line #14 has a length of ~22 km.

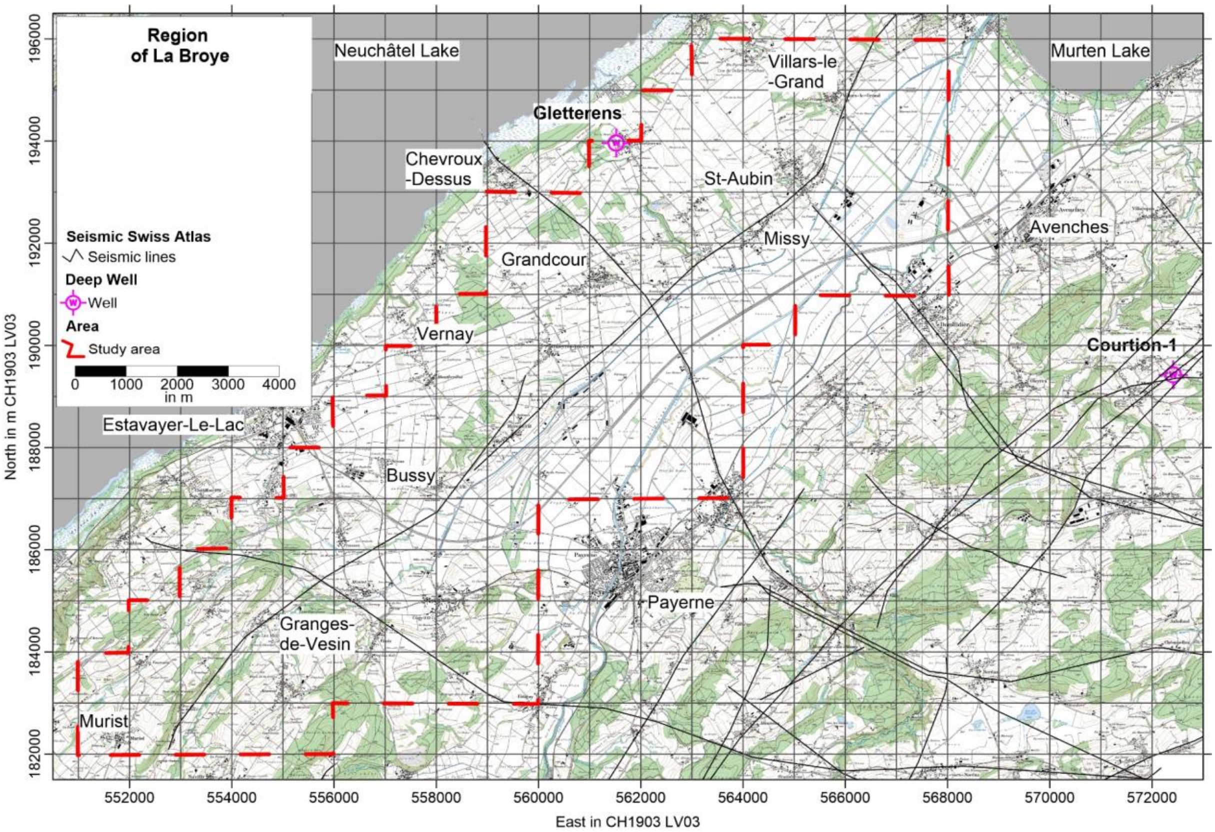


Figure 20 : Region of La Broye. Red dashed line represents the extent of the investigated area, which is of 100 square kilometres. Black lines are seismic profiles (Sommaruga et al., 2012). The seismic line #14, from the Seismic Atlas, crosses the area from NE to SW (Sommaruga et al., 2012).

In terms of Geology, a geological cross-section interpreted from the seismic data is presented in the seismic atlas of Switzerland (Sommaruga et al., 2012), in which sediment deposit of either quaternary or tertiary ages are regrouped within a same unit (Figure 21). This simplification is likely to generate a strong limitation on any forward gravity calculation, because the sediment of quaternary ages are of different density, based on their lithology. The molasses deposits of tertiary ages are likely to be of higher density that the quaternary deposit. Such, rock density variation has been well studied in the region of La Broye in the work of Lapaire (2000) and Clavien (2001).

The geological formation from Mesozoic era are also present in the interpreted geological cross-section (Sommaruga et al., 2012)(Figure 21). The interpreted cross-section presents the extent along the profile of an hypothetical structure made of uncertain Permo-carboniferous sediments (Sommaruga et al., 2012)(Figure 21). This hypothetic structure may extent outside the studied area, northward toward the city of Cudrefin and the Canal de la Broye. Outside, the study area, for reason of right of data usage, the residual gravity data cannot be used for now. Additionally, the number of gravity stations by square kilometres is significantly lower and it would be better to first do a new gravity survey to properly define in more details the gravity variation toward Cudrefin.

Therefore, the sensitivity study is made using only the interpreted geological cross-section within the limit of the studied area (Figure 22).

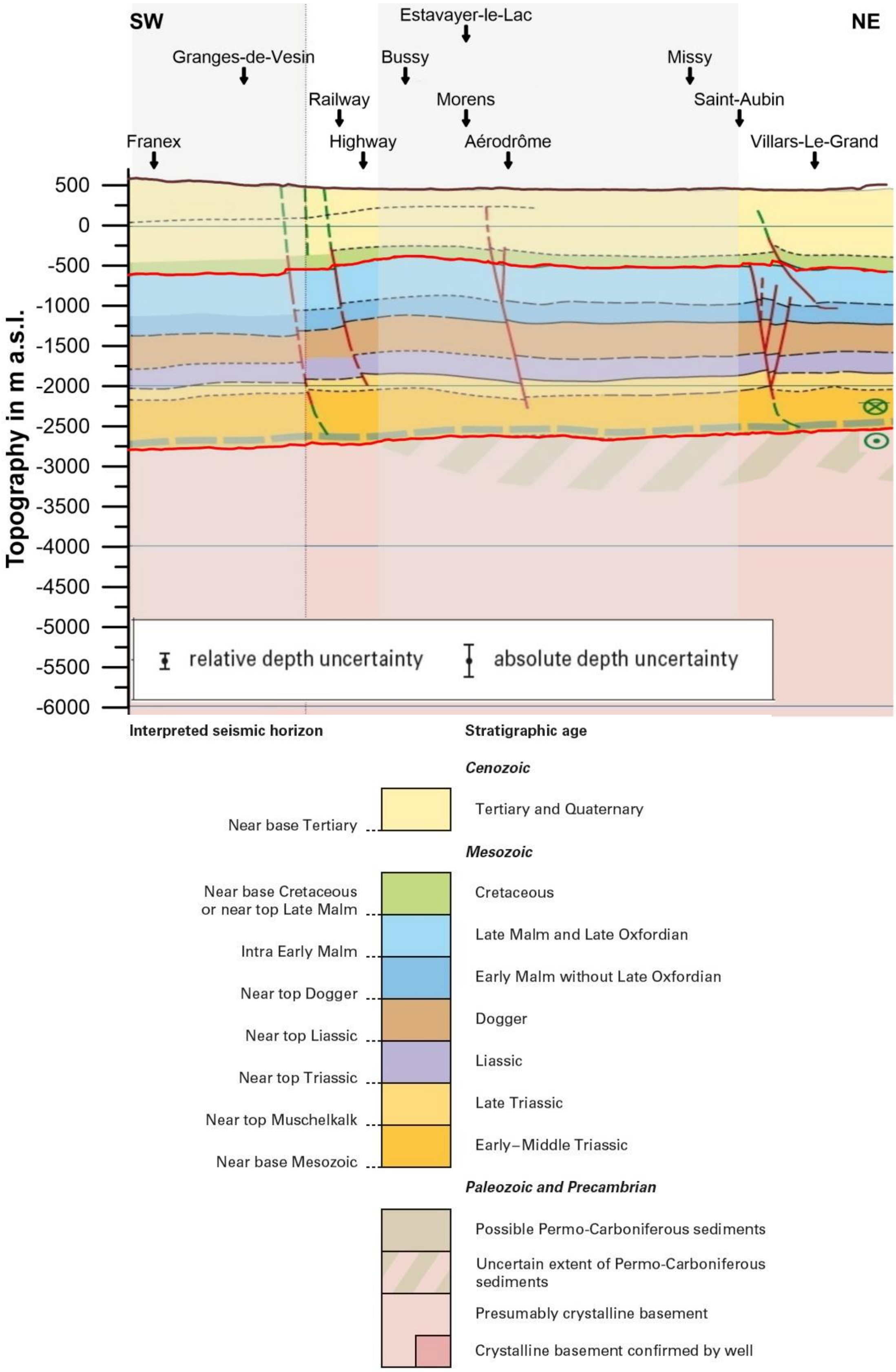


Figure 21 : Top : Geological cross-section based on the interpretation of the Seismic line #14, as presented in the Seismic Atlas of Switzerland. Modified from Sommaruga et al., 2012. Bottom: Legend from the Seismic Atlas of Switzerland (Sommaruga et al., 2012).

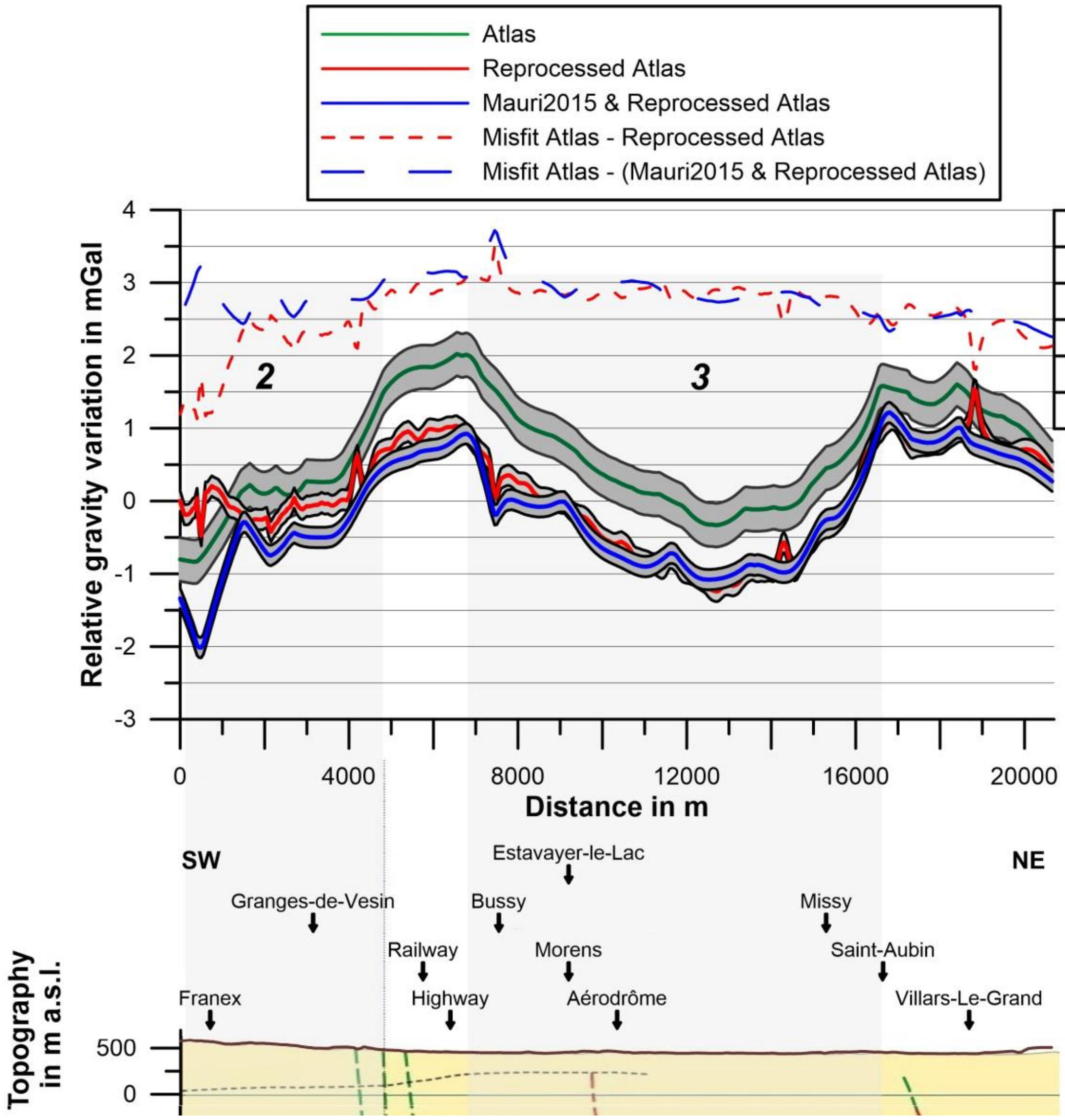


Figure 22 : Gravity profile following the seismic line #14. Green line, with grey uncertainty band: Atlas data set include: data set from 1980-Atlas (Olivier, 1983), M·Sc. Works of Lapaire (2000) and Clavien (2001) with an upper boundary for uncertainty of 0.3 mGal (Olivier et al., 2010). Red line with light grey uncertainty band: Reprocessed data set, with an estimated uncertainty of 0.140 mGal. Blue line with light grey uncertainty band: Reprocessed data set merged with the 2015-survey, with an estimated uncertainty of 0.140 mGal.

As it was shown in section 5.3 Re-processing of previous study, reprocessing the data set of previous studies (Olivier, 1983; Lapaire, 2000; Clavien, 2001) and merging them with the 2015-survey significantly help to better constrain the gravity variation in the region of La Broye (Figure 22).

In the southern part of the profile (left side on Figure 22), the gravity is significantly reduced of about 1-1.5 mGal and with a shaper transition while using the merged data sets (Figure 22).

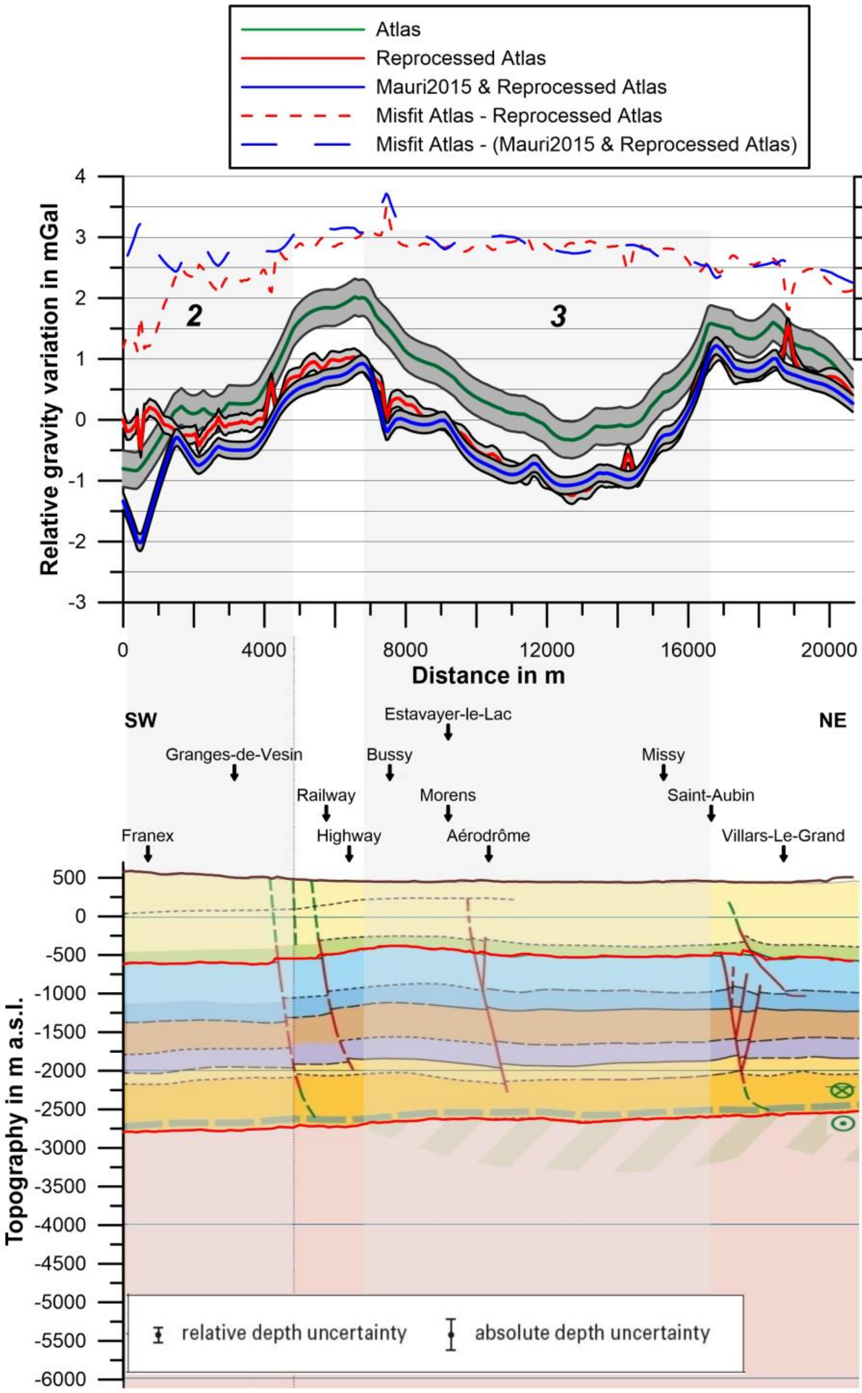


Figure 23 : TOP: Gravity profile following the seismic line #14. Green line, with grey uncertainty band: Atlas data set include: data set from 1980-Atlas (Olivier, 1983), M·Sc. Works of Lapaire (2000) and Clavien (2001) with an upper boundary for uncertainty of 0.3 mGal (Olivier et al., 2010). Red line with light grey uncertainty band: Reprocessed data set, with an estimated uncertainty of 0.0.140 mGal. Blue line with light grey uncertainty band : Final merged data, which includes the 2015-survey, as well as the reprocessed data set from previous studies (Olivier, 1983; Lapaire, 2000; Clavien, 2001).Dashed lines are the misfit in comparison to previous work before reprocessing the data (line green). BOTTOM: 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. Legend is presented on Figure 21.

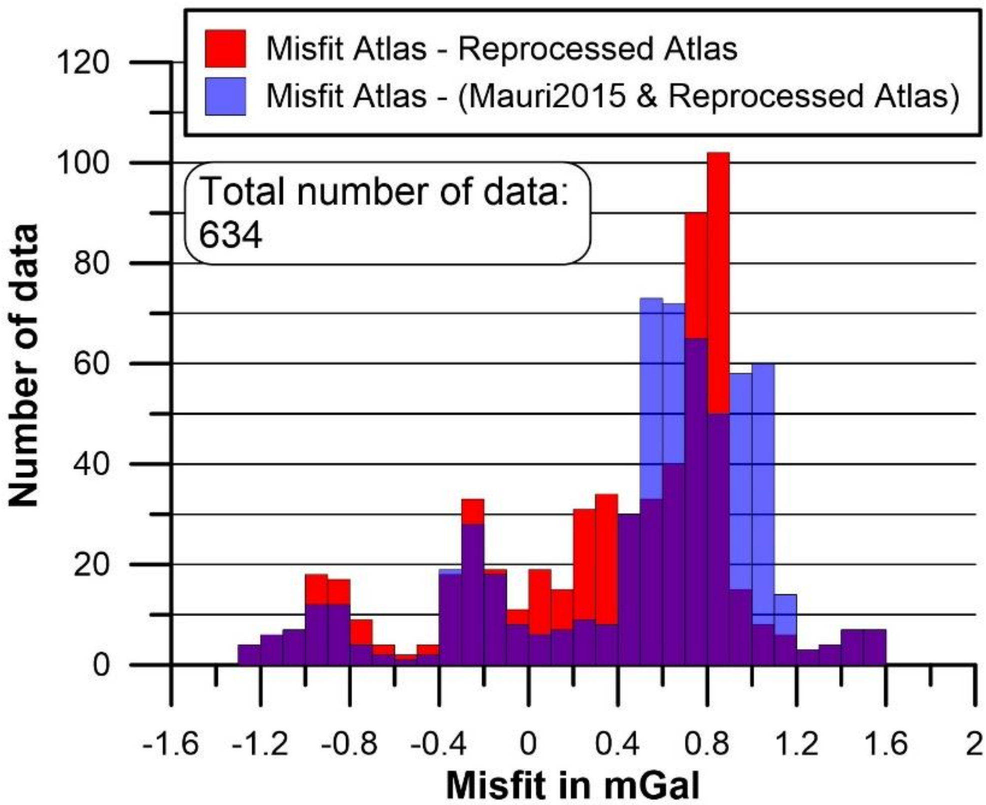


Figure 24 : Histogram presenting the misfit between the final data set (2015-survey and reprocessed data sets) and Atlas data sets before reprocessing the data. Atlas data sets include data sets from previous studies (Olivier, 1983; Lapaire, 2000; Clavien, 2001). The profiles are presented in Figure 23.

7.2 Sensitivity study on 2D model along seismic line #14

MODEL PARAMETERS AND RESULTS

A 2D model will likely not be able to reproduce well the gravity effect of the true 3D geological features. However, a 2D model can be used as first order of investigation to get a feeling on which geological formation will likely be the more important.

In the present study, the main limitation of the current 2D model used here (Sommaruga et al., 2012) is the fact that quaternary formations are merged with the tertiary formations into one single layer. As presented in literature, the contrast density between quaternary sediment and the molasses of tertiary ages can be strong (up to 0.5 g·cm^{-3} in variation)(Lapaire, 2000; Clavien, 2001).

Therefore, the present 2D sensitivity study focuses on 2 layers:

- The upper layer that is made of both tertiary molasses formation and quaternary post-glacial sediments (Figure 25).
- The deep layers that may or may not exist of the uncertain Permo-carboniferous sediment (Figure 27).

Based on the literature density variations for each of this formation (Table 2), a range of rock density value has been used, while the others formations are considered to be at 2.67 g·cm^{-3} to cancel their effect on the model, which is the density reference used for the calculation of the Bouguer anomaly.

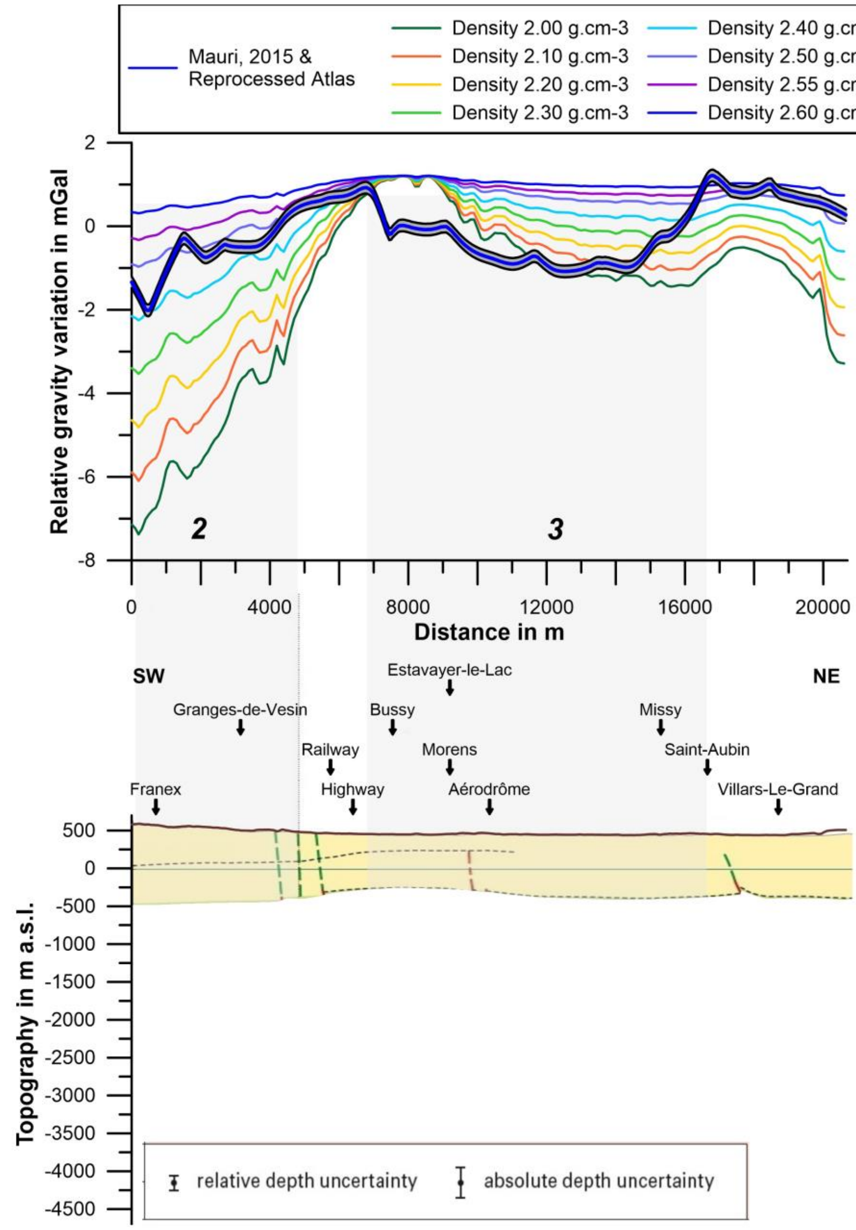


Figure 25 : Sensitivity study of the gravity effect of the combined tertiary and quaternary layer (shallowest formation, light yellow). TOP: Gravity profile following the seismic line #14. Green line, with grey uncertainty band: Atlas data sets (Olivier, 1983; Lapaire, 2000; Clavien, 2001). Dark blue line with its uncertainty band: Final merged data, which includes the 2015-survey, as well as the reprocessed Atlas. Gravity effect of the combined tertiary and quaternary layer for different density. BOTTOM: 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. Legend is presented on Figure 21.

UPPER LAYER: TERTIARY MOLASSES FORMATION AND QUATERNARY POST-GLACIAL SEDIMENTS

The range of density used in the forward 2D model range from 2.00 g·cm^{-3} to 2.60 g·cm^{-3} (Figure 25), while all the others layers (not shown in Figure 25) are the reference density (2.67 g·cm^{-3}). It is necessary, to keep in mind that the upper layer is made of different rock density formation with both lateral and vertical variation. Therefore, the results of the 2D forward model give us only qualitative information on what density variation would likely be enough to explain the observed gravity variation.

There is a lateral shift of about 1 km between the residual gravity profile and the computed gravity profiles. This shift is likely due to 1) a shift in the position of the section of seismic profile #14, while it has been digitalised; 2) an effect of the model itself, because of the fact that the upper layer combines both quaternary and tertiary formations. With only a 2D model, it is not possible to choose one or the other.

The results show that for the gravity anomaly #2, density between 2.55 g·cm^{-3} and 2.50 g·cm^{-3} could be enough to reproduce the residual gravity variations (Figure 25).

For the gravity anomaly #3 in Figure 26, the observed gravity variations could be explain if the upper layer affect has a density ranging between 2.00 g·cm^{-3} and 2.10 g·cm^{-3}.

The seismic profile is on the edge between the hilly part of La Broye (NW) and the plain of La Broye (SE) and in this study we consider that the seismic profile #14 is associated to the hilly area. However this assumption can be reconsidered. The gravity anomaly #3 is outside the plain of La Broye (Figure 26) in the hilly area (from Villars-le-grand and Bussy). Additionally, the thickness of quaternary sediment should not be as thick as in the plain, where it was reported to reach 300m of thickness (Lapaire, 2000).

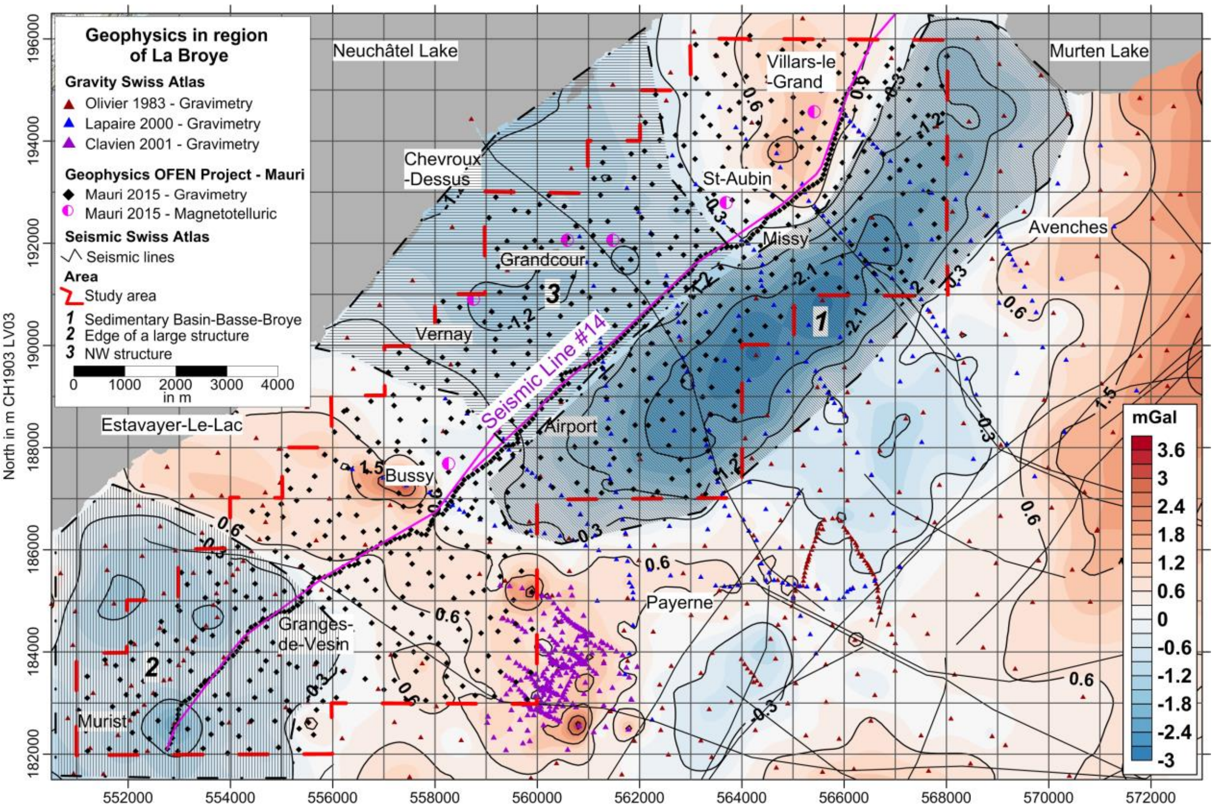


Figure 26 : Residual gravity map of the region of La Broye with the delineation of the different gravity decrease areas. Based on the Bouguer anomaly map for a density reference of 2.67 g·cm^{-3}.

DEEP HYPOTHETIC LAYER: UNCERTAIN PERMO-CARBONIFEROUS SEDIMENTS

Based on the geological interpretation from the Seismic Atlas of Switzerland (Sommaruga et al., 2012), one hypothesis suggests that it may have a deep sedimentary basin of Permo-Carboniferous age. As presented in the Seismic Atlas, this is only a hypothesis.

The choice has been made to do a sensitivity study that get a feeling of what would be the wavelength and amplitude of a gravity anomaly of a hypothetical Permo-carboniferous sediment layer beneath the studied area.

First, the proposed shape from the Seismic Atlas of the hypothetical Permo-carboniferous sediment layer has been used. As the density is unknown, a range of density has been applied based on the literature data (Table 2). The results show that the wavelet of the computed gravity effect is too big to fit the gravity variation observed in the residual gravity map (Figure 27) and a density of 2.53-2.55 $g{\cdot}cm^{-3}$ would be necessary for this layer to reproduce the measured gravity variation.

A second calculation has been made by modifying the shape of the hypothetical Permo-carboniferous sediment layer. As we have no information to constrain its shape, the choice has been made to limit the extent of the geological structure to the edge of the gravity decrease (called #3, Figure 28). The results show that the wavelength of the computed gravity anomaly is still bigger than the wavelength of the measured gravity and a density of 2.53-2.55 $g{\cdot}cm^{-3}$ would still be necessary for this layer to reproduce the measured gravity variation.

Therefore, if a deep sedimentary basin of Permo-Carboniferous age exists beneath the study area, this geological layer should be of smaller extent than the 10 km wide gravity variation measured in 2015. Additionally, the density of this hypothetical deep formation should equal or higher than 2.53 $g{\cdot}cm^{-3}$. Indeed, a density of 2.55 $g{\cdot}cm^{-3}$ would only be possible, if all the geological formation above it have a density of 2.67 or 2.55 $g{\cdot}cm^{-3}$. It is unlikely, because, based on previous study (Lapaire, 2000; Clavien, 2001), the molasses basin have a density ranging from 2.40 to 2.60 $g{\cdot}cm^{-3}$. As presented in the sensitivity study on the quaternary-tertiary sediment (Figure 25), such density for the shallowest formation would generate a gravity decrease that would be a third of the total gravity variation.

MESOZOIC ERA FORMATION

Using the geometry presented in the interpreted cross-section from the Seismic Atlas (Sommaruga et al., 2012), and based on the density used in the literature (Altwegg et al., 2015; Altwegg, 2015)(Table 2), the gravity effect of the geological formation has been computed for a homogeneous density of 2.68 $g{\cdot}cm^{-3}$. Presented on Figure 29, the results show that the gravity effect of all the geological formation from the Mesozoic Era is very small in comparison the measured gravity variation.

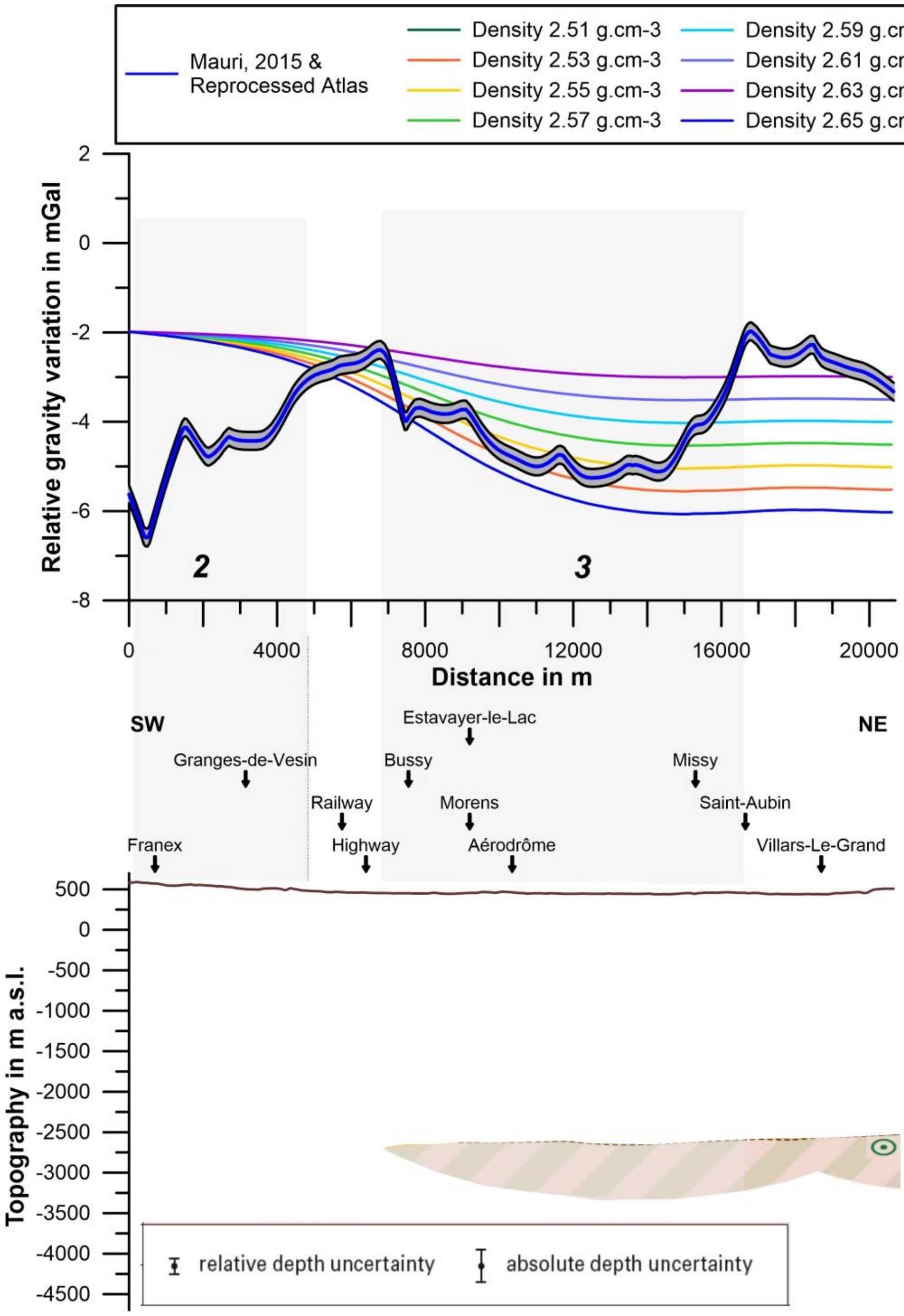


Figure 27 : Sensitivity study of the gravity effect of a hypothetic uncertain Permo-carboniferous sediment. TOP: Gravity profile following the seismic line #14. Green line, with grey uncertainty band: Atlas data sets (Olivier, 1983; Lapaire, 2000; Clavien, 2001). Dark blue line with its uncertainty band: Final merged data, which includes the 2015-survey, as well as the reprocessed Atlas. Gravity effect of the combined tertiary and quaternary layer for different density. BOTTOM: Geological cross-section based on the interpretation of the Seismic line #14, as presented in the Seismic Atlas of Switzerland. The black line underlines the shape of the uncertain Permo-carboniferous sediment. Modified from Sommaruga et al., 2012. Legend is presented on Figure 21.

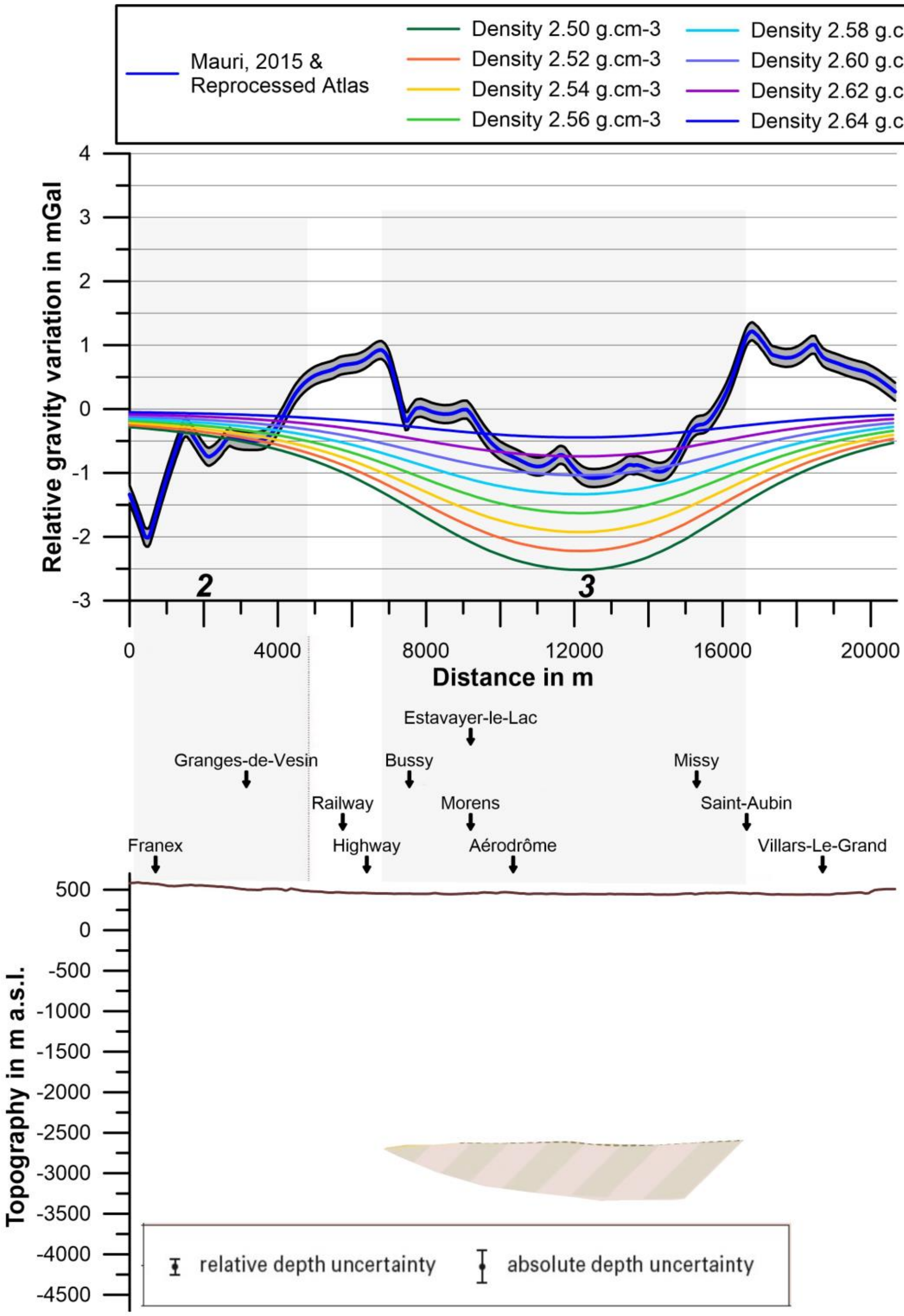


Figure 28 : Sensitivity study of the gravity effect of an arbitrary shape for a hypothetic uncertain Permo-carboniferous sediment (black line on the bottom cross-section). <u>TOP:</u> Gravity profile following the seismic line #14. Green line, with grey uncertainty band: Atlas data sets (Olivier, 1983; Lapaire, 2000; Clavien, 2001). Dark blue line with its uncertainty band: Final merged data, which includes the 2015-survey, as well as the r reprocessed Atlas. Gravity effect of the combined tertiary and quaternary layer for different density. <u>BOTTOM:</u> Geological cross-section based on the interpretation of the Seismic line #14, as presented in the Seismic Atlas of Switzerland. The shape of the uncertain Permo-carboniferous sediment has been modified for an arbitrary shape (black line). Modified from Sommaruga et al. (2012). Legend is presented on Figure 21.

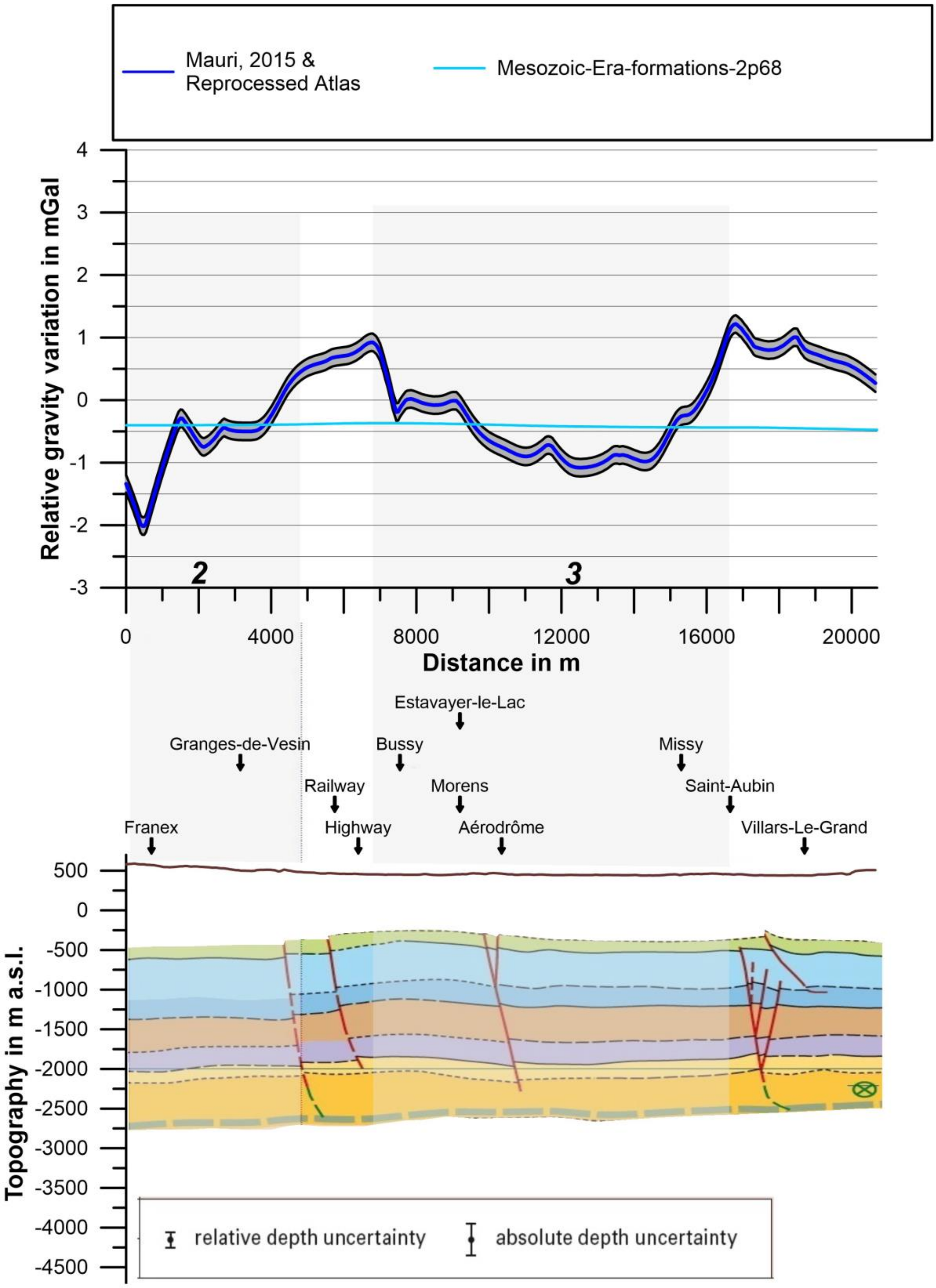


Figure 29 : Sensitivity study of the gravity effect of the geological formation from the Mesozoic Era. TOP: Gravity profile following the seismic line #14. Green line, with grey uncertainty band: Atlas data sets (Olivier, 1983; Lapaire, 2000; Clavien, 2001). Dark blue line with its uncertainty band: Final merged data, which includes the 2015-survey, as well as the r reprocessed Atlas. Gravity effect of the combined tertiary and quaternary layer for different density. BOTTOM: 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). Legend is presented on Figure 21.

7.3 Final 2D model along seismic line #14

As it is common in rock density, the range of density variation is quite significant for each geological formation (Table 1). However, for Switzerland, useful information can be found in the literature, such as the catalogue of Physical properties of rock (Wagner et al., 1999) and rock density values from the Jura Mountains with IGS-NE (Altwegg et al., 2013), or from past geothermal projects GeoNE (group de travail GeoNE, 2012), Eclépens (Altwegg, 2015), St-Gallen (Altwegg et al., 2015).

*Table 2 : Density parameters used for each of the geological formation present in the 2D forward modeling. * Values presented for the minimum and maximum density are based on the literature data (Wagner et al., 1999; Lapaire, 2000; Clavien, 2001; Group de travail GeoNE, 2012; Altwegg et al., 2013, 2015; Altwegg, 2015; Altwegg et al., 2015).*

Formation	**Minimum Density*** **$g \cdot cm^{-3}$**	**Maximum Density *** **$g \cdot cm^{-3}$**	**Used in 2D Model**
Tertiary-Quaternary	2.00	2.89	2.54
Cretaceous	2.64	2.69	2.68
Late Malm-Oxfordian	2.65	2.68	2.68
Early Malm	2.57	2.68	2.68
Dogger	2.61	2.68	2.68
Liassic	2.12	2.68	2.68
Late Triassic	2.53	2.83	2.68
Early-middle Triassic	2.13	2.83	2.68
Uncertain Permo-corboniferous sediment	2.45	2.62	2.57
Crystalline rock	2.60	2.83	2.67

In the context of the Swiss molasses plateau, the results from project on St-Gallen (Altwegg et al., 2015) and Eclépens (Altwegg, 2015) seems to be the most appropriate in term of geological context similarity with the region of La Broye. The main different would likely be for the post-glacial sediment, but the information can be found in the literature (Lapaire, 2000; Clavien, 2001).

For a 2D sensitivity study, it is not realistic to try to get the best fit by changing the density value of the different rock formation. It would be more useful to take density data from literature (Altwegg, 2015; Altwegg et al., 2015). Then, the 2D forward model result will give us an indication, as a first order of interpretation, on the relationship between the measured residual gravity data and the general geological structures along the seismic profile #14.

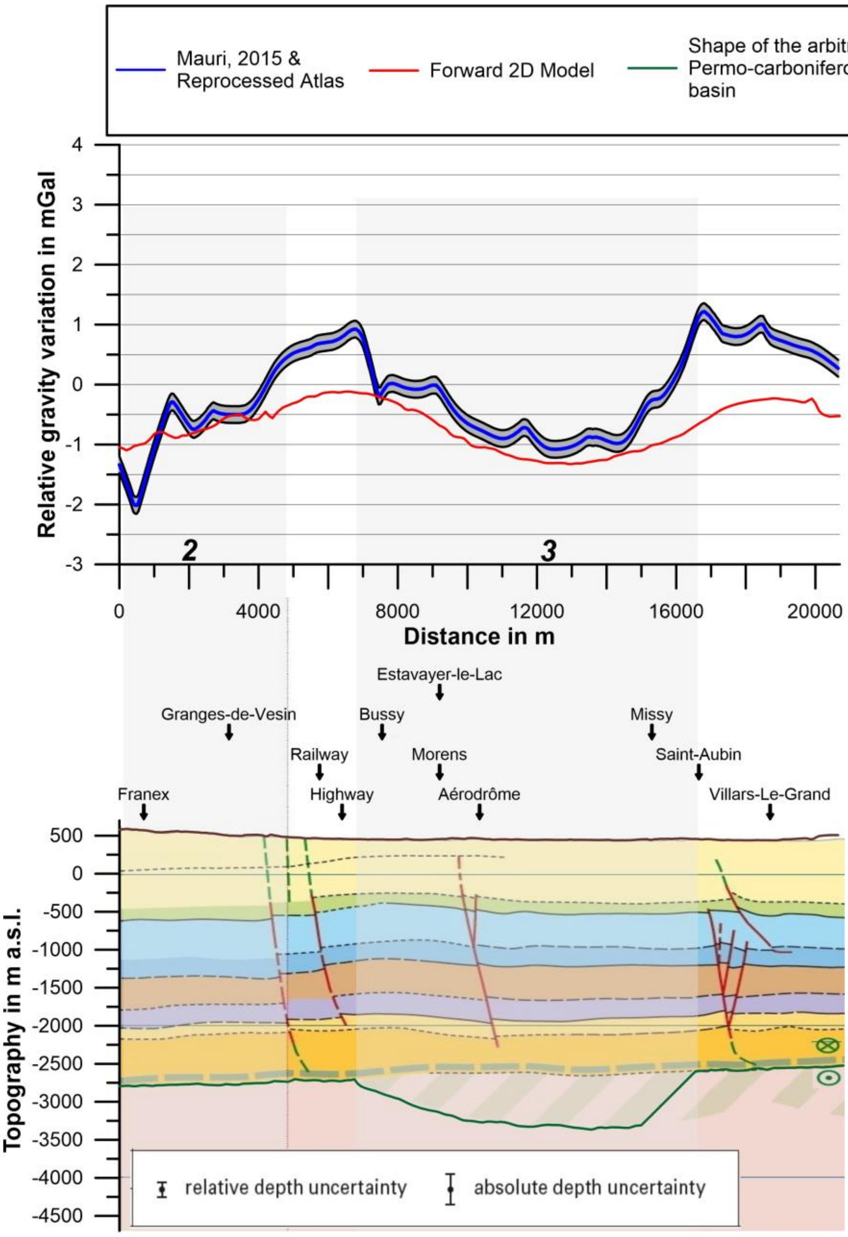


Figure 30 : Sensitivity study assess the gravity effect for 2 arbitrary shapes representing a hypothetic uncertain Permo-carboniferous sediment (brown and red lines on the bottom cross-section) for a density of 2.57 g·cm^{-3} and the effect of the combined Tertiary-Quaternary layer (upper layer on cross-section) for a density of 2.54. TOP: Gravity profile following the seismic line #14. Green line, with grey uncertainty band: Atlas data sets (Olivier, 1983; Lapaire, 2000; Clavien, 2001). Dark blue line with its uncertainty band: Final merged data, which includes the 2015-survey, as well as the reprocessed Atlas data sets. Brown line: Gravity effect of the uncertain Permo-carboniferous sediment layer for a density of 2.57 g·cm^{-3}, such as presented in the Seismic Atlas. Model 01-1 (Red line): Gravity effect of the uncertain Permo-carboniferous sediment layer for a density of 2.57 g·cm^{-3}, with an arbitrary shape. BOTTOM: Geological cross-section based on the interpretation of the Seismic line #14, as presented in the Seismic Atlas of Switzerland. The shape of the uncertain Permo-carboniferous sediment has been modified (black line). Modified from Sommaruga et al., 2012. Legend is presented on Figure 21.

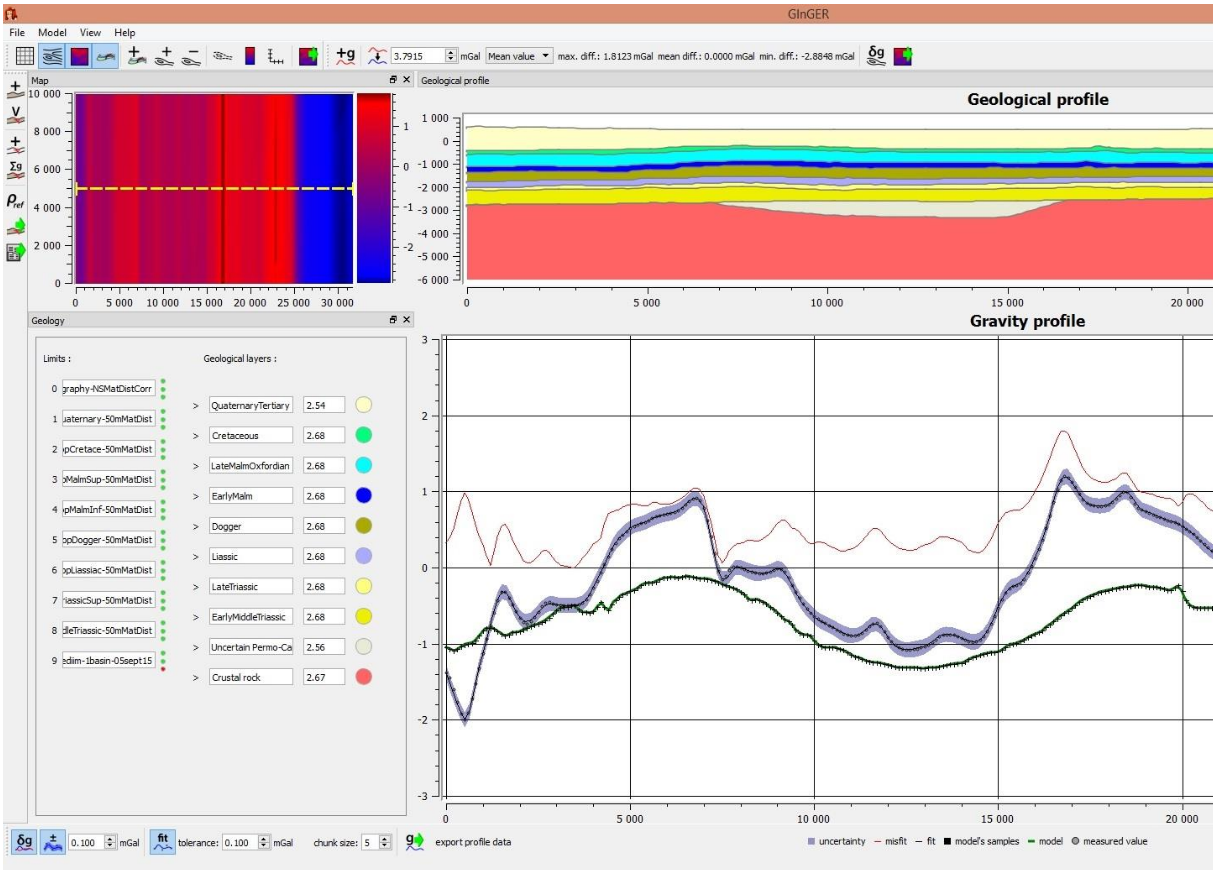


Figure 31 : Example screenshot from GINGER software to calculate the gravity effect along the 2D profile for the 2D model. Top left: view from above of the 2.5D calculation. The dashed yellow line is the trace of the cross-section. Top right: cross-section of the geological model. Bottom left: geological formation of the model with the density value and the surface layer of each formation. Bottom right: Gravity value. Black line with shaded blue is the residual gravity data. Green line is the computed gravity effect of the 2D model. Brown line is the misfit. Density value can be fine in Table 2.

Based on the literature for the density of rocks (Table 2) and based on the sensitivity studies (Figure 27 - Figure 29), it seems reasonable to say that the current model cannot reproduce properly the measured gravity variation. This point is highlighted on the final model, using average value for both the shallowest model layer (Quaternary & tertiary formations) and the deep hypothetical Permo-carboniferous layer (Figure 30). A density of 2.54 g·cm^{-3} has been used for the shallowest model layer (Quaternary & tertiary formations and a density g·cm^{-3}of has been used for deep hypothetical Permo-carboniferous layer. The choice of the extent of the deep hypothetical Permo-carboniferous layer has been to use the arbitrary shape, in order to try to better fit the gravity anomaly. However, this arbitrary shape must not be considered to represent the reality and must be view only as a hypothesis. Finally, computed gravity result shows that the amplitude of the gravity variation is half the amplitude of the measured gravity variation (Figure 30). The two main reasons are: 1) the wavelength of the gravity effect of the deep hypothetical Permo-carboniferous layer is still too big. 2) the density of the shallowest layer is likely to high.

A more detailed model need to be used to better represent the upper layer, such it has been done for the model of the quaternary sedimentary of the Plain of La Broye (Lapaire, 2000).

Based on previous work in the region of La Broye (Lapaire, 2000; Clavien, 2001), as well as from the new gravity map obtained from the presented 2015-survey and reprocessed data, it seems reasonable to assume that the gravity variation present in the studied area is only due to the gravity effect of the shallowest structures made of deposits from both quaternary and tertiary ages.

8. Forward gravity model from the 3D geological model

In August11th, 2015, the gravity survey and the 2D sensitivity study have been presented to Swisstopo in Wabern to the persons working on the geological model and the gravity monitoring in Switzerland. The persons attending the two meetings were Mr. Urs Marti, Mr. Roland Baumberger, Mr. Robin Allenbach, and Mr. Pascal Kuhn.

During the meeting with the geology group, everyone agreed that it would good to compare the 3D model of Swisstopo with the new gravity map.

A joint poster on this topic will be presented at the Swiss Geosciences Meeting in Basel in November 2015. The Abstract can be found in appendix: Abstract for the 2015 Swiss Geosciences Meeting in Basel

For now, the forward calculation has not been computed yet, but it would be before the conference in Basel.

9. Conclusion on the gravity investigation

As presented in the section 6. In residual gravity map, the studied area presents three main gravity decreases (Figure 18):

1) A decrease of gravity that extends over the plain of La Broye
2) A decrease of gravity, which is over a part of the hills that separate the plain of La Broye and Neuchâtel Lake
3) A decrease of gravity located in the south-west corner of the studied area and extent toward the south.

The first decrease of gravity extends over the plain of La Broye. This decrease of gravity is well detailed in the work of Lapaire (2000).

The second decrease of gravity is over a part of the hills that separate the plain of La Broye and Neuchâtel Lake. The strong gravity decrease (of about 3 mGal) over the plain has been explain to be due to quaternary sediment with an important thickness of glacial sediment and a of deep moraine layer at the base of the paleo-valley (Lapaire, 2000). However, the north-west extent of this gravity decrease over the hills was not explained in previous work, because it was not the focus of this previous study. The 2015-survey brings more spatial constraint on the gravity decrease, which is smaller in amplitude than in the plain. Indeed, on the north-west of the gravity decrease, the decrease is of about 1.5 mGal, while in the plain, the decrease is of about 3 mGal.

Based on the 2D sensitivity, the gravity decrease in the north-west can be explained by only change in either the thickness or the density of the quaternary layers. Such interpretation correlate well with the previous model proposed for the plain (Lapaire, 2000). In the hills area, the glacial sediment must be present, but thinner in comparison to the sediment thickness in the plain.

The third decrease of gravity is located in the south-west corner of the studied area and extent toward the south. This gravity decrease is the edge of a very large gravity decrease that extend between the Lake of Geneva and the Lake of Neuchatel. As this study only has the edge of the regional structure, it is not possible to properly characterize it. However, more details can be found on the Ph.D. work of Altwegg (2015) on the study case of Eclépens.

The Gravity data collected in winter 2015, as well as the reprocessing of the previous gravity studies, has allowed us to build a more reliable and more accurate map of residual gravity variation over the region of La Broye. The sensitivity studies based on 2D forward modelling of the interpreted seismic line #14 (such as presented in the Swiss Seismic Atlas) bring interesting insight on the potential source of the gravity anomalies, which are observed on the residual map. The results from such 2D sensitivity study can be of significant help before moving to complex and detailed 3D forward model, by bringing information on the complexity of the underground geology. However, the 2D sensitivity study, such as presented here, is only an intermediate step before the 3D forward model and cannot replace the advantage and accuracy of a 3D model.

Chapter II. **Magnetotelluric investigation of the Region of La Broye**

1. Aims of the Study

The aim of the magnetotelluric study is to assess if it is possible to record magnetotelluric data, which are not too noisy to be useful in urbanised environment, such as in Switzerland. To do so the magnetotelluric survey has been conduct in spring 2015 in the region of La Broye. In the case, where the collected magnetotelluric data are good enough to obtain reliable 2D inversion, the result should then be added to the gravimetry investigation to improve the understanding of the deep geological structure.

2. Magnetotelluric Survey

2.1 Brief introduction of gravity method

BRIEF HISTORICAL INTRODUCTION

The Magnetotelluric method is one of several electro-magnetic methods, which was made in the middle of the 20th century, by Louis Cagniard (1953). Over the last 60 years, the method has evolved in both hardware and software. Since the 2000's, the MT survey is commonly done through 2D survey and since 2010, the Magnetotelluric method is more and more often done in 3D over vast region.

This evolution from 2D to 3D was mainly possible due to the significant increase in computational power, which allowed for processing larger volume of data.

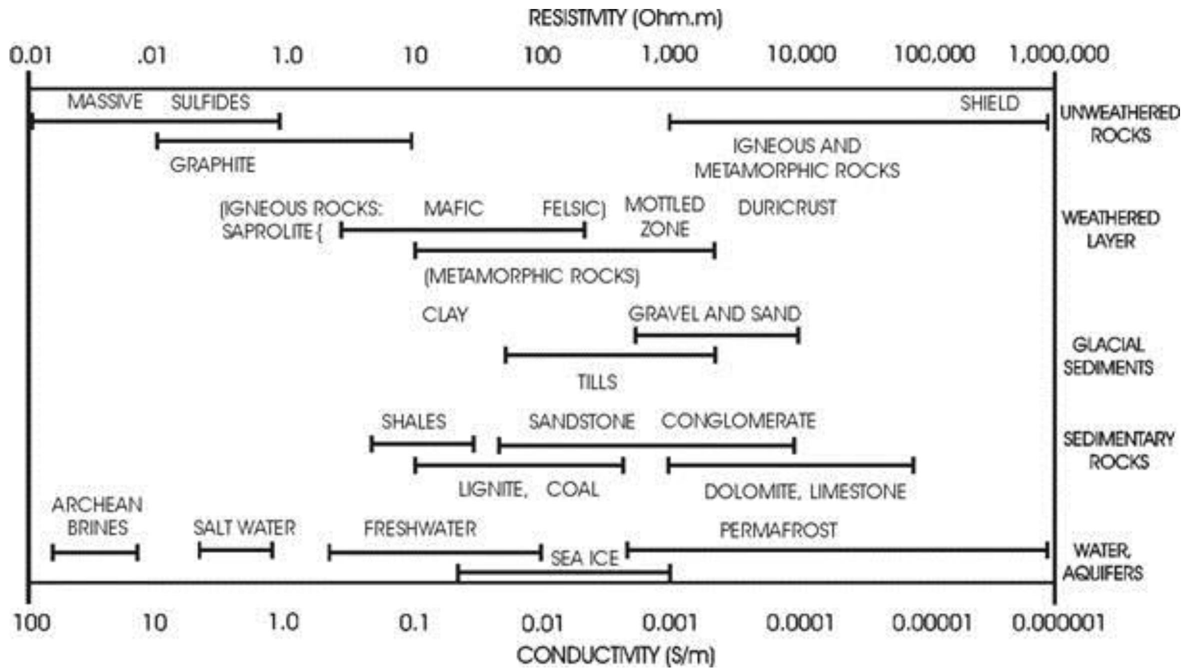


Figure 32 : Relationship between rock type and both resistivity and conductivity range value. Image from Moonbarriga (http://www.moombarriga.com.au/?ContentID=26)

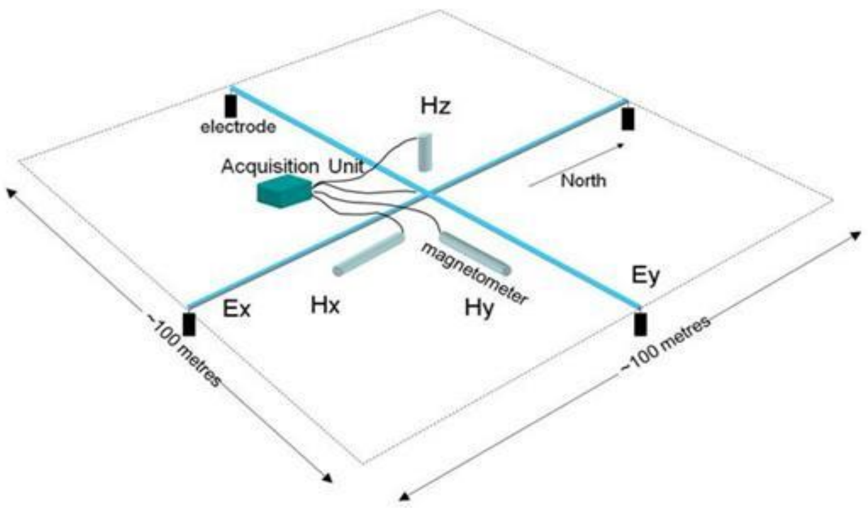


Figure 33 : Setting of one magnetotellurics station in the field. Image from Moonbarriga (http://www.moombarriga.com.au/?ContentID=26)

BRIEF OVERVIEW OF THE METHOD

The Magnetotelluric method is a passive method that allows for recording the natural variation of both magnetic and electric (Telluric) field to investigate the distribution of conductive bodies at depth.

Solar wind, as well as, thunderstorm, is the main source of electrical power within earth. When either solar wind event, or thunderstorm (even several hundreds of kilometres away) hit the surface of Earth, a strong electrical current is injected deep within the ground. This current moves throughout the entire stratigraphy of rocks and interact with each rock layer (based on conductivity property of the rock layer). The result of this interaction is the generation of an induced electro-magnetic field, which can be recorded on the Earth's surface. With increase of depth of the conductive body, its electro-magnetic frequency decrease (Chave and Jones, 2013).

Magnetotelluric surveys cover a large range of frequency, from 10^{-4}Hz to 10^{3}Hz in which some band are particularly affected by human activity noise, which are around the 1-5Hz and the 50Hz (Chave and Jones, 2013).

The conductivity property of a rock is a function of its chemical composition, its level of alteration, its content of fluids and of the composition of these fluids (Figure 32).

A complete description of the Magnetotelluric method can be found in the literature (e.g. Chave and Jones, 2013).

A magnetotelluric (MT) survey consist of several MT stations, which are scattered over the studied area. One MT station consists of (Figure 33):

- 3 magnetics induction coils to record the 3 components of the magnetic field, 2 pairs of 2 self-potential electrodes (non-polarized), which are oriented N-S and E-W.
- The electrical electrodes are for the present study 40m away from the station logger. The coils are a few meters away from the station logger. In order to be environmentally friendly, the electrodes used are made of a Silver cathode and an electrolyte made of saturated salty water.
- Each station is synchronised in time and geo-located through a GPS (a few meters of accuracy) to the logger.
- The logger is powered by car batteries.

Photos of field deployment of the magnetotelluric station are presented from Figure 34 to Figure 36 .

As any other electro-magnetic method, the magnetotelluric method is directly affected by human activity, which will disrupt either electric current moving through the soil or the magnetic field.

Human activity contain buried structures (i.e., pipeline, ruins, underground construction, electrical cables), as well as surface structure (power line, nearby construction, telephony tower, radio tower). Since more than a decade, many studied around the world focus on how to reduce noise level and improve processing data (e.g., Chave and Jones, 2013). However, no easy way exists to efficiently deal with human noise (Wawrzyniak, 2013).

Previous work in Switzerland on magnetotelluric are mostly focused on the Alps , where the strong geological contrast allows for strong conductivity contrast at depth (e.g., Schnegg, 1998, Guglielmetti, 2012). In addition, before 2000, many surveys have been done, but due to high level of man-made perturbation, only some have been published (Schnegg, 1998).

Figure 34 : Magnetotelluric station on the site 3a, in the municipality of Grandcour in spring 2015.

For the survey, the two magnetotelluric stations used are Metronix made, with the following specification (Metronix):

- Logger: ADU07-e
- Induction coil: MFS06-e
- Electrode: EFP-07

The two stations have been upgraded and calibrated by Metronix during winter 2015.

Figure 35 : Magnetotelluric station on the site 3b, in the municipality of Grandcour in spring 2015.

Figure 36 : Example of electrical Ag/AgCl electrode to record the variation of the electrical field over time. Only the grey cap of the electrode is visible on the surface of the ground (right side), while the reel of the 50m cable connects the electrode to the logger (left).

2.2 Spring 2015 survey

The 2015 survey was done in spring in the region of La Broye. Over the 10 planed locations, only 6 were possible to survey. The other stations located in the south-west of the area have been cancelled, because of inappropriate location (e.g., too much human activity, sensitive area due to cultured land). The 6 locations are located in the western part of the study area, on the NW side of the seismic profile #14 (Figure 37). The first attempt was to make a magnetotelluric profile parallel to the seismic line #14, however, due crops and cultivated land, the only location left were the forested area. The survey of each station was only possible due to the support of the each municipality that allowed us to use the municipal forested area. We are thankful to each of the municipality and we were able to deploy the MT station in the following area:

- St-Aubin, Fribourg (Stations #1 & #2, Figure 38),
- Grandcour, VD (Station #3a 6 3b, Figure 39),
- Vernay, Fribourg (Station #4, Figure 40),
- Bussy, Fribourg (Station #6, Figure 41).

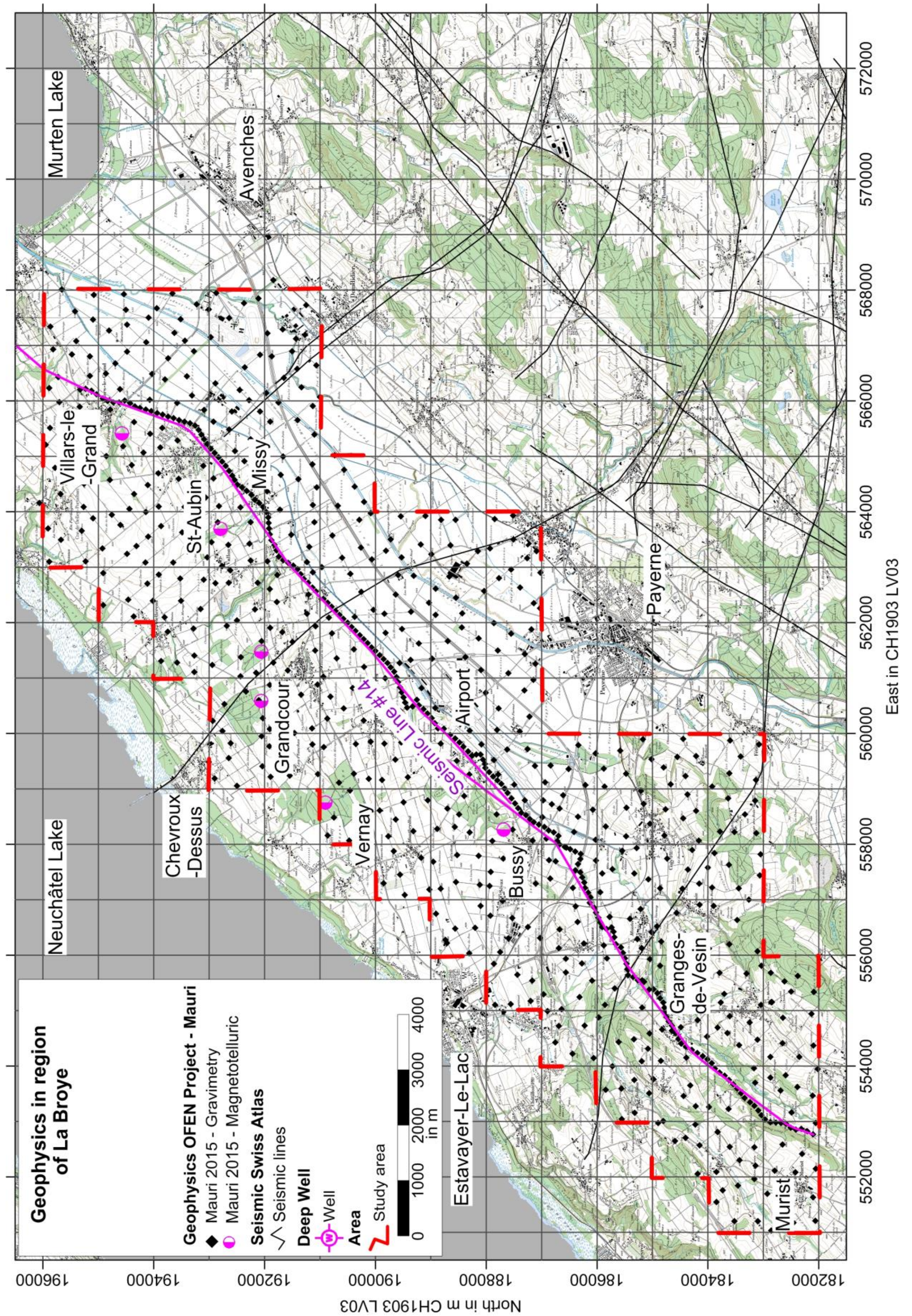
As there is no previous information on the conductivity value of each of the geological formation present at depth, the choice has been done to record a large panel of frequency by following a group of 8 different frequencies (Table 3).

The 32hz band has not been recorded for every station, because, it was thought to be more affected by the human activity noise, which include dead band of 50Hz and 15Hz.

Table 3 : Table presenting the range of frequency often used for magnetotellurics survey and the range of recording duration during the spring 2015 survey.

Frequency Hz	**Duration of sequence recording**
524288	1min – 20min
131072	2min – 30min
32768	8min – 40min
8192	32min – 1h10min
2048	1h – 1h40min
512	8h - 24h
32	14h - 24h
4	22h - 48h
4 with low passband	2h - 48h

Figure 37 : Region of La Broye. Pink circles indicates the location of magnetotelluric sites measured in 2015 and the location of gravity station surveyed in 2015 (black dots). Red dashed line represents the extent of the investigated area, which is of 100 km2. Black lines are seismic profiles (Sommaruga et al., 2012). The seismic line #14, from the Seismic Atlas, crosses the area from NE to SW (Sommaruga et al., 2012).



Geophysics in region of La Broye
Geophysics OFEN Project - Mauri
Mauri 2015 - Gravimetry
Mauri 2015 - Magnetotelluric
Seismic Swiss Atlas
Seismic lines
Deep Well
Well
Area
Study area
0 1000 2000 3000 4000 in m
Murten Lake
Neuchâtel Lake
Avenches
Villars-le -Grand
St-Aubin
Missy
Chevroux -Dessus
Grandcour
Airport
Seismic Line #14
Vernay
Bussy
Payerne
Estavayer-Le-Lac
Granges- de-Vesin
Murist
552000
554000
556000
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194000
196000
North in m CH1903 LV03

2.3 Spring 2015 MT data description

A total of 6 stations have been recorded over spring 2015 and at each station the total recording time range from 5 to 10 days.

STATION #1-#2: LES FRIQUES / ST-AUBIN, FR.

The station #1 is in the forest of the municipality of St-Aubin, about 200m away from housing area in Les Friques (Figure 38). Located in a topographic low, the southern part of the MT station, with its electrode is only a few meters away from a stream and a few meters above it.

The station #2 is in the forest of the municipality of St-Aubin, far away from any building, surrounded by crops (Figure 38). The station #2 is on the slope of a topographic depression. The stream at the bottom of the depression is about 60m away from the closest station electrode.

During the survey of both stations, several rain shower events happened, which resulted in the increase of noise.

Description of the recorded frequencies is presented on Table 4 for station #1 and on Table 5 for station #2.

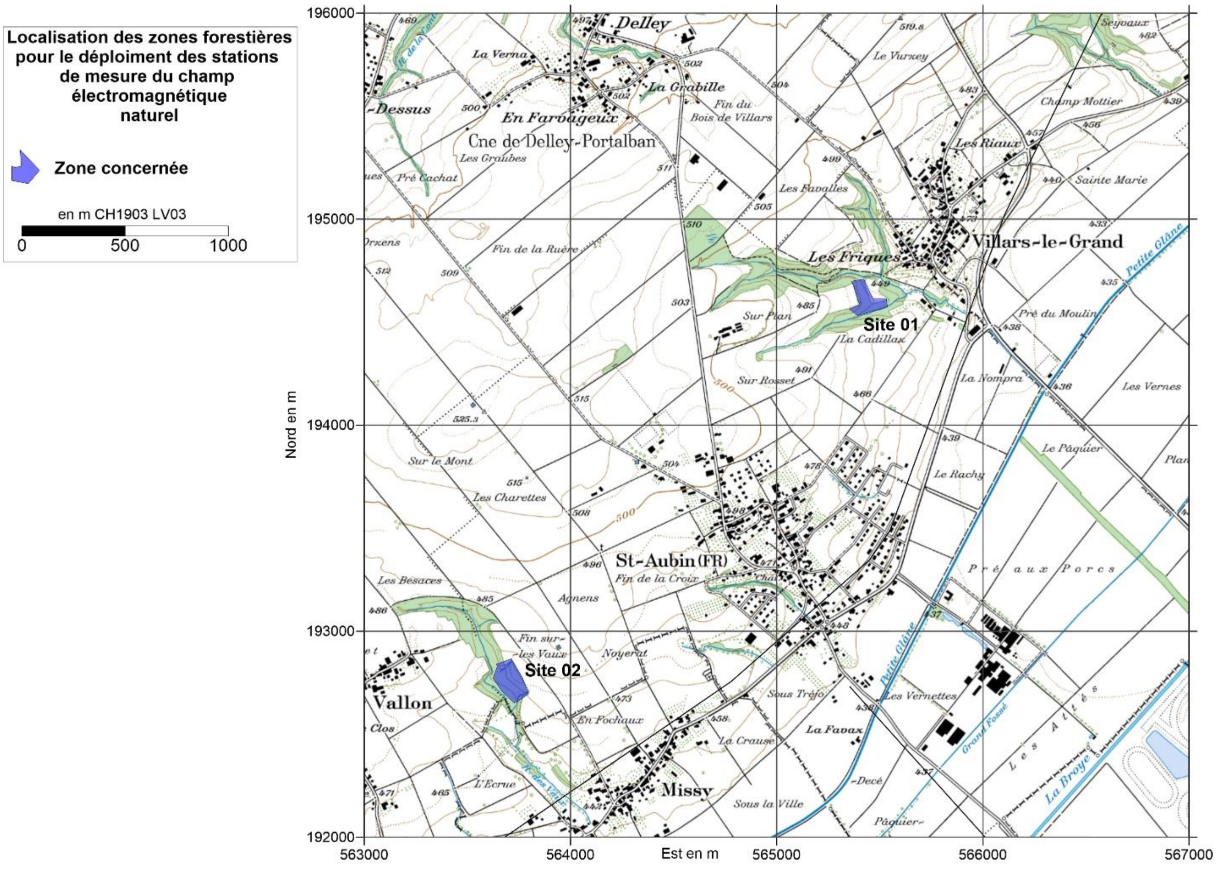

Figure 38 : Geographic location of the magnetotelluric station #1 and station #2 in the forest near Les Friques in the Municipality de St-Aubin, Fribourg.

Table 4 : Description of the magnetotelluric survey at station #1 in the forest near Les Friques in the Municipality de St-Aubin, Fribourg

Station	1	**Year**	**2015**
location	Les Friques / St-Aubin	Month	April
East CH1903 in m	565415	North CH1903 in m	194574
Elevation in m a.s.l.	461	Environment	Forest
Magnetic Component	X,Y,Z	Electrical component	X,Y
Frequency in Hz	Length of recording	unit	Low pass filter
524288	31	sec	-
131072	135	sec	-
32768	12	min	-
8192	16	min	-
2048	60	min	-
512	4	h	-
128	27	h	-
4	47	h	-
4	47	h	Yes

Table 5 : Description of the magnetotelluric survey at station #2 in the forest in the Municipality de St-Aubin, Fribourg.

Station	2	**Year**	**2015**
location	St-Aubin	Month	April
East CH1903 in m	563695	North CH1903 in m	192798
Elevation in m a.s.l.	472	Environment	Forest
Magnetic Component	X,Y,Z	Electrical component	X,Y
Frequency in Hz	Length of recording	unit	Low pass filter
524288	16	sec	-
131072	240	sec	-
32768	16	min	-
8192	32	min	-
2048	120	min	-
512	4	h	-
128	16	h	-

STATION #3A-#3B: GRANDCOUR, VD.

The station #3a is in the forest of the municipality of Grandcour, away from any building (Figure 39). The station is located on a relatively flat topography.

The station #3b is in the forest of the municipality of Grandcour, far away from any building, surrounded by crops, but only about 200-300m away from a power line (Figure 39). The topography surrounding the station is relatively flat.

Description of the recorded frequencies is presented on Table 6 for station #3a and on Table 7 for station #3b.

For station #3a, the frequency 512Hz was synchronized with the recording of the Vosges station.

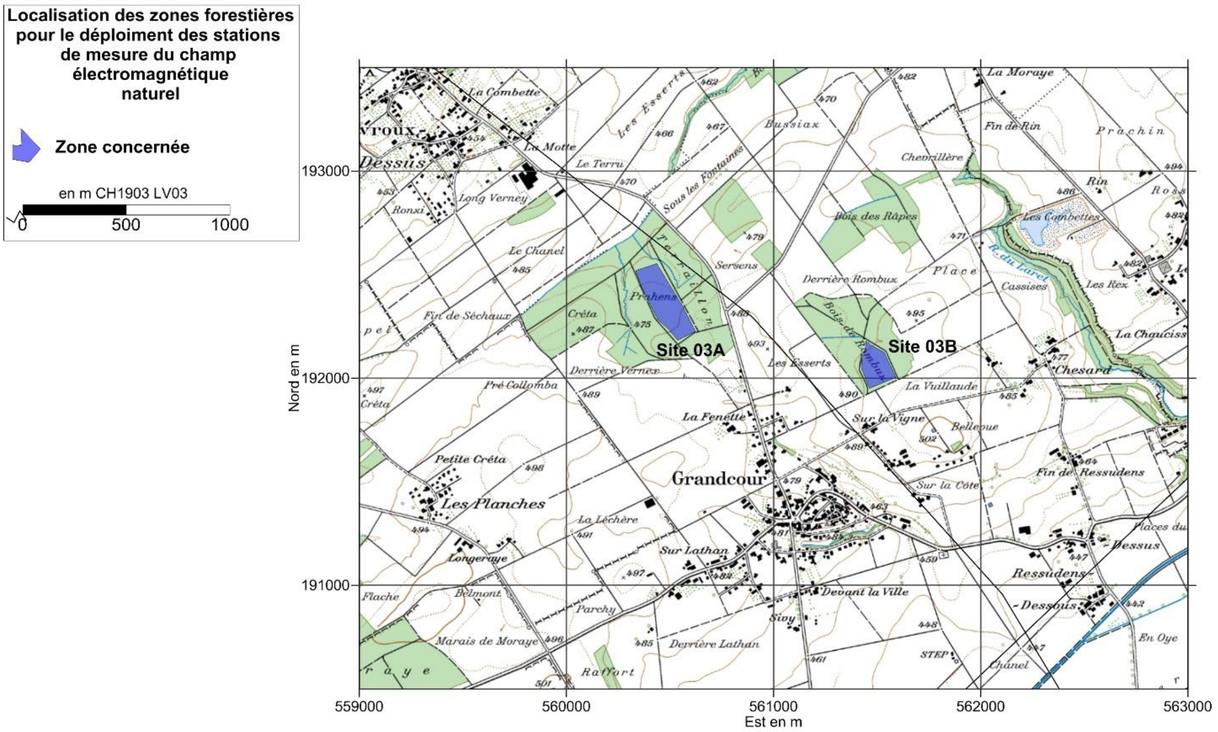

Figure 39 : Geographic location of the magnetotelluric station #3a and station #3b in the forest in the Municipality de Grandcour, VD.

Table 6 : Description of the magnetotelluric survey at station #3a in the forest in the Municipality de Grandcour, VD.

Station	**3a**	**Year**	**2015**
location	Grandcour	Month	May
East CH1903 in m	561477	North CH1903 in m	192061
Elevation in m a.s.l.	491	Environment	Forest
Magnetic Component	X,Y,Z	Electrical component	X,Y
Frequency in Hz	Length of recording	unit	Low pass filter
524288	45	sec	-
131072	596	sec	-
32768	100	min	-
8192	130	min	-
2048	368	min	-
512	46	h	-
4	23	h	-
4	23	h	Yes

Table 7 : Description of the magnetotelluric survey at station #3b in the forest in the Municipality de Grandcour, VD.

Station	**3b**	**Year**	**2015**
location	Grandcour	Month	May
East CH1903 in m	560586	North CH1903 in m	192061
Elevation in m a.s.l.	481	Environment	Forest
Magnetic Component	X,Y,Z	Electrical component	X,Y
Frequency in Hz	Length of recording	unit	Low pass filter
524288	47	sec	-
131072	362	sec	-
32768	66	min	-
8192	152	min	-
2048	411	min	-
512	28	h	-
128	18	h	-
32	23	h	-
4	23	h	-
4	5	h	Yes

STATION #4: VERNAY, FR.

The station #4 is in the forest of the municipality of Vernay, away from any building, (Figure 40). The station is located on a relatively flat topography.

Description of the recorded frequencies is presented on Table 8.

For station #4, the frequency 512Hz was synchronized with the recording of the Vosges station.

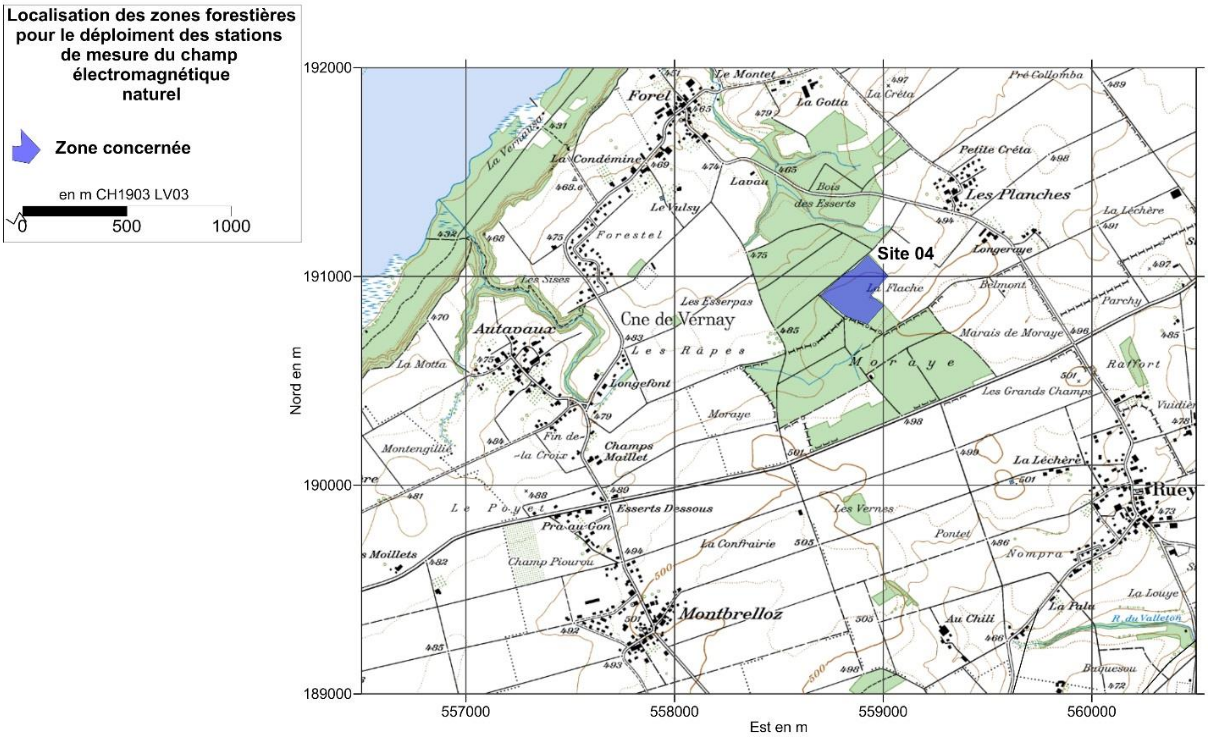

Figure 40 : Geographic location of the magnetotelluric station #4 in the forest in the Municipality de Vernay, Fribourg.

Table 8 : Description of the magnetotelluric survey at station #4 in the forest in the Municipality de Vernay, Fribourg.

Station	4	**Year**	2015
location	Vernay	Month	May
East CH1903 in m	558754	North CH1903 in m	190903
Elevation in m a.s.l.	490	Environment	Forest
Magnetic Component	X,Y,Z	Electrical component	X,Y
Frequency in Hz	Length of recording	unit	Low pass filter
524288	31	sec	-
131072	485	sec	-
32768	90	min	-
8192	180	min	-
2048	351	min	-
512	26	h	-
128	9	h	-
64	5	h	-
32	11	h	-
16	10	h	-
4	36	h	-
4	23	h	Yes

Station #6: Bussy, Fr.

The station #4 is in the forest of the municipality of Bussy, away from any building (Figure 41). The station is located on a topography low.

Description of the recorded frequencies is presented on Table 9.

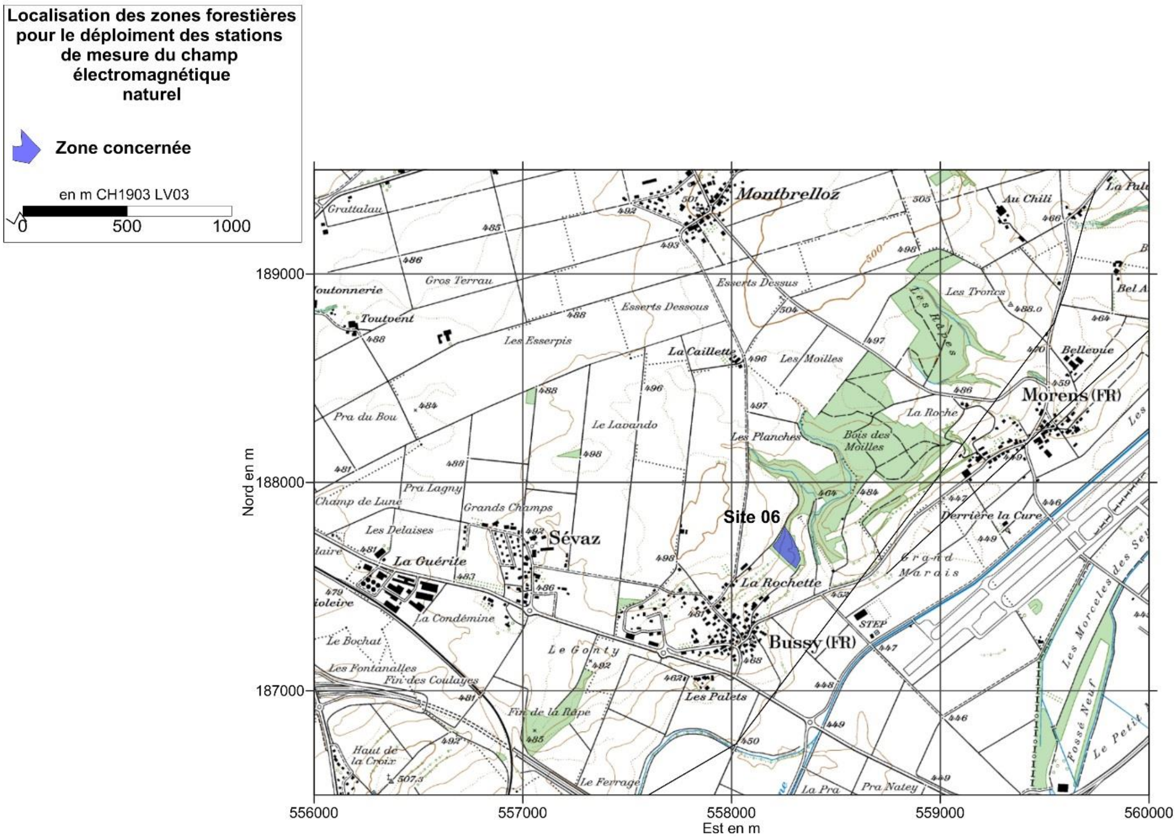

Figure 41 : Geographic location of the magnetotelluric station #6 in the forest in the Municipality de Bussy, Fribourg.

Table 9 : Description of the magnetotelluric survey at station #6 in the forest in the Municipality de Bussy, Fribourg.

Station	6	**Year**	**2015**
location	Bussy	Month	June
East CH1903 in m	558262	North CH1903 in m	187688
Elevation in m a.s.l.	471	Environment	Forest
Magnetic Component	X,Y,Z	Electrical component	X,Y
Frequency in Hz	Length of recording	unit	Low pass filter
524288	31	sec	-
131072	330	sec	-
32768	80	min	-
8192	140	min	-
2048	200	min	-
32	13	h	-
4	23	h	-
4	23	h	Yes

3. Magnetotelluric processing

3.1 Overview of the processing

The processing of the magnetotelluric data was done using ProcMT from Metronix (Ellinghaus, A. 1997).

Due to high quantity of data, processing all the data together for each station was not possible, therefor the processing was done by processing each recorded frequency separately.

Several attempts were done using the de-spike software include in procMT, however, the de-spiking of the rain events was unsuccessful.

Additionally, it was not possible to process the data from the remote station of the Vosges Mountain, because the data of the Vosges mountain need first to be recalibrated and procMT does not allow to do recalibration of the data.

Data are available and if needed, further work can be done on the magnetotelluric data.

3.2 Results of the processing

The processing results of each station will not be presented in this reports, because, the results for all station look very similar in term of noise effect on the different range of frequency. Additionally, as presented in the previous section Spring 2015 MT data description, the MT data collected in 2015 is a large data set. Therefore, the results for the station 3a will be used as example. The recording of station 3a is summarised on Table 6.

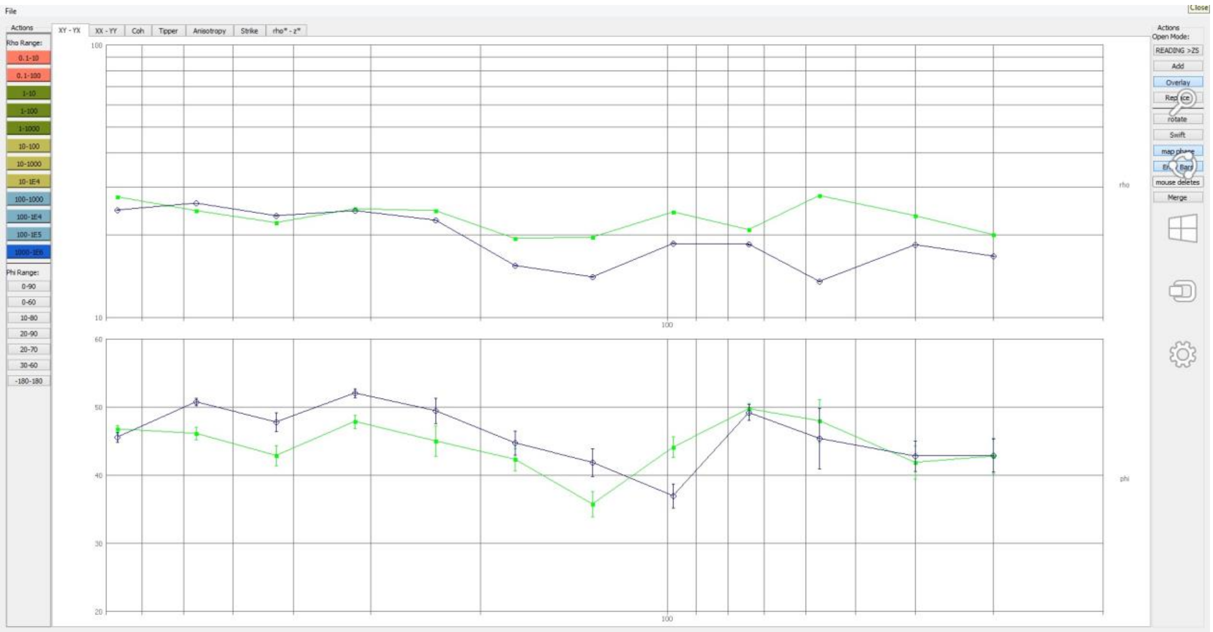

Figure 42 : Screen shot of the High frequency range (from 524288 to 2048 Hz) of the entire stack, which can be characterised for the station 3a during the 2015 spring survey. The blue line is XY component, while the green line is YX component. <u>Top:</u> Rho value, which represents the apparent resistivity (Ohm.m). <u>Bottom</u>: Phi value, which represents phase of the signal (degree).

From the high frequencies (above 2048 Hz) to the lower frequencies (4 Hz) recorded, a relatively large range of magnetic frequency can be inferred from the processed data sets (from Figure 42 to Figure 45). For each data set, the results of the processing are presented through the tensor element XY and YX (e.g., Figure 42). In order to avoid miss-interpretation, the choice has been made to present only the results of the processed data through the all stack data. Doing so, we avoid the increase of uncertainty by using only the mean value of each data set.

For the higher frequencies (from 524288 Hz to 2048 Hz; Figure 42), the inferred frequencies obtained by the recorded data set range from 170 Hz to 30 Hz. Over this range of inferred frequencies, the apparent resistivity values present variation comprised between 10 and 30 Ohm.m, and the associated phase variation present a relatively low level of noise. Less than 20 Ohm.m of apparent resistivity variation is very small and if we consider the uncertainty on the associated phase value (lower plot, Figure 42), we can consider that the resistivity variation is relatively homogeneous for this range of inferred frequency.

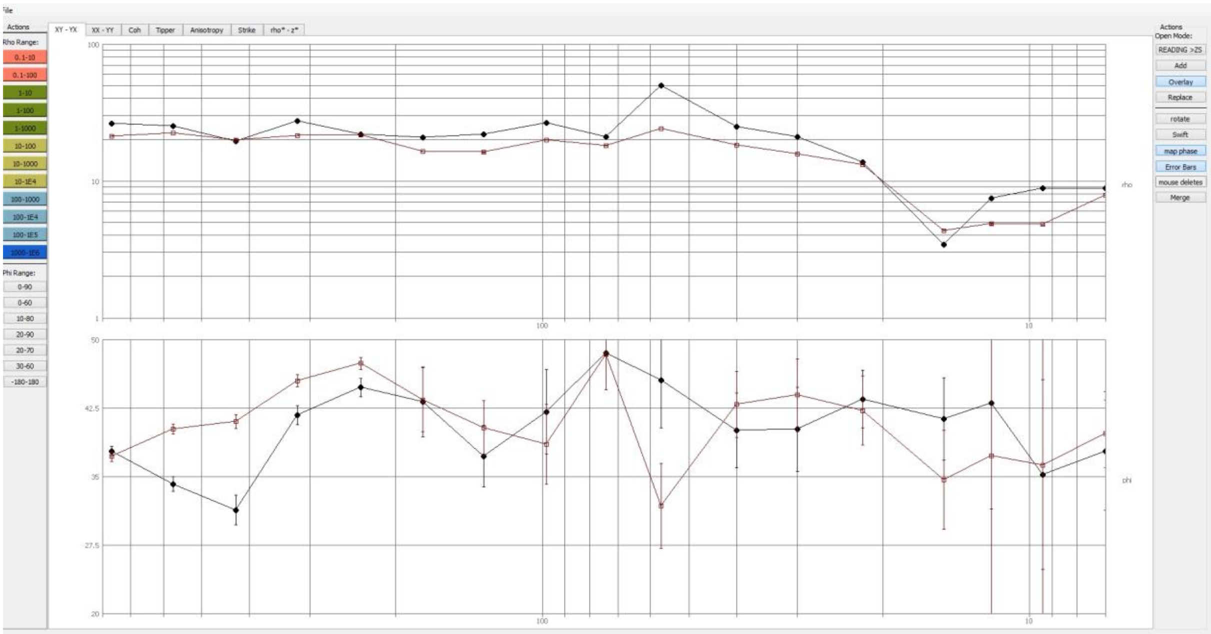

Figure 43 : Screen shot of the High frequency range (from 2048 to 512 Hz) of the entire stack, which can be characterised for the station 3a during the 2015 spring survey. The red line is XY component, while the black line is YX component. Top: Rho value, which represents the apparent resistivity (Ohm.m). Bottom: Phi value, which represents phase of the signal (degree).

For the frequencies ranging from 2048 Hz to 512 Hz (Figure 43), the inferred frequencies range from 170 Hz to 7 Hz. Over this range of inferred frequencies, the apparent resistivity values present variation comprised between 10 and 50 Ohm.m; however only one value is above 30 Ohm.m. Then, in comparison to the higher frequencies from 524288 Hz to 2048 Hz; (Figure 42), the 2048 Hz to 512 Hz range shows very similar variation.

The difference between the sets of frequencies become clearly visible when looking at the phase value variation of the inferred frequencies. Indeed from 2048 Hz to 512 Hz range shows a higher level uncertainty for the phase values (error bar on lower plot, Figure 43) than for the range from 524288 Hz to 2048 Hz. This increase of uncertainty shows that the recording sampling frequency of 2048 Hz and 512 Hz are more affected by ambient noise. This is especially true for the inferred frequency around 50 Hz and 7 to 20 Hz, which correspond to the common magnetic dead band in Europe. For the inferred frequency, between 7 to 20 Hz, the error bar is out of scale and therefore only very little to no confidence can be put on the apparent resistivity values obtained for the 7 to 20 Hz range.

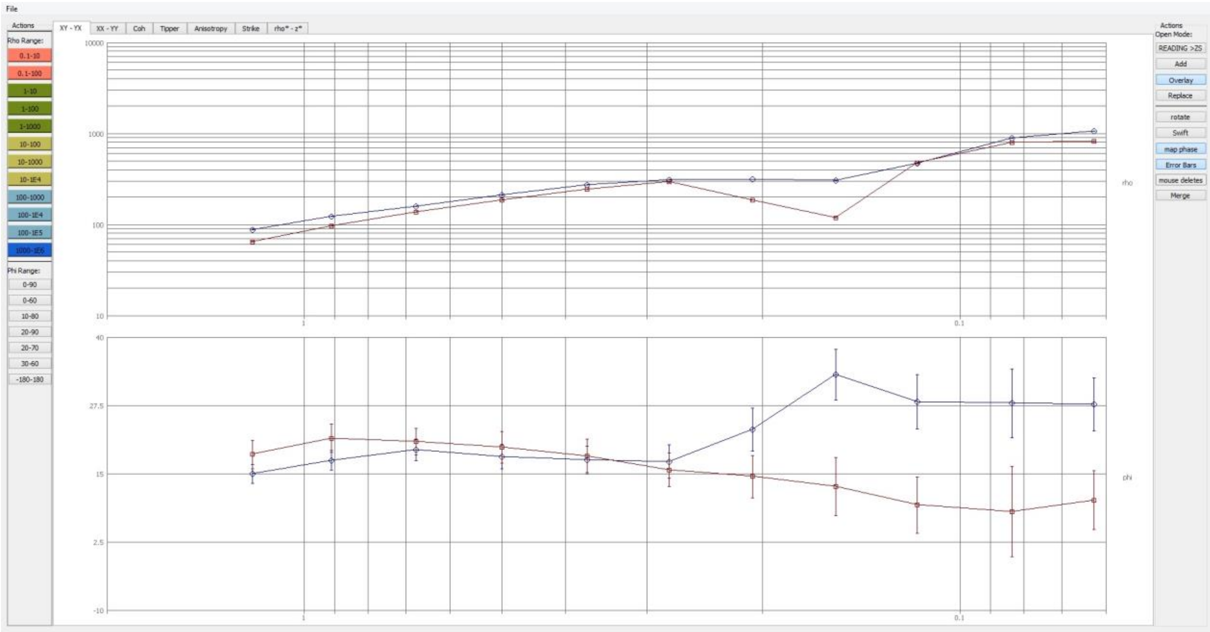

Figure 44 : Screen shot of the low frequency range (4Hz) of the entire stack, which can be characterised for the station 3a during the 2015 spring survey. The blue line is XY component, while the black line is YX component. Top: Rho value, which represents the apparent resistivity (Ohm.m). Bottom: Phi value, which represents phase of the signal (degree).

The lower recorded frequency is the 4 Hz, this choice of this frequency is motivated by the fact that 4 Hz is the lowest frequency, which can be recorded by the ADU logger. With the 4 Hz, there is two options: recording the data with or without an analogue low pass filter. The analogue low pass filter removes all frequency effects that are above 4 Hz and should then help to remove a significant amount of noise before recording the data. Then, both options have been used. Figure 44 presents the results when the analogue filter is turned off, while Figure 45 presents the results with the filter is turned on.

For the 4 Hz frequencies without filter (Figure 44), the inferred frequencies obtained by the recorded data set range from 1.5 Hz and 0.06 Hz. Over this range of inferred frequencies, the apparent resistivity values increase from ~6 Ohm.m to ~100 Ohm.m. This increase of almost two orders of magnitude of the apparent resistivity is correlated with the change in the phase value (bottom plot, Figure 44). However, with decrease of the inferred frequency, the uncertainty on the phase value increase significantly, making difficult to interpret the phase variation has been due to a change in the lithology at depth.

In order to obtain a better view of the significance of the low pass analogue filter on the recorded data, the choice has been made to overlap results from processed data with and without analogue filter (Figure 45). Results from the data set without analogue filter are in blue and red, while results with analogue filter are in black and green (Figure 45).

The comparison of the two data sets, for station 3a, shows that for inferred frequency between 1.5Hz and 0.3Hz, the results are the same for both data sets. The difference in both apparent resistivity and phase appears below 0.3Hz. Regarding the apparent resistivity (below 0.3Hz), both trend and amplitude is quite similar, but not the same. The difference is on the component YX, which decrease in apparent resistivity while the analogue filter is turn on. For the phase value, the difference is on the component YX. While the trend phase is similar, the amplitude change slightly for the component XY (red and green) and is more significant for the component YX. Additionally, the uncertainty is smaller for results while using the analogue filter during the recording of the data.

Therefore, the analogue filter helps to reduce the impact of the noise on the inferred frequency. Within the uncertainty of the inferred frequencies, it is reasonable to interpret that there is an increase of a little less than 2 order of magnitude in the apparent resistivity, while the phase show that there is a change in the lithology at depth.

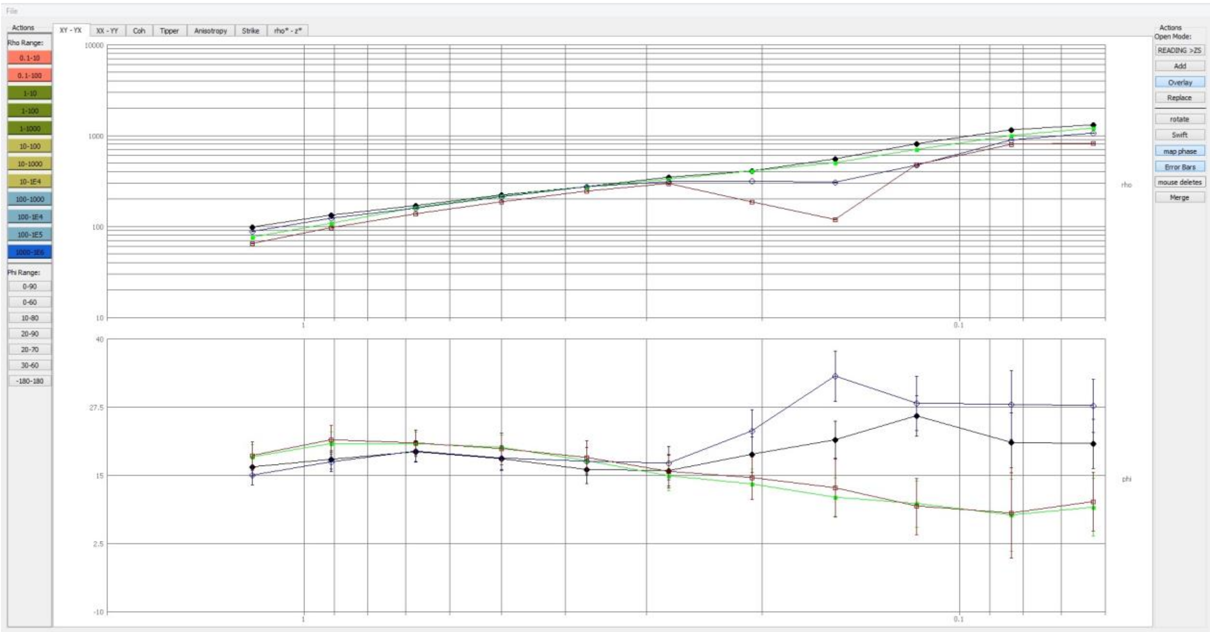

Figure 45 : Screen shot of the low frequency range (4Hz) of both the entire stacks with and without physical low pass filter, which can be characterised for the station 3a during the 2015 spring survey. For 4Hz without filter: The blue line is XY component, while the black line is YX component. For 4Hz with filter: The green line is XY component, while the red line is YX component. Top: Rho value, which represents the apparent resistivity (Ohm.m). Bottom: Phi value, which represents phase of the signal (degree).

Finally for the example of station 3a, all the data sets have been represented together on the same plot to obtain a view for the entire range of inferred frequency (Figure 46). Within the uncertainty of the results (errors bar, Figure 46), for the inferred frequencies from 170 Hz to 30 Hz, both apparent resistivity and associated phase values are more or less constant, with a low resistivity value of ~20Ohm.m. For the inferred frequencies from 1.5 Hz to 0.06Hz, the apparent resistivity increase of a little less than two orders of magnitude and the phase indicate a change in lithology at depth (below 0.2Hz).

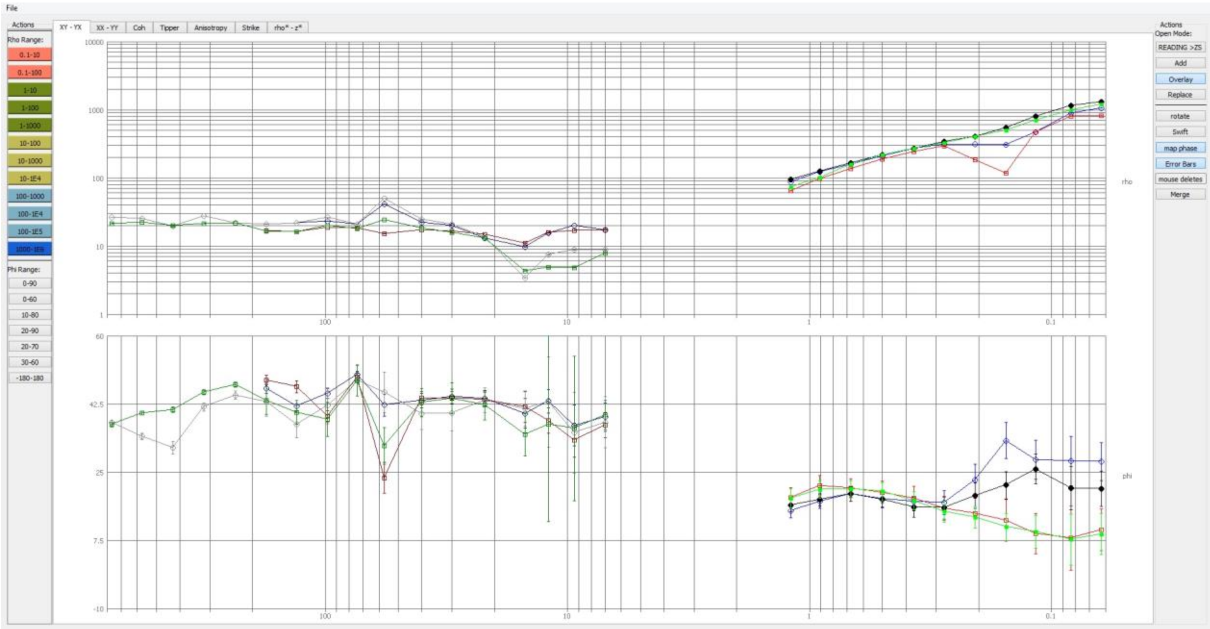

Figure 46 : Screen shot of the total range of frequency of the entire stacks, which can be characterised for the station 3a during the 2015 spring survey. The figure synthetize the results from Figure 42 to Figure 44.The blank between 1.5 Hz and 7 Hz is due to a gap in the data set. Top: Rho value, which represents the apparent resistivity (Ohm.m). Bottom: Phi value, which represents phase of the signal (degree).The low frequencies are on the right and the high frequency on the left.

3.3 Inversion of the magnetotelluric data

As presented in the previous section, the magnetotelluric data are affected by noise, which will likely have a significant impact on the 2D inversion. While no reliable model can for now be obtained due the noise on the data set, the choice has been made to present 3 examples of 2D inversion to exemplified the strong impact of the noise on the inversion (from Figure 47 to Figure 49).

Then the results from the 2D inversion presented here must not be used to determine what is happening at depth, but should rather been seen as study case on noise impact on 2D model.

Each inversion is done using ZondMT2D, which is well-known in the magnetotelluric community to be reliable, however the quality of the inversion is first determined by the quality of the data used.

The mesh of the model is each time made of 24 horizontal layers, the inversion is computed over 50 iterations and the error is based on the relative error computation and the inversion is based on the apparent resistivity values for both Hx and Hy components.

Other inversion models have been done on the inferred frequency based on the high frequency recorded data (recorded frequency above 2000Hz), however, the 2D inversion that such data set can only be useful to characterize the first 10m beneath the surface. Such depths are not appropriate for deep structure investigation.

Similarly, the 512Hz recorded show a higher level of noise in comparison to the 32Hz and 4Hz, which is mostly due to the 50Hz frequency that is known to be strongly affect by human activity, such as power line. Therefore, the 512Hz are not presented in the inversion.

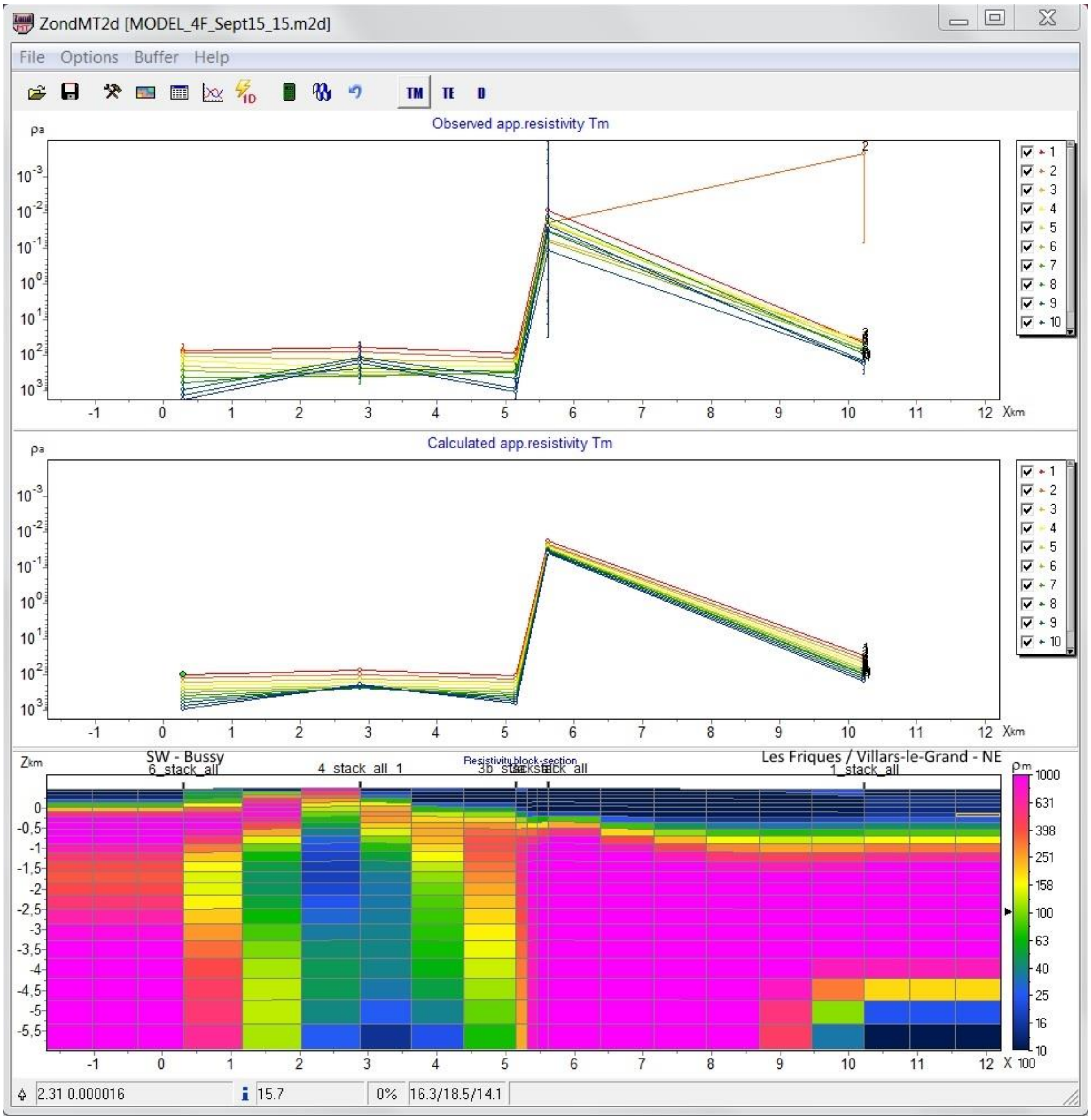

Figure 47 : Magnetotelluric inversion using ZondMT2D over the region of La Broye. Only the 4Hz recorded frequency is used. The right side is the NE corner of the profile with station 1 (Les Friques commune de St-Aubin (Fr), near Villars –le-Grand). The left side is the SW corner of the MT profile with the station 6 (Bussy).The MT data sets have not been rotated. Top: Observed apparent resistivity in Ohm.m. Middle: Model apparent resistivity in Ohm.m. Bottom: Model representing the result of the inversion. The colour scale is in Ohm.m.

First model using only the 4Hz recoded data

The first 2D inversion model used only the inferred frequencies from the 4Hz recording without analogue filter (Figure 47). The profile is made of stations: 1, 3a, 3b, 4 and 6. The result of the inversion allows us to highlight the existence of 3 conductive bodies:

- 1) The first conductive body is characterized by an apparent resistivity < 60 Ohm.m. The shallowest conductive body at the surface is about 500m thick in the SW and thicken to 1 km toward the NE.

- 2) A second conductive body (Apparent resistivity < 60 Ohm.m) is located in the NE (Near Villars-le-Grand), for which the upper limit is around 4 km below sea level.
- 3) A third conductive body is present at depth, in the SW part of the model (near Bussy), with its top near seal level. As the MT inversion can only constrain the upper limit of the conductive body, it is not possible to say at what depth this deep conductive body end.

In this first model, it seems very likely that the second conductive body is a pure artefact due to the very high uncertainty on the observed apparent resistivity, which is a strongly affect by the noise on the station 3b (Figure 47). Similarly, the third deep body, on the NE bottom corner of the model is poorly constrained. It is not realistic in term of geology to have such geometry in the region.

SECOND MODEL USING ONLY THE 4HZ RECODED DATA WITH ANALOGUE LOW PASS FILTER.

The second model used only the inferred frequencies from the 4Hz recording with the analogue low pass filter (Figure 48). As seen on the processed data with the example of station 3a, the low pass filter helps to remove some of the noise (Figure 45). Consequently, the reduction of the noise has a direct impact on the 2D MT inversion. The profile is made of stations: 1, 3a, 3b, 4 and 6. The result of the inversion allows us to remove one artefact and to highlight the existence of 2 conductive bodies:

- 1) The shallowest conductive body (Apparent resistivity < 60 Ohm.m) is at the surface. In comparison to the first model, the second model shows that this conductive body is now thicker with a thickness of 1 km. The top of this conductive body is in the SW part of the model at the surface and deepen a few hundred meters below station 4 (Figure 48). Then it goes back to the surface and in the NE corner, the conductive body become thinner (~500m). It is significant, to notice that the MT can only constraint properly the top of the conductive body, not the bottom of it. Therefore, it is possible that the conductive body is thicker than 1km in the SW and thicker than 500m in the NE part of the model.
- 2) The second conductive body is in the NE corner (Apparent resistivity < 60 Ohm.m) near Les Villars-le-Grand. As the MT inversion can only constrain the upper limit of the conductive body, it is not possible to say at what depth this deep conductive body end.

In comparison to model 01 (Figure 47), model 02 does show significant variation in the structure of the conductive bodies, however, it still doesn't seems to be a reliable model, because the uncertainty on the observed apparent resistivity is still relatively high (station 3b and 6, Figure 48).

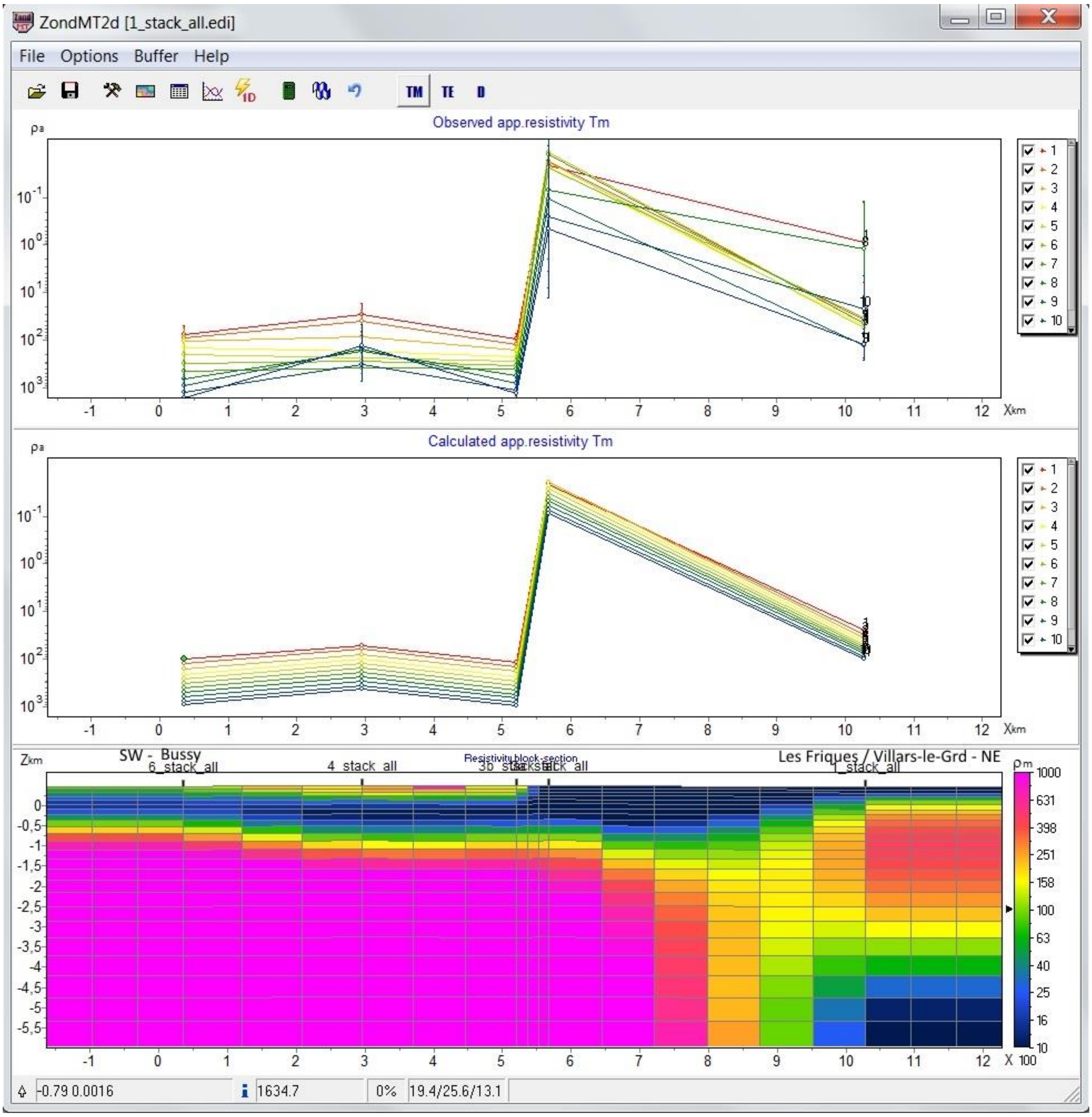

Figure 48 : Magnetotelluric inversion using ZondMT2D over the region of La Broye. Only the 4Hz recorded frequency with analogue low pass filter is used. The right side is the NE corner of the profile with station 1 (Les Friques commune de St-Aubin (Fr), near Villars –le-Grand). The left side is the SW corner of the MT profile with the station 6 (Bussy). The MT data sets have not been rotated. Top: Observed apparent resistivity in Ohm.m. Middle: Model apparent resistivity in Ohm.m. Bottom: Model representing the result of the inversion. The colour scale is in Ohm.m.

THIRD MODEL USING THE 4HZ RECODED DATA WITH ANALOGUE LOW PASS FILTER AND THE 32 HZ RECORDED DATA

The last model, model 063, used both inferred frequencies from the 4Hz recording with the analogue low pass filter (stations: 1, 3a, 3b, 4, 6) and the 32Hz (station 2, Figure 49). By adding station 4 with its inferred frequencies from the 32Hz recorded frequency data, model 03 become simpler.

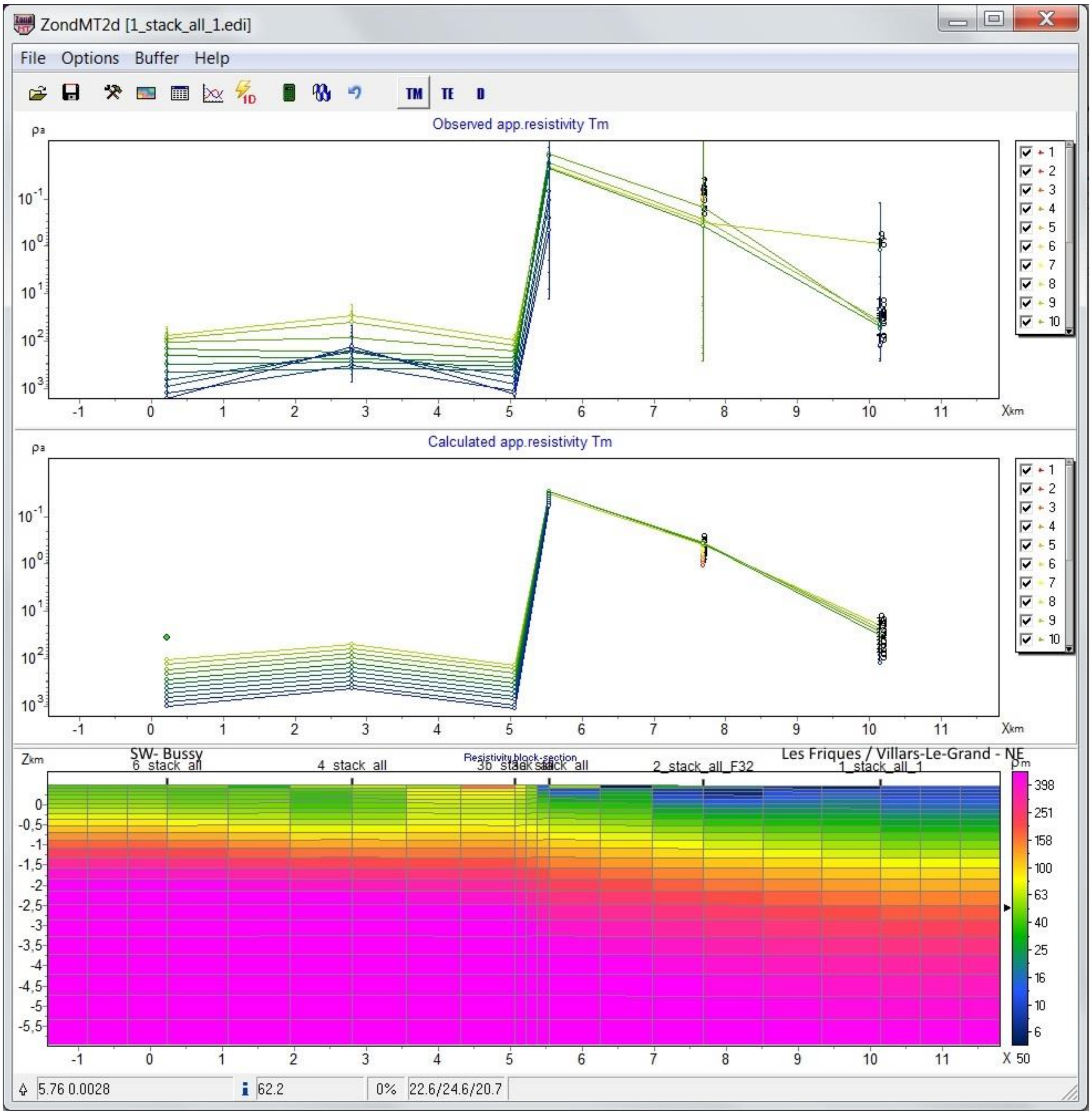

Figure 49 : Magnetotelluric inversion using ZondMT2D over the region of La Broye. Only the 4Hz recorded frequency with analogue low pass filter (Stations: 1, 3a, 3b, 4, 6) and the 32Hz (Station 2) are used. The right side is the NE corner of the profile with station 1 (Les Friques commune de St-Aubin (Fr), near Villars –le-Grand). The left side is the SW corner of the MT profile with the station 6 (Bussy). The MT data sets have not been rotated. Top: Observed apparent resistivity in Ohm.m. Middle: Model apparent resistivity in Ohm.m. Bottom: Model representing the result of the inversion. The colour scale is in Ohm.m.

Indeed, only the surface conductive body remains after the 2D data inversion. The conductive body is 1 km thick in the SW corner of the model and thicken toward the NE to reach about 1.5 km.

The deep conductive bodies have been completely removed from the 2D inversion; however, the observed apparent resistivity, at station 2, is too big for some of the inferred frequencies and makes it not possible to obtain a reliable model.

3.4 Attempt to assess the noise

The attempts of 2D inversion of the magnetotelluric data have shown that the noise is too strong to allow for obtaining reliable models.

The noise sources can be grouped into two groups:

- The natural noise sources include wind solar eruption, rainfall events, and thunderstorm.
- The human activity based noise include source of electromagnetic generation, such as power line, pipeline, buried structures, telecommunication tower, car/trucks passing by.

In the literature, numerous works present computing workflows to improve data set and reduce noise (e.g., Egbert, 1997; Fontes et al., 1988; Spichak & Popova, 2000; Oettinger et al., 2001; Wawrzyniak et al., 2013); however, surprisingly it is very difficult to obtain existing code. Noise reduction workflows are not straightforward and building a computing code is clearly outside the aim of the present study.

Since more than three decades, various research groups either work or worked on the noise issue on magnetotelluric data and no one has for now found a perfect way to deal with the noise (e.g., Egbert, 1997; Fontes et al., 1988; Spichak & Popova, 2000; Oettinger et al., 2001; Wawrzyniak et al., 2013).

It is not in the aim of the present project to build a new computing tool to resolve the noise issue on the measured magnetotelluric data in the region of La Broye, but rather to collect new data and see if such data could be processed or not, based on the level of noise.

The present work uses only ProcMT (Metronix) to process the data, however for future work the choice of the computing code to process the data should be different. Such decision is motivated by the results from the present study and follows a discussion with different persons in the magnetotelluric community. Indeed, it appears that the code of Egbert (Egbert, 1997) is more robust. Therefore, while it is too late to use it in the present work, future work should be testing the program of Egbert on MT data collected in Switzerland. Very recent work from Samrock et al. (2015, ETH-Zurich) on magnetotelluric data obtained interesting result on a study case in Ethiopia.

4. Conclusion on the magnetotelluric investigation

In spring 2015, a magnetotelluric campaign has been conducted in the region of La Broye to assess if modern magnetotelluric equipment could help to overcome the noise generate by the human activity.

2 MT stations (ADU #58, #59) from the University of Neuchâtel have been used for the survey, which include 6 sites of measurement across the NE part of region of La Broye.

The recorded data set for each site is consequent and include between 5 to 10 days of recording. While this large amount of data was impossible to process in one time, because the need in computational power was too high in comparison of what was available at the time of the study, the process of the data has been done by range of frequency. Doing so, it has been possible to qualitatively compare the noise effect on each range of frequencies.

Processing data by range of frequency has clearly showed that recording magnetotelluric data using the analogue low pass filter at the frequency of 4Hz was useful to reduce noise level on the recorded data.

Two tests of 512Hz survey (stations 3a and 4) have been conducted with the remote station located in the Vosges Mountain, which has been done in collaboration with the IPG Strasbourg. Unfortunately, the difference in calibration setting between the remote station and the stations in La Broye is for now an obstacle to process the MT data using the reference station.

The noise level on the data is significant near the known dead band frequency and adapted computational tools are required, which imply the necessity of developing new programming code that would allow for both filtering and combine different type of processing in order to reduce noise effect on the data set.

2D inverse modelling has been done in order to attempt to assess the impact on the noise on the inversion. Results of the inversion show clearly that the current data set, with the current noise level, cannot provide reliable model.

Future work on magnetotelluric data should focus on:

- 1) Developing appropriate computation tools to efficiently reduce and remove noise from recorded data in order to extract the magnetotelluric signal from the deep structure.
- 2) Developing a computing tool that allows the process between the Metronix magnetotelluric stations (used in the study) and the reference station in the Vosges Mountain.
- 3) Increasing the number of magnetotelluric stations along a profiles, likely 1 station by kilometres, in order to better constrain lateral variation in conductivity at depth.

Chapter III. **Conclusion on the investigation of the Region of La Broye**

The present study on the region of La Broye has brought new information on the gravity variation by collecting new data in winter 2015 and by reprocessing the data from previous studies. As presented this study, the new residual map clearly delineates three main gravity decreases (Figure 18):

1) A decrease of gravity that extends over the plain of La Broye
2) A decrease of gravity, which is over a part of the hills that separate the plain of La Broye and Neuchâtel Lake
3) A decrease of gravity located in the south-west corner of the studied area and extent toward the south.

The sensitivity studies based on 2D forward modelling of the interpreted seismic line #14 (such as presented in the Swiss Seismic Atlas) bring interesting insight on the potential source of the gravity anomalies, which are observed on the residual map. The results from such 2D sensitivity study can be of significant help before moving to complex and detailed 3D forward model, by bringing information on the complexity of the underground geology. However, the 2D sensitivity study, such as presented here, is only an intermediate step before the 3D forward model and cannot replace the advantage and accuracy of a 3D model. A copy of the 2015 gravity data will be transferred to Swisstopo, in order to be added to the federal data base of the Swiss Atlas of gravity.

Future works would likely benefit by adding the new residual gravity map to the 3D geological model, because of the accuracy and the high density of gravity stations by square kilometre over the region of La Broye. The new residual gravity map could also help to better constrain either the geometry of the shallow formation (i.e., quaternary sediment deposit, tertiary molasses formation) or the 3D effect of the faults in the region of La Broye, by bringing reliable information on the spatial gravity decrease.

With the magnetotelluric survey in spring 2015, the present study has collected a large data set for 6 stations. The noise on the recorded data is still for now a problem and does not allow for calculating reliable 2D inverse models. Nevertheless, the collected magnetotelluric data could be used as a baseline to develop and test news computational tools that could isolate and remove noise from the data.

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Appendix

1. Abstract for the 2015 Swiss Geosciences Meeting in Basel

13th Swiss Geoscience Meeting, Basel 2015

Gravity prospection in region of La Broye

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The aim of the study is to bring new insight on the gravity variations in the region of La Broye. Recent gravity work on the western molasse bassin suggested that the region of La Broye was possibly on the rim of a large Permo-carboniferous sediment structure, but more information is required to properly define it. (Altwegg, 2015).

In the winter and spring of 2015, 100 km^2 were surveyed using a CG-5 gravimeter in the La Broye region to increase the measurement spatial density of gravity variations. A total of 824 new gravity stations were surveyed, and which includes 70 locations also measured in previous studies. The data set surveyed in 2015 is organised as follows:
- one profile, 22-km long and 100m sampling step (220 stations), and following the seismic line #14 (Sommaruga et al., 2012).
- a spatial survey with 4 to 6 gravity stations by square kilometer (604 stations).

In addition, gravity data sets from the 1983-gravity atlas (Klingele & Olivier, 1980; Olivier, 1983), as well as data from two M.Sc. work of the University of Lausanne (Lapaire, 2000; Clavien, 2001) were used in addition to our own measurements. Previous studies reported 1031 stations, which were scattered over an area of 30 km by 31km.

To reduce uncertainty when merging data sets, and to reduce uncertainty on each gravity data set, all data sets from previous surveys were re-processed using the Corr-Topo software (Altwegg, 2015) and the 2m digital elevation model from Swisstopo (Swisstopo, 2010). A regional gravity trend was calculated from the Bouguer values from all gravity data through a bilinear regression. The calculated regional trend was then subtracted from the new Bouguer anomaly map to obtain a residual gravity map for the region of La Broye.

Additionally, in order to remove gravity variations due to the surrounding Lakes of Neuchâtel and Murten, the gravity effect of each lake was calculated using both high resolution bathymetry data from the work of Reusch et al. (2015) and bathymetry data from the 1:25000 map from Swisstopo (Swisstopo, 2005; Swisstopo & SITN, 2010).

Gravity effects of potential underground structures were computed and synthetised into a sensitivity study to assess any potential effect on measured gravity variation. The sensitivity study was performed using the GINGER software (Altwegg et al., 2015).

A sensitivity study was also performed using a 2D approach to assess the gravity effects of a) the geological formation of either Tertiary or Quaternary ages and b) the possibility of a hypothetical deep formation of Permo-carboniferous sediment beneath the profile following the seismic line #14. The study was done using GINGER software.
The 2D structure of geological formation is based on the geological interpretation of Seismic line #14, such as presented in the Seismic Atlas (Sommaruga et al., 2012).

Finally, based on the result from the 2D sensitivity study, the choice was made to calculate the gravity response of the 3D geological model of Swisstopo for the area. Density values of each formation used for the model are based on previous studies on rock density (Wagner et al., 1999; Altwegg et al., 2013) and gravity studies (CREGE, 2012; Altwegg, 2015). The results of this forward gravity modelling have been compared to the residual gravity map to assess the possibility of the extent of a local deep formation of Permo-carboniferous sediment.

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