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# GRAVIMETRY FOR GEOTHERMAL EXPLORATION

METHODOLOGY, COMPUTER PROGRAMS AND TWO CASE  
STUDIES IN THE SWISS MOLASSE BASIN

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Le Doyen, Prof. B. Colbois





To my beloved wife and children,  
Alexandrine, Elanor and Aurèle.



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# Abstract

**Keywords:** Geothermal exploration, gravimetry, fault zone porosity assessment, computer program, forward modeling, density inversion, Sankt Gallen geothermal project, Eclépens geothermal project.

In Switzerland and neighboring countries, most deep geothermal projects target deep aquifers associated with major fault zones. The objective of this thesis is to develop and test a methodology for the estimation and localization of such high porosity rock volumes in the underground using gravity data and 3D geological modeling.

To reach that aim, the computer program GInGER – GravImetry for Geothermal ExploRation - was developed. It allows to compute rapidly and efficiently the intensity of the gravity field in surface from 3D geological models. Then the user can compare the calculated response with measured gravity data and strip the effect of geological structures that are not relevant for the project. One of the main originality of GInGER is that it permits to directly assess the porosity of fault damage zones when providing their geometry. The software is also endowed with a graphical user interface and density inversion capabilities to be user friendly. In addition, for sensitivity analysis, an independent sister software named GInGERSP, based on the same principles allow to compute the gravity effects of simple geometrical shapes which can be superposed to a given geological model. This tool is particularly designed for rapid sensitivity analysis.

The two computer programs and the underlying methodology were tested on two ongoing geothermal projects in Switzerland, the projects of Sankt Gallen and Eclépens. Both projects are targeting deep aquifers associated with major faults zones affecting the Mesozoic sediments under the Swiss Molasse Basin.

In both case studies, a preliminary step was to conduct a sensitivity analysis to determine the prerequisites allowing the assessment of faults damage zone porosity. This was done in 2D for the case study of Sankt Gallen and it appeared that, if the geometry of the fault zone is constrained enough, if the damage zone of the fault represent a sufficient volume and the error on gravity measurement is kept as small as possible, typically under 0.1 mGal. It should be possible to assess the porosity induced by the damage zone of the fault using gravity data and that even if the induced porosity is rather small, under 1-2 % if the affected volume is big enough.

In Sankt Gallen, the 3D geological model was established using 3D seismic data. Comparing the gravity effect of this model with gravity data specifically acquired, we were able to make a first estimation of fracture porosity that compared well with later measurements obtained from drilling. However, the presence of a Permo-Carboniferous graben in the vicinity of the fault zone prevents us from removing all ambiguities on the result.

In Eclépens, the 3D geological model was established using only 2D seismic data and oil exploration wells. As no accurate geometry of the different fault zones exist, it was not possible to assess precisely the porosity of the damage zones. However, using gravity measurements, acquired during this study, and the two computer programs, GInGER and GInGERSP, it was possible to make a sensitivity analysis, compare the possible effects of the various fault zones porosity and highlight the most suitable targets. This demonstrates how a user could use these two tools for any case study. Note also, that this work also revealed that a major Permo-Carboniferous graben of regional extent likely crosses the northern part of the model. This could, to a certain extent, explain the high geothermal gradient found in the Eclépens-1 oil prospection well which is located in the central part of the targeted area of the geothermal project.

For these two case studies, the application of the proposed methodology and the combined use of 3D modelling, gravity data, GInGER, and GInGERSP allowed to bring new and useful information for the geothermal projects.

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## Chapter 1

# Introduction



## 1.1 Motivation

The growing concern about fossil fuel, nuclear energy and global warming means that the debate on energy supplies is part of our everyday life. Heat from the Earth is an almost inexhaustible source of energy used since ancient times for thermal applications. Today, geothermal energy is frequently part of a mixed solution to the energy problem.

Fundamentally a project aiming at the recovery of heat at depth should extract fluid from an underground reservoir in a manner that ensures its economic viability. In this respect, even if the nature of geothermal reservoirs is diverse, two main parameters are fundamental: the temperature, which is mainly related to depth and to the geothermal gradient, and transmissivity, which is related to porosity, permeability and thickness of the geological formation bearing the reservoir.

In recent years, most of the deep geothermal projects developed in Switzerland and neighboring regions targeted the exploitation of aquifers. More specifically, a majority of these projects targeted major fault zones affecting deep aquifers as faults can, locally, increase the open porosity and thus may enhance reservoir transmissivity. The detection and assessment of porosity at depth is a challenge for most geophysical methods. However, the local increase of porosity is correlated with a decrease of the rock bulk density and can therefore be measurable by gravity measurement.

The aim of this work is, thus, to investigate the possibility that fracture porosity can, to a certain extent, be inferred by gravity data in conjunction with accurate 3D geological models based on seismic data. In this respect, a methodology and a computer program were developed and tested on two ongoing geothermal projects in Switzerland: the projects of Sankt Gallen (SG) and Eclépens (VD).

## 1.2 Structure of the thesis

The structure of the thesis is briefly presented hereafter. **Chapter 2** describes the fundamentals of deep geothermal energy before presenting the general geological setting of the Swiss Molasse basin and the basics of the gravity exploration method. Concerning deep geothermal energy, the different geothermal systems and resources as well as their possible uses are presented on a worldwide scale before focusing on Switzerland. This focus is carried out by presenting the history of deep geothermal energy in Switzerland before explaining the present day situation. A state of the geothermal exploration is

also presented as well as the different regional studies showing the geothermal potential of Switzerland.

The geological formations of the Swiss Molasse Basin, where our two case studies are located, are given in the geological settings. The hydrogeology of these formations and the geothermal conditions within this basin are also presented.

Finally the bases of gravity exploration are described through the history of the method and its basic principles. A section is also dedicated to the density of the rocks present in the Swiss Molasse Basin as it is the driving factor of the gravity method.

**Chapter 3** first develops the different methods and tools created for this study. It starts with a description of the different techniques used for the treatment of the gravity data. The second section presents the basic principles used for the gravity modeling, as well as the first tool used for 2D forward modeling in the early stage of this thesis and its validation.

The main tool developed for this work is a computer program with a Graphical User Interface (GUI) named GInGER, GravImetry for Geothermal ExploRation. Its main feature is to calculate the gravity effect of the different elements of a 3D geological model and to allow inversion on densities. These different features are presented in section 3.4.

A tool allowing the forward modeling of gravity using simple geometrical shapes was also developed. This tool name GInGERSP (GInGER Synthetic Profile) can be used either in combination with GInGER or as a standalone tool. Its different features are presented in section 3.5.

**Chapter 4** describes how our methodology was applied for the geothermal project of Sankt Gallen. Indeed, this project offered a rare opportunity to test our methodology and tools on an ongoing project for which a detailed 3D geological model based on 3D seismic data were available. This study was conducted in two phases: first, a sensitivity analysis made on synthetic profiles (section 4.3) allowed us to confirm that our methodology was applicable. This sensitivity analysis also permitted us to obtain a first estimate of the extension of the gravity anomalies linked with the different geological structures and to better design our gravity survey.

The second part of this case study is related to the gravity survey that we conducted in the vicinity of Sankt Gallen. These data allowed us to apply the proposed methodology and tools resulting in the estimation of the dimensions

of the Permo-Carboniferous graben and in a first assessment of the fault zone porosity, which was the main target of this geothermal project.

**Chapter 5** presents the use of our methodology on the geothermal project of Eclépens (VD). This ongoing geothermal project, which is the second case study of this work, also targets a deep fault. The region of Eclépens was explored by the oil industry in the 1980's and its geology is therefore relatively well known. The main aim of this case study, beside the use of our methodology and tools, is to detect and to size a suspected Permo-Carboniferous graben and to give a first qualitative estimation of the porosity of the different fault zones. In this respect, we used the 3D geological model of the geothermal project to carry out a preliminary study (section 5.3) using existing gravity data in order to better size our gravity campaign. The details of the gravity survey as well as the results are presented in the sections 5.4 and 5.5 respectively. The validity of the results as well as their significance are then discussed in section 5.8 and 5.9.

The final conclusions are presented in **chapter 6** together with a general discussion on the significance of this work regarding geothermal exploration. In this chapter we also present which further works should be conducted to improve the methodology and the tools. The applicability on other topics is also explored in this chapter.

Some sections of this work are adapted from:

Altwegg, P., Renard, P., Schill, E., Radogna, P.-V., 2015. GInGER (GravImetry for Geothermal ExploRation): A New Tool for Geothermal Exploration Using Gravity and 3D Modelling Software, in: Proceedings World Geothermal Congress 2015. Proc. World Geothermal Congress 2015, Melbourne, Australia.

Altwegg, P., Schill, E., Abdelfettah, Y., Radogna, P.-V., Mauri, G., subm. to Geothermics. Towards fracture porosity assessment by gravity forward modelling for geothermal exploration (Sankt Gallen, Switzerland).

Altwegg, P., Schill, E., Radogna, P.-V., Abdelfettah, Y., Mauri, G., 2011. Geothermal project St. Gallen: Joint interpretation of 3D seismic and gravity data. Laboratoire de géothermie - CREGE, report for Sankt Galler Stadtwerke, Neuchâtel, Switzerland.



## Chapter 2

# Fundamentals



## 2.1 Deep geothermal energy

By definition, geothermal resources are present everywhere on earth as it represents the heat naturally stored underground. A geothermal reservoir is thus a volume of rock from which heat can be extracted for specific uses and a geothermal system is “*any regionally localized geological setting where naturally occurring portions of the Earth’s thermal energy are transported close enough to the Earth’s surface by circulating steam or hot water to be readily harnessed for use*” (Williams et al., 2011). A geothermal system is thus made of three main elements: a heat source, a reservoir and a fluid (Dickson and Fanelli, 2003). It implies that temperature and permeability are the two predominant physical parameters of the geothermal reservoir.

This leads to different classifications of the geothermal resources depending on the parameters considered. In general, they are classified according to their enthalpy level, which is a measurement of the energy of the system, and is determined by the temperature of their reservoir (Lee, 2001). Therefore a limit is fixed to distinguish the possible uses and the fluid that will be present in the geothermal installation, liquid-dominated for low enthalpy and vapor-dominated or liquid-dominated for high-enthalpy resources. Some authors also add a third class of medium enthalpy (table 2.1). The main reason for choosing temperature for the classification is that it controls the use that can be made with the energy and therefore if power production is possible and under which conditions.

Table 2.1: Classification of geothermal systems based on enthalpy of geothermal fluids (from Dickson and Fanelli, 2003). Temperatures are expressed in °C. [1] Muffler and Cataldi, 1978; [2] Hochstein, 1990; [3] Benderitter and Cormy, 1990; [4] Nicholson, 1993; [5] Axelsson and Gunnlaugsson, 2000.

| Reference | [1]    | [2]      | [3]       | [4]       | [5]   |       |
|-----------|--------|----------|-----------|-----------|-------|-------|
| Enthalpy  | Low    | < 90     | < 125     | < 100     | ≤ 150 | ≤ 190 |
|           | Medium | 90 – 150 | 125 – 225 | 100 – 200 | -     | -     |
|           | High   | > 150    | > 225     | > 200     | > 150 | > 190 |

The temperature of a geothermal resource is strongly related to the geological and tectonic context of the region and is dependent on the geothermal gradient, which expresses the increase of temperature with depth. The mean value of this gradient is 30 °C·km<sup>-1</sup> for the upper crust but is much higher in regions such as active volcanic areas.

Permeability is the second driving parameter characterizing geothermal reservoirs. Indeed, it controls the amount of geothermal fluid that can move through a given geothermal reservoir and thus has a major impact on the amount of heat that can be extracted. Geothermal reservoirs containing a natural aquifer are called hydrothermal reservoirs (hydrothermal or natural systems). Unlike temperature, reservoir permeability can be artificially enhanced by different means, like hydraulic and chemical stimulations. It is even possible to artificially create a reservoir from a very low permeability host rock. This enhancement of the original permeability leads to different geothermal systems called Enhanced (or Engineered) Geothermal Systems (EGS), which are defined by MIT (2006) as “*engineered reservoirs that have been created to extract economical amounts of heat from low permeability and/or porosity geothermal resources*”.

EGS projects differ from projects targeting hydrothermal systems in concept. Indeed, as expressed by Rybach (2010), the EGS principle is: “*in the deep subsurface where temperatures are high enough for power generation (150-200 °C), an extended fracture network is created and/or enlarged to act as new fluid pathways and act at the same time as a heat exchanger*”. Even if the principle is the same, other terms referring to the type of reservoir are used: Hot Dry Rock or petrothermal system when the formations does not contain sufficient fluid volume for heat extraction; Hot Wet Rock or Hot Fractured Rock (Breede et al., 2013; Moeck, 2014). Nevertheless, hydrothermal and petrothermal reservoirs are the two end-members that allow the classification of the geothermal reservoirs regarding permeability as presented in figure 2.1 and all the cases in-between are considered EGS.

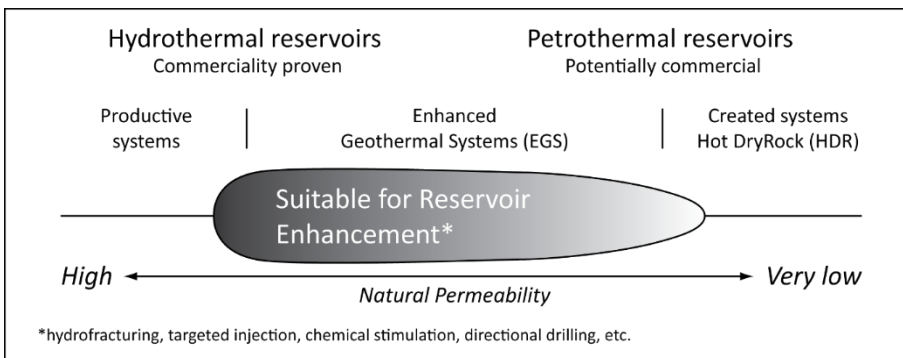


Figure 2.1: Illustration of the permeability range for different types of geothermal systems.

### 2.1.1 Power production

Presently more than 90 % of the world's geothermal power production comes from high enthalpy resources at high pressure located at shallow depth like in volcanic regions (Bertani, 2012). In such favorable conditions, power can be generated by using geothermal steam under pressure. However, these conditions are rare worldwide and thus other systems must also be used for power production. When geothermal fluid temperature is below 150 °C the most commonly used systems are binary Organic Rankine Cycle (ORC) units (DiPippo, 2004). The basic principle is to use a heat exchanger to transfer the heat of the geothermal fluid to a closed loop containing a working fluid. This fluid is typically composed of an organic fluid such as isobutene or isopentane, which will be vaporized at a lower temperature than water. This vapor will then pass through a turbine coupled with an alternator that generates power. The working fluid will then be cooled to begin a new cycle. Typical cooling devices are air or water coolers. A similar but more complex system is the Kalina cycle: the power units function on the same principle as ORC, except that the working fluid is a mixture of water and ammonia. With such systems (ORC and Kalina) power production is possible with temperatures as low as 75 °C (Erkan et al., 2008) but 110 °C is generally considered as the lowest temperature to ensure the economic viability. Binary cycle units are generally of smaller size and capacity (3-25 MW) compared to the power plants installed on high enthalpy resources with an average between 31-46 MW depending on the system used (Bertani, 2012).

### 2.1.2 Direct use

Power generation is not the only use that can be made of geothermal energy. This is especially true concerning low enthalpy resources (< 150 °C) for which the conversion efficiency for power generation is low, between 6.5 and 15 % with ORC plants for fluid temperature between 90 and 150 °C (DiPippo, 2004). This conversion rate depends on the mineralization of the geothermal fluid and on the use of the fluid. Indeed, the conversion rate will be higher if power production is the only purpose of the project than if the heat is also used i.e. for district heating. Therefore, lots of geothermal projects based on low enthalpy geothermal resources use the heat for different purposes such as thermal bathing, district heating, snow melting or various industrial processes as presented in figure 2.2. This can also be achieved after power production, as geothermal fluid is still hot at the heat exchanger.

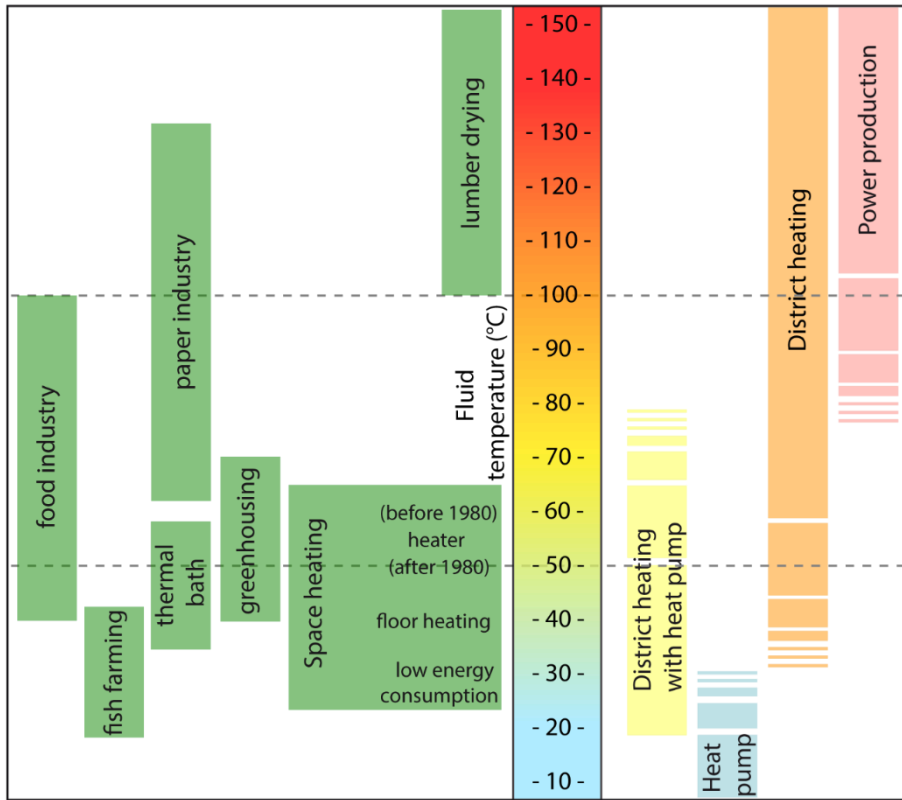


Figure 2.2: Uses of geothermal energy for low enthalpy resource at different temperatures (left) and temperature range of different uses (right).

### 2.1.3 Deep geothermal energy in Switzerland

In Switzerland three types of geothermal resources can be distinguished:

- Shallow depth low-enthalpy resources coupled with heat pumps.
- Resources in Alpine regions.
- Deep geothermal resources in the Swiss Molasse Basin.

The depth at which the distinction between shallow and deep geothermal resources is made in Switzerland may differ between authors but usually ranges between 300 and 500 m (e.g. Rybach and Signorelli, 2010; Vuataz and Fehr, 2000). However, as the resources targeted for the two case studies of the present work are much deeper, they are considered deep aquifers. These case studies being located in the Swiss Molasse Basin, the following geothermal resources and their associated installations will be presented:

- Deep aquifers: low to medium enthalpy hydrothermal reservoirs (figure 2.3, A heat only and C heat and power production)
- Enhanced Geothermal Systems (EGS): medium to high enthalpy petrothermal reservoirs (figure 2.3, B).

The principle of geothermal projects on deep aquifers is to pump the geothermal fluid naturally present in the permeable rock at depth and to use it for district heating and/or power production. With this aim, generally two boreholes are drilled: one to pump the geothermal fluid (production well) and another (injection well) to push it back into the formation (figure 2.3). This scheme is mainly carried out for two reasons: Firstly, it avoids the treatment of the brine. The Federal Office for Environment (FOEN) recommends a doublet system if the total mineralization of the geothermal fluid exceeds  $2 \text{ g}\cdot\text{l}^{-1}$  (FOEN, 1998). Secondly, pushing back the fluid into the aquifer allows keeping the hydraulic pressure within the aquifer unchanged and thus avoids an increase of pumping cost with time. The distance between the two boreholes at depth is calculated to exclude an important thermal breakthrough (cooling of the production well) during the economic lifetime of the installation.

### ***History of geothermal energy in Switzerland***

The modern use of geothermal energy for heat production in Switzerland began in the mid-1970s. According to Vuataz and Fehr (2000), before this period geothermal energy exploration and exploitation was limited to very few specialists and projects, and the main use was for spas. Major milestones of the geothermal development in Switzerland are summarized in table 2.2. During the 1970s the first oil crisis occurred leading the Swiss Federal Office of Energy (SFOE) to begin an incentive and promoting policy for renewable energy. Concerning geothermal energy this went mainly through the creation of the “Federal Commission for Geothermics and Underground Heat Storage” (KGS) in 1975. Its task was to clarify scientific, technical and economic aspects concerning geothermal energy and to promote and develop this knowledge (Vuataz and Fehr, 2000). The KGS was involved in various national and international projects and published many studies such as “Geothermische Datensynthese der Schweiz” (Rybach et al., 1981).

However, concerning deep geothermal energy, the interested communities and investors were not able to sustain the high costs and geological risks of deep boreholes. Therefore to help develop geothermal energy on deep aquifers the Swiss federal government decided to create insurance called

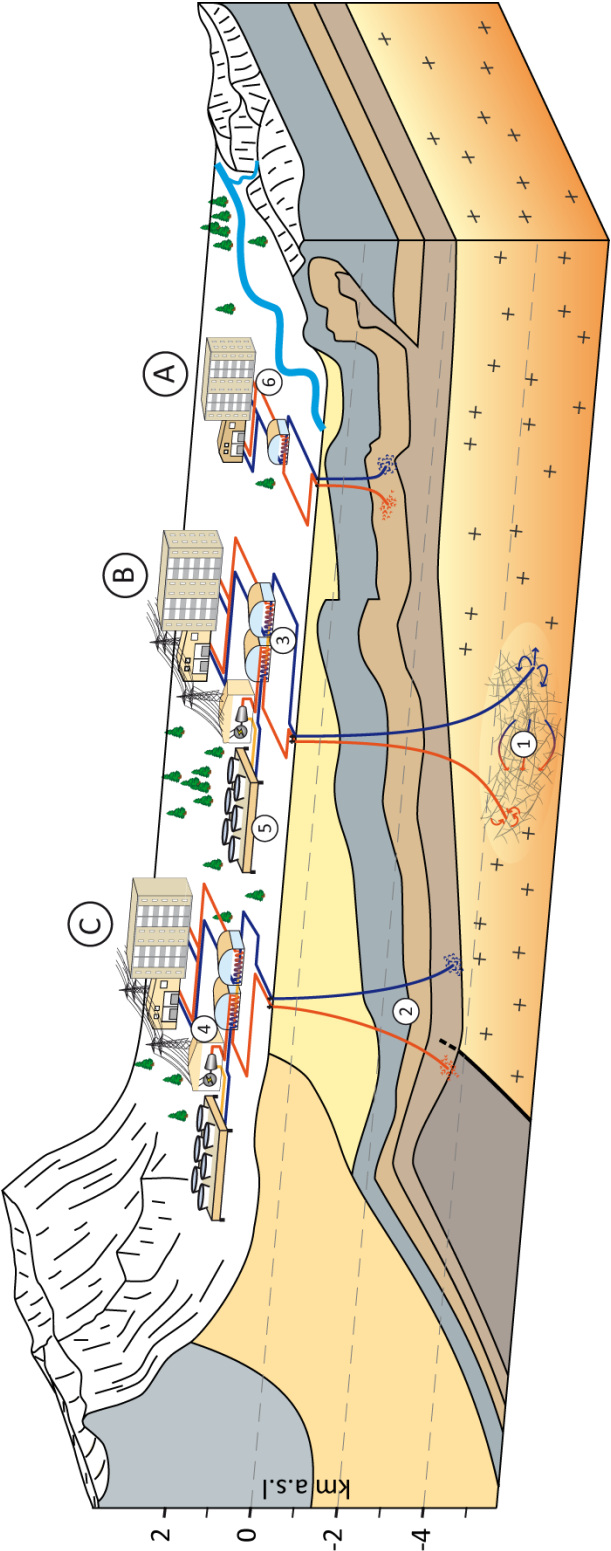


Figure 2.3 (previous page): Possibilities of deep geothermal energy exploitation on the Swiss Molasse Plateau. A. Deep aquifer exploitation for thermal use. B. Enhanced Geothermal system for heat and power production. C. Heat and power production from deep aquifer. 1. Enhanced Geothermal Reservoir; 2. Production and injection boreholes; 3. Heat exchangers; 4. Electricity production: ORC turbine and generator; 5. Air cooler; 6. District heating. The geological profile is modified after (Sommaruga et al., 2012).

“geological risk coverage” for a ten year duration starting in 1988 (Vuataz and Fehr, 2000). This risk insurance was available under the recommendation of the KGS and, in case of partial or total failure of the project (insufficient flow rate), up to 50 % of the drilling and testing costs were refunded. Moreover an incentive measure covering 25 % of these costs was also implemented later. The consequence was a first small boom in the exploration and exploitation of hydrothermal resources with the drilling of 14 deep boreholes (400 to 2600 m) from 1987 to the end of the risk coverage in 1998. From these boreholes, seven are commercially exploited but only four were considered as fully successful (figure 2.4). The first geothermal doublet system in Switzerland in Riehen was one of these. The extension of its district heating to Lörrach across the border with Germany even made this project the first transnational geothermal utilization.

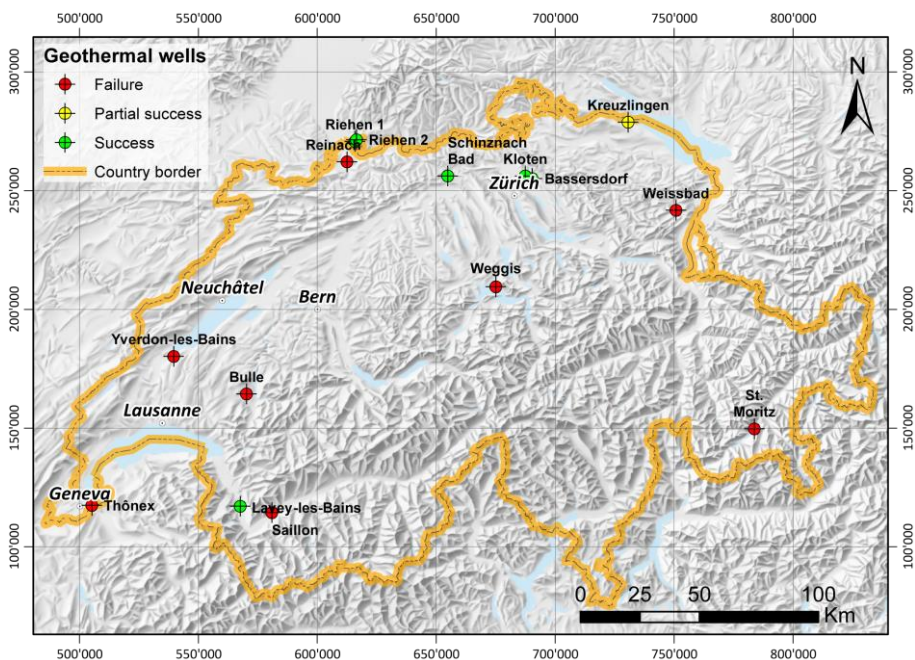


Figure 2.4: Results of the deep geothermal boreholes drilled from 1980 to 1998, as evaluated by the experts of the geological risk coverage. Swiss Coordinates are used, border and background relief courtesy of Swisstopo.

In the beginning of the 2000s the growing concern of global warming linked with the extensive use of fossil fuels led the SFOE to start a new 10-year promotional program called SwissEnergy. Its main objective was to decrease fossil fuel consumption, to reduce the growth of electricity demand and to increase electricity production from renewable sources. The basic strategy of the program was to employ voluntary measures to avoid new “command and control measures” or a CO<sub>2</sub> tax (Rybach and Gorhan, 2005). This, together with the end of the geological risk coverage, led to the situation where no deep drilling occurred in Switzerland for nearly ten years with the exception of the Deep Heat Mining (DHM) project of Basel. Nevertheless, from the 1970s to the start of the 2000s, Switzerland became one of the leaders for geothermal heat production, although most of it was produced by very low enthalpy resources and shallow geothermal installations, mainly borehole heat exchangers for family houses.

In 1996, the EGS Deep Heat Mining project started in Switzerland. Its objective was to artificially create a reservoir at 5 km depth for power generation and to supply heat to district heating. From a selection of ten sites, two were selected for pilot projects: Basel and Geneva. The DHM project of Basel was the first to start and led to the successful drilling of a 5000 m borehole in 2006. However during the stimulation of the reservoir, several seismic events, up to a magnitude of 3.4 frightened the local population and caused some damage to buildings. This led the project being halted. A seismic risk assessment was then commissioned and the project was definitely stopped in 2009. The DHM project of Geneva, which followed the same planning than the project of Basel with a postponement of 2 years, was also stopped due to this event.

*Table 2.2: Summary of major dates and events concerning deep geothermal energy in Switzerland until 2009.*

| Date        | Event                                                                                                                  |
|-------------|------------------------------------------------------------------------------------------------------------------------|
| 1975 – 1994 | Activity of the Federal Commission for Geothermics and Underground Heat Storage                                        |
| 1978        | Creation of the research group Geothermics and Radiometrics at ETH Zürich                                              |
| 1987        | Start of geological risk guarantee                                                                                     |
| 1990        | Foundation of the Swiss Society for Geothermics (presently Géothermie.ch)                                              |
| 1994        | First operational doublet for district heating at Riehen                                                               |
| 1996 – 2006 | Deep Heat Mining project in Basel; project stopped after induced seismic event during hydraulic stimulation in 2006    |
| 1998        | End of geological risk guarantee                                                                                       |
| 1999        | Extension of district heating of Riehen to Lörrach (Germany)                                                           |
| 2001        | Initiation of SwissEnergy program                                                                                      |
| 2004        | Creation of the CREGE association (Centre de Recherche en Géothermie, Neuchâtel)                                       |
| 2009        | Start of the chair on geothermics, creation of a Master in hydrogeology and geothermics at the University of Neuchâtel |

### ***Present situation of deep geothermal energy in Switzerland***

The context for deep geothermal projects has changed since 2008, as an electricity gap was expected in the following 5 to 10 years (Wyss and Rybach, 2010). Thus a feed-in tariff for renewable energy and a new risk guarantee were introduced. This guarantee of geological risk will refund a maximum of 50 % of the drilling and testing costs if the objectives are not fulfilled. However, only projects with at least 1.5 % electricity production may apply. This measure combined with the regional geothermal potential studies that were available has created an incentive context for the realization of deep geothermal projects, hydrothermal and petrothermal, targeting combined power and heat production (table 2.3).

This context was reinforced on May 25<sup>th</sup> 2011, when the Swiss Federal Assembly decided to get stepwise back out of nuclear energy and to enhance power production by renewable energy (Link et al., 2013). To that purpose, the SFOE established a set of measures called “Swiss Energy Strategy 2050”. In this strategy, due to its important potential, geothermal power production is expected to supply 4400 GWh until 2050. In order to achieve this ambitious goal the main following measures are planned (Link et al., 2013):

- Increase of the risk guarantee to 60 %, covering other costs such as exploration and increasing of risk guarantee funds.
- Maintenance of the feed-in tariff.
- Create funds for applied research.
- Make available to the public an information system about the deep underground.
- Intensify public relations.

This new energy law is planned to come into effect in January 2015 but a major legal flaw remains. This concerns the deep geothermal concessions for exploitation and for exploration, which have no specific legal framework. Separately, several cantons have recently started to modify their mining laws and to include geothermal resources in them.

Table 2.3: Recent deep geothermal projects in Switzerland targeting power production (modified after Link et al., 2013). The two case studies of this work are highlighted in gray; [a] EGS projects; [b] Drilling stopped due to an induced seismic event that occurred on June 20<sup>th</sup> 2014. This seismic event is likely to be linked with actions taken after the detection of a natural gas flow in the borehole (Király et al., 2014).

| Project                                           | Project developers                                                                | Phase                                                 |
|---------------------------------------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------|
| Lavey-les-Bains (VD)                              | Several municipalities and electric utilities                                     | Drilling in preparation                               |
| Arbon, Romanshorn, Amriswil (TG)                  | Electric power company of canton Thurgau EKT, Axpo Power AG                       | Preliminary studies, presently halted                 |
| Avenches (VD) <sup>[a]</sup>                      | Geo-Energie Suisse AG                                                             | Planning phase, public relations                      |
| Haute-Sorne (JU) <sup>[a]</sup>                   | Geo-Energie Suisse AG                                                             | Planning phase, detailed project, public relations    |
| Eclépens(VD)                                      | BKW / Sol-E Suisse AG and others                                                  | Planning phase                                        |
| Etwilen (TG) <sup>[a]</sup>                       | Geo-Energie Suisse AG                                                             | Planning phase, public relations                      |
| Sankt Gallen (SG)                                 | Sankt Galler Stadtwerke                                                           | Drilling ended, project halted <sup>[b]</sup>         |
| Herisau-Gossau (SG)                               | Axpo Power AG, Sankt Galler Stadtwerke, St. Gallisch-Appenzellische Kraftwerke AG | Preliminary studies, feasibility study in preparation |
| Several sites north of Luzern (LU) <sup>[a]</sup> | Geo-Energie Suisse AG                                                             | Planning phase, public relations                      |

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***Geothermal exploration and potential studies***

The deep underground of Switzerland is not well known as there is almost no exploitation of deep natural resources like oil or mineral ore. The main information comes from oil exploration that occurred from the 1960s to the 1990s with the drilling of deep boreholes and numerous seismic surveys in the Swiss Molasse Basin (see section 2.2 for detail). However these data are mostly proprietary and are not readily available, as every canton has its own legislation. The recent publication of the Seismic Atlas of the Swiss Molasse Basin (Sommaruga et al., 2012) by the Swiss Commission of Geophysics (SGPK) improved this situation by interpreting hundreds of these seismic lines and by making 14 transects and horizon depth maps available to the public and to the geothermal projects.

It is also important to mention that the “National Cooperative for the Disposal of Radioactive Waste” (NAGRA) ran an intensive exploration in the north of Switzerland to find a suitable site for nuclear waste disposal. As NAGRA is a public institution lots of these data are available, even published.

As mentioned, during the very early 2000s no deep geothermal boreholes were drilled with the exception of the DHM Basel project. However interest was still present and during this period several studies assessing the regional geothermal potential were carried out using, essentially, existing data. A selection of these studies is presented in table 2.4. Since 2009, four deep geothermal boreholes have been drilled in Triemli (ZH, 2009), Schlattingen (TG, 2011 and 2013) and in Sankt Gallen (SG, 2013).

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*Table 2.4 (next pages): Selection of geothermal potential studies carried out in Switzerland.*

| Year | Name                                                                          | Regional extension            | Resources type  | Commissioned by        | Reference                   |
|------|-------------------------------------------------------------------------------|-------------------------------|-----------------|------------------------|-----------------------------|
| 1986 | Recherche d'un site favorable, Gisement géothermique du Littoral Neuchâtelois | Lake of Neuchâtel's coastline | HS, DA          | SFOE                   | (Matthey, 1986)             |
| 1992 | Geothermal potential of the Swiss Molasse basin                               | SMB                           | LT, HS, DA, EGS | SFOE, KGS              | (Rybach, 1992)              |
| 1993 | Programme Géothermoval                                                        | Canton of Valais              | HS              | Canton of Valais, SFOE | (Vuataz et al., 1993)       |
| 2003 | Evaluation du potentiel géothermique du canton de Vaud - PGV                  | Canton of Vaud                | LT, HS, DA, EGS | Canton of Vaud, SFOE   | (Groupeement PGV, 2003)     |
| 2005 | Evaluation du potentiel géothermique du canton de Fribourg – PGF              | Canton of Fribourg            | LT, HS, DA, EGS | Canton of Fribourg     | (Groupeement PGF, 2005)     |
| 2006 | Geothermischer Ressourcenatlas der Nordschweiz                                | North – East SMB              | DA, EGS         | SFOE, SGPK             | (Signorelli and Kohl, 2006) |
| 2007 | Geothermische Energie im Kanton Zürich                                        | Canton of Zürich              | LT, DA, EGS     | Canton of Zürich       | (Geowatt AG, 2007)          |

HS: hot springs; DA: deep aquifers; LT: low temperature shallow depth systems; EGS: Enhanced geothermal systems. SMB: Swiss Molasse Basin. CREGE: Centre de Recherche en Géothermie, Neuchâtel.

| Year | Name                                                                    | Regional extension                 | Resources type <sup>[a]</sup> | Commissioned by                    | Reference                           |
|------|-------------------------------------------------------------------------|------------------------------------|-------------------------------|------------------------------------|-------------------------------------|
| 2007 | Atlas des ressources géothermiques de la Suisse occidentale             | South – West SMB                   | DA, EGS                       | SFOE, SGPK                         | (Baujard et al., 2007)              |
| 2008 | Evaluation du potentiel géothermique du canton de Neuchâtel – PGN       | Canton of Neuchâtel                | LT, HS, DA                    | CREGE                              | (Groupe de travail PGN, 2008)       |
| 2009 | Geothermie–Potenzialstudie Thurgau-Schaffhausen                         | Canton of Thurgau and Schaffhausen | LT, DA, EGS                   | Canton of Thurgau and Schaffhausen | (Dr. Roland Wyss GmbH et al., 2009) |
| 2010 | Grundlagenstudie Tiefengeothermie, Espace Bern                          | Canton of Bern                     | HS, DA, EGS                   | Energie Wasser Bern                | (Geothermie Espace Bern, 2010)      |
| 2010 | Programme cantonal de développement de la géothermie à Neuchâtel – PDGN | Canton of Neuchâtel                | LT, HS, DA                    | Canton of Neuchâtel                | (Groupe de travail PDGN, 2010)      |
| 2011 | Evaluation du potentiel géothermique du canton de Genève - PGG          | Canton of Geneva                   | LT, HS, DA, EGS               | Canton of Geneva                   | (Groupe de travail PGG, 2011)       |

HS: hot springs; DA: deep aquifers; LT: low temperature shallow depth systems; EGS: Enhanced geothermal systems. SMB: Swiss Molasse Basin. CREGE: Centre de Recherche en Géothermie, Neuchâtel.

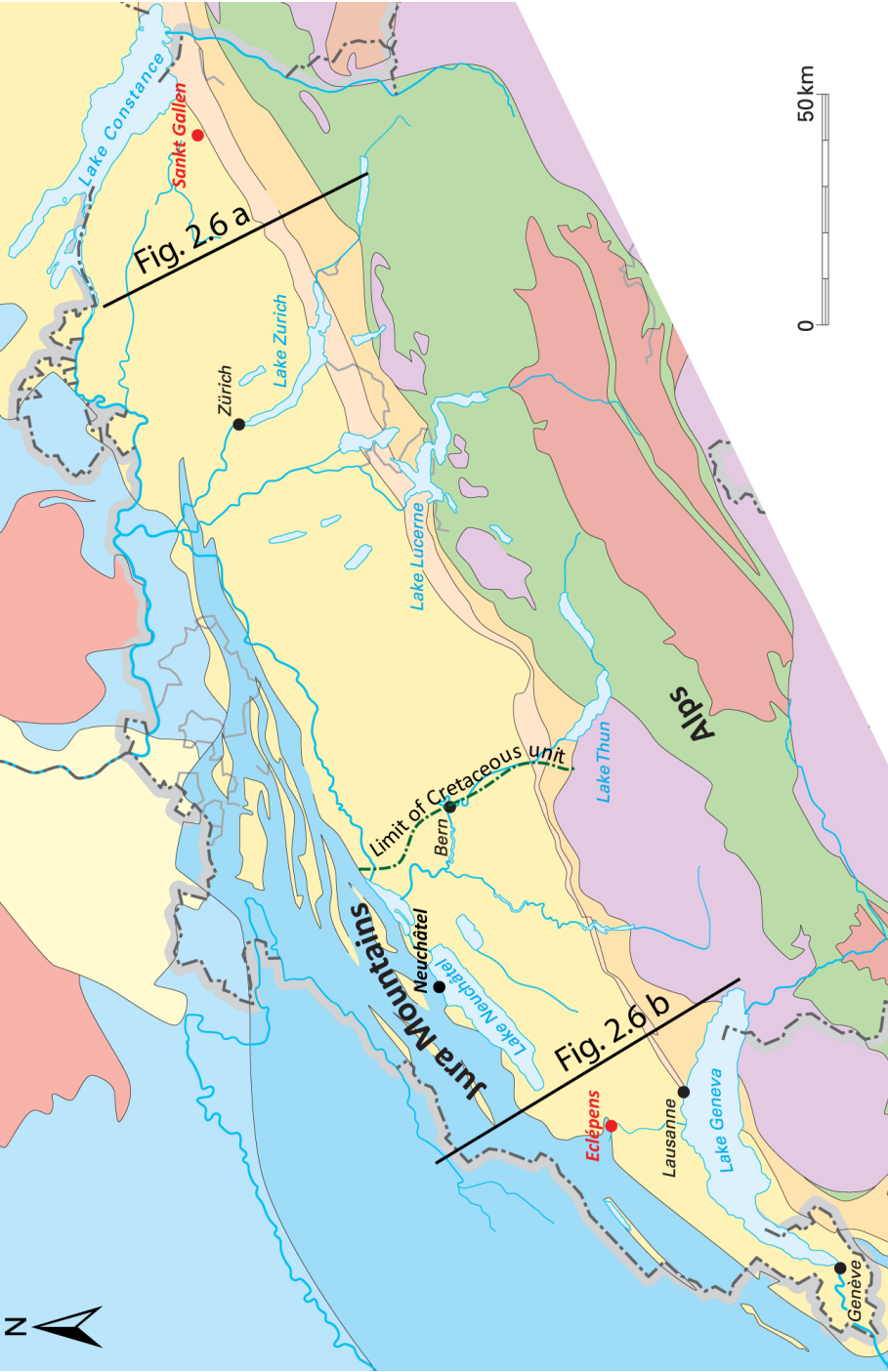
## 2.2 Geological setting<sup>1</sup>

Our two case studies, Sankt Gallen and Eclépens, are located in the Swiss Molasse Basin (SMB), which extends from the Jura to the Prealps and from Geneva to Lake Constance (figure 2.5). The Swiss Molasse Basin is part of the North Alpine Foreland Basin that runs parallel to the Alpine chain and extends from the region of Savoy (France) in the West to Linz (Austria) in the East (Kuhlemann and Kempf, 2002). Actually, the Western part is a wedge-top basin and the Eastern part a flexural basin. Four major formations occur at depth (e.g. Kempf and Pfiffner, 2004; Kuhlemann and Kempf, 2002; Mazurek et al., 2006): the crystalline basement s.l. (including the Permo-carboniferous often in troughs), its sedimentary cover composed of Mesozoic, Tertiary and Quaternary sediments. These units, whose present day settings are closely linked to the different evolutionary stages of the basin, are briefly described in the following pages from bottom to top and can be viewed in figure 2.6, with the exception of Quaternary deposits.

The crystalline basement originates from the Variscan orogeny and was during and prior to it affected by intensive metamorphism and by hydrothermal alteration (Mazurek et al., 2006). Top basement dips gently from the Vosges and Black Forest Massifs where it outcrops towards the Alps. In the final stage of the Variscan orogeny, during Permo-Carboniferous time, the region was affected by a strike-slip dominated extensional regime which resulted in the formation of 5-20 km wide graben systems filled with fluvial clastic and lacustrine sediments, as well as partly with coal (e.g. Marchant et al., 2005; Mazurek et al., 2006). The thickness of these deposits is highly variable but can reach several hundreds of meters in the troughs (<1500 m, McCann, 2008).

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<sup>1</sup> This section is modified after (Altwegg et al., subm. to Geothermics)



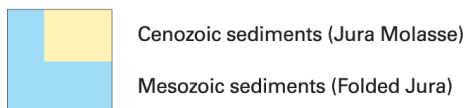
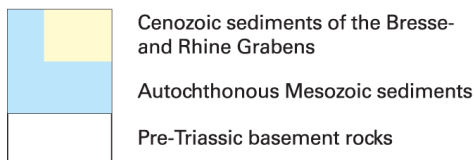
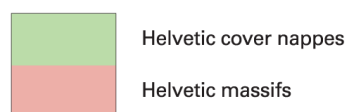
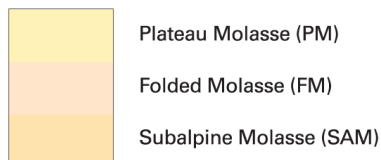
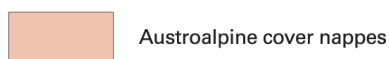
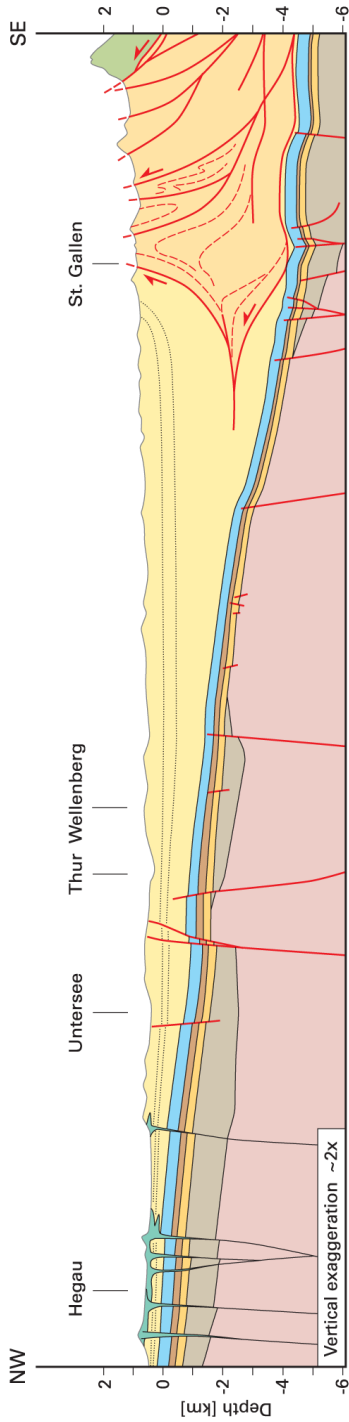
**North-Alpine foreland****Helvetic nappe system****Molasse basin****Penninic nappe system****Austroalpine nappe system**

Figure 2.5: (previous page): Main tectonic units of the Swiss Molasse Basin and surrounding areas (after Sommaruga et al., 2012). Red dots represent the geothermal projects of Eclépens and Sankt Gallen. Legend here above.

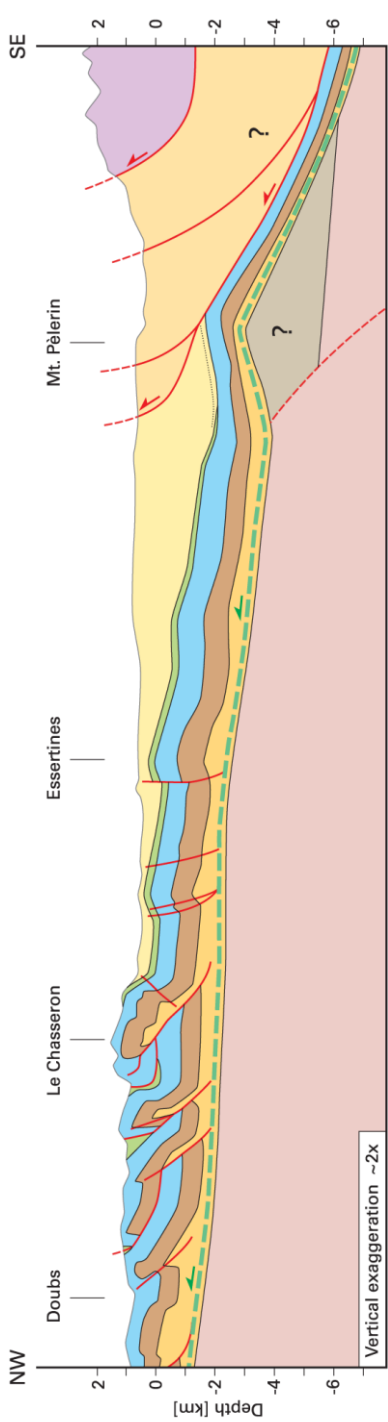
In Northern Switzerland, these graben structures are generally SW-NE to WSW-ENE oriented, e.g. the North-Swiss trough (Diebold and Noack, 1997). This graben is relatively well defined even in its geometry by 2D seismics (NAGRA, 2008; Sommaruga et al., 2012) others are comparably difficult to identify, since seismic evidence is provided by a few internal reflectors only (Marchant et al., 2005). The most complete compilation of these structures in northern Switzerland is given in a technical report of Nagra (NAGRA, 2008). More regional interpretations are also available in McCann (2008) and Ustazewski (2004). However, the definition of the trough is slightly different in the two interpretations. In figure 2.7 (NAGRA), the troughs are identified at places where Carboniferous sediments were found in wells. In the other studies a trough is only considered when the estimated thickness of the Permo-Carboniferous sediments is greater than 250 m (Ustazewski, 2004).

In the vicinity of Sankt Gallen and Eclépens only uncertain localization of Permo-Carboniferous graben structures are indicated from 2D seismic (Sommaruga et al., 2012). Due to difficult identification, the crystalline basement and the Permo-Carboniferous grabens are often regrouped under the name “basement s.l.”.

a) North eastern cross section



b) South western cross section



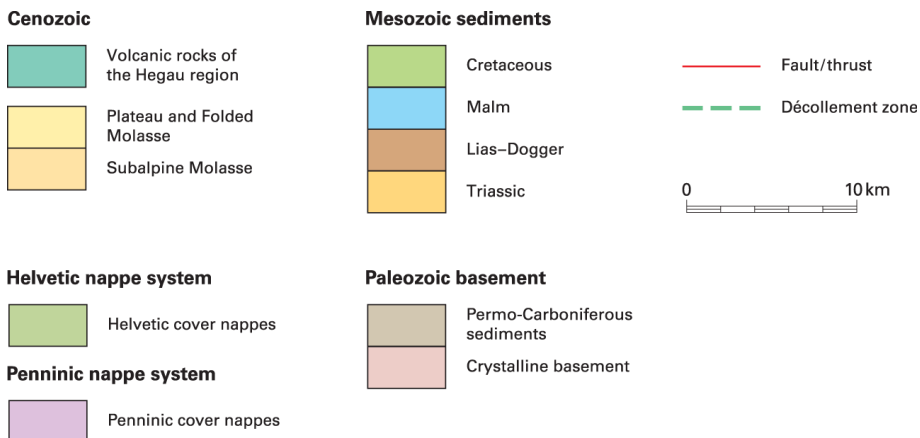


Figure 2.6 (previous page): a) Cross-section of the northeastern Swiss Molasse Basin. b) Cross-section of the south-western basin. Profile location see figure 2.5 (Sommaruga et al., 2012).

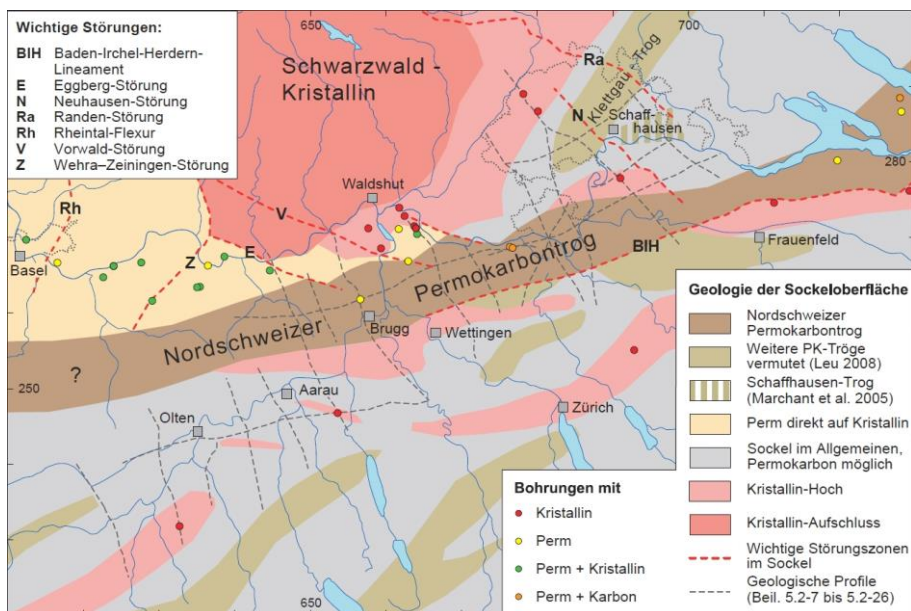


Figure 2.7: Late Paleozoic troughs and highs in the southernmost Upper Rhine Graben and adjacent areas (NAGRA, 2008).

Concerning the geometry of the trough, based on the North-Swiss Graben, they seem to be highly asymmetrical with borders of different geometry as illustrated in figure 2.8. Moreover, the thickness of the deposits varies considerably from nothing or a few meters on the trough's shoulder to several kilometers at the thickest part. The faults linked with these structures are likely of variable geometry and importance but can be of high interest for geothermal exploration as they can allow fluids convection. Sommaruga et al. (2012) mention that in the western SMB the Permo-Carboniferous grabens seem to be a rather narrow sized flat ramp with steep borders.

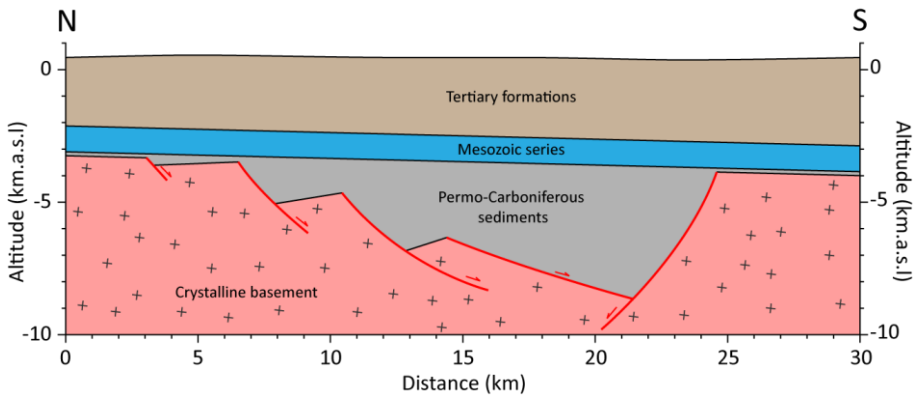


Figure 2.8: Schematic illustration of a Permo-Carboniferous graben in the Swiss Molasse Basin. Red lines represent faults.

On top of the crystalline basement s.l., continental sandstones of the Buntsandstein formation underlay the Triassic marine sediments of the Muschelkalk formation (Chevalier et al., 2010). During this period mainly dolomite, clays, marls, sandstone and limestone were deposited in an epi-continental sea (NAGRA, 2008). Evaporites were also deposited during Triassic; however this concerns mainly the area north of the Lausanne-Zürich-Munich line and therefore will be treated in more detail for the case study of Eclépens. The collision of the European and the Adriatic plate caused the bending and bulging of the European plate and this led to the exhumation of the Mesozoic and Cretaceous formations.

Thus, part of these sediments was exposed to weathering and karstification especially in the eastern part of the basin (Mazurek et al., 2006; Pfiffner, 2010). This together with differences in deposition thickness leads to a diminution factor of four regarding the thickness of the Mesozoic layers from Lake Geneva to Lake Constance (Sommaruga et al., 2012). It furthermore caused the erosion of most of the Cretaceous deposits (figure 2.5) and part of the Malm formations.

During the Tertiary, the Swiss Molasse Basin was filled during two cycles with detrital sediments resulting from the erosion of the Alps and shallow marine deposits during sea ingression. These sediments are mainly composed of turbiditic series, sandstone, sandy marls and conglomerates and divided into four successive depositional groups (Berger et al., 2005a, 2005b; Burkhard, 1990; Homewood et al., 1986; Kempf et al., 1999; Kempf and Pfiffner, 2004; Kuhlemann and Kempf, 2002; Mazurek et al., 2006; Pfiffner, 1986a). In ascending stratigraphic order these are: Lower Marine Molasse (UMM); Lower Freshwater Molasse (USM); Upper Marine Molasse (OMM); Upper Freshwater Molasse (OSM). In terms of structural units, three types can be distinguished: the well bedded, erected, and the anticline of the sub-Alpine molasses (Berger et al., 2005a, 2005b; Burkhard, 1990).

In the Swiss Molasse Basin, Quaternary deposits are linked with glaciers and hydrology. In the region of our two case studies their extension is typically relatively small and local. They will therefore be presented in detail for each of the case studies.

### 2.2.1 Hydrogeology

Hydrogeological properties of the different geological layers of the SMB have been studied for different reasons: nuclear waste disposal by NAGRA (e.g. NAGRA, 2008), CO<sub>2</sub> storage (Chevalier et al., 2010). Their potential for geothermal exploitation (table 2.4) has been evaluated by Baujard et al. (2007), Signorelli and Kohl (2006), and Rybach (1992). They also have been studied on a more local scale for the geothermal potential studies (table 2.4): Bern, Fribourg, Geneva, Neuchâtel, Thurgau, Vaud, and Zürich. Table 2.5 presents the different potential aquifer formations of the SMB together with the commonly admitted name of the aquifer (e.g. Chevalier et al., 2010), which is used in this work. These formations are presented in table 2.5 and figure 2.9 from the youngest to the oldest.

*Table 2.5: Potential aquifer formations of the SMB from the youngest to the oldest. The commonly admitted aquifer's name is given for further use in the text.*

| Geological formation                                                     | Aquifer's name       |
|--------------------------------------------------------------------------|----------------------|
| Sandstone of the OMM (Early Miocene)                                     | OMM                  |
| Limestones and dolomites of the lower Cretaceous                         | Cretaceous           |
| Limestones of the Upper Malm                                             | Malm                 |
| Limestones of the Dogger                                                 | Dogger               |
| Limestones and dolomites of the Upper Muschelkalk                        | Muschekalk           |
| Sandstone of the Buntsandstein                                           | Bunsandstein         |
| Altered and/or fractured Ante-Triassic crystalline rocks of the basement | Crystalline basement |

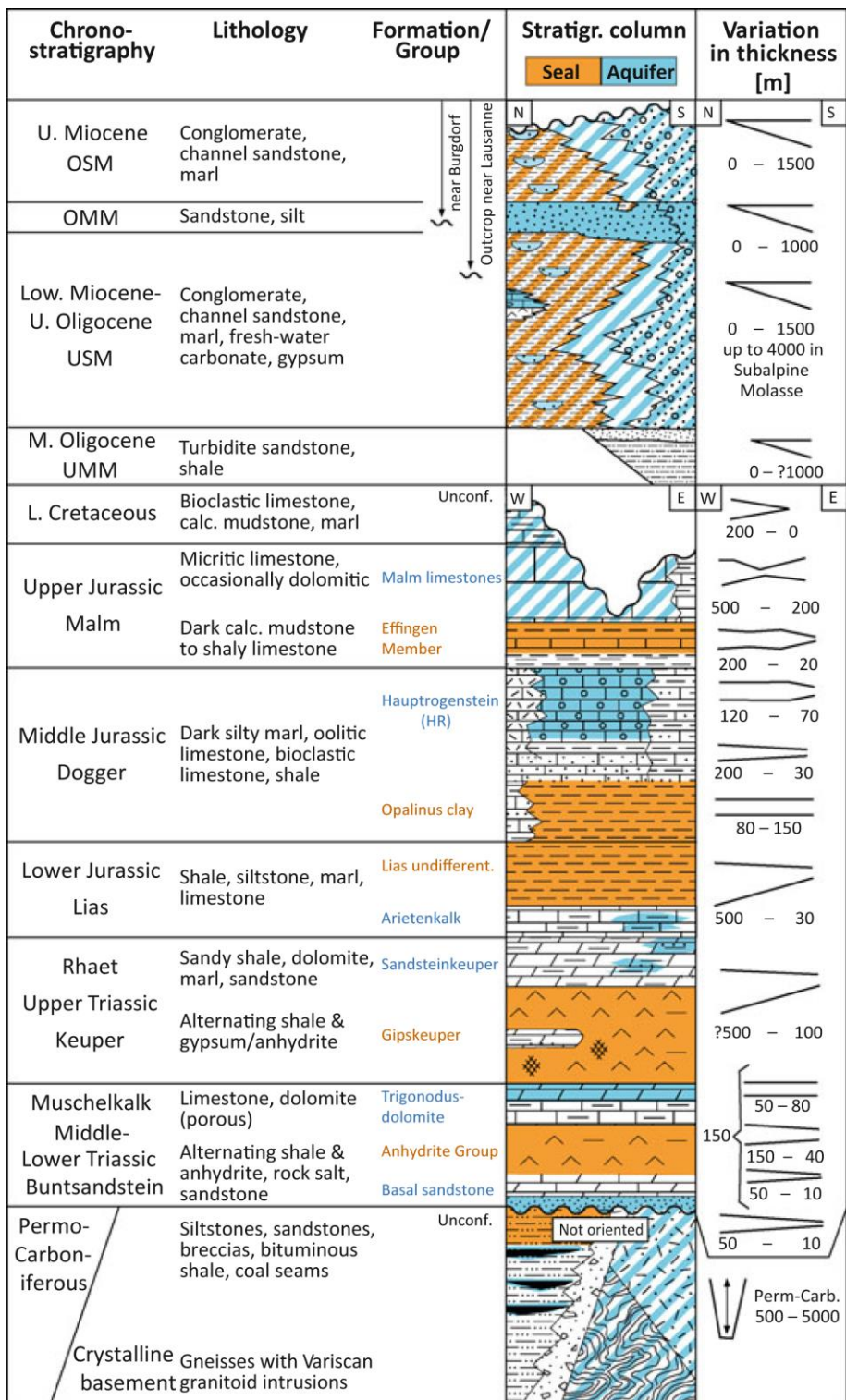
### **OMM**

This formation is a well-known porous potential aquifer in the East of Switzerland, where it is exploited for drinking water and sometimes for heat. An example of its combined use can be found in Seon (AG), where water is pumped at 300 m with a temperature of 19.5 °C from a single borehole. Water is then cooled to 10 °C by a heat pump; this allows heating of several buildings before being used as drinking water. However in most cases this Tertiary unit is quite shallow and therefore does not represent a target for major geothermal projects, even if the quality of the water allows its exploitation from a single borehole without reinjection.

### **Cretaceous**

In the Jura Mountains, the lower Cretaceous limestone is a well-known, essentially karstic, aquifer but is often not considered for geothermal projects for the following reasons. Firstly, as shown on figure 2.5 the Cretaceous formation is only present in some parts of the basin. Secondly, the karst and fractures can be filled with deposits resulting from its erosion or secondary mineral transferred by fluid flow, as it is the case in the Thônex (canton of Geneva) borehole (Jenny et al., 1995). Finally this formation is often too shallow to be exploited without heat pumps, even if it can still be interesting for low to medium depths projects.

*Figure 2.9 (next page): Generalized stratigraphic column (not to scale) of the Swiss Molasse Basin and the adjacent Folded Jura with aquifer properties. Aquifers are blue, aquitards orange, from Chevalier et al. (2010).*



### ***Upper Malm***

The name Upper Malm is often given to the potential aquifer of the Kimmeridgian and Portlandian formations. These formations are composed of limestones and dolomites (Portlandian only) and can be an aquifer especially when affected by fractures and/or karstification. This represents the main aquifer for drinking water all along the Jura range. Moreover, this formation reveals aquifer properties to considerable depths greater than 3300 m in Germany and Austria (e.g. Schellschmidt et al., 2010). In Switzerland an important number of wells were drilled in the Malm (e.g. Muralt, 1999) especially near the foot of the Jura range for different reasons: water prospection, oil exploration or geothermal prospection. This leads to a relatively good knowledge of its aquifer properties. Due to its important thickness and to the major infiltrating area in the Jura Mountains, this aquifer has been the main target of several geothermal projects in Switzerland.

### ***Dogger***

The Dogger series are also a well-known aquifer in the Jura Mountains, where they have been drilled for drinking water e.g. at Muriaux (canton of Jura, Hessenauer et al., 2001). Several formations of the Dogger series represent potential aquifers, but the only ones that can be of regional importance are the “Dalle nacrée” (Callovian) and the “Hauptrogenstein” of Bajocian – Bathonian (figure 2.9). However there are significant and rapid facies changes in these formations, resulting in considerable spatial variations of the hydrogeological parameters. For example, at Yverdon-les-Bains, the geothermal well F5 reached the Bajocian formations, which was composed of a micritic limestone, whereas at 3 km in the oil exploration well of Treykovagnes it was an oolitic limestone (Vuataz et al., 1999). Therefore Dogger formations are not commonly considered as a major and regional target a geothermal project.

### ***Muschelkalk***

The Muschelkalk is a well-known aquifer in the north-eastern Jura, where it was the target of three geothermal projects, two of which were successful. This aquifer is hosted by limestones and dolomites of the Upper Muschelkalk, representing generally a total thickness of more than 70 m (Burger and Gorhan, 1986). This aquifer is often considered as the main target for deep geothermal project (e.g. Baujard et al., 2007; Signorelli and Kohl, 2006) due to the relative evenness of its characteristics, such as thickness and aquifer properties. In Riehen (canton of Basel Stadt) it has been used for district heating since 1994 and in Schinznach Bad (canton of Aargau), the resource is used for thermal bathing and space heating (Sonney and Vuataz, 2008).

### ***Buntsandstein and crystalline basement***

Buntsandstein represents the most basal formation of the Mesozoic. It is a sandstone formed by the alteration of the basement and was recognized as an aquifer east of Geneva in France i.e. in the Charmont-1 well (PGG, 2011) and in northern Switzerland. Schmassmann et al. (1992) established that there is a hydraulic connection between the altered basement aquifer and the Buntsandstein. Therefore where Buntsandstein overlies crystalline basement they form together a single aquifer, but where it overlies Permo-Carboniferous sediments, Buntsandstein alone must be considered. The aquifer parameters of the altered crystalline basement have been studied by NAGRA in northern Switzerland, where it shows a considerable permeability heterogeneity (Pearson et al., 1991; Schmassmann et al., 1992; Signorelli and Kohl, 2006), but could be an interesting aquifer for geothermal projects in several regions of Switzerland, although information about this formation is quite limited (Baujard et al., 2007).

## **2.2.2 Geothermal condition under the SMB**

In the Swiss Molasse Basin the geothermal gradient is considered mostly normal ( $30\text{ }^{\circ}\text{C}\cdot\text{km}^{-1}$ ), with regional or local values ranging from 25 to  $40\text{ }^{\circ}\text{C}\cdot\text{km}^{-1}$  (figures 2.10 and 2.11).

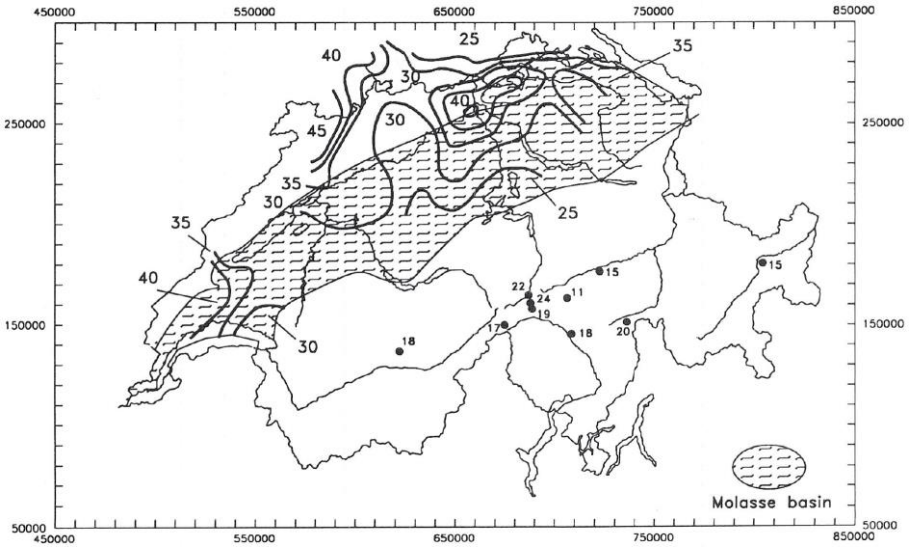


Figure 2.10: Geothermal gradient data from Switzerland in  $^{\circ}\text{C}\cdot\text{km}^{-1}$  (Rybach, 1992).

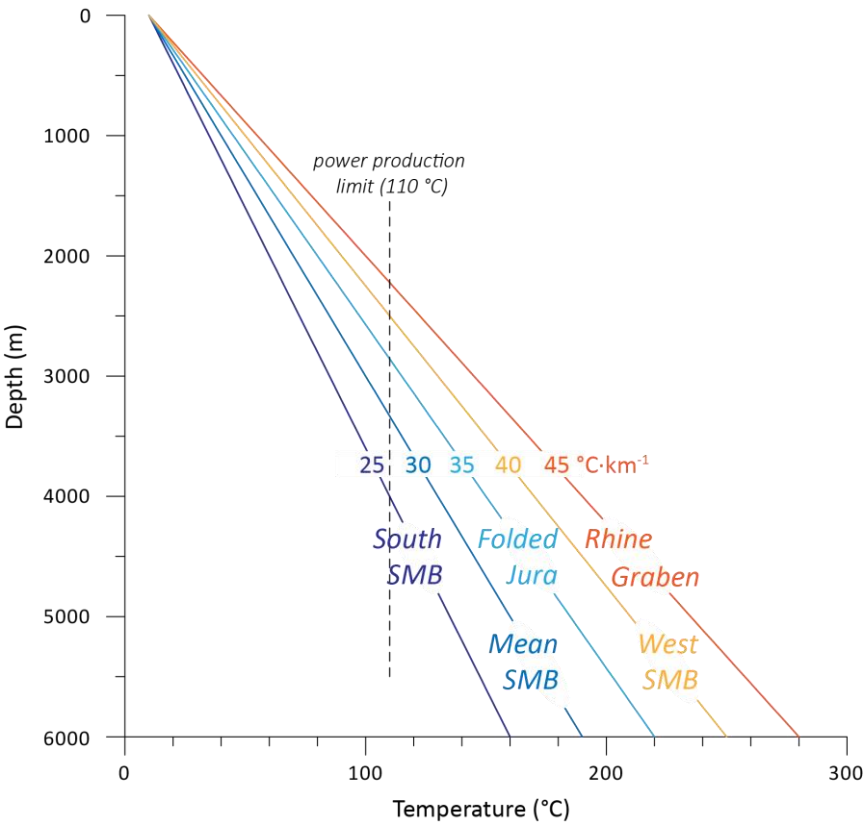


Figure 2.11: Range of the mean regional geothermal gradients in the Swiss Molasse Basin (SMB) (after Chevalier et al., 2010).

## 2.3 Gravity exploration

The gravity method is based on accurate measurement of the vertical component of the Earth gravity field and their interpretation to detect underground variations of density. This method has a variety of applications, which are principally geodesy, determination of deep earth structures and geophysical exploration. It was historically firstly used for geodesy.

### 2.3.1 History

The history of gravity method is most often divided into four broad and overlapping periods (Hinze et al., 2013), which are strongly related to technological innovation. It is not the purpose of this work to give a complete review of the gravity method history, but to present it briefly in order to give context to the proposed methodology.

#### ***First period: Renaissance – end of the 19<sup>th</sup> century***

The interest in gravity measurements began in ancient Greece when Aristotle made the distinction between heavy (i.e., stones) and light bodies (i.e., feather). Things remained almost the same until the end of the 16<sup>th</sup> century when Galileo Galilei wrote his theory of the falling of bodies. Legend says that he let heavy and light objects fall from the tower of Pisa and then measured the time of the fall. In fact, he performed this experiment on an inclined plane. Nevertheless, this allowed him to conclude that the time was the same for every object regardless of its weight and was thus the first approach of the effect of the Earth gravity field. It is therefore the date marking the beginning of the first development of the gravity method development.

A century later in 1687, Sir Isaac Newton published his famous *Philosophiae Naturalis Principis Mathematica*. In this work, Newton explained for the first time the law of universal gravitation, which allows the calculation of the force of attraction between two bodies.

Nevertheless, the founding father of gravity measurements is Pierre Bouguer (1698-1758) a French mathematician. In 1735, he undertook a scientific expedition to Peru with Charles Marie La Condamine, Louis Godin and Joseph de Jussieu to measure a degree of the meridian arc near the equator. This expedition allowed Bouguer to establish many of the basic gravitational relationships including the "free air correction", "plate correction" (often called Bouguer plate) and also the mass of the Earth. He also succeeded in measuring gravity at several points. Bouguer also tried to measure the attraction of a single mountain in Chimborazo, but he made some mistakes in

his calculations, which led him to failure (Goguel, 1984). This experiment was made by measuring the deviation of the vertical in two far away points near the mountain with a pendulum.

### ***Second period 1800 – 1950***

The first gravimeter was the Kater's pendulum introduced in 1817 by the physicist and Captain Henry Kater. The center of gravity and the center of oscillation were not fixed, this allowed more precision in gravity measurements. Then in 1890, Baron Roland von Eötvös, a Hungarian physicist, developed a torsion balance, which allowed the measurement of differences in gravity between two points rather than the total value of gravity. Before the invention of modern gravimeters in 1940, numerous gravity measurements were made using both systems, but the difference between absolute and differential gravimeter remained.

The availability of more portable instruments and their increased precision allowed, in the first years of the 1900s, to use gravity measurements for subsurface studies. This led to an important increase of gravity measurements and the torsion balance was used for oil exploration from the end of World War I. According to Nabighian et al. (2005) it was used over a salt dome in Germany in 1918 and the instrument was then bought as war reparation and used in the USA. In 1922, this led to the first oil discovery by geophysical method in America when it was used over the Nash dome in Texas (Hinze et al., 2013).

During the first half on the 20<sup>th</sup> century gravity was thus extensively used in oil exploration, which allowed the establishment of the concepts of mapping geology with gravity and the basic principle of gravity data processing. During this period, international standard data reduction for pendulum and gravimeter were internationally accepted and the *Gal* was accepted as the CGS system (Centimeter Gram Second system) unit for acceleration. The next step in the development of the gravity method was done through the works of L. L. Nettleton (1939, 1940, 1942) and of S. Hammer (1939, 1945, 1950) which are critical in gravity exploration and for density determination. During this period instruments were also improved with the discovery of the zero length spring of L. J. B. La Coste (1934) which made the relative gravimeter easier to use and to calibrate (Nabighian et al., 2005).

### ***Third period: 1950s – 1980***

The development of gyrostabilized gravity platforms in 1960 allowed extensive measurements on moving platforms such as planes and ships (Hinze

et al., 2013). Nevertheless, this period is mainly marked by the rapid increase in digital computational capacity and speed; this led to improvements in the processing and modeling of gravity data. This resulted in the development of algorithms for the computation of the gravity effect of 2D and 3D arbitrary shapes (e.g. Talwani et al., 1959) and thus allowed forward and inverse calculation. The increase of computer capacity also permitted the use of Fourier transforms for potential field analysis. From the 1970s the use of geographic information systems (GIS) allowed better representation and understanding of the multiple geological and geophysical data.

#### ***Fourth period: 1980s – today***

As this period is still ongoing, the present methodology used in gravity exploration will be presented in the next sections of this work. However, we must highlight some of the major changes that have occurred during this period. Firstly the availability of cheaper workstations and personal computers allowed migrating computer software to these platforms (Unix and Windows). The emergence of the personal computer and of the internet resulted in better access to previous gravity data sets (commercial or scientific) and to Digital Elevation Models (DEM), which are becoming far more accurate (see section 3.2.1 dedicated to terrain correction). This has also resulted in faster data processing and interpretation.

Finally, the instrumentation has evolved and gravity can now be acquired with high precision digital gravimeters using a quartz sensor with partially automated levelling such as the relative gravimeter CG-5 from Scintrex Ltd. used during this study with an accuracy of 5  $\mu\text{Gal}$ . Positioning of the gravity measurements stations has also evolved with the discontinuing degradation of the GPS signal in 2000 which allows high-accuracy surveys. Presently, the use of real-time correction gives an almost instantaneous precision to a few centimeters in three dimensions.

Regarding geothermal exploration, gravity has also been used in combination with magnetotelluric methods to help identify deep geothermal aquifers linked with faults (Tulinius et al., 2008) and in the Alps (Guglielmetti, 2012; Guglielmetti et al., 2013). Filtering of gravity data was also used by Abdelfettah et al. (2014) in order to characterize geothermally relevant structure in the crystalline basement in Switzerland. Finally, Bailleux et al. (2013) used gravity data in order to localize temperature anomalies in the Upper Rhein Graben.

### 2.3.2 Theory

The theory of gravity measurements is presented extensively in literature (e.g. Hinze et al., 2013; Kearey et al., 2009; Reynolds, 1997; Telford and Sheriff, 1990). In the following section, we will summarize some important considerations in order to better explain the methodology used in the present work.

#### ***Physical basis***

Basically the gravity force between two bodies is expressed by Newton's Law of Universal Gravitation presented here after:

$$F = G \frac{M_1 M_2}{d^2} \quad (2.1)$$

with  $F$ : the attraction force in  $\text{kg} \cdot \text{m} \cdot \text{s}^{-2}$ ;  $G$ : the universal gravitation constant  $6.674 \cdot 10^{-11} \text{ m}^3 \cdot \text{kg}^{-1} \cdot \text{s}^{-2}$ ;  $M_1, M_2$ : the respective mass of the two bodies in kg;  $d$ : the distance between the center of the bodies in m.

The acceleration implied by a force is expressed by Newton's Second Law of Motion:

$$F = m \cdot a \quad (2.2)$$

where  $F$  is the force acting on a body in  $\text{kg} \cdot \text{m} \cdot \text{s}^{-2}$ ;  $m$ : the mass of the body in kg;  $a$ : the acceleration in  $\text{m} \cdot \text{s}^{-2}$ . In the case of a point mass at the surface of the Earth equation 2.1 and 2.2 can be combined in order to calculate the acceleration induced by the Earth ( $g$  in equation 2.3):

$$F = G \frac{M_e \cdot m}{R^2} = m \cdot g \rightarrow g = G \frac{M_e}{R^2} \quad (2.3)$$

with  $F$ : attraction force in  $\text{kg} \cdot \text{m} \cdot \text{s}^{-2}$ ;  $G$ : the universal gravitation constant  $6.674 \cdot 10^{-11} \text{ m}^3 \cdot \text{kg}^{-1} \cdot \text{s}^{-2}$ ;  $M_e, m$ : the mass of the Earth and of the body respectively in kg;  $g$ : the acceleration in  $\text{m} \cdot \text{s}^{-2}$ ;  $R$ : the radius of the Earth in m.

Equation 2.3 shows that earth's acceleration is independent from the mass of the body and is proportional to the Earth mass and radius. The acceleration of gravity is a conservative vector field, which implies that the work needed by a particle to go from point A to point B is independent from its route and is

the product of the force of gravity by the displacement. With this consideration, we are able to calculate the gravitational potential of a punctual body everywhere in the gravitational field. It allows us to plot equipotential curves. These equipotential curves connect all points in space where the gravitational potential of a body of constant mass is the same and is called an equipotential surface. In the case of a motionless and spherical (or with layered densities) earth, this surface is a sphere. However, the Earth rotates on itself and this has two main effects concerning the measurement of gravity: the rotation implies a centripetal acceleration that will be opposed to gravity and will be at its maximum at the equator and null at the poles (figure 2.12). The rotation also deforms the Earth which is therefore more an ellipsoid than a perfect sphere. This induced radius difference is 21 km between the poles and the equator.

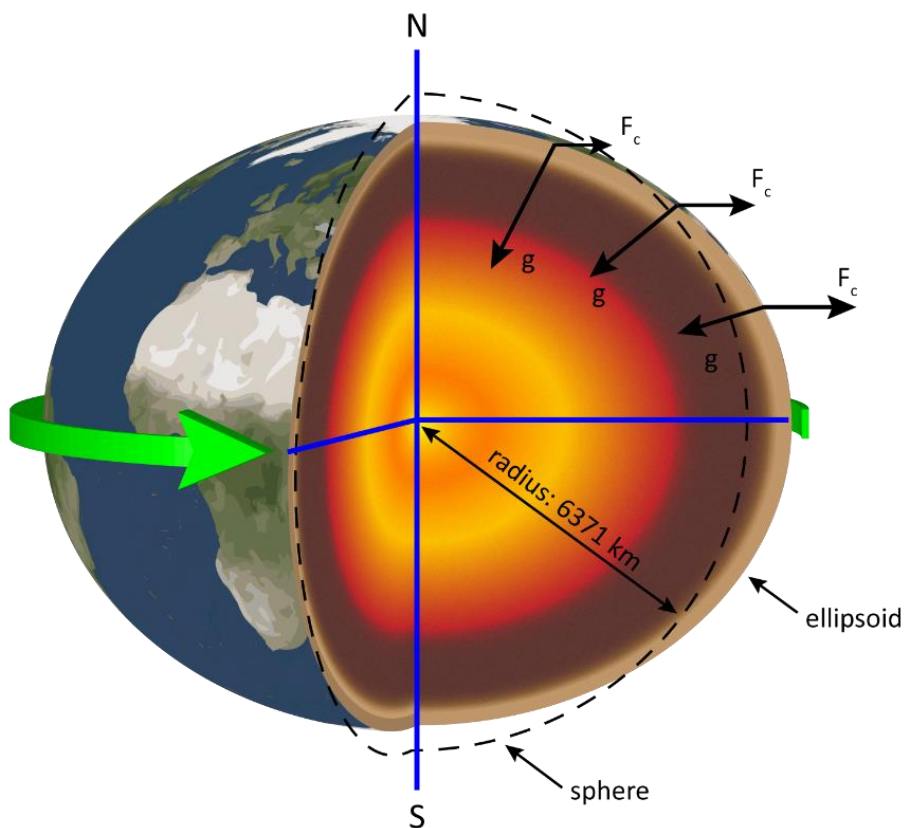


Figure 2.12: Difference between spherical Earth and ellipsoid and its consequences on gravity (not to scale);  $g$ : gravity neglecting effect of rotation;  $F_c$ : centrifugal force.

### ***Standard gravity and units***

The previous considerations allowed the determination of a standard formula for the theoretical value of gravity at any point of the ellipsoid. This was done in 1930 when the International Union of Geodesy and Geophysics adopted the International Gravity Formula (e.g. Reynolds, 1997, p. 37) whose general form is given hereafter:

$$g_{\phi} = g_0(1 + \alpha \sin^2 \phi - \beta \sin^2 2\phi) \quad (2.4)$$

where  $g_{\phi}$ : gravity acceleration at latitude  $\phi$ ;  $g_0$ : gravity at the equator;  $\alpha, \beta$ : are constants discussed hereunder.

This commission also decided to use the Gal as the unit for gravity measurement. This name was chosen to honor Galileo Galilei for his pioneering work on the planets' motion at the end of the 16<sup>th</sup> century. Even though it was adopted at the beginning of the 20<sup>th</sup> century and thus in the CGS system it is still in use today, see table 2.6 for equivalence between CGS and SI units. The CG-5 gravimeter from Scintrex Ltd. used in this study can make measurements with an accuracy of 0.005 mGal or 5  $\mu$ Gal.

*Table 2.6: Equivalence of CGS (Centimeter Gram Second system) and SI units (International System of Units) for gravity.*

| CGS       | SI                                    |
|-----------|---------------------------------------|
| Gal       | $10^{-2} \text{ m}\cdot\text{s}^{-2}$ |
| mGal      | $10^{-5} \text{ m}\cdot\text{s}^{-2}$ |
| $\mu$ Gal | $10^{-8} \text{ m}\cdot\text{s}^{-2}$ |

In 1967, the increasing computational capabilities of computers, as well as better value for earth parameters given by satellite measurements allowed scientists to refine the parameters of equation 2.4 to define the new standard. The International Gravity Formula (IUGG, 1967), presented here (2.5) allows the determination of the theoretical value of  $g$  on the ellipsoid at a given latitude ( $\phi$ ):

$$g_{\phi} = 978031.846(1 + 0.005278895\sin^2 \phi - 0.000023462\sin^4 \phi) \quad (2.5)$$

Even if a more refined and precise formula was adopted in 1980 (Moritz, 1980) differences are very small and most gravity data available in Switzerland were determined using equation 2.5 (Olivier et al., 2010).

Therefore we also used this equation for the determination of the theoretical value of  $g$ .

### ***Gravity models and variations***

In geophysics, gravity measurements ( $g_{obs}$ ) are compared to a modeled value of  $g$  ( $g_{mod}$ ). The difference between these values is called the gravity anomaly ( $\Delta g$ ). This anomaly can therefore be positive or negative, as it is related to a model and not to an absolute measurement of the gravity intensity:

$$\Delta g = g_{obs} - g_{mod} \quad (2.6)$$

However, the amplitude of anomalies studied in geophysical exploration are very small, typically a few mGal, and thus equation 2.5 cannot be used alone as model, and several other effects affecting  $g$  must be taken into account.

Firstly, the value from equation 2.5 gives the acceleration induced by the Earth, but  $g$  is influenced by other astral bodies, mainly the Sun and the Moon. This effect follows Newton's law of universal attraction and is thus linked with the mass of the body and the square of the distance. The concrete effect of this variation on Earth is represented by the tides (marine and terrestrial) and this gravity effect can reach 0.3 mGal in amplitude. However, the latter is not constant due to astral movement. It is thus related to the position and the time of the observation. Nevertheless, on recent gravimeters such as the CG-5, this effect is directly calculated and subtracted to the measurements.

Secondly, the commonly used instruments for geophysical survey are unstable gravimeters. Their null reading will change with time mainly due to the aging of the spring. However, when surveys are short enough this drift can be considered as linear. To calculate this drift correction the measurements always begin and end on a station called the base station and which is located where the measurement should be perturbed as little as possible. So the drift correction is considered as the difference between the reading at the start and at the end of the measurements. This is the reason why gravity measurements are always made in so called "cycles".

Thirdly, the measurements are rarely made on the ellipsoid and this must be taken into account. For that purpose most land surveys use what is called the Bouguer Anomaly (BA). It is presented hereunder with its classical corrections (equation 2.7), with  $g_{mod}$  model value for the Bouguer Anomaly and classical corrections;  $g_{th}$ : theoretical value of  $g$ ;  $\Delta g_{fa}$ : free-air correction;

$\Delta g_{pl}$ : plateau correction;  $\Delta g_t$ : terrain correction. Specific adaptations or methods used in this work are described in the next chapter:

$$g_{mod} = g_{th} - \Delta g_{fa} + \Delta g_{pl} - \Delta g_t \quad (2.7)$$

Replacing  $g_{mod}$  in equation 2.6 by equation 2.7 gives the formula of what is generally referred to as the complete Bouguer Anomaly.

$$\Delta g_{BA} = g_{obs} - g_{th} + \Delta g_{fa} - \Delta g_{pl} + \Delta g_t \quad (2.8)$$

As previously mentioned gravity measurements are rarely made on the ellipsoid and this altitude difference must thus be corrected. This is called the free-air correction (equation 2.9,  $\Delta g_{fa}$ ) and is calculated with the following formula:

$$\Delta g_{fa} = 0.3086 \cdot \Delta h \quad (2.9)$$

with  $\Delta g_{fa}$ : free-air correction in mGal;  $\Delta h$ : height difference between the measurement and the ellipsoid in m. However, the free-air correction does not take into account that this height difference is filled with matter (in the case of land survey). The effect of this mass is taken into account by the plateau (or Bouguer) correction ( $\Delta g_{pl}$ ) and consists in calculating the effect of an infinite slab with given density.

$$\Delta g_{pl} = 2\pi G \cdot \rho \cdot \Delta h = 0.0419 \cdot \rho \cdot \Delta h \quad (2.10)$$

where  $\Delta g_{pl}$ : the plateau correction mGal;  $G$ : the universal gravitation constant  $6.674 \cdot 10^{-11} \text{ m}^3 \cdot \text{kg} \cdot \text{s}^{-2}$ ;  $\rho$ : density in  $\text{kg} \cdot \text{m}^{-3}$ ;  $\Delta h$ : the ellipsoidal height in m.

The last classical correction is the terrain correction ( $\Delta g_t$ ). Its value represents the gravity effect of masses present above and under the measurement station and which were not taken into account by the plateau correction (figure 2.13).

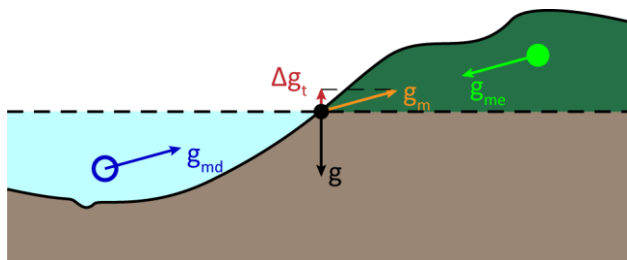


Figure 2.13: Effect of mass excess (in green,  $g_{me}$ ) and mass deficiency (blue,  $g_{md}$ ) on  $g$  at a measurement station (black dot) compared with the plateau (dashed line);  $\Delta g_t$ : vertical component of mass difference effect ( $g_m$ ). As presented on this figure this correction is always opposed to gravity.

Historically this correction was made by applying a template made of sectors of annular rings on topographic maps (figure 2.14). The mean elevation of every sector was then determined and the effect on gravity calculated using a data table determined by Hammer (1939). With the emergence of DEM this correction is often made numerically using different methods. Nevertheless, the basic principle remains the same and the exact method used will be presented in the chapter dedicated to methodology.

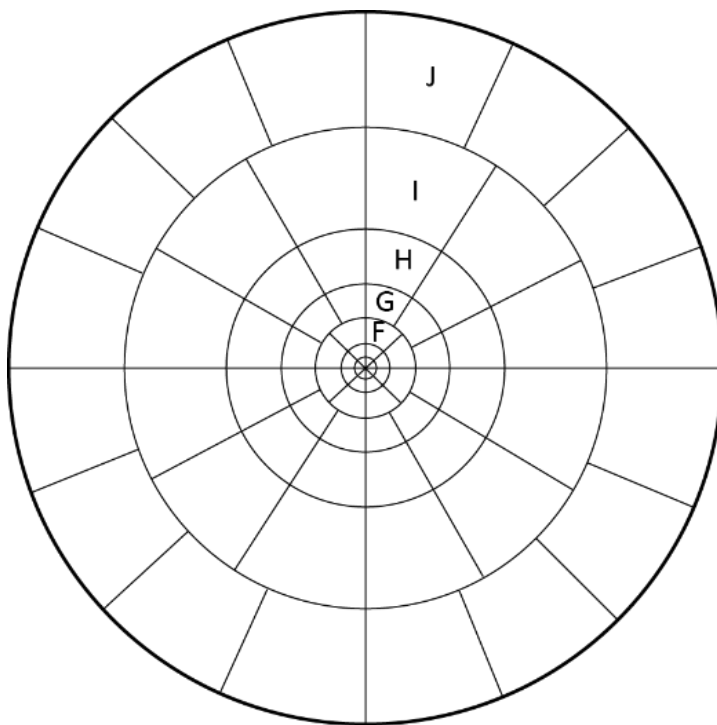


Figure 2.14: Typical template (not to scale) used for topographic correction from Hammer (1939, in Kearey et al., 2009).

### Data processing

The Bouguer Anomaly is considered representative the effect of density change in the subsurface which is linked with geology. It thus represents the sum of all of the anomalies induced by the geological structures at all scales from structures of Earth scale to very local structures. However this is rarely the aim of a survey. Therefore it must be refined in order to highlight the anomalies linked to the targeted geological structures and to allow its interpretation.

The most common case is the removal of the anomaly induced by very deep structures, such as mountain roots resulting in a residual anomaly, which is only affected by local structures (figure 2.15). The methods used in order to determine the regional effect or regional anomaly vary widely, since it is also linked with the target of the study: common methods range from graphical to spectral filtering (e.g Hinze et al., 2013). Therefore only the basic principle is presented here, the method used in this study will be presented in the next chapter.

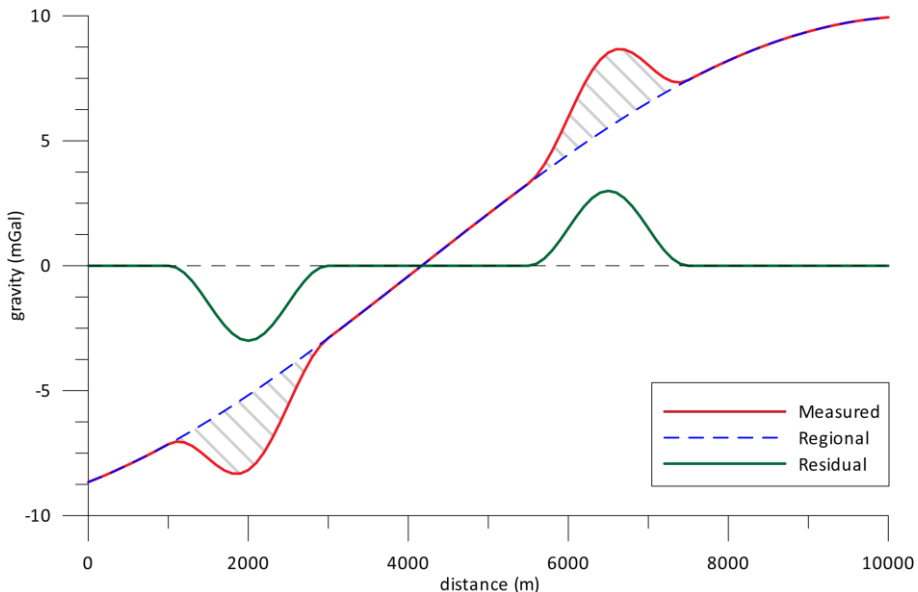


Figure 2.15: Schematic gravity anomaly with a regional trend and two local anomalies. The regional effect is removed in order to obtain the residual which highlights local anomalies.

### Gravity anomaly interpretation

Interpretation of gravity anomalies can be made in two ways, directly or by building a gravity model. Concerning the latter, the gravity anomaly generated by the model will be compared with the measured gravity. In all cases the nature of the gravity makes its interpretation ambiguous, as several different bodies can induce the same anomaly as presented in figure 2.16. Therefore gravity is often used in combination with other geophysical methods to avoid or decrease the ambiguity.

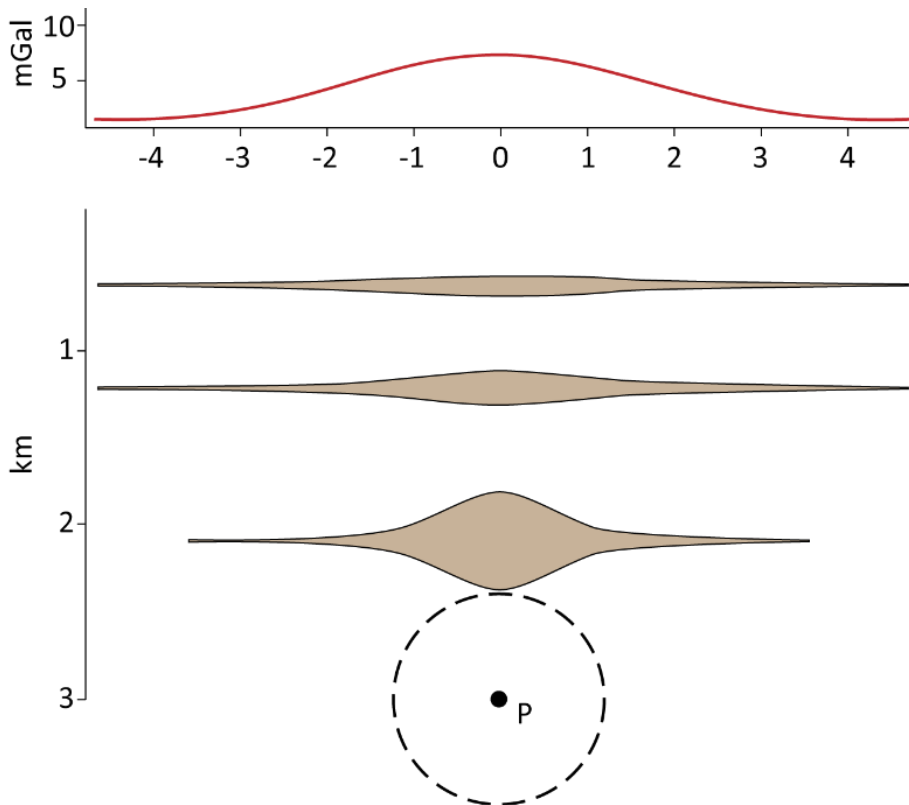


Figure 2.16: Ambiguity in geological models, all three bodies produce the same anomaly presented at the top. The lens-shaped bodies have a gravity anomaly identical to that of a sphere with its center at  $P$  of radius 600m and a density contrast of  $10 \text{ kg}\cdot\text{m}^{-3}$ . For better visualization, the thickness of the bodies is exaggerated by a factor 3. Adapted from Griffiths and King (1981).

In gravity modeling, there are two main components: the measured gravity and the modeled gravity. Measured gravity can be a Bouguer Anomaly or, more often, a residual anomaly, which was corrected from unwanted effects. The modeled gravity can be obtained by two methods, inversion or forward modeling, which are also common in other geophysical methods. This can be done either in 2D or in 3D. Inversion consists of “determining the geometry

*and physical properties of the source of the anomaly*” (Telford and Sheriff, 1990). Due to the above-mentioned ambiguity or nonuniqueness of the gravity interpretation, constraints must be set to allow the resolution of this inverse problem. This is typically done by giving some prior information on physical parameters, such as density distribution, on geometry and/or by giving constraints to the model. In the direct or forward method, the model is first produced and its gravity effect calculated and compared to the measured value. The model is then modified by trial-and-error until a best fit is reached. This is classically done either by using a simple shape (or idealized body) such as a sphere, a slab, etc., or by computing the effect of a geological model. The latter is, in most cases, done by subdividing the model into simple elements. The resulting model anomaly is the sum of the gravity effect of all these elements.

### 2.3.3 Density

As mentioned above, gravity measurements will detect the lateral change of density in the subsurface rocks. Commonly the density of rocks represents its volumetric mass density or its bulk density expressed in  $\text{kg}\cdot\text{m}^{-3}$  and with the symbol  $\rho$ . However when used in gravity exploration, density is often expressed in CGS units  $\text{g}\cdot\text{cm}^{-3}$  as for the gravity itself. When expressed in CGS units, it is equal to its “relative density” which is dimensionless as it expresses the ratio of a body's density to the density of water which is  $1\text{ g}\cdot\text{cm}^{-3}$  at  $20\text{ }^{\circ}\text{C}$ . The densities of most common rocks present in the Swiss Molasse Basin and nearby areas are presented in figure 2.17, together with the effect of local conditions (table 2.7). A map of the density of the outcropping formations of Switzerland is presented in figure 2.18 based on Zappone et al. (2011).

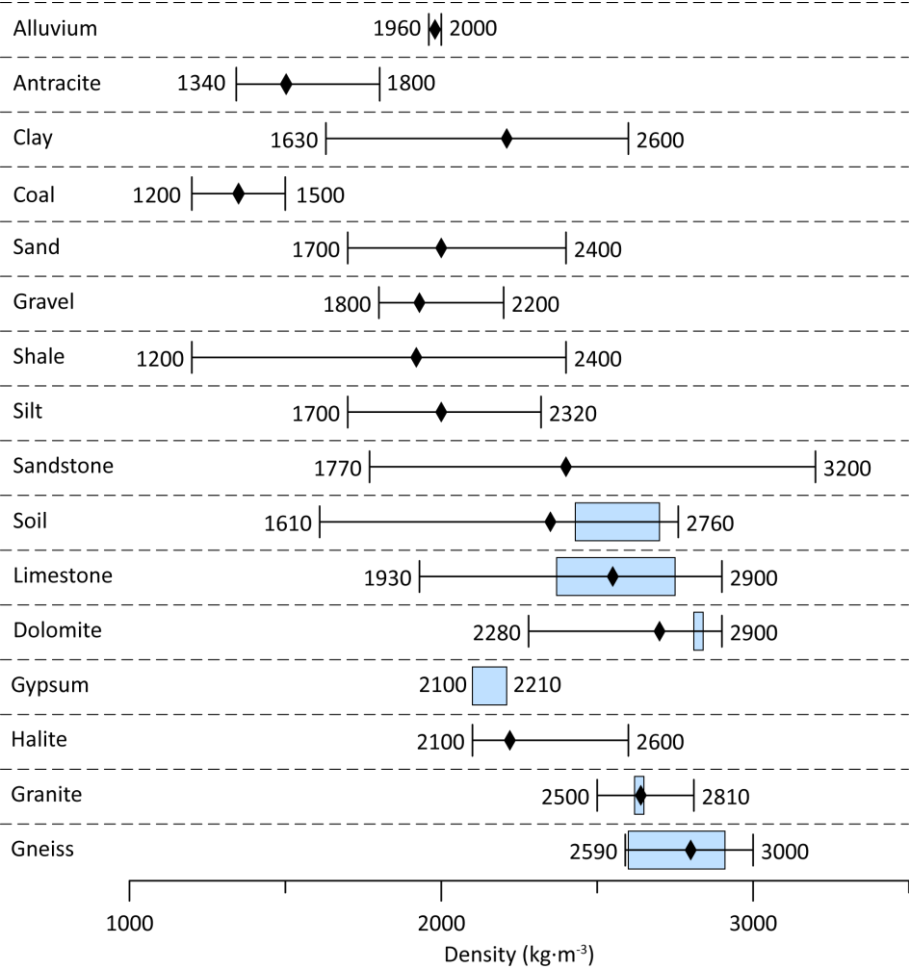


Figure 2.17: Density of most common rocks present in the Swiss Molasse Basin and nearby areas. Bars represents worldwide data ranges from textbooks (Kearey et al., 2009; Milsom, 2003; Reynolds, 1997; Telford and Sheriff, 1990) and diamond are the commonly used average values. Blue bars represent data ranges for Switzerland (Altwegg et al., 2013; Wagner et al., 1999).

Table 2.7: Effect of different physical factors on rock density (Reynolds, 1997)

| Factor                   | Approximate percentage change in density (%) |
|--------------------------|----------------------------------------------|
| Composition              | 35                                           |
| Cementation              | 10                                           |
| Age and depth of burial  | 25                                           |
| Tectonic processes       | 10                                           |
| Porosity and pore fluids | 10                                           |

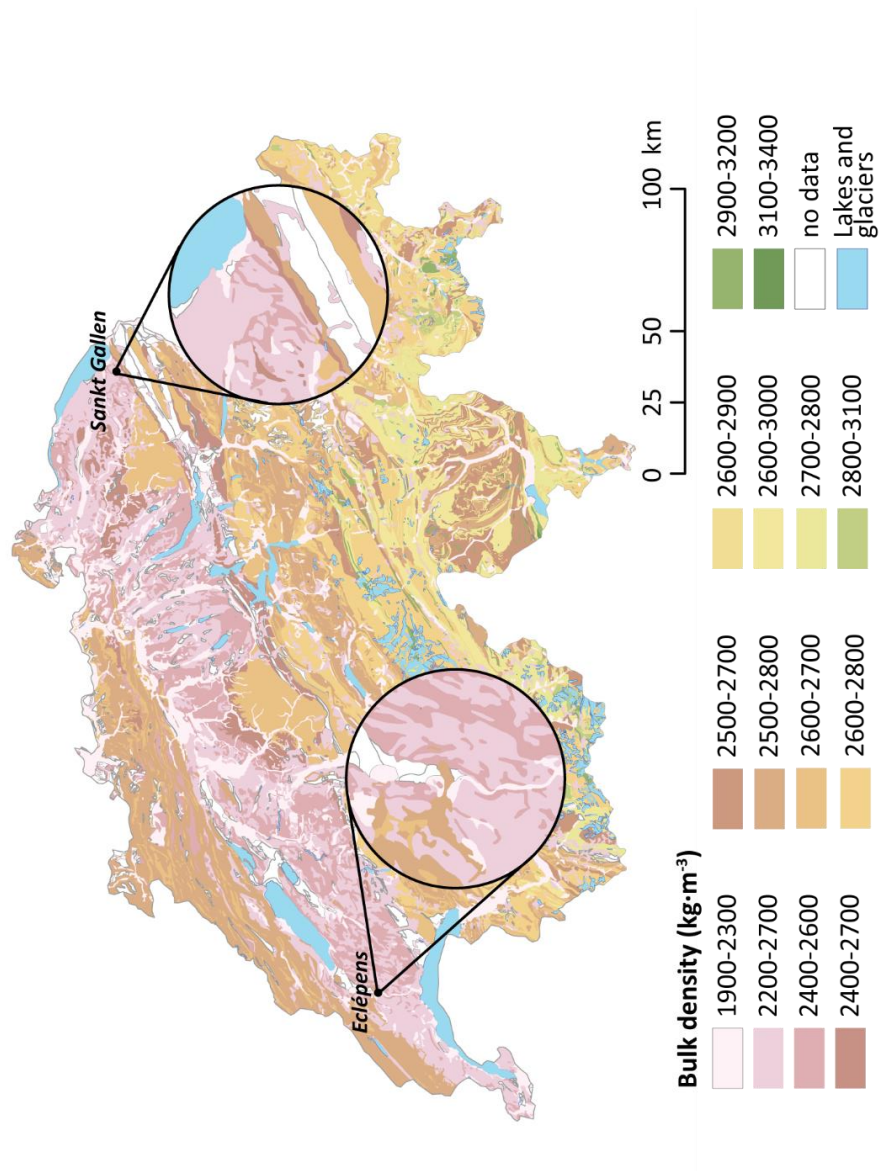


Figure 2.18: Density of outcropping rocks in Switzerland after Zappone et al.(2011). The area around the two case studies of this work where zoomed in the two inserts.

### ***Porosity assessment***

As previously discussed (section 2.1), the dominant hydrogeological parameter for the economic viability of a geothermal project is the transmissivity of the reservoir. The latter is related to the thickness and porosity of the host geological formation through hydraulic conductivity and permeability.

Gravity data were largely used for porosity determination in off-shore exploration surveys (Cochran et al., 1999; Gilbert and Johnson, 1999; Holmes and Johnson, 1993; Johnson et al., 2000; Korenaga et al., 2001; Luyendyk, 1984; Pruis and Johnson, 1998; Stevenson et al., 1994; Yamamoto et al., 1989). In these surveys the density determined by gravity measurements for the upper seafloor ( $\rho_{mes}$ ) is considered as the resultant of the density of the grain matrix of the rock ( $\rho_{matrix}$ ) and of the seawater ( $\rho_{fluid}$ ) present in primary and secondary porosity ( $\phi_{tot}$ ). It can thus be expressed by a simple linear mixing equation with two components (McCulloh, 1967 in Murty and Raghavan, 2002; Pruis and Johnson, 1998):

$$\rho_{mes} = (1 - \phi_{tot}) \cdot \rho_{matrix} + \phi_{tot} \cdot \rho_{fluid} \quad (2.11)$$

Porosity can also be directly expressed (Gilbert and Johnson, 1999):

$$\phi_{tot} = \frac{\rho_{matrix} - \rho_{mes}}{\rho_{matrix} - \rho_{fluid}} \quad (2.12)$$

These formulas were used on-shore for hydrogeological exploration (Murty and Raghavan, 2002), for geothermal reservoirs management (Allis et al., 2000; Atkinson and Pederseen, 1988) and for understanding of hydrothermal systems (Suharno et al., 2005). As porosity determination by gravity measurement is a central topic of this work, it is treated in more detail in section 3.4.3, p. 78.



## Chapter 3

# Methodology and tools



### 3.1 Introduction

As presented in the previous chapter there are two main geological parameters controlling the success of geothermal projects: temperature and flow rate. If the first one can be relatively well estimated in the subsurface, it is not the case of flow rate, which is related to porosity and permeability. Thus, the major aim of the present work is to develop methodology and tools allowing us to determine areas of high porosity and to quantify it by the combined use of gravity and detailed 3D geological models established with a high density of data, i.e. made with seismic measurements, such as 3D seismic data. The principle is to use seismic data to determine the 3D geological structures (as it is far more precise than gravity for this purpose) and then to calculate the gravity effect of this model to compare it with gravity measurements. If the model is accurate enough it is possible to determine the porosity and in all cases to bring qualitative information about the model. The general steps of our methodology are the following:

1. A sensitivity study is carried out to determine the shape, extent and intensity of the gravity anomalies linked to the different geological structures of the target area. This allows us to determine to what extent a gravity survey can bring information, to detect if there is inconsistency in the data and to better size the survey itself i.e. by determining the offset between the measurement stations. For that purpose existing gravity data with low spatial density and a range of densities taken from literature can be used. Depending on the data available, this study can be carried out on an existing 3D model (second case study, chapter 5) or on a synthetic model (first case study, chapter 4).
2. A gravity survey is carried out to obtain a precise Bouguer Anomaly of the region of investigation. The different methods used in this work in order to increase accuracy are presented in section 3.2. Also, when possible, samples from outcropping geological formations were collected in order to determine their density. The main aim of this step is to decrease the error on gravity measurements as much as possible.
3. The regional anomaly linked with lithospheric scale structures is determined and then subtracted from the Bouguer anomaly. The resulting residual anomaly is thus considered to be only influenced by local geological structures (section 3.2.1).

4. The different geological structures are modelled in 3D and their respective gravity effect is calculated (forward modeling, section 3.3 and 3.4). This step is also used to precisely determine the density of the different formations by a joint use of the results of the sensitivity study, the measured rock density and the inversion methods developed in this work (section 3.4.4).
5. The final step is the stripping of all the known gravity effects so that the final residual (or misfit) highlights the gravity variation associated to the targeted structures. It is also possible here to use our inversion method, as it will indicate the uncertainties linked with the different densities.

## 3.2 Gravity data treatment

Gravity data sets were acquired following the standard cycle methods using a CG-5 Autograv relative gravimeter (Scintrex, Canada), which has an accuracy of  $\pm 5 \mu\text{Gal}$ . Geographic coordinates of the measurement stations were acquired using a Leica differential GPS (DGPS) GS 15 with an accuracy of 1-3 cm (real time correction). The Bouguer Anomaly was then calculated using the standard corrections. However in order to combine accuracy and time-efficiency, a new approach was developed to calculate both plateau and terrain correction.

### 3.2.1 Terrain effect

The availability of precise DEMs (described later) allows us to develop a different methodology compared to the one presented in the previous chapter (section 2.3.2). Firstly, this methodology allows us to merge the plateau and terrain correction into what is called by Hinze (2013) the terrain effect. Doing so, the final corrections on the gravity measurements are more accurate as there is no need to first calculate the gravity effect of a plateau before correcting it by the effect of topography. Secondly, the use of precise DEMs avoids the use of templates such as the one proposed by Hammer (1939, Figure 2.10). Indeed as these templates were created to approximate the topography, this approximation automatically induced an error on the corrections.

The effect of topography is considered to be the classical distance of 167 km which is equal to an arc of  $1.5^\circ$  on the Earth. This distance is also chosen to be consistent with the existing regional data from the Swiss Atlas of Gravity (Olivier et al., 2010) that were used, i.e. to calculate regional effect (see below). As the gravity effect decreases with the square of the distance, we used three different DEMs of different resolutions to calculate this effect:

1. From the station to the distance of 200 m, a high resolution DEM with a grid size of 2 m and a vertical accuracy of  $\pm 0.10$  m (SwissALTI3D, Swisstopo, 2010a).
2. From 200 m to 20 km, a DEM with a grid size of 25 m and a vertical accuracy  $< 2$  m and  $< 5$  m in mountainous area (DHM25, Swisstopo, 2010b).
3. From 20 km to 167 km, a DEM with a grid size of almost 400 m and a vertical accuracy  $< 15$  m (SRTM from ASTER GDEM METI and NASA, 2009).

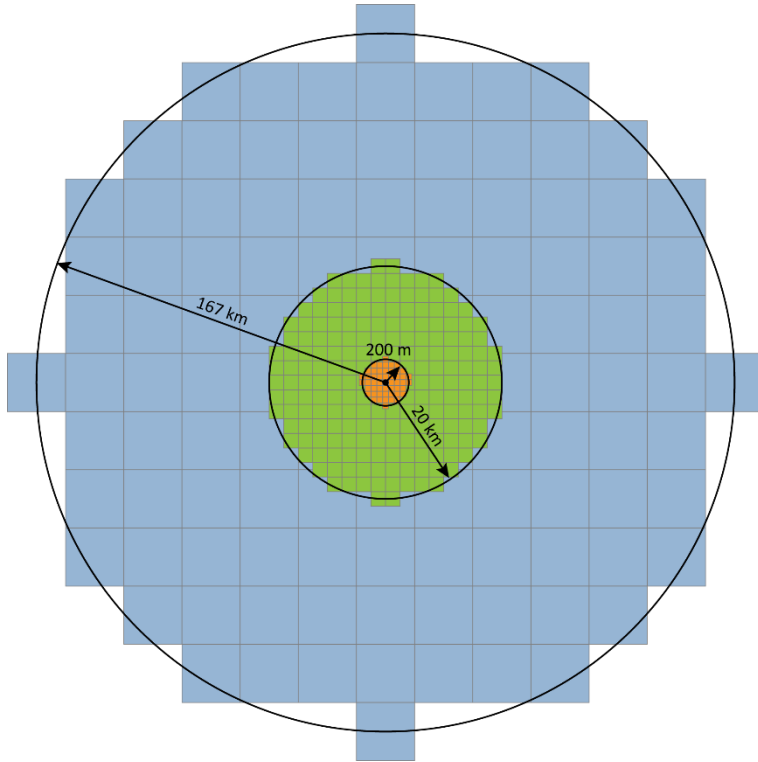


*Figure 3.1: Schematic representation of the use of DEMs with different cell size for terrain effect (not to scale).*

The terrain effect is then the sum of the gravity effects on the measurement station of each cell present within the respective range of the different DEM (figure 3.1). This effect is calculated using the algorithm of Blakely (1996), which has been coded in C++ and built into a dedicated computer program. It is presented in more detail later in this chapter. Nevertheless, before calculating the effect of the DEMs, some more consideration must be taken into account.

### ***Correction of the buildings gravity effect***

The first consideration is that geothermal plants are likely to be located in urban areas. Thus the effect of surrounding buildings must be considered. To that purpose a computer program using the above mentioned algorithm was created to calculate the effect of a single prism representing a building. Each case used in table 3.1 and in figure 3.3 is described here below and its name is specified. The example of Nowell (1999) was first modeled to validate the program (building 1, figure 3.2). However in Switzerland most of the buildings are much smaller than the tall building in that study and thus other cases were generated. The first case is a six-floor building (building 2) and the other one is a small house (house) (see details in table 3.1). Density of the whole building is fixed to  $340 \text{ kg}\cdot\text{m}^{-3}$  consistently with Nowell (1999).

The gravity effect of the different buildings and their respective basements that were taken into consideration are presented in figure 3.3 (case basement 3 m and basement 6.9 m). This effect was computed by considering a density contrast of  $2670 \text{ kg}\cdot\text{m}^{-3}$  for the basement. In this figure it can be noticed that, especially for small buildings, the dominant gravity effect does not come from the building itself but from its basement as it has also been shown in the works of Radogna et al. (2004) and Altwegg (2006).

*Table 3.1: Dimensions of prisms taken into account to calculate the gravity effect of a building presented in figure 3.3. \*building size based on the study of Nowell (1999).*

| Case           | Width x length<br>(m) | Height above<br>ground (m) | Basement<br>height (m) |
|----------------|-----------------------|----------------------------|------------------------|
| Building 1*    | 27 x 27               | 100                        | 6.9                    |
| Building 2     | 27 x 27               | 18                         | 6.9                    |
| House          | 15 x 15               | 7                          | 3                      |
| Basement 6.9 m | 27 x 27               | 0                          | 6.9                    |
| Basement 3 m   | 15 x 15               | 0                          | 3                      |

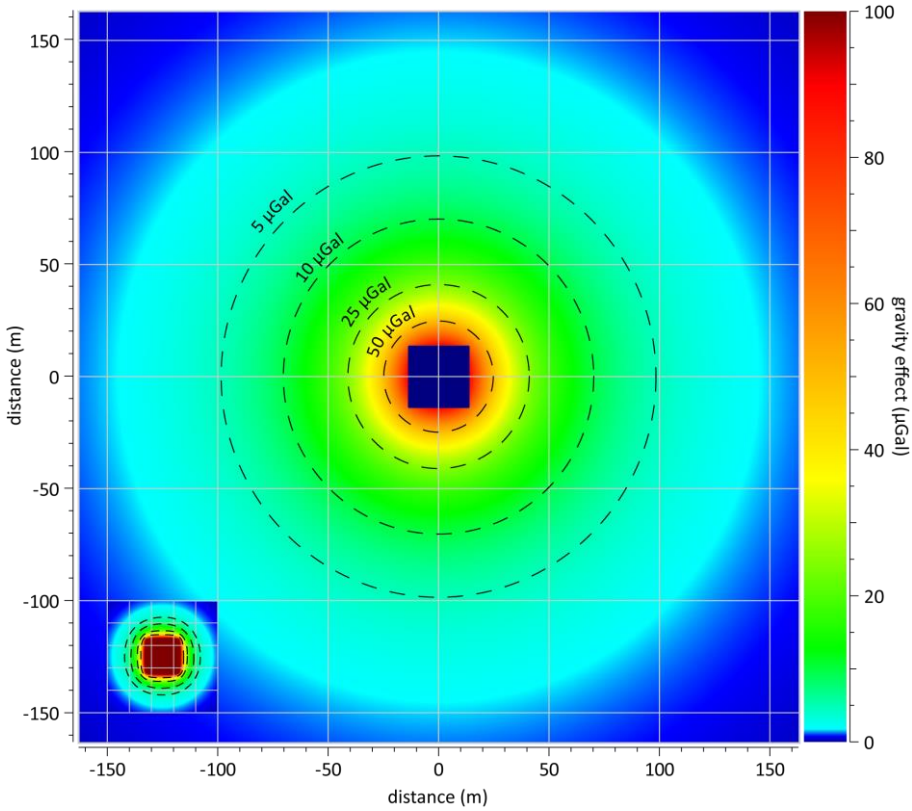


Figure 3.2: Gravity effect of a 27 x 27 m square building of 100 m height with basement's height of 6.9 m and an average density of  $340 \text{ kg}\cdot\text{m}^{-3}$  as presented in Nowell (1999). Bottom left: effect of the basement of a small house (basement 3 m case of table 3.1) density contrast  $2670 \text{ kg}\cdot\text{m}^{-3}$ . Scale is the same for the two presented cases.

This gravity effect of the buildings decreases quickly with distance and rapidly becomes negligible (figure 3.3). Even if this effect seems trivial, in urban environments gravity stations will not be influenced by a single building but by several and the sum of these small effects can reach several tenths of  $\mu\text{Gal}$ . Therefore it should be taken into account.

For the above-mentioned reasons only the effect of building basements will be considered and it can be directly computed with terrain correction. However, in the high accuracy DEM of Switzerland (Swisstopo, 2010a) terrain is continued straight through buildings and thus basements are not considered (figure 3.4, left). We thus corrected the DEM by removing a height of 2.5 m to the minimum altitude of every building, which is located at a distance of less than 200 m from each gravity station (figure 3.4, right) before calculating the terrain correction.

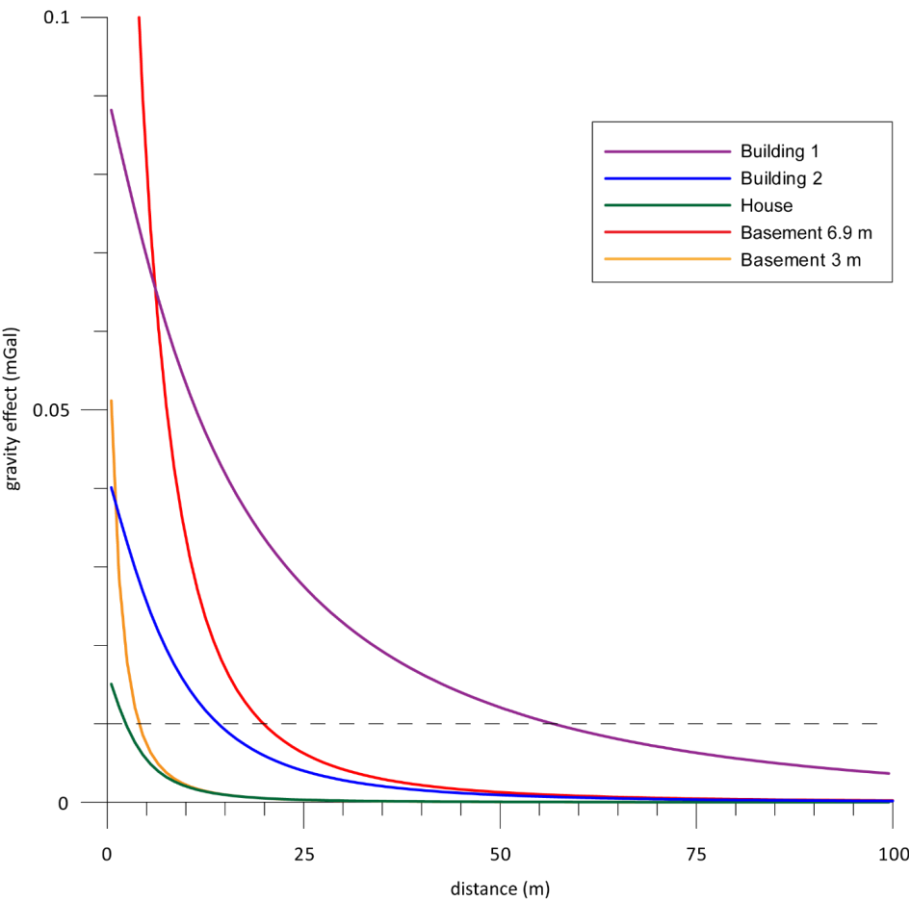


Figure 3.3: Gravity effect of the cases presented in table 3.1. The dashed line represents the measurement uncertainty limit of 0.01 mGal that can be considered for a CG-5 gravimeter. Distances are given from the outer limit of the buildings.

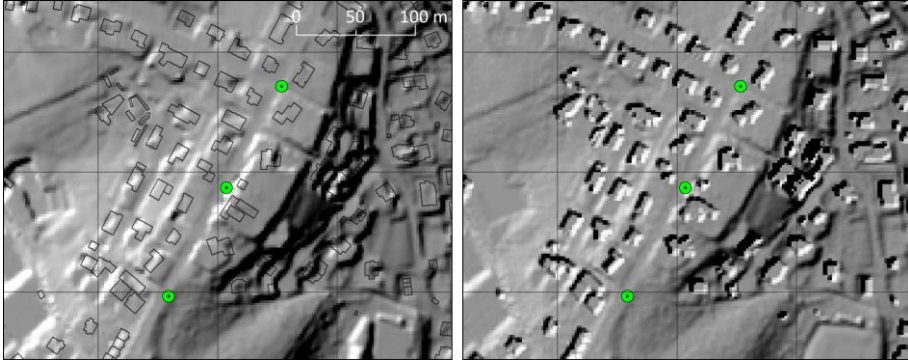


Figure 3.4, left: SwissAlti3D (Swisstopo, 2010a) 2m DEM in the north of the city Sankt Gallen with gravity stations (green dots) and position of the buildings from land registry. Right: DEM used for terrain correction: building basements were corrected (see text for explanations).

### Curvature correction

The classical terrain correction removes the effect of the plateau, also called Bouguer plate. However, the calculation represents the gravity effect of a flat disk and thus does not take earth's curvature into account. This can be done through the curvature or Bullard-B correction, which gives a correction value in mGal for every sector of Hammer's chart for terrain correction (Hinze et al., 2013; Nowell, 1999). However, as we want to calculate the terrain effect directly, so to say without using the Bouguer plate, we calculate the altitude difference induced by earth's curvature (figure 3.5) before calculating the effect of a prism.

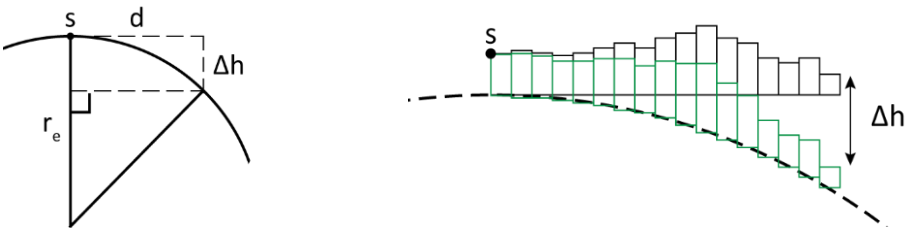


Figure 3.5, left: Altitude difference between a flat plane and earth. Right: Illustration of the effect of earth curvature on a DEM (not to scale). S: Measurement station;  $r_e$ : earth average radius;  $d$ : distance to measurement station;  $\Delta h$ : height difference.

If earth is considered as a perfect sphere with its radius equal to the Earth's average radius of 6371 km, the height difference can be calculated using the following simple formula:

$$\Delta h = r_e - \sqrt{r_e^2 - d^2} \quad (3.1)$$

where  $\Delta h$  is the height difference induced by earth's curvature;  $r_e$  is the Earth average radius and  $d$ , the distance to measurement station. Consistent units between the parameters must be used.

The use of the Earth's average radius in equation 3.1 causes a maximum error of 7.4 m at 167 km and therefore can be neglected. The effect on height is plotted on figure 3.6 together with an example of the curvature effect on terrain correction. For this latter, the difference on the gravity effect induced by earth's curvature was calculated from 5 to 167 km for a station at an altitude of 500 m, for a prism of 5 x 5 km, a height of 4 km and a bottom altitude of 0 m.

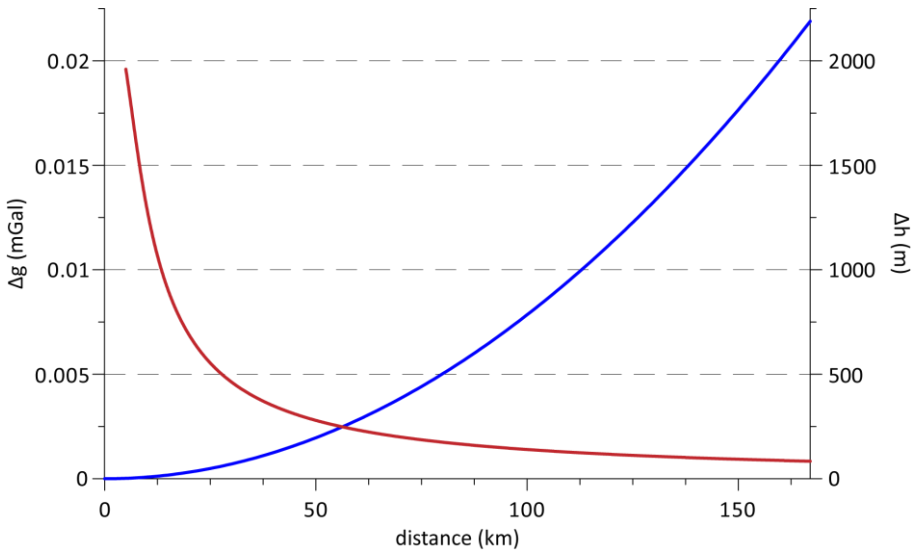


Figure 3.6: Height difference induced by earth curvature relative to the distance to the measurement station calculated using equation 3.1 (blue line) and difference on the gravity effect of a prism induced by earth's curvature (red line). Parameter of the prism: base, 5 x 5 km; height, 4 km, bottom is at an altitude of 0 m. Its gravity effect was calculated from 5 to 167 km for stations at an altitude of 500 m.

### ***Uncertainties linked with the terrain effect***

In order to quantify the uncertainty induced by the terrain correction, we calculated the terrain correction at the station of the first case study with DEM of decreasing cell size and for a density of  $1 \text{ g}\cdot\text{cm}^{-3}$ . This density is chosen as it, afterwards, allows us to quantify the uncertainty for any density. In this respect we only have to multiply the uncertainty obtained for the density of  $1 \text{ g}\cdot\text{cm}^{-3}$  by the desired density in  $\text{g}\cdot\text{cm}^{-3}$ .

The absolute difference between the calculated values is considered to represent the increase of uncertainty due to the increase of the cell size. For the inner zone, we used the 2 m DEM as reference and then resampled it to a cell size of 5, 10, 25, 50 and 100 m. Concerning the latter two, we also resampled the DEM used for the intermediate zone to the same cell size. We then plotted the average and maximum values for each cell size on a graph and used a power function regression considering that a DEM with a cell size of 0 m will induce no error (figure 3.7). Using these functions we can thus determine the maximum and average value of the uncertainty for a DEM with a 2 m cell size. However this number must still be multiplied by the chosen density for the Bouguer anomaly to obtain a usable value.

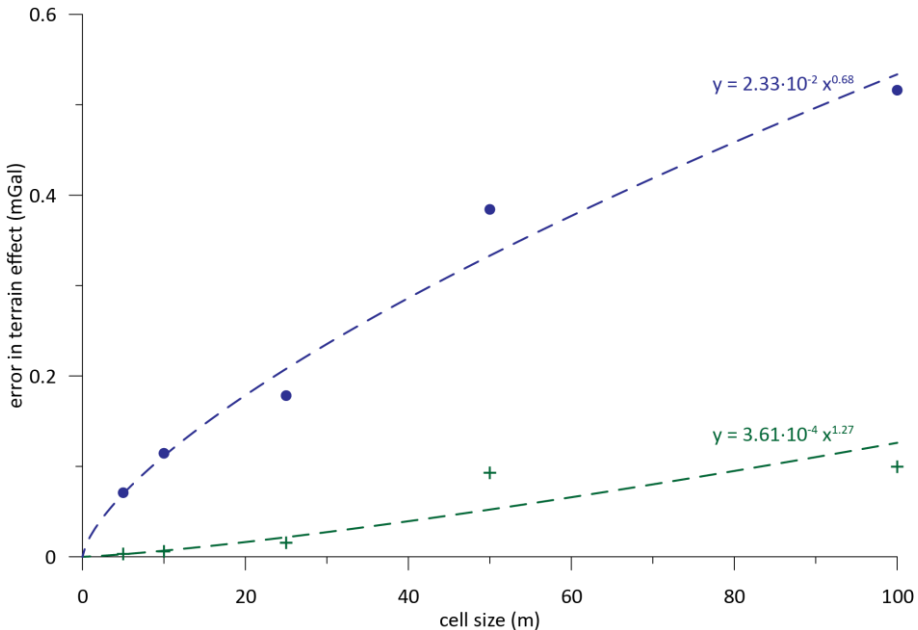


Figure 3.7: Maximum (blue dots) and average (green crosses) error in terrain effect induced by an increase of the cell size of the DEMs used for terrain effect determination. Regression using power functions (dashed line) was used in order to determine the value for the DEM with 2 m cell size used for the two case studies.

We also wanted to quantify the average and maximum effect of the building on the terrain effect and therefore calculated the terrain effect before and after its modification as presented previously. The absolute difference on the terrain effect value is thus induced by buildings and can be quantified. The value of the error on terrain effect linked with the cell size of the DEM as well as the effect of the buildings basements are presented in table 3.2. These values allowed us to determine that, for a DEM with a cell size of 2 m, an uncertainty of 0.1 mGal is realistic, and that the effect of the buildings can reach several tenths of  $\mu\text{Gals}$ .

*Table 3.2: Maximum and average error in terrain effect (in mGal) induced by an increase of the cell size of the DEMs used for terrain effect determination for three different densities. The effect of the buildings on the terrain effect was also determined. The cell size of 2 m is highlighted as it represents the cell size of the DEM used in our case studies.*

| DEM<br>cell size<br>(m) | $\rho = 1.0 \text{ (g}\cdot\text{cm}^{-3}\text{)}$<br>Unitary |       | $\rho = 2.57 \text{ (g}\cdot\text{cm}^{-3}\text{)}$<br>Case study:<br>Sankt Gallen |       | $\rho = 2.67 \text{ (g}\cdot\text{cm}^{-3}\text{)}$<br>Case study:<br>Eclépens |       |
|-------------------------|---------------------------------------------------------------|-------|------------------------------------------------------------------------------------|-------|--------------------------------------------------------------------------------|-------|
|                         | avg.                                                          | max.  | avg.                                                                               | max.  | avg.                                                                           | max.  |
| 0.5                     | 0.000                                                         | 0.015 | 0.000                                                                              | 0.037 | 0.000                                                                          | 0.039 |
| 1                       | 0.000                                                         | 0.023 | 0.001                                                                              | 0.060 | 0.001                                                                          | 0.062 |
| 2                       | 0.001                                                         | 0.037 | 0.002                                                                              | 0.096 | 0.003                                                                          | 0.100 |
| 5                       | 0.003                                                         | 0.070 | 0.008                                                                              | 0.179 | 0.008                                                                          | 0.186 |
| 10                      | 0.007                                                         | 0.112 | 0.019                                                                              | 0.287 | 0.020                                                                          | 0.298 |
| 25                      | 0.024                                                         | 0.208 | 0.061                                                                              | 0.534 | 0.064                                                                          | 0.555 |
| 50                      | 0.058                                                         | 0.333 | 0.148                                                                              | 0.856 | 0.154                                                                          | 0.890 |
| 100                     | 0.139                                                         | 0.534 | 0.356                                                                              | 1.372 | 0.370                                                                          | 1.425 |
| Building                | 0.002                                                         | 0.013 | 0.006                                                                              | 0.033 | 0.006                                                                          | 0.034 |

### 3.2.2 Regional – residual determination

Bouguer anomaly over the Swiss Molasse Basin shows a clear trend towards the Alps (figure 3.8). This trend is well known (e.g. Kahle et al., 1976; Klingelé, 2006) and represents the effect of lithospheric scale structures that are irrelevant for geothermal exploration. Therefore a regional anomaly was calculated by using the gravity stations from the Swiss Atlas of Gravity (Olivier et al., 2010) that are located within a maximum distance of 50 km from the limits of the case studies survey. Fitting a plane by polynomial regression then generated the regional anomaly. This method is used to ensure that no gravity effect linked with local or regional structures is removed.

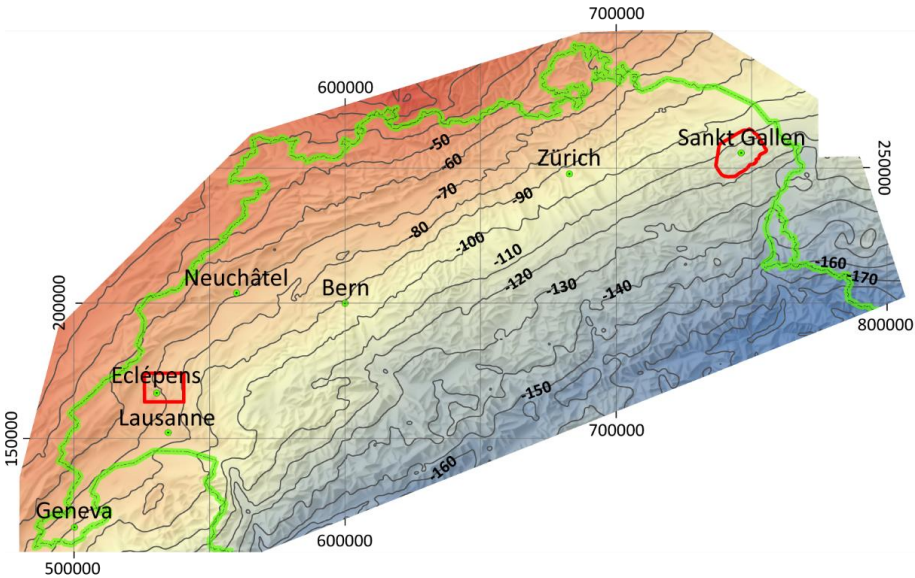


Figure 3.8: Bouguer Anomaly over the Swiss Molasse Basin calculated from the data of the Swiss Atlas of Gravity (Olivier et al., 2010) for a density of  $2670 \text{ kg}\cdot\text{m}^{-3}$ . Values of the anomaly are given in mGal, the red lines represent the survey areas of both case studies.

### 3.3 Gravity modeling

In this section we will present the different tools that were developed to follow the methodology presented previously. Two new computer programs created and tested during this work are presented below:

- GInGER - GravImetry for Geothermal ExploRation: this is the main software for 3D forward modeling and porosity determination.
- GInGERSP - GInGER Synthetic Profile: this is a standalone application which can be linked with GInGER for simple shapes modeling.

They are both written in C++ using the Qt framework (Digia plc., 2013) and Qwt – Qt widget for Technical Application (Rathmann and Wilgen, 2013) for efficient computation and a user-friendly Graphical User Interface (GUI). The dedicated sections for these tools are strongly modified after Altwegg et al. (2015).

#### 3.3.1 Base principles

When using Newton's Law of Universal Gravitation (section 2.3.2, p. 38) the mass of the considered body is concentrated at its mass center (figure 3.9, left). However, this simplification is only possible when the considered body is far from the measurement point and this is not the case in gravity exploration. It is not possible to simply calculate the gravity effect of a complex body. Therefore its shape must be approximated by much simpler form allowing easier calculation. In this study, we use rectangular prisms for forward modeling and thus the gravity effect of a body will be the sum of all the gravity effects of each prism made to approximate its shape (figure 3.9, right). The error induced by the approximation will decrease as the size of prisms become smaller. As the algorithm used in this work is from Blakely (1996), the following theoretical consideration are also adapted from this author.

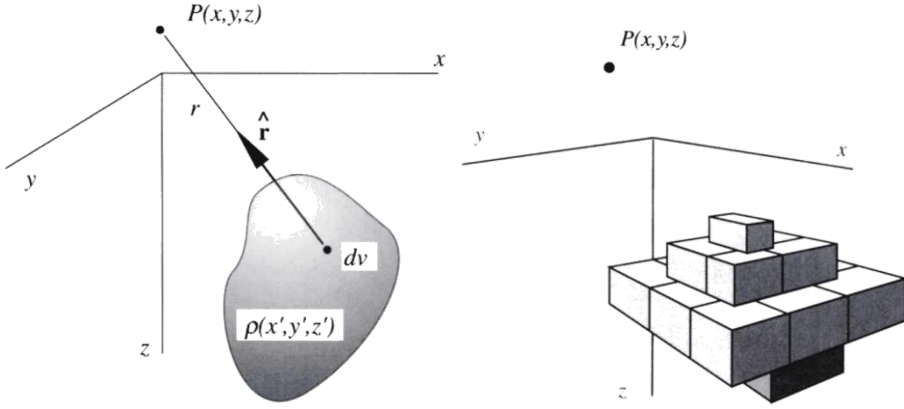


Figure 3.9: Modeling of a complex body using prisms (Blakely, 1996). Approximation is made using rectangular prisms small enough to render the shape and volume of the initial complex corpse. Coordinate system is Cartesian  $x$ ,  $y$  axes are right-handed and  $z$  axis is positive downward.

The gravity attraction due to a body of a given volume and density ( $\rho$ ) at point  $P$  is:

$$g_{(P)} = -G \int \rho \frac{\hat{r}}{r^2} dv \quad (3.2)$$

where  $r$  is the distance from  $P$  to an element of the body  $dv$  and  $G$  is the gravitational constant ( $6.674 \cdot 10^{-11}$  in  $\text{m}^3 \cdot \text{kg}^{-1} \cdot \text{s}^{-2}$ ). However, gravimeters measure the vertical component of gravity. The vertical effect of the considered body at point  $P$  in a Cartesian system with  $x$ ,  $y$  axes in a right-handed system and  $z$  direction downward, hereafter denoted as  $g$  is:

$$g = -G \int_{z'} \int_{y'} \int_{x'} \rho_{(x', y', z')} \frac{(z - z')}{r^3} dx' dy' dz' \quad (3.3)$$

where:

$$r = \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2} \quad (3.4)$$

The gravity effect of the body is the sum of the effect of each rectangular prism at point  $P$  (figure 3.9). The effect of a single prism is obtained through the integration of equation 3.3 within its limits ( $x_1 \leq x \leq x_2$ ,  $y_1 \leq y \leq y_2$  and  $z_1 \leq z \leq z_2$ ).

$$g = G\rho \int_{z_1}^{z_2} \int_{y_1}^{y_2} \int_{x_1}^{x_2} \frac{z'}{[x'^2 + y'^2 + z'^2]^{\frac{3}{2}}} dx' dy' dz' \quad (3.5)$$

Equation 3.5 can be simplified by moving the observation point to the origin. Then the following derivation can be obtained (Plouff, 1976; in Blakely, 1996):

$$g = G\rho \sum_{i=1}^2 \sum_{j=1}^2 \sum_{k=1}^2 \mu_{ijk} \left[ z_k \tan^{-1} \frac{x_i y_i}{z_k R_{ijk}} - x_i \log(R_{ijk} + y_i) - y_i \log(R_{ijk} + x_i) \right] \quad (3.6)$$

where:

$$R_{ijk} = \sqrt{x_i^2 + y_j^2 + z_k^2}$$

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

Thus, equation 3.6 allows for the calculation of the contribution of a rectangular prism from any given point in space. It is thus possible to calculate the effect of every prisms of figure 3.9 (right) and sum them to obtain the effect of the complex body. To that purpose, we used the algorithm “gbox” based on this equation and presented in Blakely (1996) translated into C++/Qt. The C++ version is given in Appendix A as it is the core algorithm that allows the computation of model’s gravity effect. Nevertheless, care must be taken with the placement of the observation point. Indeed as it can be noticed in equation 3.6, if the observation point is equal to one of the vertex of the prism there is no solution.

### 3.3.2 2D forward modeling

The tool developed for 2D forward modeling was used both to make the synthetic case study of the Sankt Gallen case study (chapter 4) and to validate the algorithm presented before. It is also important to mention that this tool is the predecessor of the 3D forward modeling tool which uses the same algorithm and base principle. Thus, the validation of the 2D tool will also validates the implementation of the algorithm in the tool developed for 3D forward modeling (section 3.4).

The 2D forward modeling follows the workflow presented here below:

1. Creation of a synthetic vector model
2. Setting of densities for every polygon
3. Conversion to raster grid
4. Calculation of model's gravity effect

This process is repeated from point 1 if the model must be changed or from point 2 if only the densities must be changed.

The synthetic vector model is created using ArcGIS (ESRI, 2011) with a polygon shapefile, which covers all the model extension. A density value is then given as an attribute to every polygon. This vector model is then converted into a raster grid. Indeed, a raster grid is formed of cells, in our case, of constant dimensions, that simplify the use of the above presented “gbox” algorithm (Blakely, 1996, appendix A).

In this purpose, each cell of the grid is considered to be a rectangular prism of infinite length perpendicular to the profile, and its density is the value stored in the grid. The effect of the model is thus obtained by summing the gravity effect of each prism at the different chosen point along the profile.

### ***Tool validation***

In order to validate the implementation of the “gbox” algorithm into our computer program, we compared the gravity effect from simple bodies calculated with our application with the one calculated using a commercial application (figure 3.10 and 3.11). We used the lab version of GM-SYS, Gravity/Magnetic Modeling Software (v. 4.8.43, Northwest Geophysical Association, 2002), which is based on the work of Talwani et al. (1959) and Won and Bevis (1987). These two latter works allow the calculation of the gravity effect of polygonal shaped bodies, but as the modeling concept of the two applications are not the same, we expect some little differences.

The first step of the validation consists in modeling a body with a rectangular cross section of a given density in the two programs (Figure 3.10). This shape was chosen mainly to quantify the difference implied by the use of the different algorithms and to minimize the error linked with the approximation of the model into a grid.

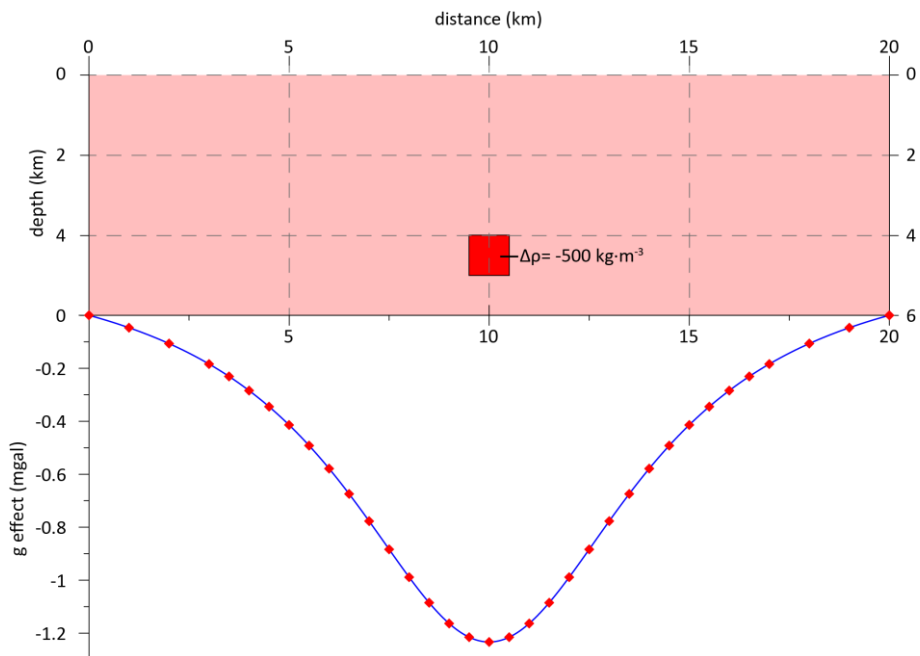


Figure 3.10: Gravity effect of an infinite, horizontal and rectangular prism of 1x1 km, the top of the prism being at a depth of 4 km. This gravity effect was calculated once with GM-SYS (Northwest Geophysical Association, 2002) (red diamonds) and once with our 2D forward modeling tool (blue line).

For the second model we wanted to test if the multiplication of the prisms, their depth, their size or the use of multiple densities has an effect (figure 3.11). For this purpose we added two bodies of square cross section to the model of figure 3.10. A smaller prism with the same density contrast (compared with the first model) at a depth 1 km shallower and a prism of the same size but with a lower density contrast closer to the surface.

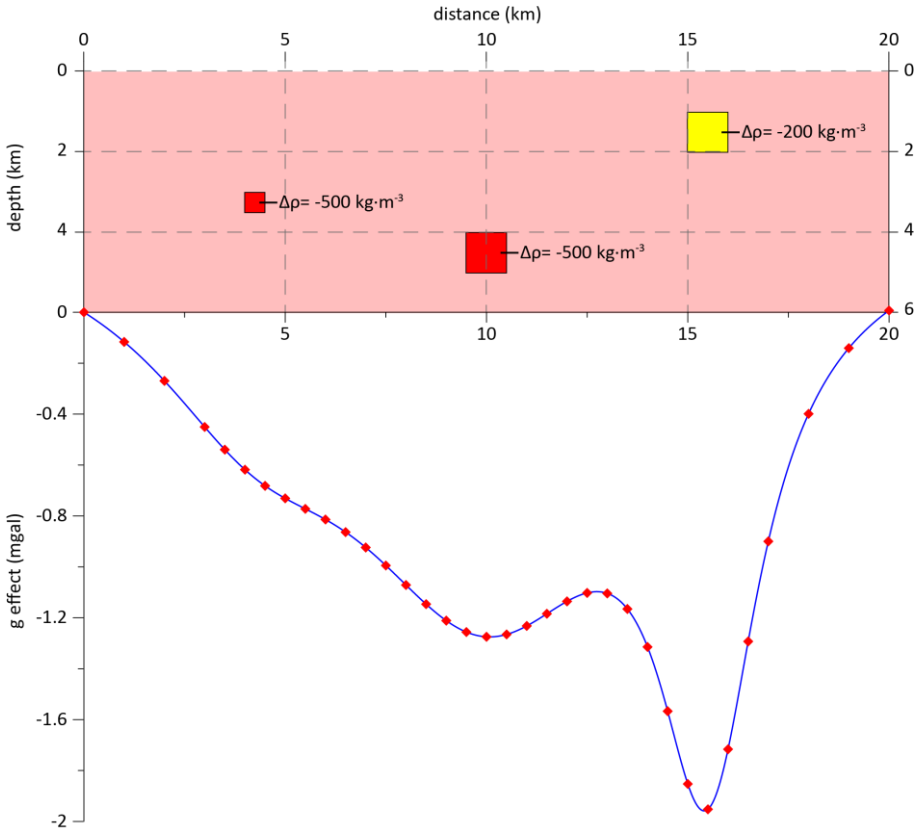


Figure 3.11: Gravity effect of three infinite, horizontal and rectangular prisms. This gravity effect was calculated once with GM-SYS (Northwest Geophysical Association, 2002) (red diamonds) and once with our 2D forward modeling tool (blue line). Parameters for the prisms from left to right, and the given depth represents the top of the prism: 0.5x0.5 km and 3 km deep; 1x1 km and 4 km deep; 1x1 km and 1km deep.

Given that the standard error of a CG-5 gravimeter is 5  $\mu\text{Gal}$ , we can see in table 3.3 that the observed difference between the two programs is at least 20 times under the measurement error and, is probably due to the difference of algorithm used for the calculus. As it can be noticed on figures 3.10 and 3.11 the number of observation points for GM-SYS is limited to a maximum of 35 points for the lab version. This is not the case for our program, and may thus also be a source of these differences.

Table 3.3: Difference between the gravity effects calculated with GM-SYS and the 2D forward modeling program for the two cases with prisms.

| Case     | Mean difference (μGal) | Maximum difference (μGal) |
|----------|------------------------|---------------------------|
| 1 prism  | 0.017                  | 0.036                     |
| 3 prisms | 0.17                   | 0.25                      |

Therefore, we chose to make a test case closer in scale to a real case: a synthetic model of the Rhine Graben located between south-western Germany and north-eastern France. For this case, the gravity effect of the model was calculated using the two programs on every virtual observation point (figure 3.12). These points were placed every 100 m along the 60 km of the profile and a simple topography was also considered. As for the previous models the observed difference between the two programs is very small: the maximum difference is 1 μGal and the mean difference is 0.6 μGal. This implies that with an anomaly range of almost 29 mGal, it represents less than 1 ‰ (0.03 ‰ exactly) and can thus be considered as negligible.

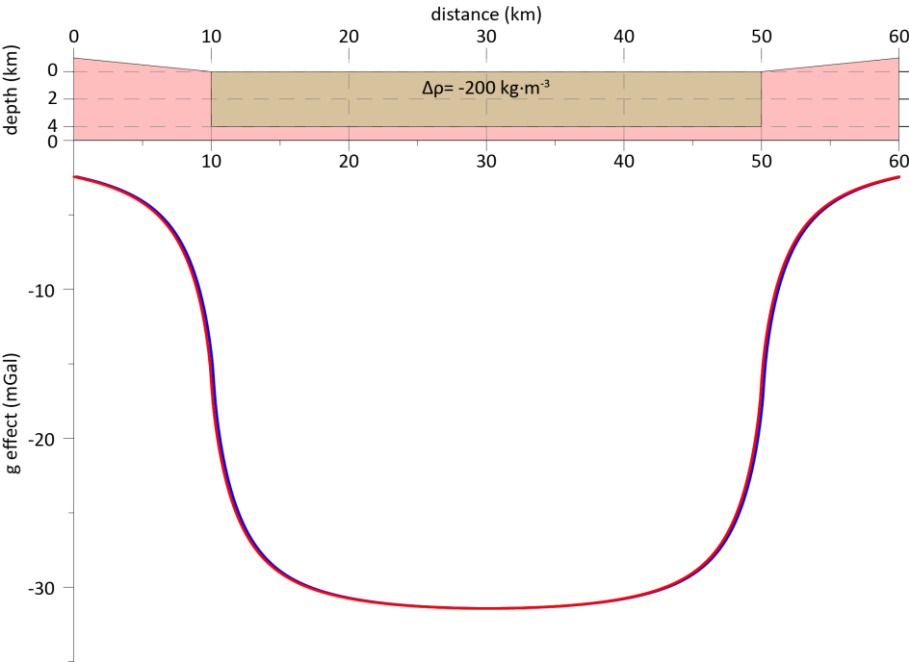


Figure 3.12: Gravity effect of a synthetic model of the Rhine Graben. This gravity effect was calculated with GM-SYS (Northwest Geophysical Association, 2002) (red line) and with our 2D forward modeling software (blue line).

### 3.4 GInGER: GravImetry for Geothermal ExploRation

The main aim of GInGER is to provide a user-friendly tool for computation of the gravity effect of a 3D geological model on the topography.

The main simplified workflow is presented in figure 3.13. The different key elements are described in this subchapter following the order of this workflow. The first section (3.4.1) describes how the different geological layers are loaded, discretized and handled in the application. The next section (3.4.2) is dedicated to the calculation of what is named “unitary gravity effect” of the model and how the final gravity effect is calculated.

As previously mentioned, fault zones are often targeted by geothermal projects as they may present an increase of porosity which could be an indicator of better permeability. Section 3.4.3 describes how fault zones are implemented and handled in GInGER as well as how their linked increase of porosity is calculated.

The setting of the density for each geological element of the model is central as it directly controls the gravity effect of the model. In this respect, in GInGER, two approaches are possible (figure 3.13). The densities can directly be set by the user and refined using a trial-and-error method (forward method) or densities can be determined using inversion. We would like also to point out that this latter option allows determining the uncertainty linked with the different densities. Section 3.4.4 describes how inversion on densities is carried out and also presents its validation.

To be users-friendly, we wanted all of the program’s functions to be able to be used through a Graphical User Interface (GUI). To this purpose we used the Qt framework (Digia plc., 2013), which has the advantage to be cross platforms (Unix, Windows, MacOS, Android, iOS). In addition, we used the Qwt – Qt widget for Technical Application (Rathmann and Wilgen, 2013), because it allows the use of graphics and the representation of georeferenced raster and grids. Finally section 3.4.5 presents the elements of the GUI, for a more precise description of every elements, check the user manual (Altwegg, 2015).

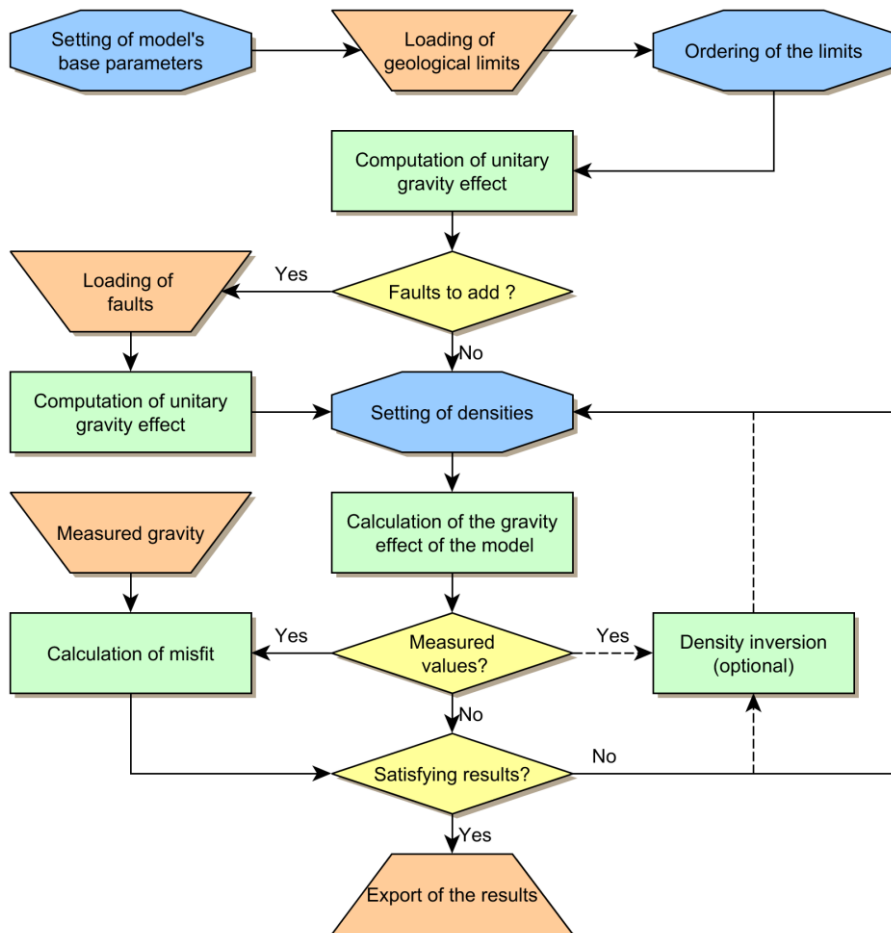


Figure 3.13: Simplified general workflow of GInGER. Orange shapes represent external files; green shapes calculation; blue shapes user actions, and yellow shapes are logical tests. Dashed lines represent optional actions.

### 3.4.1 Geological model

In GInGER the geological model is defined as a stack of geological layers. It is limited at its top by the topography and at the bottom by an altitude chosen by the user. A geological layer is determined as the volume contained between its top and bottom geological limits. This is done in order to reduce as much as possible the number of prisms, for which gravity effect must be calculated, without losing accuracy in the z direction. Each layer is also considered to have a constant density.

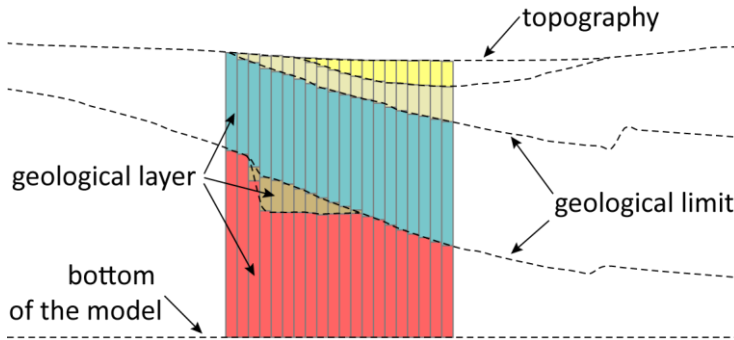


Figure 3.14: Conceptual 2D profile presenting how the geological layers (colored areas) are created from the geological limits (dashed lines). The gray rectangles represent the different prisms from the input grids.

The geological limits are defined by at least one grid containing its altitude within the extent of the model. Two cell sizes are possible for the grids and will be referred as “fine” and “coarse”. These cell sizes are determined when loading the topographic grids, which happens when creating a new project. The fine cell size is used to allow a precise calculation of the gravity effect of the topography and of near-surface limits in the vicinity of the points where gravity is calculated.

However these two cell sizes must be compatible, namely the coarse cell size must be a multiple of the fine cell size and all the grids must have the same x, y extent. The accepted grid formats are the ESRI ASCII grid (.txt or .asc), presented in the manual (Altwegg, 2015), the ESRI binary grid format (.ovr) and GInGER binary grid (.gbg) a specific binary format developed specially for our program. Binary format were added in order to speed up the loading time, which can become quite long for large ASCII file, i.e. the fine topographic grid.

The user has the possibility to change the order of the limits in the stratigraphic pile. The number of layers is determined by the number of limits. The top and

bottom limits of each layer are determined by the stratigraphic pile. Figure 3.15 presents the geological dockable window containing the geological information. Geological limits are on the left, the number is the stratigraphic position that is followed by the name of the limit. The three little circles give information on which grids are contained (green) or not (red) by the limit: The first circle is for the fine grid which is not mandatory except for topography; the second is for the coarse grid and the third is for the unitary gravity effect grid (see next section for detail). On the right the geological layers are shown with their name, density and the color used on the geological profile (see section dedicated to the GUI for details).

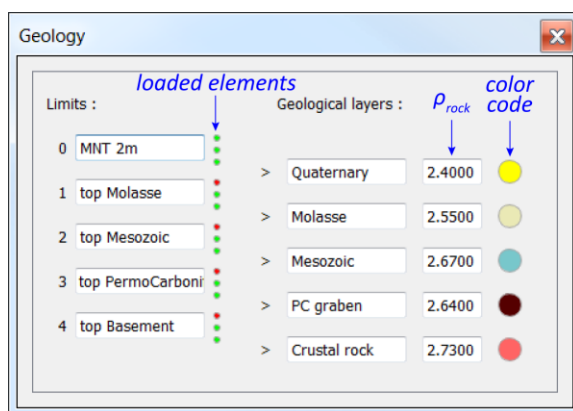


Figure 3.15: Geological information contained in the dockable window of GInGER, see text for detailed description.

### 3.4.2 Calculation of gravity effect

The gravity effect of the model is obtained by calculating and summing the gravity effect of every layer at virtual observation points located at the center of each cell of the coarse topographic grid. As the grid determining the top and bottom of each layer has the same extent and cell size, prisms geometry determination is straightforward. The gravity effect of each prism can then be calculated using the “gbox” algorithm (Blakely, 1996, appendix A) presented previously. Moreover, this calculation has been parallelized using the QtConcurrent API to speed up calculation.

To avoid unwanted effects due to approximation of the geological limits which are close to the virtual measurement station, we use the same principle as for topographic correction: the effect close to the station is calculated with a finer grid compared to the rest of the model (figure 3.16).

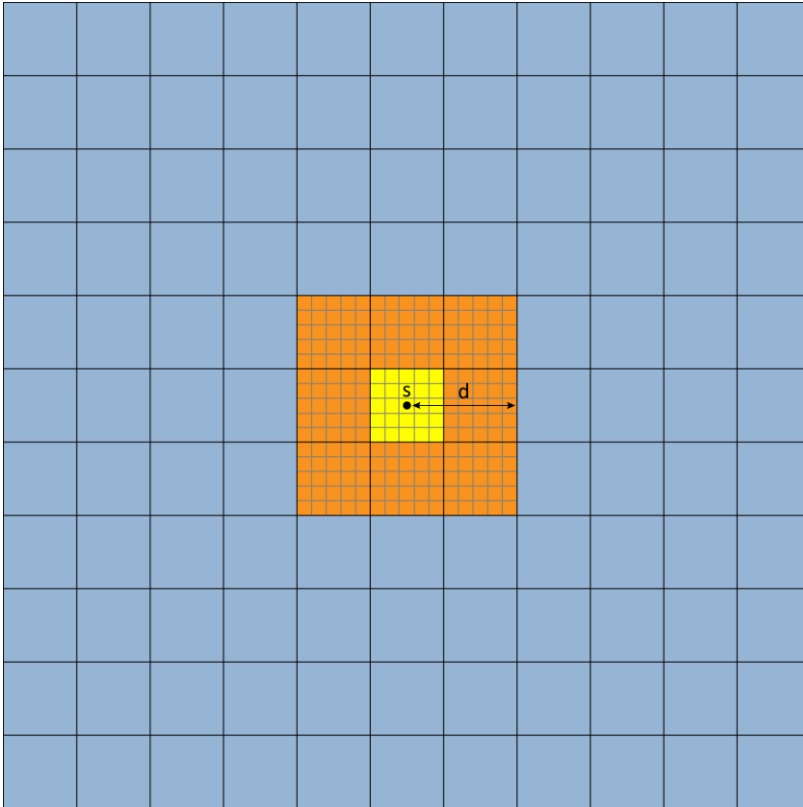


Figure 3.16: Calculation of the gravity effect of the geological model (blue square) at a virtual observation station ( $s$ ) located at the center of a cell (yellow square). A finer grid (orange square) is used to a distance  $d$  (see text for explanation) to the station to avoid averaging errors due to coarse size.

For that purpose, the cells of the coarse grid near the station are “replaced” by the fine grid. This is the reason why the two cell sizes must be compatible: to avoid the creation of holes, or that the gravity effect of part of the model is considered twice. The number of cells of the coarse grid that must be removed is calculated using equation 3.7, and 200 m was chosen as a limit to be coherent with terrain correction.

$$n = \frac{200}{c} - 1 \quad (3.7)$$

with  $n$ : the number of cells (in orange and yellow in figure 3.16) that are replaced by the fine grid and  $c$ : the coarse cell size.

Equation 3.6, is used for the calculation on the gravity effect of a single prism, shows that the density  $\rho$  is outside the summation. This observation allows optimization of the code, using what we called unitary gravity effect (i.e. figure 3.13). Indeed, instead of multiplying the effect of the prism by the layer’s density, it is multiplied by one and the result is stored in a grid which has the same extent and cell size as the coarse topographic grid. All the values of this grid are then multiplied by the layer’s density only when needed. This unitary gravity calculation implies that when the user wants to change the density of a layer, only this multiplication must be made again and not the whole gravity model calculation. This allows the user to see the effect of a layer’s density change in real-time.

### 3.4.3 Faults management<sup>1</sup>

By definition a fault is: “Approximately plane surface of fracture in a rock body caused by brittle failure, and along which observable relative displacement has occurred between adjacent blocks” (Allaby, 2013). Available data from the seismic interpretation are linear single fault sections indicated by offset in the reflectors. These traces are then used to interpolate the fault plane but as these planes have no volume, the only gravity effect will be the effect induced by the possible shift of the geological layers. Nonetheless “...faults are not simple planar features but highly complex zones within which displacement and strain are concentrated onto one or several discrete slip surfaces or zones of intense shearing, enclosing variably strained rock volume” (Childs et al., 2009). Due to this complexity nomenclature of the different components of a fault varies (e.g. Chester and Logan, 1986; Childs et al., 2009, figure 3.17) and it is not the aim of this work to make a comparison between the different proposed terminologies. Therefore we will use the term of fault zone as used by Child et al. (2009, figure 3.17 left) which is the zone where most of the slip has occurred and which includes fault planes, fault gouge and cataclasis.

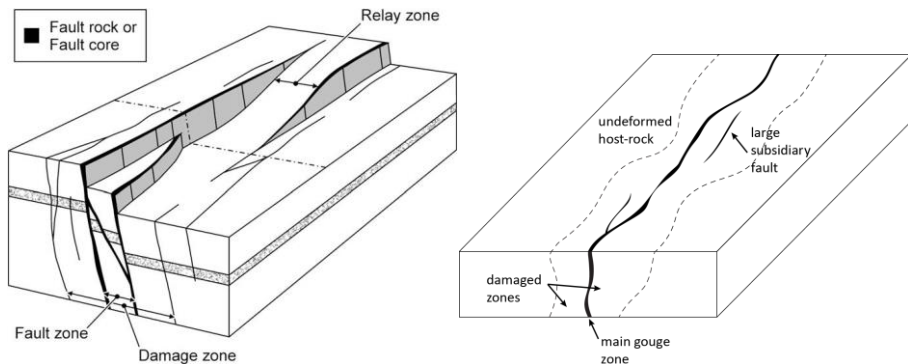


Figure 3.17: Different block diagram used for fault components nomenclature. Left: schematic diagram comparing the terms fault rock, fault zone and relay zone (after Childs et al., 2009). Right: block diagrams with structural-mechanical units of an idealized brittle fault zone (after Chester and Logan, 1986).

<sup>1</sup> This section is modified after Altwegg et al., subm.

Fault zones are also surrounded by a damage zone which is an associated zone of fracture (Kim et al., 2004; Shipton et al., 2006). Both, the damage zone and the fault zone are of critical importance as, if the fractures are not filled with mineralization, they will locally increase rock porosity which may results in a local increase of permeability. Therefore lots of attention has recently been given to damage zones as they are of critical importance for fluid flow in the crust (Faulkner et al., 2011). Another point is if this fracture porosity stays open and is filled with fluid (e.g. gas, water), this will decrease the rock bulk density and thus have an effect on gravity.

The effect of the shift of the geological layers is included in the calculation of the effect of the geological model. However, in order to calculate the gravity effect of fracture porosity, we have to create volumes, which are considered to be affected by the fault. In GInGER this volume of different density is represented by an upper and a lower grid. These grids can either be directly loaded or generated in GInGER. The simplified workflow is presented in figure 3.19. The determination of the damage zone of a fault zone is still debated as its size will depend on lots of factors such as rock type, type of fault, constraint etc. (e.g. Shipton et al., 2006). We however present as an example the proposition of Faulkner et al. (2011) who suggest that the damage zone width is correlated with the displacement of the fault zone (figure 3.18).

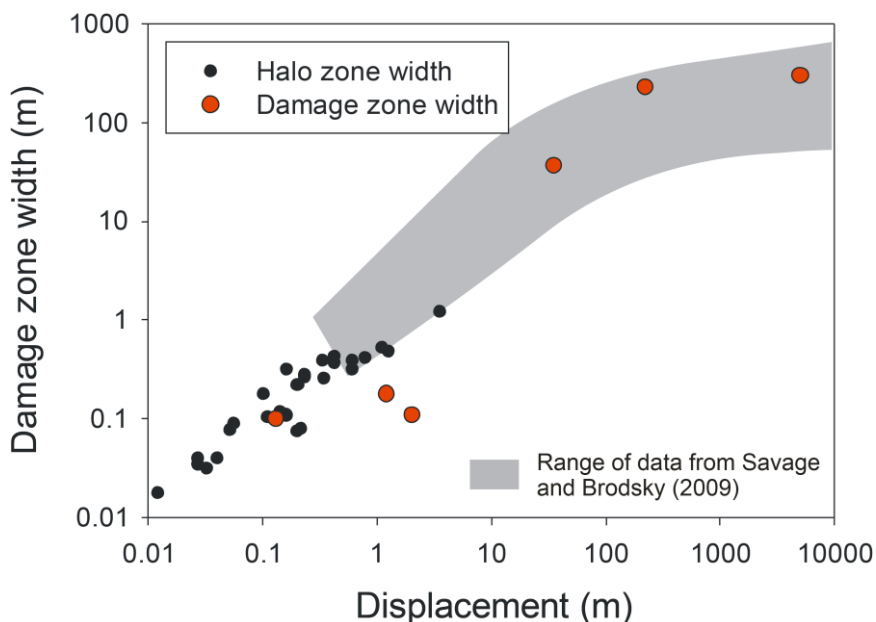


Figure 3.18: Compilation of data for damage zone width versus displacement (Faulkner et al., 2011).

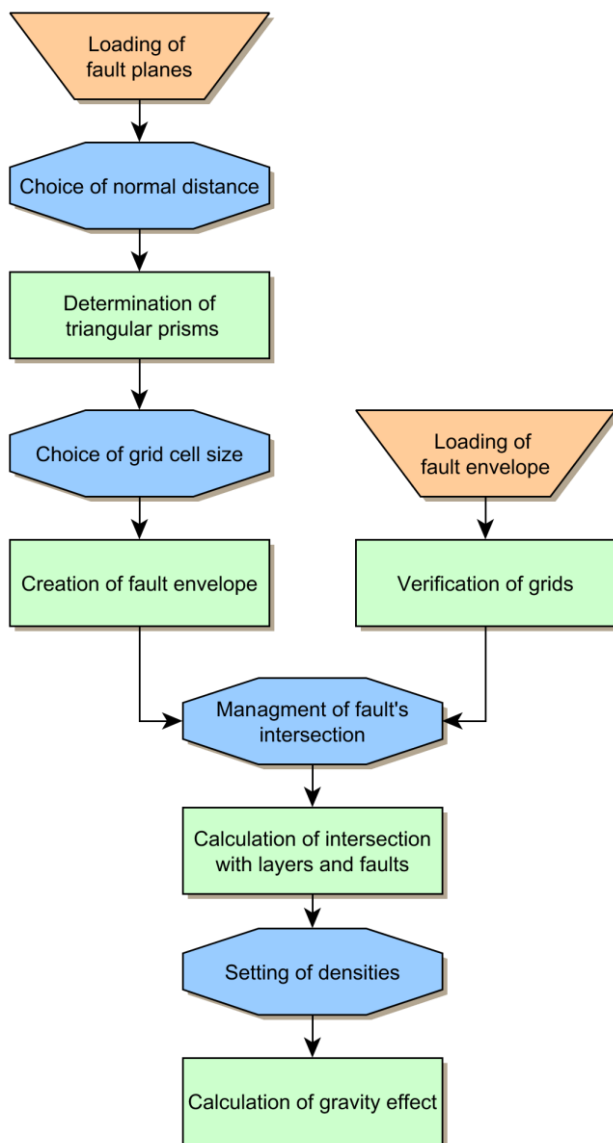


Figure 3.19: Simplified workflow for faults management in GInGER. Orange shapes represent external files; green shapes calculation and blue shapes user actions.

### ***Determination of the damage zone***

In the case where the affected volume cannot be directly loaded by the user, it is possible to generate it using GInGER. This section presents the methodology used to generate the damage zone (volume) using fault planes. Once generated, this volume is approximated by an upper and a lower grid representing the envelope or outer limit of the damage zone. These two grids have the same extent and the same cell size, to allow the calculation of the gravity effect in GInGER. The basic principle of the generation of the damage zone, presented in figure 3.20 on a profile, is to translate the fault plane perpendicularly, on both sides, by a distance ( $d$ ) chosen by the user.

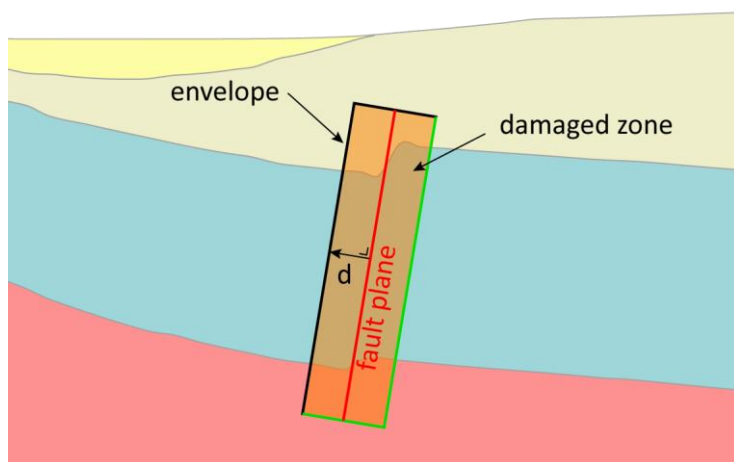


*Figure 3.20: Principle for the determination of the damage zone (orange area) using a fault plane (red line) and its envelope (black and green lines). The envelope approximated by an upper (black line) and lower (green line) grid.  $d$  is the distance by which the fault plane is translated perpendicularly.*

However, one of the most common ways to represent 3D surfaces in geological modeling programs is to use triangulated surfaces as presented in figure 3.21. To load the fault plane in GInGER, we use the ASCII drawing exchange format (.dxf), as it is a common export option of modeling software like GeoModeller (Intrepid Geophysics, 2013), GOCAD (Paradigm Software, 2011), as well as in mapping and GIS application i.e. ArcGIS (ESRI, 2011). It also allows representing complex or curved structures as shown on figure 3.21.

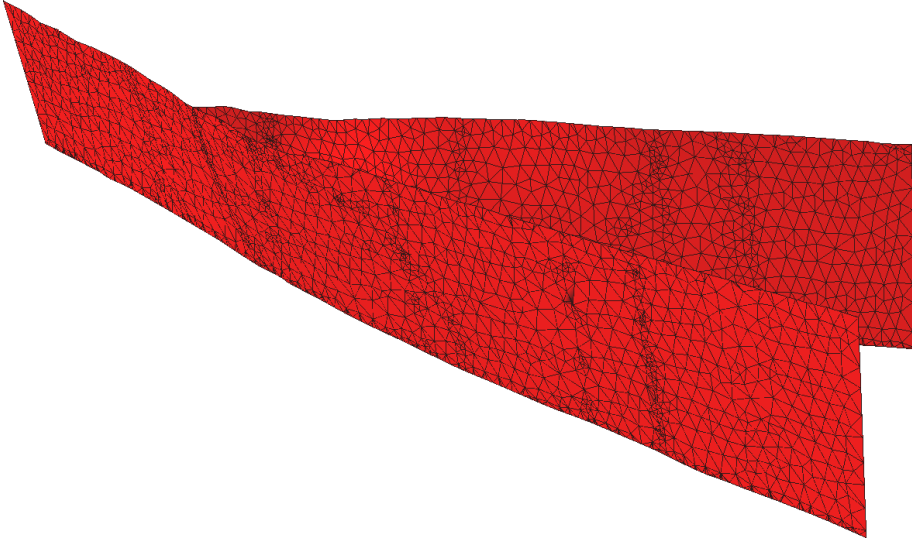


Figure 3.21: Example of triangulated surface of two fault planes in GOCAD.

In this respect, the generation of the damage zone follows the following steps described in more detail further in this section:

1. Every triangle of the surface is transformed into a volume, in our case a prism with a triangular cross-section.
2. The envelope of the damage zone is computed and is defined as the outer limit of the volume formed by all of the generated prisms.
3. The envelope of the damage zone is approximated by an upper and a lower grid.

### ***Creation of the prisms***

Given that the system is orthonormal and is defined by:

$$O \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}; \vec{e}_1 \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}; \vec{e}_2 \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}; \vec{e}_3 \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad (3.8)$$

The plane passing by the three vertices of a triangle A, B and C is defined by the  $\overrightarrow{AB}$  and  $\overrightarrow{AC}$  vectors; the dip angle ( $\alpha$ ) is equal to the angle formed by the line of steepest slope with the horizontal plane and is equal to the angle formed by the vertical vector  $\vec{e}_3$  and  $\vec{n}$ , normal vector to the plane (figure 3.22):

$$\vec{n} = \overrightarrow{AB} \times \overrightarrow{AC} \text{ and } \cos \alpha = \frac{\vec{n}}{\|\vec{n}\|} \cdot \vec{e}_3 \quad (3.9)$$

M is the centroid of the A, B and C triangle:

$$M = \frac{1}{3}(\overrightarrow{OA} + \overrightarrow{OB} + \overrightarrow{OC}) \quad (3.10)$$

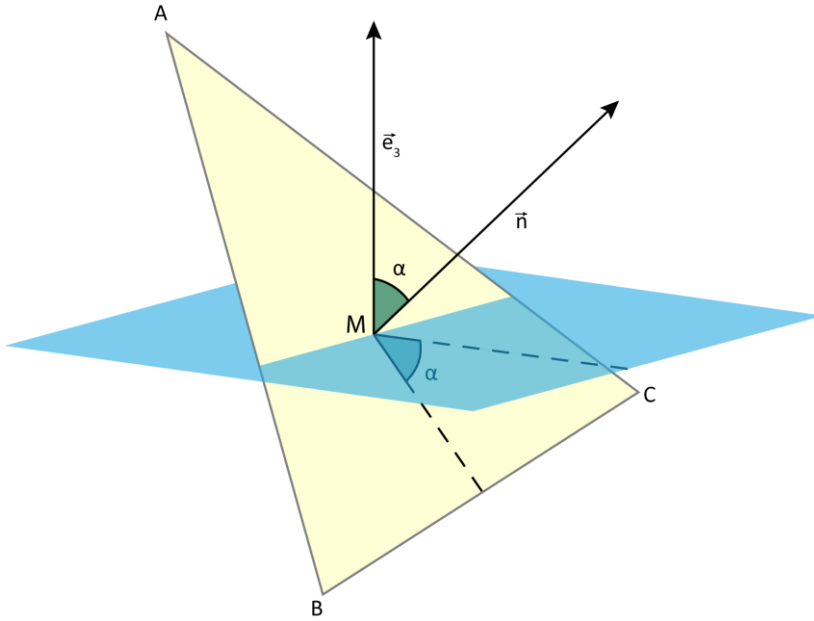


Figure 3.22: Triangle with base parameters used for the calculus in GInGER. A, B, C: vertices of the triangle; M centroid of the triangle;  $\alpha$ : dip angle;  $\vec{e}_3$ : vertical vector;  $\vec{n}$ : normal vector to the plane passing by A, B and C. The blue plane is horizontal.

In order to simplify the calculus of the conversion between volume and grid and to reduce the induced approximation as much as possible, we project the triangle either on a vertical or a horizontal plane. This projection is, naturally, only carried out if the plane is not already vertical or horizontal. The dip angle ( $\alpha$ ) is used to determine on which plane it will be projected. Indeed, if the dip angle is above or equal to  $45^\circ$  the triangle is projected on a vertical plane, if not it is projected on a horizontal plane. The proof of this projection, given here below is given for the vertical projection but is equally valid for the projection on the horizontal plane (refer to figure 3.23 for the naming).

The vertical plane ( $\pi$ ) on which the projection is carried out is defined by the vertical line passing by M (with  $\vec{e}_3$  for director vector, figure 3.22 and 3.23),  $\vec{n}'$ , the projection of  $\vec{n}$  on the horizontal plane (blue plane, figure 3.22) and  $\vec{d}$ , perpendicular to the normal:

$$\vec{n}' = \begin{pmatrix} n_1 \\ n_2 \\ 0 \end{pmatrix}; \vec{d} \perp \vec{n}' \Rightarrow \vec{d} = \begin{pmatrix} n'_2 \\ -n'_1 \\ 0 \end{pmatrix} \quad (3.11)$$

$\pi$  is, as defined previously, a vertical plane perpendicular to  $\vec{n}'_u$  and passing by M. Thus a point P will belong to  $\pi$  if:

$$\overrightarrow{OP} = \overrightarrow{OM} + \lambda \vec{d} + \mu \vec{e}_3 \quad (3.12)$$

The projection on  $\pi$  is made by computing the intersection between  $\pi$  and the lines passing by the vertex of the triangle and with  $\vec{n}$  as director. Projection of A, B, C on  $\pi$ , with  $A_p$ ,  $B_p$ ,  $C_p$  the projected points:

$$\begin{aligned} \overrightarrow{OA_p} &= \overrightarrow{OA} - (\overrightarrow{MA} \cdot \vec{d}) \vec{d} \\ \overrightarrow{OB_p} &= \overrightarrow{OB} - (\overrightarrow{MB} \cdot \vec{d}) \vec{d} \\ \overrightarrow{OC_p} &= \overrightarrow{OC} - (\overrightarrow{MC} \cdot \vec{d}) \vec{d} \end{aligned} \quad (3.13)$$

These points are then translated by vector  $\vec{t}$ , and  $-\vec{t}$ , this vector is equal to  $k$  times the normalized normal vector of the initial planes ( $\vec{n}_u$ ). Thus:

$$\vec{n}_u = \frac{\vec{n}}{\|\vec{n}\|} \text{ and } \vec{t} = k \vec{n}_u \quad (3.14)$$

where  $k$  is the distance chosen by the user. We can thus obtain the six vertices of the prism ( $A'_p$ ,  $B'_p$ ,  $C'_p$ ,  $A''_p$ ,  $B''_p$ ,  $C''_p$  of Figure 3.23).

$$\begin{aligned} \overrightarrow{OA'_p} &= \overrightarrow{OA_p} + \vec{t} & \overrightarrow{OA''_p} &= \overrightarrow{OA_p} - \vec{t} \\ \overrightarrow{OB'_p} &= \overrightarrow{OB_p} + \vec{t} & \overrightarrow{OB''_p} &= \overrightarrow{OB_p} - \vec{t} \\ \overrightarrow{OC'_p} &= \overrightarrow{OC_p} + \vec{t} & \overrightarrow{OC''_p} &= \overrightarrow{OC_p} - \vec{t} \end{aligned} \quad (3.15)$$

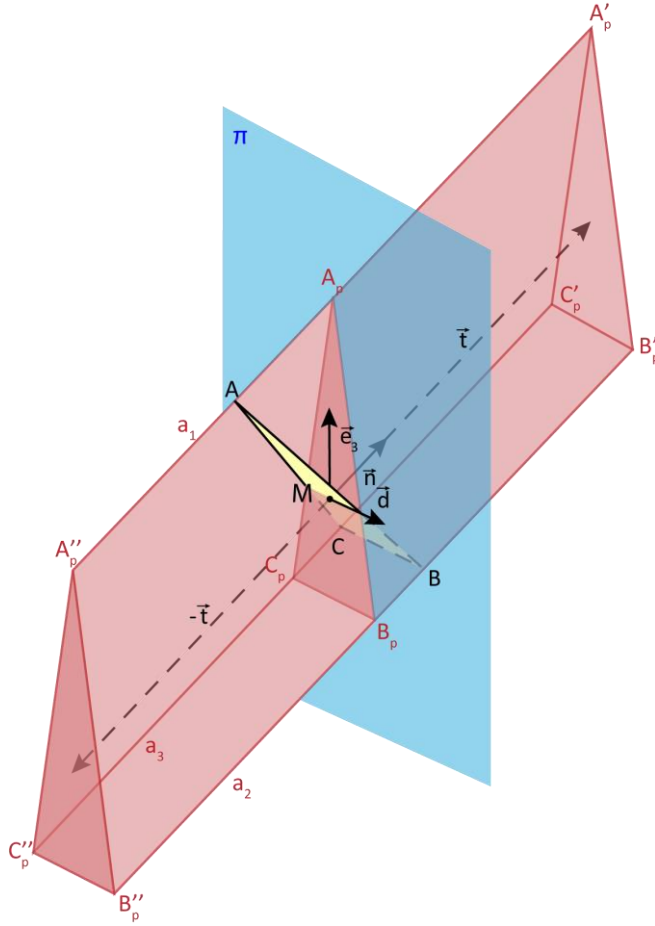


Figure 3.23: Transformation of a triangle  $(A, B, C)$  into a triangular prism with vertical top and bottom, see text for detailed description.

We can therefore define the line containing the edges  $(a_1, a_2, a_3)$  and the plane bearing the rectangular sides  $(f_1, f_2, f_3)$  of the prism:

$$\begin{aligned}
 f_1: \overrightarrow{OP} &= \overrightarrow{OA} + \lambda \frac{\overrightarrow{AB}}{\|\overrightarrow{AB}\|} + \mu \vec{n}_u & a_1: \overrightarrow{OP} &= \overrightarrow{OA} + \lambda \vec{n}_u \\
 f_2: \overrightarrow{OP} &= \overrightarrow{OB} + \lambda \frac{\overrightarrow{BC}}{\|\overrightarrow{BC}\|} + \mu \vec{n}_u & a_2: \overrightarrow{OP} &= \overrightarrow{OB} + \lambda \vec{n}_u \\
 f_3: \overrightarrow{OP} &= \overrightarrow{OC} + \lambda \frac{\overrightarrow{AC}}{\|\overrightarrow{AC}\|} + \mu \vec{n}_u & a_3: \overrightarrow{OP} &= \overrightarrow{OC} + \lambda \vec{n}_u
 \end{aligned} \tag{3.16}$$

### ***Damage zone envelope***

As previously mentioned, in order to calculate the gravity effect of the damage zone induced by a fault, we use a grid of fixed cell size. The damage zone is the volume formed by all prisms computed using the previously presented method. The envelope is thus the outer limit of this volume and we approximate it using an upper and a lower grid (figure 3.20).

In this respect two empty grids of the same size are created. The dimensions of the grids are optimized using the maximum and minimum value of the envelope which was determined during the generation of the different prisms. The cell size is fixed by the user. To reduce the number of cells to be tested, the  $x_{min}$ ,  $x_{max}$ ,  $y_{min}$ ,  $y_{max}$  of each prism are calculated from  $A'_p$ ,  $B'_p$ ,  $C'_p$ ,  $A''_p$ ,  $B''_p$ ,  $C''_p$ , which is straightforward. Thus a prism will only be tested if:

$$G \begin{pmatrix} g_1 \\ g_2 \\ g_3 \end{pmatrix}; x_{min} \leq g_1 \leq x_{max} \text{ and } y_{min} \leq g_1 \leq y_{max} \quad (3.17)$$

Where  $G$  is the point located in the center of the cell which is tested. In order to set the value of a cell, we create a vertical line ( $v$ ) passing by  $G$ , whose definition is:

$$v: \overrightarrow{OP} = \overrightarrow{OG} + \lambda \vec{e}_3 \quad (3.18)$$

If the conditions of equation 3.17 are fulfilled, we calculate the intersection point ( $I$ ) of the line  $v$  with the planes ( $f_1$ ,  $f_2$ ,  $f_3$ ) bearing the sides of the prisms defined in equation 3.16. The proof given below is made for the  $f_1$  plane, but is equally true for  $f_2$  and  $f_3$  using their respective definitions of equation 3.16.

$$I \begin{pmatrix} I_1 \\ I_2 \\ I_2 \end{pmatrix}; I = \vec{v} \cap f_1 \quad (3.19)$$

The distance between  $I$  and the  $a_l$  side is:

$$\delta(I; a_1) = \frac{\|\overrightarrow{OA} \times \vec{n}_u\|}{\|\vec{n}_u\|} = \|\overrightarrow{OA} \times \vec{n}_u\| \text{ as } \|\vec{n}_u\| = 1 \quad (3.20)$$

Similarly its distance to  $a_2$  and to  $\pi$  is:

$$\delta(I; a_2) = \|\overrightarrow{OB} \times \vec{n}_u\| \quad (3.21)$$

$$\delta(I; \pi) = \|\overrightarrow{OA} \times \vec{e}_3\| \quad (3.22)$$

Using equations 3.20, 3.21 and 3.22, we can thus define that  $I$  will belong to the  $AB$  side of the prisms only if:

$$\delta(I; a_1) + \delta(I; a_{12}) = \|\overrightarrow{A_p B_p}\| \text{ and } \delta(I; \pi) \leq k \quad (3.23)$$

Where  $k$  is the distance chosen by the user for the determination of the prism (see previous section) and  $A_p B_p$  is the segment between point  $A_p$  and point  $B_p$  (figure 3.23).

Once the different parameters of  $I$  are determined and if the conditions of equation 3.23 are met, the value of the grids can be set. Then the value of the upper grid will be set to  $I_3$  if  $I_3$  is bigger to the actual value, or if there is no value. Similarly, for the lower grid, the value will be set to  $I_3$  if  $I_3$  is smaller than the actual value or if there is no value. The workflow used for the creation of the grids is presented in figure 3.24.

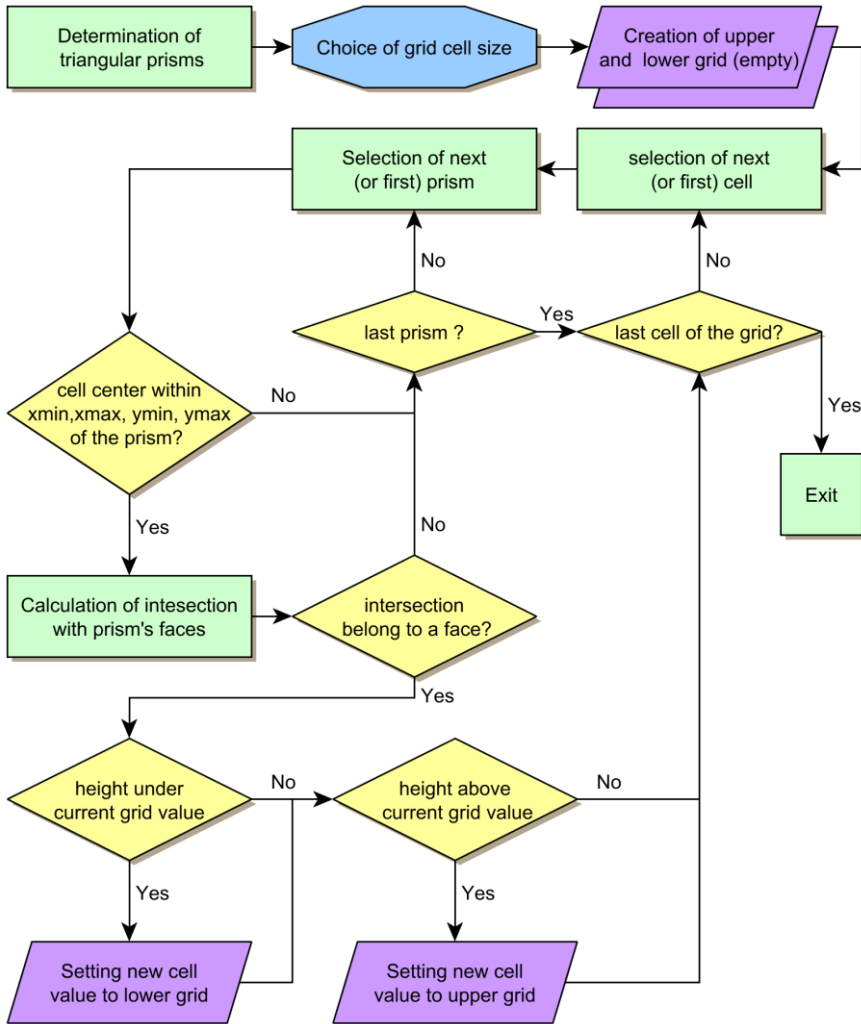


Figure 3.24: Simplified workflow for the fault envelope creation in GInGER. Purple shapes represent internal data; green shapes calculation; blue shapes user actions and yellow shapes are logical tests.

Nevertheless creating the reservoir using the normal of every triangle may not always be the best way for creating a volume, namely the potential geothermal reservoir. For this reason the user can also directly load the upper and lower grid of a fault envelope, which thus was created by other ways.

In all cases, once the envelope is determined, we compute its intersection first with the existing fault. If such an intersection exists the user must choose if this intersection between two faults will be part of the existing fault (and thus subtracted from the new one), if it will be part of the new volume (and thus be

subtracted from the existing fault), or if this volume will be part of the fault envelopes of both faults.

Finally the intersection of the envelope with the geological layers is computed and the envelope is divided in fault compartments (figure 3.25). Every compartment represents the damage zone of the fault zone for a given geological layer. Then one can handle each compartment separately for the porosity assessment, as presented in the next section.

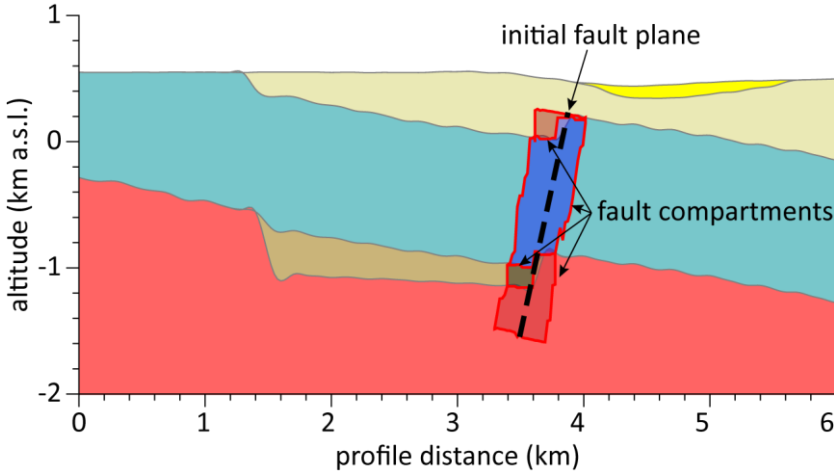


Figure 3.25: Envelope of the damage zone computed with GInGER for an initial fault plane (dashed black line). This envelope is divided in fault compartments, one for each geological layer, represented by different colors.

### Porosity assessment

As presented previously (section 2.3.3, p. 49), the measured density of a rock ( $\rho_{mes}$ ) can be expressed as a simple mixing equation between the density of the rock matrix ( $\rho_{matrix}$ ) and the total porosity of the rock ( $\phi_{tot}$ ) filled with a fluid of a given density ( $\rho_{fluid}$ ).

$$\rho_{mes} = (1 - \phi_{tot}) \cdot \rho_{matrix} + \phi_{tot} \cdot \rho_{fluid} \quad (2.11)$$

However, neither the rock porosity nor the density of the matrix are generally known. In GInGER geological layers are considered to have a constant density except when they are affected by a fault. Thus  $\rho_{mes}$  can be identified by gravity measurements and corresponds to the density of the intact rock ( $\rho_{rock}$ ), namely a rock which is not affected by fracturing but retains its formation porosity. In this respect, equation 2.11 can be adapted to the case of a fault zone affecting a rock of known density (equation 3.24). Indeed, in this case, the observed

density  $\rho_{mes}$ , of a given volume is the result of the linear mix of the previously presented intact rock of density  $\rho_{rock}$ , with a fluid of density  $\rho_{fluid}$ .  $\Delta\phi$  represents the part of the volume occupied by the fluid and corresponds to the increasing porosity induced by fracturing and or dissolution (considered null outside of fracture zone). Thus equation 2.11 becomes:

$$\rho_{mes} = (1 - \Delta\phi) \cdot \rho_{rock} + \Delta\phi \cdot \rho_{fluid} \quad (3.24)$$

$$\text{or} \quad \Delta\phi = \frac{\rho_{rock} - \rho_{mes}}{\rho_{rock} - \rho_{fluid}} \quad (3.25)$$

Concerning the fluid, the hypothesis of a single monophasic fluid at early stage of exploration seems reasonable as, in most cases, only few information about fluid at depth are available. However, it is also possible to consider that the fluid density is the result of the mixing of the different fluid types using a linear mixing equation. Therefore  $\rho_{fluid}$  of equation 3.24 and 3.25 can be expressed as:

$$\rho_{fluid} = \sum_{i=0}^n \lambda_i \cdot \rho_i \quad (3.26)$$

$$\text{where:} \quad \sum_{i=0}^n \lambda_i = 1$$

With  $\rho_i$  the fluids densities and  $\lambda_i$  the fluid saturation/fraction. This distinction can be made at any moment as it does not affect porosity or  $\rho_{fluid}$  but was not implemented in GInGER.

Equation 3.24 and 3.25 are used in GInGER, the user can choose either to fix the porosity or the density in the part dedicated to fault zones in the geology panel (dashed red rectangle, figure 3.26). This part is composed of a tab for every fault zone present in the model. Each of these tabs contains the following main elements in form of columns (from left to right): name of the affected geological layer; initial density of the geological layer ( $\rho_{rock}$ , in  $\text{g}\cdot\text{cm}^{-3}$ ); amount of fracturing ( $\Delta\phi$ , in %); fluid density ( $\rho_{fluid}$ ,  $\text{g}\cdot\text{cm}^{-3}$ ); an arrow indicating the direction of the calculus: fracturing  $\rightarrow$  density (equation 3.24) or density  $\rightarrow$  fracturing (equation 3.25); the final density for the fault volume ( $\rho_{mes}$ , in  $\text{g}\cdot\text{cm}^{-3}$ ).

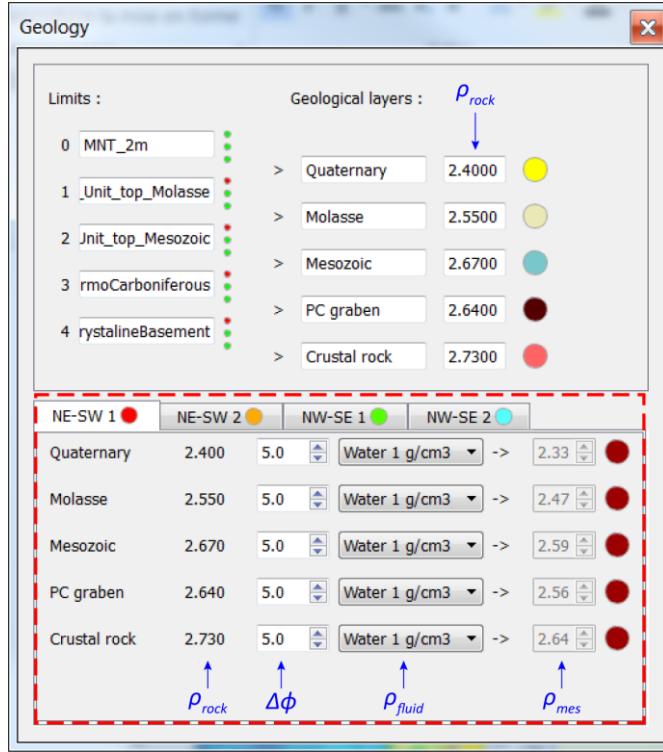


Figure 3.26: Geological information contained in the dockable window of GInGER with a part dedicated to faults (dashed red rectangle; see text for detailed description), the different elements of equations 3.24 and 3.25 are indicated in blue.

### 3.4.4 Density inversion

The gravity effect of the geological model ( $g_m$ ) is calculated by summing the unitary gravity effect (calculated for a density of  $1 \text{ g}\cdot\text{cm}^{-3}$ ) of each geological feature (layers and faults;  $ug_i$ ) multiplied by their respective densities ( $\rho_i$ ) and it should correspond to the measured gravity ( $g_{mes}$ ):

$$g_m = \sum_{i=0}^n ug_i \cdot \rho_i \quad (3.27)$$

In our case, each geological element (layer or fault part) is represented by a  $n$  columns by  $m$  rows grid, which is its value matrix containing the unitary gravity effect of each cell. To be able to conduct inversion this value matrix is transformed into a single column matrix with  $n \times m$  rows ( $k$  values). Equation 3.27 thus becomes:

$$g_m = G\tilde{\rho}$$

$$\begin{pmatrix} ug_{l1,1} & ug_{l2,1} & \dots & ug_{li(1,i)} \\ ug_{l1,2} & ug_{l2,2} & \dots & ug_{li(2,i)} \\ \vdots & \vdots & \ddots & \vdots \\ ug_{l1,k-1} & ug_{l2,k-1} & \dots & ug_{li(k-1,i)} \\ ug_{l1,k} & ug_{l2,k} & \dots & ug_{li(k,i)} \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \\ \vdots \\ \rho_{i-1} \\ \rho_i \end{pmatrix} = \begin{pmatrix} g_{m,1} \\ g_{m,2} \\ \vdots \\ g_{m,k-1} \\ g_{m,k} \end{pmatrix} \quad (3.28)$$

where  $ug_{li,p}$  is the  $p^{\text{th}}$  value of the unitary gravity effect grid of layer  $i$ .  $\rho_i$  is the density of geological layer  $i$ ;  $g_{mes,p}$  is the  $p^{\text{th}}$  value of the measured gravity grid;  $k = n \times m$  with  $n$  and  $m$ : the number of columns and rows of the grids respectively. Equation 3.28 is an over determined linear system, as long as there are more measurements than the number of geological layers. The aim of the inversion is to identify the densities ( $\tilde{\rho}$ ) that minimize the misfit ( $\Phi^2$ ) between the measured value ( $g_{mes}$ ) and the model ( $g_m$ ):

$$\Phi^2 = (G\tilde{\rho} - g_{mes})^2 \quad (3.29)$$

Minimizing  $\Phi^2$  allows identifying these densities:

$$\tilde{\rho} = (G^t G)^{-1} \cdot G^t \cdot g_{mes} \quad (3.30)$$

Nevertheless, we want to include prior information, as it will reduce final uncertainty and constrain inversion. To this aim we followed the methodology described by Tarantola (2005). Consequently, the posterior probability  $\sigma_M(\rho)$  must be Gaussian and, as the misfit function (equation 3.29) is quadratic, the prior information must also be considered as Gaussian. We therefore add to equation 3.30 the covariance matrix of the prior densities ( $C_\rho$ ), the prior densities ( $\rho_{prior}$ ) and the covariance matrix of the measurements ( $C_{mes}$ ). The average of the posterior densities thus became (after Tarantola, 2005):

$$\tilde{\rho} = \rho_{prior} + (G^t C_\rho^{-1} G + C_{mes}^{-1})^{-1} G^t C_\rho^{-1} (g_{mes} - G \rho_{prior}) \quad (3.31)$$

and the posterior covariance matrix is:

$$\tilde{C}_\rho = (G^t C_\rho^{-1} G + C_{mes}^{-1})^{-1} \quad (3.32)$$

In our case we consider all parameters independent and thus the prior covariance matrix is a diagonal matrix with the variance of each density, thus:

$$C_\rho = \begin{pmatrix} \sigma_{\rho_1}^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \sigma_{\rho_i}^2 \end{pmatrix} \quad (3.33)$$

with  $\sigma_{\rho_i}^2$  the variance of each prior densities. These variances are determined by the user using a dedicated user interface presented later in this section. In our case, as we only have one measured parameter, the determination of the measurements covariance matrix is also straightforward:

$$C_{mes}^{-1} = 1/\sigma_m^2 \quad (3.34)$$

Thus, the final (posterior) misfit by:

$$\tilde{\Phi}^2 = (G\rho_{prior} - G\tilde{\rho})^t (G\rho_{prior} - G\tilde{\rho}) \quad (3.35)$$

and the final variance on the posterior densities is:

$$\tilde{C}_\rho = \tilde{\sigma}_m^2 = \frac{\Phi^2}{k - i} \quad (3.36)$$

With  $k$  the number of measurements and  $i$  the number of densities that are determined through the inversion process.  $\tilde{C}_\rho$  can then be used to express the variance for each posterior density:

$$\tilde{\sigma}_{\rho_i}^2 = G^t (\tilde{\sigma}_m^2)^{-1} G \quad (3.37)$$

To be able to make matrix algebra in GInGER we used the Newmat 11 library (Davies, 2008) compiled directly with Qt. The simplified workflow is presented hereunder (Figure 3.27):

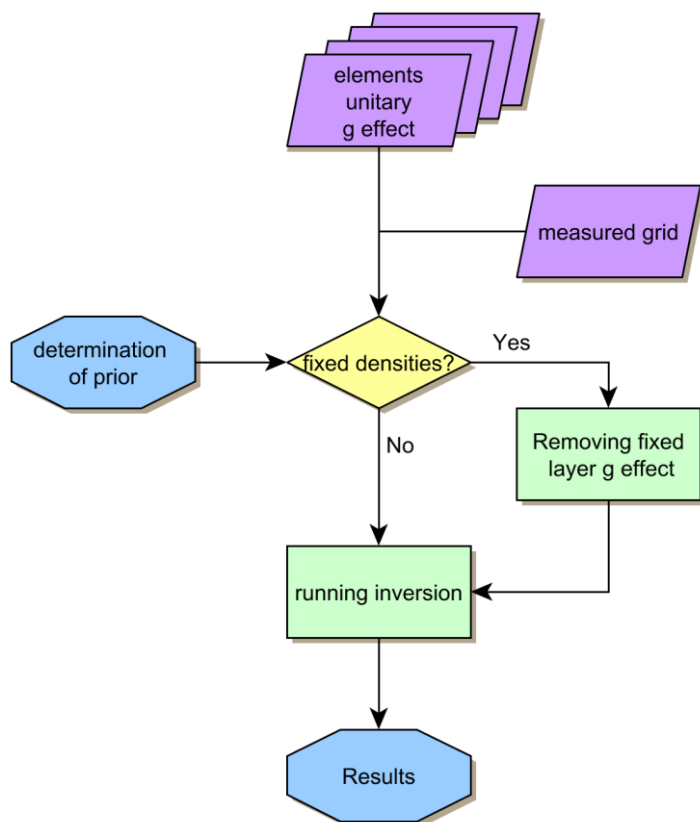
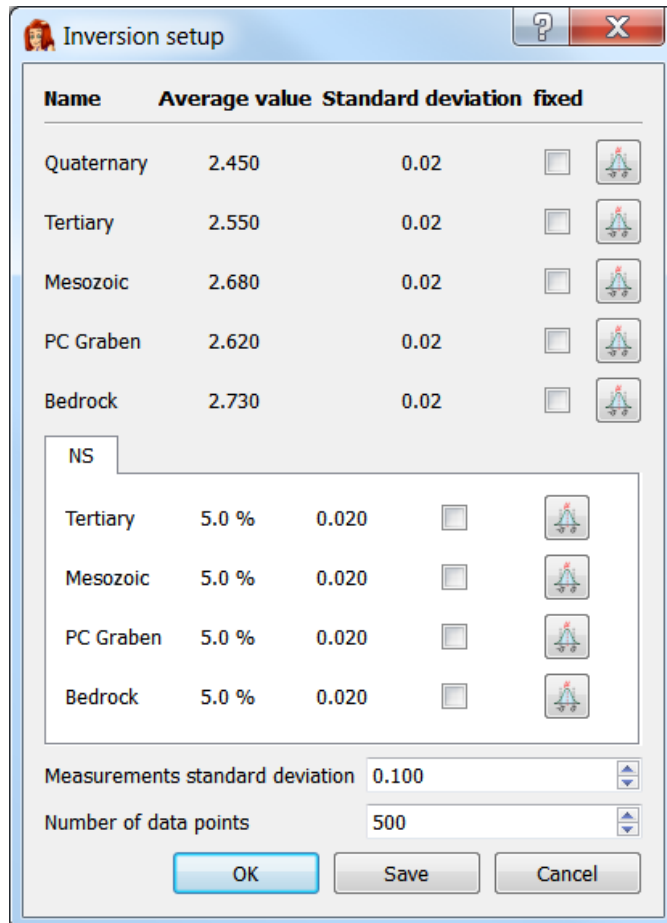


Figure 3.27: Simplified workflow for density inversion in GInGER. Purple shapes represent internal data; green shapes calculation; blue shapes user actions and yellow shapes are logical tests.

The base prior values of each geological element are determined using the geology panel of the GUI (figure 3.26) and are presented in a dedicated window (figure 3.28). To help the user, these values can be modified by clicking the button on the right, which will cause new windows to open (figure 3.28). The user can also choose to fix a density in the model by checking a box; in this case the gravity effect of this element is removed from the measured values before running the inversion.



The dialog box is titled "Inversion setup" and contains a table for geological layers and a section for fault compartments. At the bottom, there are input fields for "Measurements standard deviation" and "Number of data points", and three buttons: "OK", "Save", and "Cancel".

| Name       | Average value | Standard deviation | fixed                    |                                                                                   |
|------------|---------------|--------------------|--------------------------|-----------------------------------------------------------------------------------|
| Quaternary | 2.450         | 0.02               | <input type="checkbox"/> |  |
| Tertiary   | 2.550         | 0.02               | <input type="checkbox"/> |  |
| Mesozoic   | 2.680         | 0.02               | <input type="checkbox"/> |  |
| PC Graben  | 2.620         | 0.02               | <input type="checkbox"/> |  |
| Bedrock    | 2.730         | 0.02               | <input type="checkbox"/> |  |

NS

|           |       |       |                          |                                                                                   |
|-----------|-------|-------|--------------------------|-----------------------------------------------------------------------------------|
| Tertiary  | 5.0 % | 0.020 | <input type="checkbox"/> |  |
| Mesozoic  | 5.0 % | 0.020 | <input type="checkbox"/> |  |
| PC Graben | 5.0 % | 0.020 | <input type="checkbox"/> |  |
| Bedrock   | 5.0 % | 0.020 | <input type="checkbox"/> |  |

Measurements standard deviation: 0.100

Number of data points: 500

Buttons: OK, Save, Cancel

Figure 3.28: Inversion setup dialog with prior information. Geological layers are in the top part, and fault compartments in the lower part. The two last lines are used to determine the variance of the model (equation 3.36). The square buttons on the right gives access to a new window to determine the parameters (figure 3.29).

Standard deviations of the density value of the geological elements are determined using the confidence bar under Gaussian assumption. The probability value of this bar corresponds to  $n$  times the standard deviation (i.e.  $98.76\% = 2.5\sigma$ ). Therefore the average density value is simply the average between the *min* and *max* boxes (figure 3.29) and the standard deviation ( $\sigma$ ) is:

$$\sigma = \frac{\max - \min}{2n} \quad (3.38)$$

The *min* and *max* values represents the lower and upper bound of the confidence interval selected by the user.

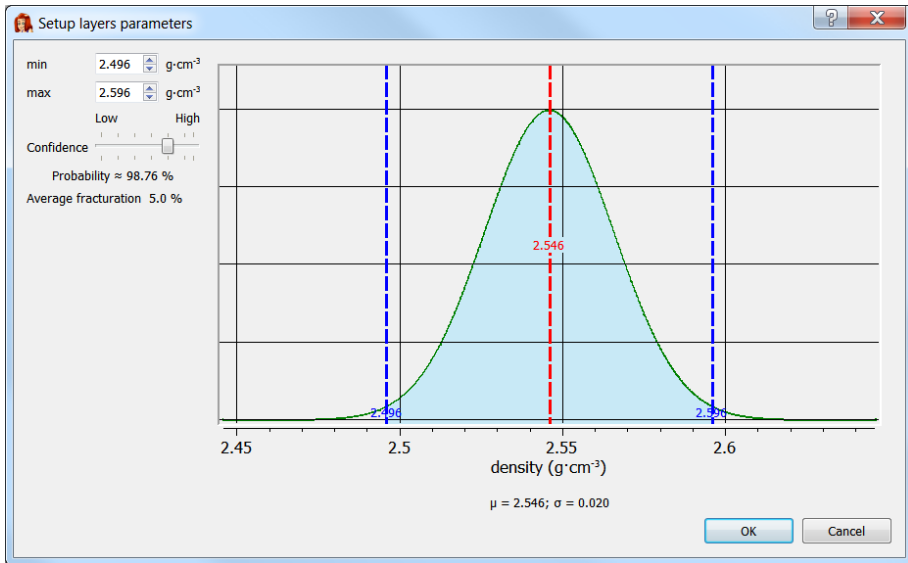


Figure 3.29: Parameter setup window of inversion for a fault compartment. The prior average density ( $\mu$ ) and standard deviation ( $\sigma$ ) are determined using this window (see text for details).

Once the inversion calculus is achieved, a new window summarizing the prior and posterior values is shown to the user. By clicking the same button as presented in the setup window (figure 3.28), a new window with the detail information of the inversion is presented and allows the user to gain access to a range determined by the confidence interval (figure 3.30).

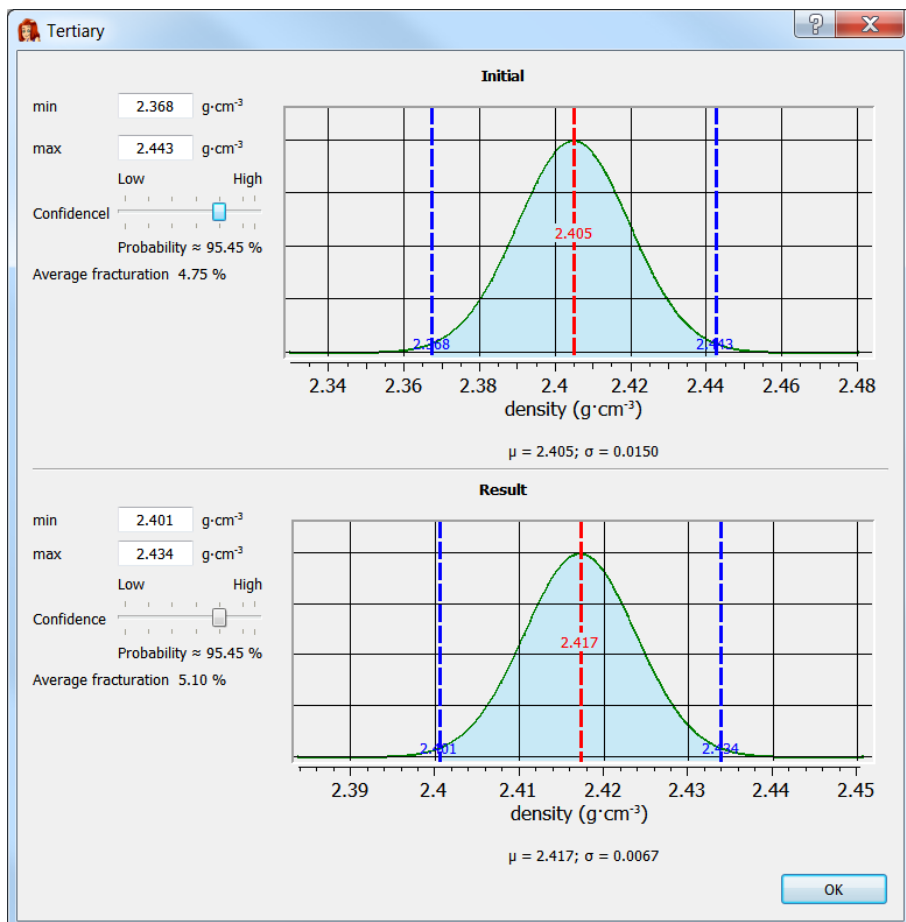


Figure 3.30: Inversion detail window for a geological element. The prior values are in the top part and the results in the bottom part (see text for details).

### Validation of the inversion

In order to test the inversion process of GInGER, we created a synthetic 3D geological model using GeoModeller (Intrepid Geophysics, 2013). We then imported this model into GInGER and calculated its gravity effect. The resulting modeled gravity effect was then resampled using bilinear extrapolation on points placed every  $300 \pm 25$  m. These points were used to create a new gravity grid using minimum curvature in Surfer (Golden Software Inc., 2012). This process allowed us to have a “measured” grid with associated error in the same range as real measurements.

The geological model is composed of five geological layers (figure 3.31), from top to bottom: Quaternary, Tertiary, Mesozoic, Permo-Carboniferous and Crystalline basement. It is also used as tutorial in the manual (Altwegg,

2015). The model is limited at its top by a topographic grid also specially generated for this model. Quaternary sediments are considered to be local and thus of relatively small extent and thickness. Tertiary and Mesozoic formations dip to the East-South-East and are affected by a major north-south fault, which also is the eastern limit of a Permo-Carboniferous graben of small extent located in the middle of the model.

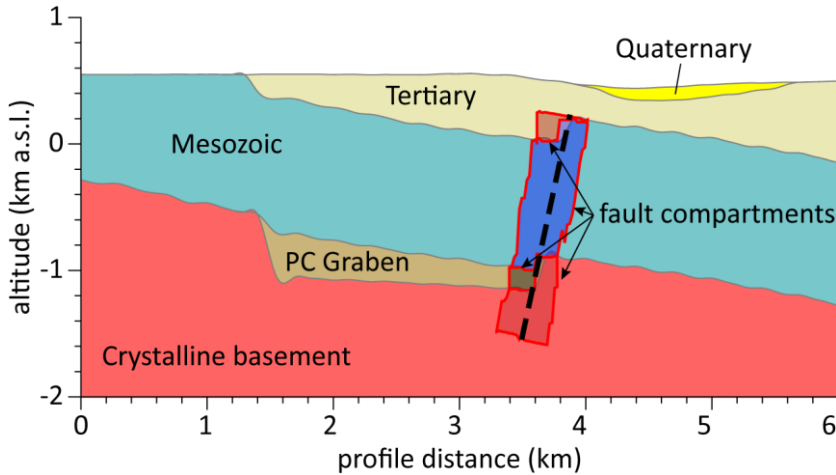


Figure 3.31: Representative cross-section exported from GInGER through the 3D model and used for the inversion test.

The initial parameters of the inversion were determined using classical literature values (see section on density of section 2.3.3), the aim being to test the accuracy of the process. The parameters of the inversion as well as the results are presented on figure 3.32, where we can clearly see that the inversion results (final values) are close to the reference values with the exception of the fault zone compartment of Permo-Carboniferous. This is likely due to the very small volume of this compartment, to the regular sampling used and also because the initial parameters were set far from the reference value. Nevertheless, the overall error on the model was generally reduced. The only exception is again the fault compartment of the Permo-Carboniferous for which the error increased. However this increase of the error implies that the reference value is inside of the range and this was not the case for the initial value. This is a good example of what the quantification of uncertainty can bring, highlighting the less constrained rock volume.

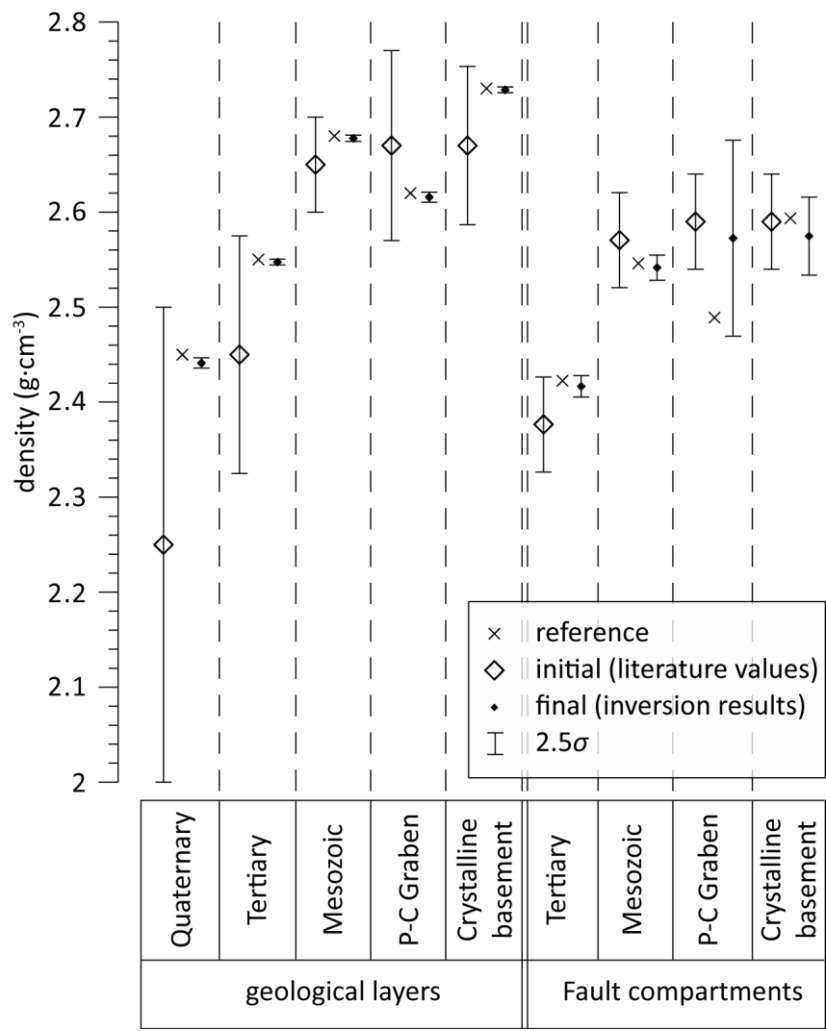


Figure 3.32: Results of the test of the inversion process on density of GInGER. Initial, final and reference values are represented. The error bar corresponds to  $2.5\sigma$ .

### 3.4.5 Graphical User Interface

The Graphical User Interface (GUI) of GInGER is divided into six parts (figure 3.33): menu; toolboxes; a list of geological objects (figure 3.26); 2D geological profile; 2D gravity profile; and gravity map. With the exception of the menu, all elements are movable. The user chooses the different points for the profile by clicking on the map. The geology is then displayed in the geological profile part, as well as the modeled and measured gravity, which are displayed within their dedicated parts. As previously presented, the user can also alter the density of the different geological elements and see the effect in real time on the gravity profile. All the different functions and options are detailed in the manual (Altwegg, 2015) and only the main elements will be presented hereafter. Note that all the toolboxes' actions are duplicated in the menu. The part dedicated to the geological elements will not be described here as it was presented previously.

#### **Menu**

There are four menus (File; Model; View; Help) from which the main functions are presented here below. The usual File menu allows the user to load, save and save as... the project. It also allows the direct import of models generated by Terre\_3D (Tacher, 2013) used to establish the 3D geological model of the second case study (chapter 5) and to print reports, as well as to export different elements present in the model (effects of layers, parameters, map, etc.). The model menu and the view menu contain a copy of the action present in the different toolboxes described later. The Help menu allows access to the manual and to information on the application.

#### **Toolboxes**

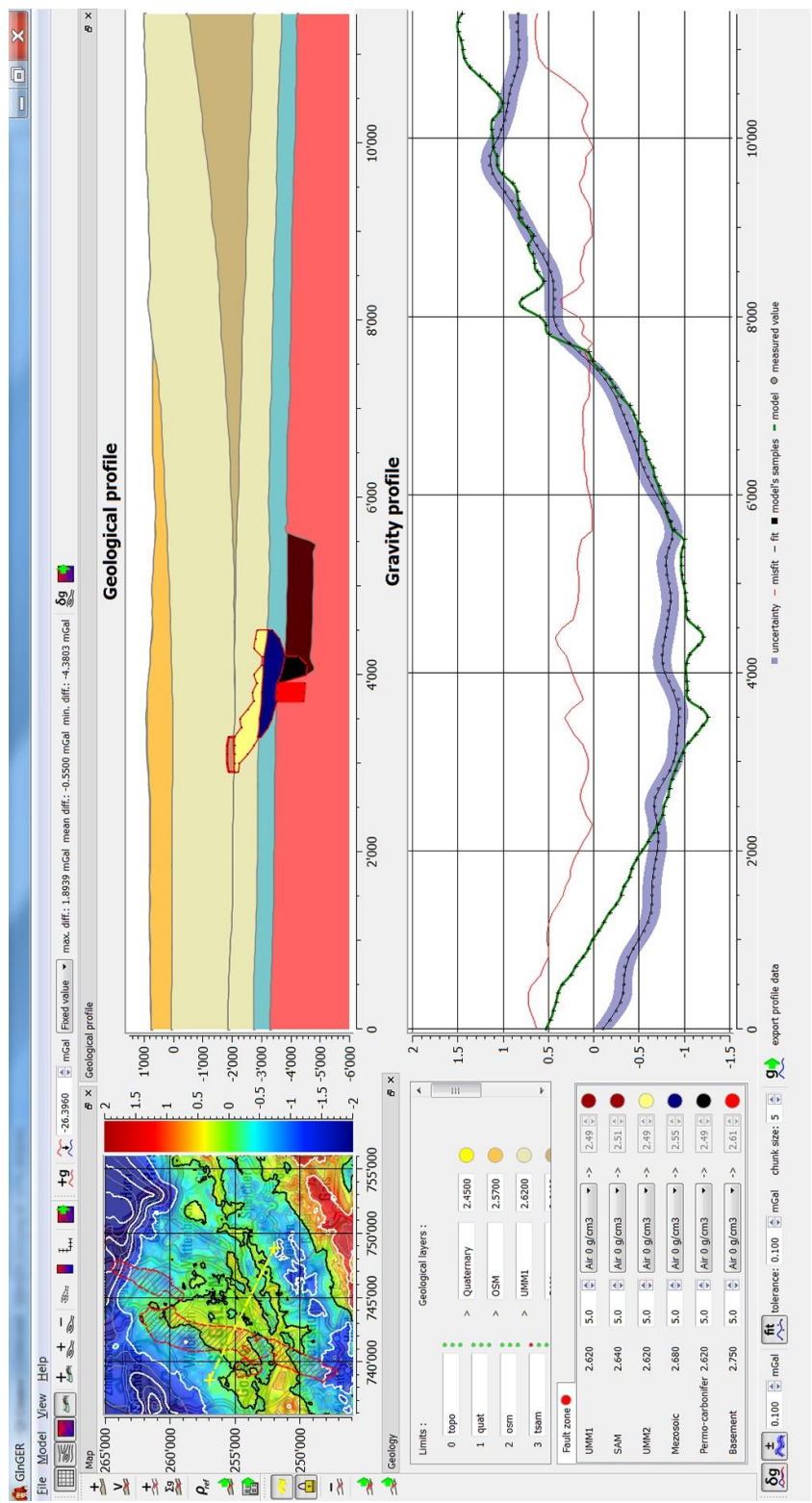
There are five separated and movable toolboxes, one for each element of the GUI except for geological elements, which has one for geological layers and limits and one for the faults. All functions are described in the manual (Altwegg, 2015).

#### **Map**

The map is a central element of the GUI as it provides the visualization of the different gravity effects (model, measurements, misfit, etc.). The user can also add some elements such as a grid, a background map or curves.

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*Figure 3.33 (next page): Graphical user interface of GInGER; menu on the top; toolboxes on the left and top edge; map top left and geology and gravity profile on the right.*



***Geological profile***

This part of the GUI shows a geological profile along the profile chosen by the user. The color of the different geological elements can be changed in the geological elements list.

***Gravity profile***

This part presents the different values of the gravity (modeled, measured, misfit) for the same profile as the one presented on the geological profile. This allows the user to determine the effect of the different structures and the main options are: display uncertainty and/or misfit and fitting.

### 3.5 Simple shapes modeling: GInGERSP

GInGER allows the fast and efficient calculation of the gravity effect of a 3D geological model and the determination of the best densities for each geological element. However, modifying such models is often time-consuming and cannot be carried out routinely and thus we developed GInGERSP (GInGER Synthetic Profile): a separate computer program to compute the gravity effect of simple shapes in 2D. As the gravity profiles of GInGER can be directly imported it allows the testing of different hypotheses before changing the model and computing its gravity effect again (figure 3.34). The separation between the two programs permits an independent use of GInGERSP. This was also done because the basic principles of gravity interpretation for these two computer applications (2D and 3D) are quite different. Another objective was to provide a simple and efficient tool to make quick preliminary or sensitivity studies.

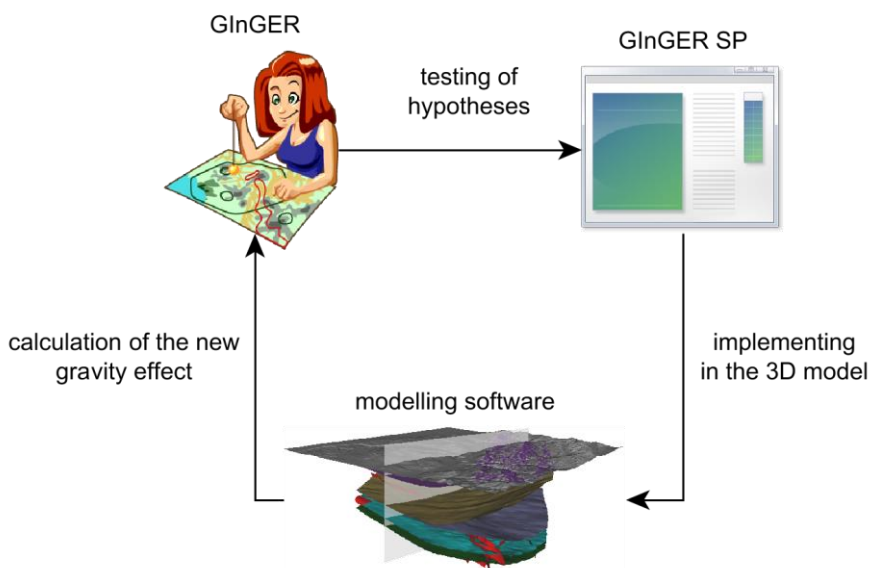


Figure 3.34: Workflow between GInGER, GInGER SP and 3D modeling software.

### 3.5.1 Simple shapes

In GInGERSP four different simple shapes can be used. The formula used for the calculation of their respective gravity effect and maximum gravity effect are given in table 3.4.

Table 3.4: 2D gravity effect ( $\Delta g_p$ ) and maximum gravity effect ( $\Delta g_0$  or  $\Delta g_\infty$ ) in ( $m \cdot s^{-2}$ ) of simples shapes along a profile.  $G = 6.674 \cdot 10^{-11} m^3 kg^{-1} s^{-2}$ ;  $\Delta \rho$  is the density difference between the shape and its surrounding in  $kg \cdot m^{-3}$ ; parameters are given in figure 3.35.

|                                    |                                                                                                      |                                                                 |
|------------------------------------|------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------|
| Sphere <sup>[1]</sup>              | $\Delta g_p = \frac{4}{3} \pi r^3 G \Delta \rho \frac{z}{(x^2 + z^2)^{\frac{3}{2}}}$                 | $\Delta g_0 = \frac{4}{3} \pi r^3 G \frac{\Delta \rho}{z^2}$    |
| Horizontal cylinder <sup>[2]</sup> | $\Delta g_p = \frac{2 \pi r^2 G \Delta \rho}{z \left( 1 + \left( \frac{x}{z} \right)^2 \right)}$     | $\Delta g_0 = \frac{2 \pi r^2 \Delta \rho}{z}$                  |
| Vertical dyke <sup>[3],[4]</sup>   | $\Delta g_p = 2 G \Delta \rho t \ln \left[ \frac{(z + h)^2 + x^2}{x^2 + z^2} \right]$                | $\Delta g_0 = 2 G \Delta \rho t \ln \left( \frac{z}{h} \right)$ |
| Horizontal slab <sup>[3],[4]</sup> | $\Delta g_p = 2 t G \Delta \rho \left[ \frac{\pi}{2} + \tan^{-1} \left( \frac{x}{z} \right) \right]$ | $\Delta g_\infty = 2 \pi G t \Delta \rho$                       |

<sup>[1]</sup>Telford and Sheriff (1990); <sup>[2]</sup>Lowrie (2007); <sup>[3]</sup>Hinze et al. (2013); <sup>[4]</sup>Reynolds (1997).

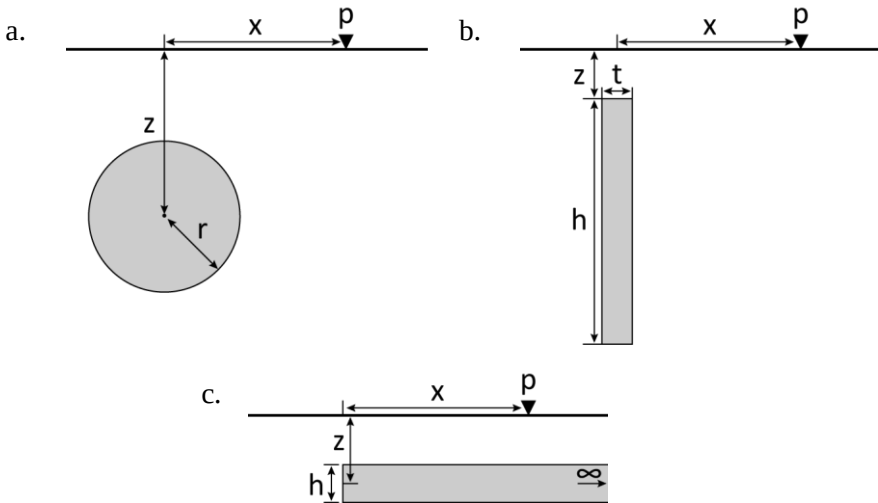


Figure 3.35: Parameters for the gravity effect ( $\Delta g_p$ ) of simple shapes of Table 3.4; a. sphere and horizontal cylinder; b. vertical dyke; c. horizontal slab.

Note that these formulas are assuming a 2D geometry and in particular they imply that in general the shapes are infinite in the direction perpendicular to the cross section. In addition, the horizontal slab is infinite along the x direction within the 2D section.

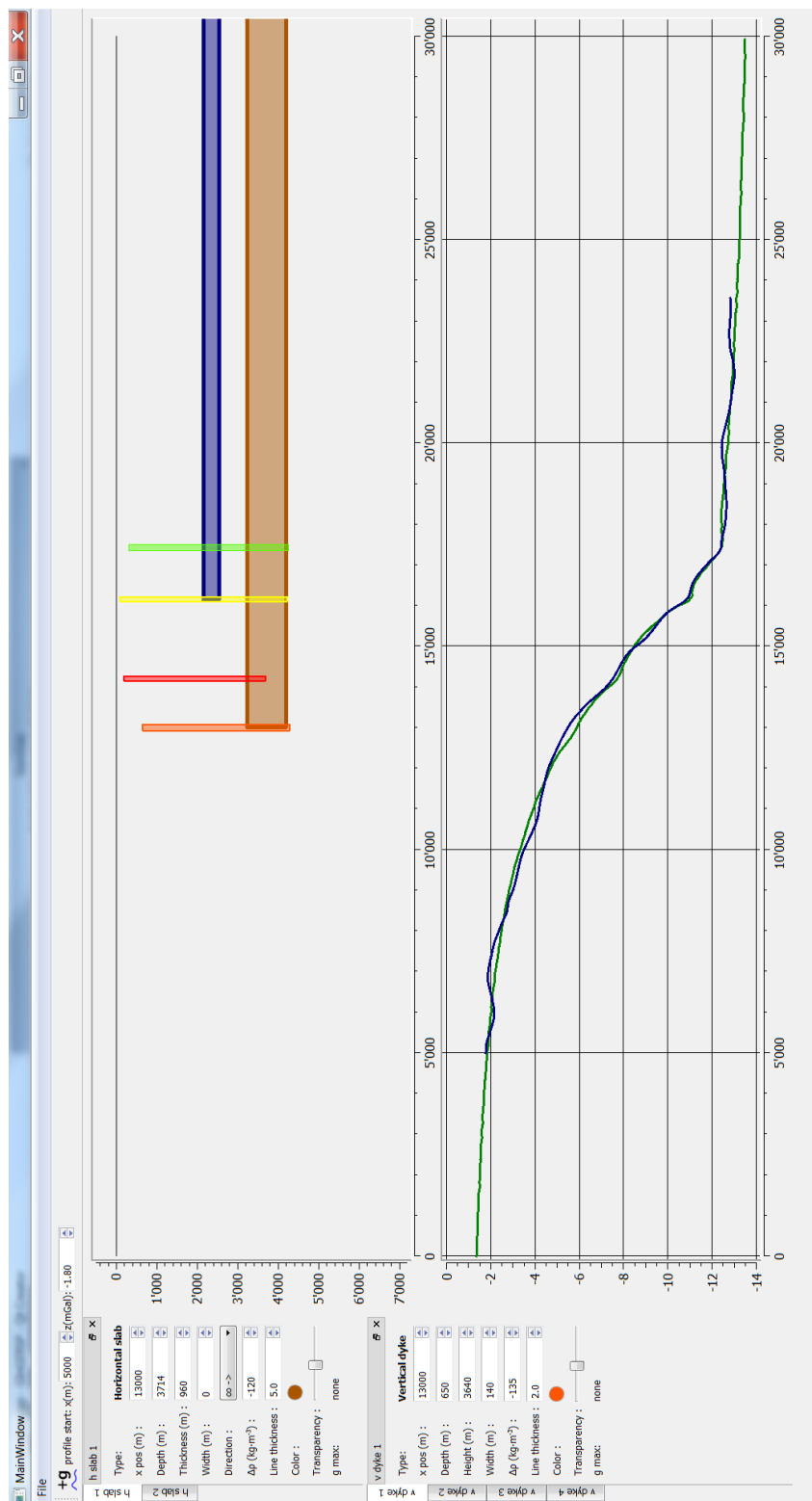
### 3.5.2 Graphical User Interface

The GUI of GInGERSP is organized in four parts (figure 3.36): toolbox, shapes profiles, gravity profile and shapes details.

The toolbox makes possible to load a measured value (blue line) and modeled gravity value (green line), which can be generated through GInGER. It also allows determining where these data start and if there is a shift. This action can also be accessed through the File menu, where simple shapes can be added to the profile. To do this, the user simply has to select the desired shape and it will appear in the shape profile, as well as a floating window with all the needed parameters. The user can then move or scale the shape using the mouse or change the parameters directly in the parameters window. The gravity effect of the shape is added on the model gravity profile (green line of figure 3.36). This effect is calculated in real time so the user can directly view the effect of his change. There is no limitation to the number of shapes that can be created.

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*Figure 3.36 (next page): GUI of GInGERSP from Altwegg et al., (2015). Bottom: gravity effect of the model and the shapes (green line); measured gravity (blue line); top: localization of the simple shapes on the profile; left: parameters of the simple shapes (geometry, density difference etc.)*



## Chapter 4

### Case study: Sankt Gallen



## 4.1 Introduction<sup>1</sup>

The Sankt Gallen geothermal project has been targeting a fault zone that affects Mesozoic sediments at about 4500 m depth. Spatial extension of these sediments, a major fault zone and indication for graben structures in the crystalline basement are observed in 3D seismic. Both, graben and fault zone coincide with negative gravity anomalies acquired and analyzed during this study. Forward modelling of gravity anomalies based on a 3D seismic survey is used to estimate possible fracture porosity. After stripping gravity effects of geothermally irrelevant geological units from the residual anomaly, only local structures related to the fault zone most likely account for remaining anomalies. A synthetic case study on the effect of density variation (section 4.3) and considerable gas content in the deep geothermal well suggest possible fracture porosity between 4 and 8 % (SGSW, confidential report).

In addition to the increasing exploration of fractured reservoirs by hydrocarbon and geothermal industries, fracture porosity turns out to be also a controlling factor in low-enthalpy hydrothermal regions such as the North Alpine Foreland Basin. The interplay between hydrothermal aquifer conditions and fault zones is well-known in the Upper Malm (e.g. Signorelli and Kohl, 2006), which reveals aquifer properties in Germany and Austria to a considerable depth of > 3300 m allowing for electricity production from thermal water at temperatures as low as 130 °C and flow rates up to 150 l·s<sup>-1</sup> (e.g. at the Unterhaching power plant; Schellschmidt et al., 2010). In contrast, such aquifer conditions have not been observed in wells in Northern Switzerland located about > 50 km to the West of Sankt Gallen (e.g. Signorelli and Kohl, 2006). Following the concept of hydrothermal aquifer utilization as practiced in the Munich Molasse Basin, fault zones have been targeted in order to connect geothermal wells to the reservoir and to the regional flow field, which may be contained in the reef-facies (Böhm et al., 2013). Recent failures of geothermal projects that targeted only the reef-facies confirm the increasing importance of fracture porosity. Other concepts in low enthalpy reservoir utilization are based on regional circulation along fault zones generating free convection such as the projects in Soultz-sous-Forêts and Landau among others in the Upper Rhine Graben (Bächler, 2003; Kohl et al., 2000). In both concepts, fracture porosity linked to fault zones is of major importance as it controls the aquifer conditions at depth to a certain extent. It is thus also crucial

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<sup>1</sup> This chapter is modified from Altwegg et al. (subm. to Geothermics)

for our case study of the Sankt Gallen geothermal well as it controls the economic viability of the project.

Recently, gravity has been mainly used to carry out mass-balancing in this type of reservoir (e.g. Oka et al., 2012). The determination of porosity in geothermal systems by means of gravity measurements has been applied, for example at the Geysers geothermal field (northern California) where, according to the fluid phase, porosity changes in the order of 0.5 to 1.6 % have been attributed to density changes of 40 to 60 kg·m<sup>-3</sup> for reservoir zones of an extension of several kilometers (Denlinger et al., 1981). In this case, density changes were related to porosity through measurements of the interconnected porosity on samples. In Alpine low-temperature geothermal systems, negative gravity anomalies have been linked to faulting along which geothermal fluid rises naturally (Guglielmetti et al., 2013). First estimates of porosity by gravity in the European EGS reservoir area at Soultz-sous-Forêts reproduce the order of magnitude obtained from logging data (Schill et al., 2010). In recent studies, gravity in combination with 3D geological modeling has proven to be an appropriate tool for visualization of fracture porosity in the granitic basement (Baillieux et al., 2013).

The aim of this chapter is to present the application of our methodology to the geothermal project of Sankt Gallen and to discuss the possibility that fracture porosity can, to a certain extent, be inferred by the interpretation of gravity data based on geological structures obtained by 3D seismic data. In this perspective we will first present the local specificities of the geology (section 4.2). The following section (section 4.3) is dedicated to the synthetic case study that was carried out to determine if our methodology was applicable in Sankt Gallen. Then we explain how the different structures of the 3D model were implemented (section 4.4) before presenting the gravity survey itself (section 4.5). Finally, we present the results of the survey (section 4.6) and discuss them in the context of geothermal exploration (section 4.7) before presenting the conclusions of this case study (section 4.8).

## 4.2 Geological setting

Sankt Gallen is located near the southern edge of the present day Swiss Molasse Basin, which is limited towards the Alps by the folded molasse deposits also called subalpine molasse (figure 4.1). At Sankt Gallen, the Molasse basin stretches over about 80 km in the N-S direction. The geological formations present at depth are already described in the geological setting of chapter 2 (section 2.2, p. 23) and thus only local specificities will be presented here.

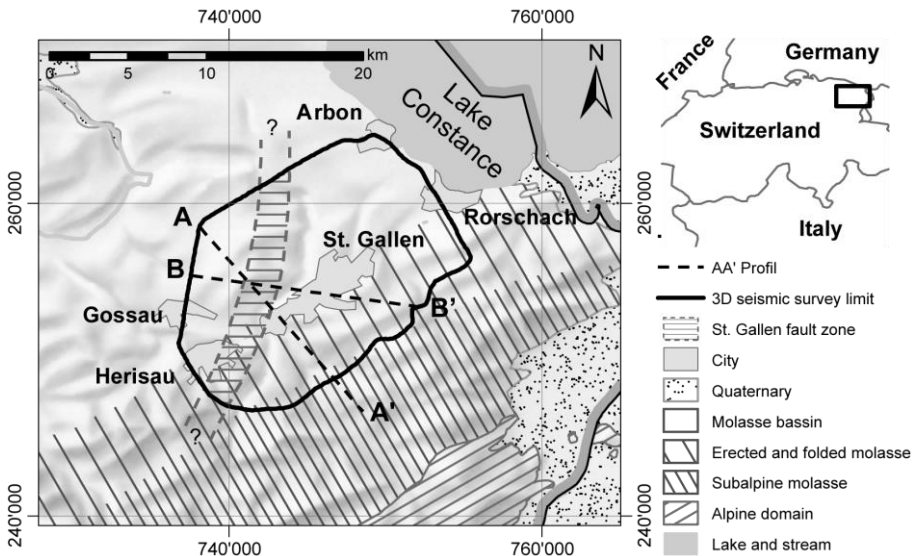


Figure 4.1: Simplified tectonic map of the Sankt Gallen area (from Altwegg et al., *subm. to Geothermics*). The thick black line represents the limit of the 3D seismic survey, corresponding also to the limit of the investigated area. The N-S horizontally dashed area represents the extent of the main deep fault targeted by the geothermal project mapped at the top Malm (Sankt Galler Stadtwerke, pers. comm.). Swiss coordinates (CH 1903) are used.

At the drilling site, the Mesozoic formations are at a depth of around 4500 m and are gently dipping toward the Alps (figure 4.2). As previously mentioned, the erosion of the Mesozoic formations is stronger near the Alps and thus Cretaceous, as well as a part of the upper Malm is likely eroded. Evaporite deposits are also not expected in this area (figure 2.3). This results in a thickness of the Mesozoic formations of about 700 m. Initially the 3D seismic survey was sized to get information on two fault zones inferred from old petroleum seismic lines. However the fault zone that was expected to be east of the city was not found by the 3D survey and thus the project focused on the fault zone localized to the west. It is also important here to mention

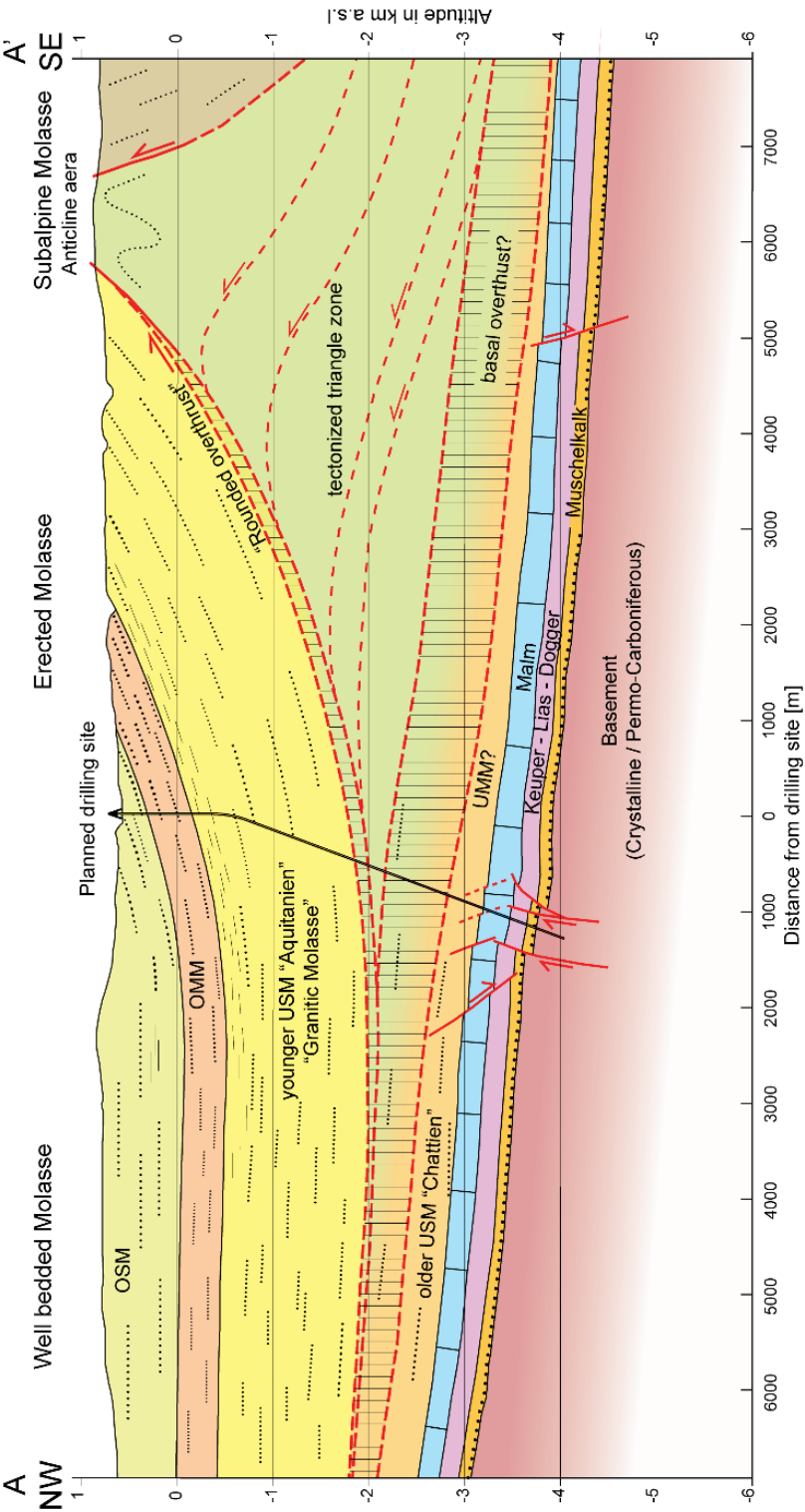


*Figure 4.2 (previous page): Regional, geological NW-SE profile across the deep drilling site at Sankt Gallen interpreted using 3D seismic data and surface geology and including the planned trajectory for the first well GT-1 (Sankt Galler Stadtwerke, pers. comm. in Altwegg et al., subm. to Geothermics).*

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that the aim of the survey was to obtain data on the potential geothermal reservoir of the two expected fault zones in the Mesozoic layer. Another result of the survey was the discovery of a Permo-Carboniferous through to the East of the fault zone. However since it was not a geothermal target of the project and due to low reflectivity of large parts of the graben, its structure was not further interpreted.

In the region of Sankt Gallen the thickness of the entire Molasses package reaches about 4000 m. At the planned geothermal site, the Molasse sediments start to be affected by internal folding and faulting ('erected molasses') with increasing intensity towards the Alps (figure 4.2; Hofmann, 1973; Ludwig, 1930; Ludwig et al., 1949; Pfiffner, 1986a; Saxer, 1965). The Subalpine Molasse is internally deformed along a series of thrust planes that lead to significant thickening of the Tertiary sediments (Pfiffner et al., 1997) and forms a triangle zone with back-thrusts and complex duplex cores called Dreieckzone (Burkhard, 1990; Kempf et al., 1999; Pfiffner, 1986b; Sommaruga et al., 2012).

Quaternary sediments are distributed locally, following the extension of the paleo-glaciers and recent fluvial system (Hofmann, 1973; Ludwig, 1930; Ludwig et al., 1949; Saxer, 1965) They are composed of fluvial deposits (alluvium, gravel, sand and silt), lacustrine sediments (mainly silt) and glacial tills (moraines, ground moraines, etc.). The density of Quaternary deposits is typically low.

In the study area, distribution and thickness of the Quaternary deposits were determined from 1265 shallow wells to depths from a few to 300 m, (figure 4.3; Naeff, unpublished) and static seismic measurements from 200 shot points providing additional indication on the thickness of Quaternary sediments (Sankt Galler Stadtwerke, unpublished) as well as the regional Quaternary geology (Hofmann, 1973; Ludwig, 1930; Ludwig et al., 1949; Saxter, 1965). The thickness of these deposits varies considerably, but its maximum depth is estimated to be < 60 m (figure 4.3).

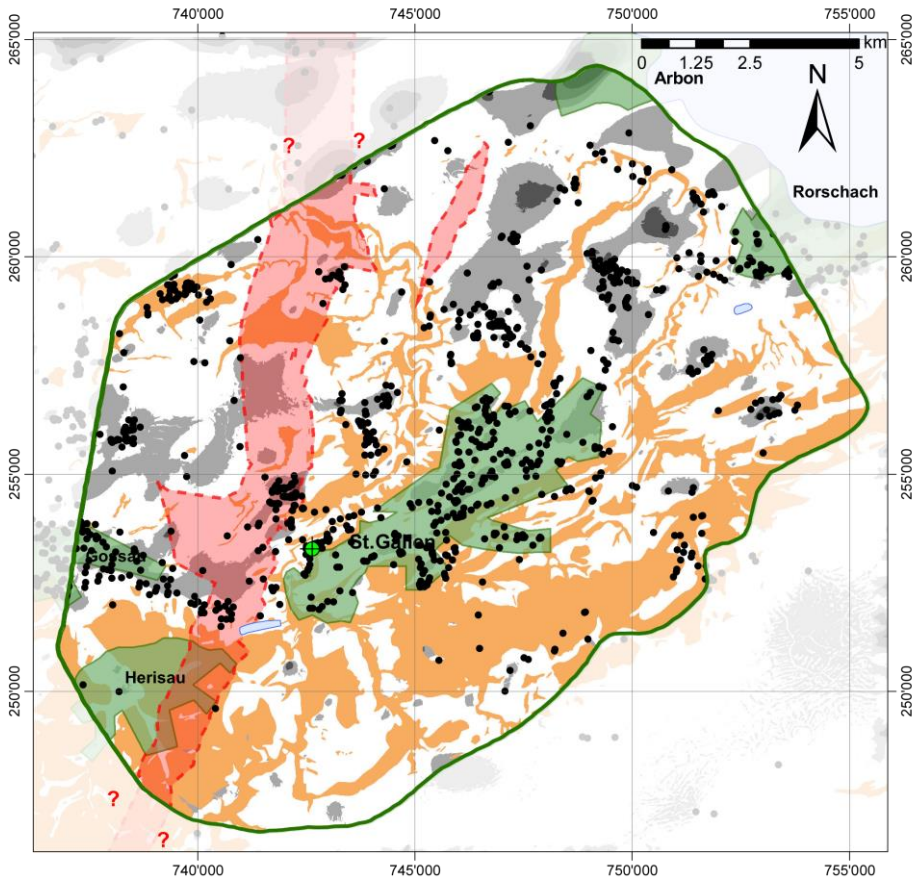


Figure 4.3: Map of Quaternary thickness (white < 20m, gray < 50m, dark gray > 50m). Red area: extent of the modeled fault zone; green area: populated areas, orange area: outcropping or near outcropping Molasse, black dots: boreholes used for Quaternary modeling, green circle: location of the GT-1 geothermal well, Swiss coordinates (CH 1903) are used (from Altwegg et al., *subm. to Geothermics*).

The 3D seismic survey (figure 4.4) suggests that the faulted zone of St. Gallen consists, near the drilling site, of a network of several steeply dipping normal faults with 500 to 5,000 m in length in the Mesozoic formations. First large-scale and kinematic interpretations of the fault zone show that the youngest phase of deformation is in agreement with the present stress field (figure 4.5) and probably induced lateral displacement and led to both compressive (thrust faults) and extensive (normal faults) structures. As the Sankt Gallen fault zone is critically stressed, this indicates that at least some of the fractures and related fissures are open elements, which can tend to create new cavities. Whether this will have a positive effect on the permeability depends on to what extent these cavities are filled with material or by crystallization (calcite, clay minerals).

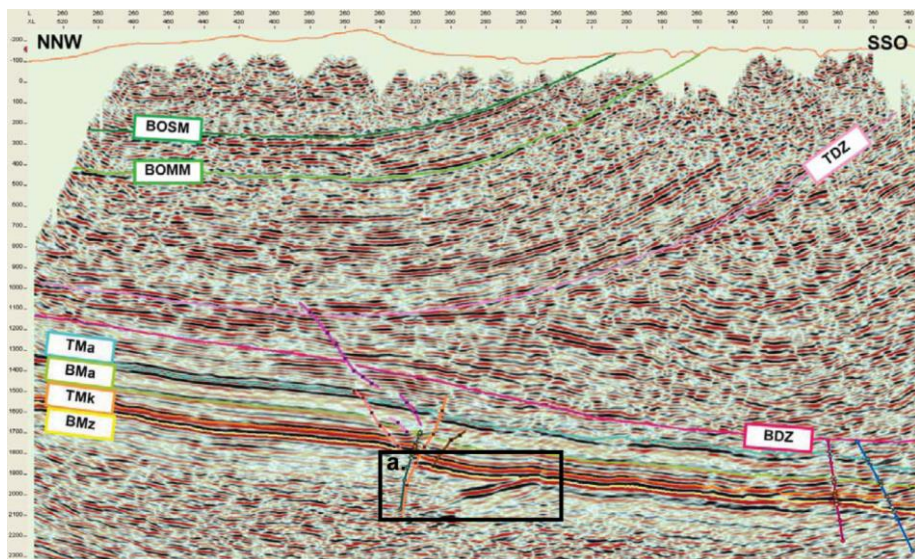


Figure 4.4: Representative interpreted 2D profile (line 260) located near the profile AA' of figure 4.1 (exact location not available for confidentiality reasons). With top Malm (TMa), top Muschelkalk (TMk), base Mesozoic (BMz), base Malm (BMa), base Upper Freshwater Molasse (BOSM), base Upper Marine Molasse (BOMM), top triangle zone (TDZ) and base triangle zone (BDZ), and indication for a Permo-Carboniferous graben located to the East of the fault zone (a.). Swiss coordinates (CH 1903) are used (Sankt Galler Stadtwerke, pers. comm. In Altwegg et al., *subm. to Geothermics*).

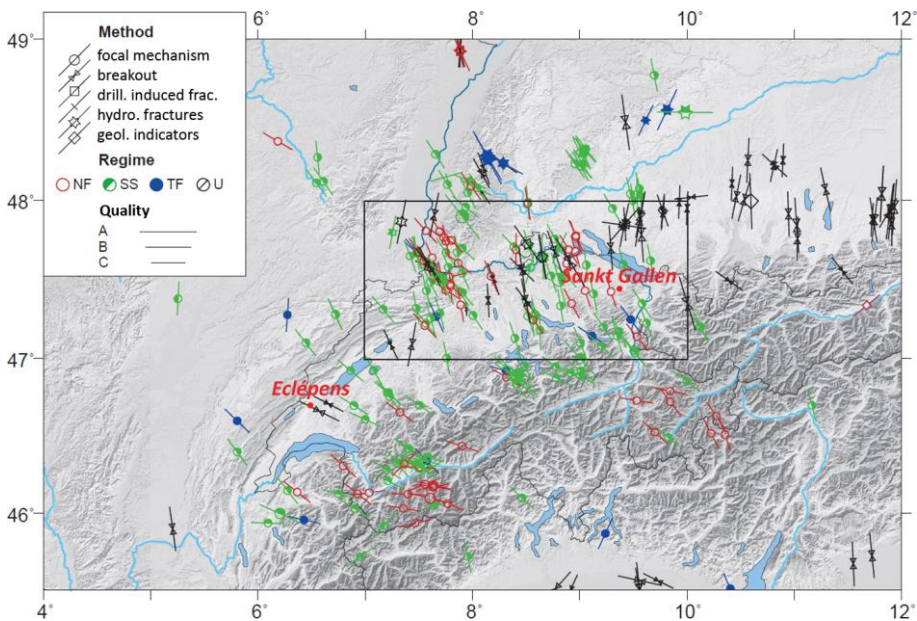


Figure 4.5: Stress field in Switzerland and surrounding regions (NAGRA, 2014). NF: normal faulting (red); SS: strike-slip (green); TF: thrust faulting (blue); U: Unknown (black). Symbols represent the different stress indicators.

### 4.3 Synthetic case study<sup>1</sup>

The aim of this study is to determine the influence on gravity of various underground parameters. This is done mainly to determine which prerequisites are needed in order to apply our methodology in Sankt Gallen. This also helped to plan a gravity survey by determining the amplitude and length of the anomalies, as well as to facilitate the interpretation of collected data. In this respect, simplified 2D or 2.5D models of the region have been used and the following parameters were investigated:

- Effect of Quaternary structures;
- Change of density of the geological formations;
- Depth and thickness of Mesozoic;
- Effect of a faulted zone;
- Effect of a Permo-Carboniferous graben.

#### 4.3.1 Methodology

The models are made from a geological cross-section of the region of Sankt Gallen but without topography and with very simplified structures. For every structure of this model a density is attributed which can be absolute or relative. The only difference between relative and absolute density is that relative densities are related to a constant absolute density, usually  $2.67 \text{ g}\cdot\text{cm}^{-3}$ , which is the mean bulk density of the upper continental crust. However, the response of a profile will be exactly the same by using absolute or relative densities, there will be only two differences, a shift of the value and the time of calculation. Indeed, in our case, when using relative densities, the basement density is set to  $0 \text{ g}\cdot\text{cm}^{-3}$  and therefore has no gravity effect. Therefore there is no need to calculate its effect and this shortens the time needed for calculation of the gravity effect of the model.

The expected ranges of densities of the geological formations described in the introduction and used in the models are presented in table 4.1. The gravity effect of the profiles are calculated using the 2D forward modeling tool presented in the previous section and the calculated values are then shifted to have the same origin than the model based on the Swiss Atlas of Gravity (Klingel  et al., 1980).

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<sup>1</sup> This section is modified after Altwegg et al. (2011)

*Table 4.1: Expected ranges of absolute and relative densities of the geological formations in the St. Gallen region. The relative densities are related to crustal rock density. The selected values represent the values used when nothing is specified.*

| Geological formation | Absolute density, $\rho$<br>( $\text{g}\cdot\text{cm}^{-3}$ ) |          | Relative density, $\Delta\rho$<br>( $\text{g}\cdot\text{cm}^{-3}$ ) |          |
|----------------------|---------------------------------------------------------------|----------|---------------------------------------------------------------------|----------|
|                      | Range                                                         | Selected | Range                                                               | Selected |
| Quaternary           | 2.0 – 2.4                                                     | 2.2      | -0.67 – -0.47                                                       | -0.47    |
| Tertiary             | 2.4 – 2.55                                                    | 2.45     | -0.27 – -0.12                                                       | -0.22    |
| Mesozoic             | 2.5 – 2.6                                                     | 2.55     | -0.17 – -0.07                                                       | -0.12    |
| PC Graben            | 2.45 – 2.55                                                   | 2.45     | -0.22 – -0.12                                                       | -0.22    |
| Crustal rock         | 2.67                                                          | 2.67     | 0                                                                   | 0        |

### 4.3.2 Effect of Quaternary deposits

The aim of this part is to characterize the shape and intensity of an anomaly due to a Quaternary structure. In this scope, Quaternary structures have been exaggerated compared to expected structures in the Sankt Gallen region (figure 4.3) so it is possible to see their effect on the profile (figure 4.6), and also to determine what will be the extreme value that we can expect in our field survey. Thus, the first modeled structure is 2 km wide and 100 m thick, as we use 2D profile, the 3D extension is considered to be infinite. The second structure, with its size of 2 km wide and 50 m thick is more realistic for the region. For each structure different  $\Delta\rho$  were tested -0.27, -0.47 and  $-0.67 \text{ g}\cdot\text{cm}^{-3}$ .

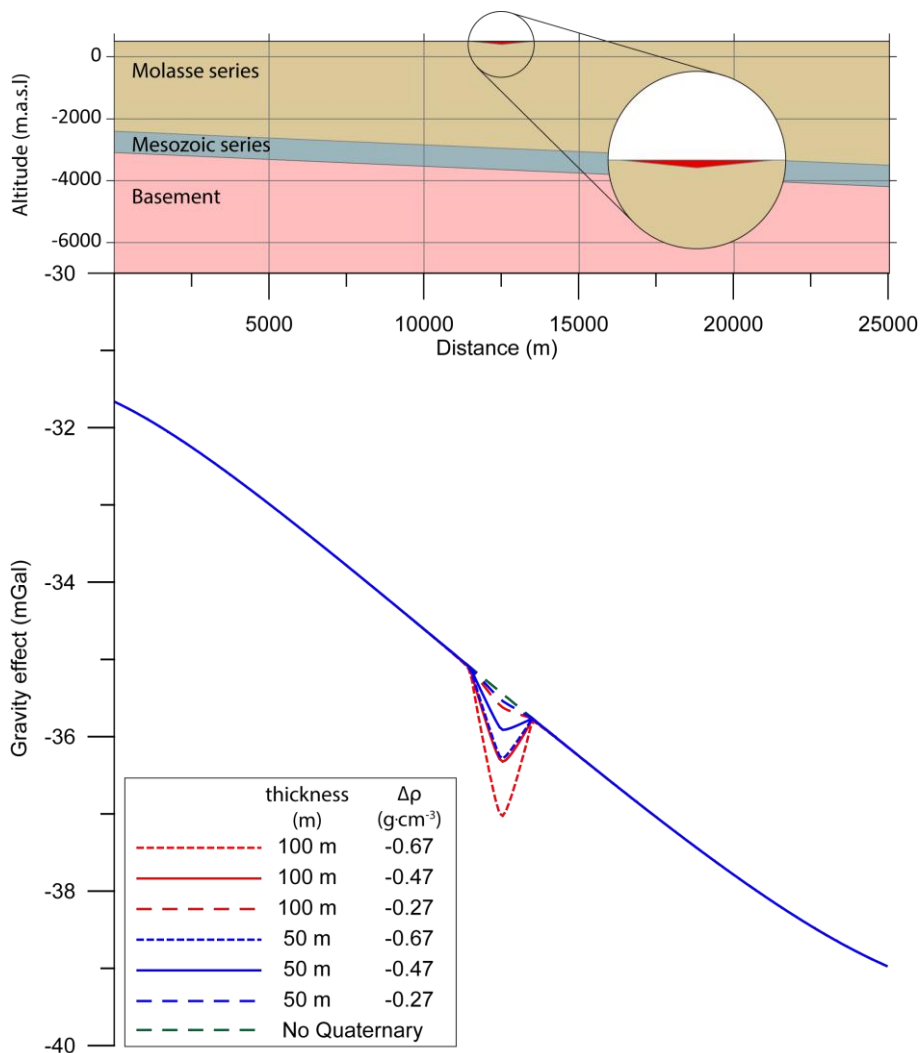


Figure 4.6: Gravity effect modeled from two different sizes of Quaternary deposits (in red in the profile). The green dashed line represents the effect of a model without Quaternary deposits; red line: structure with a maximum thickness of 100 m; blue line: structure with a maximum thickness of 50 m. Values have been shifted to have the same origin.

To allow the quantification of the anomaly due to a Quaternary structure, all effects have been subtracted except the Quaternary structures one (figure 4.7). To do so, only the anomaly due to deep structures, symbolized by a green dashed line on figure 4.6, has been subtracted from the other values.

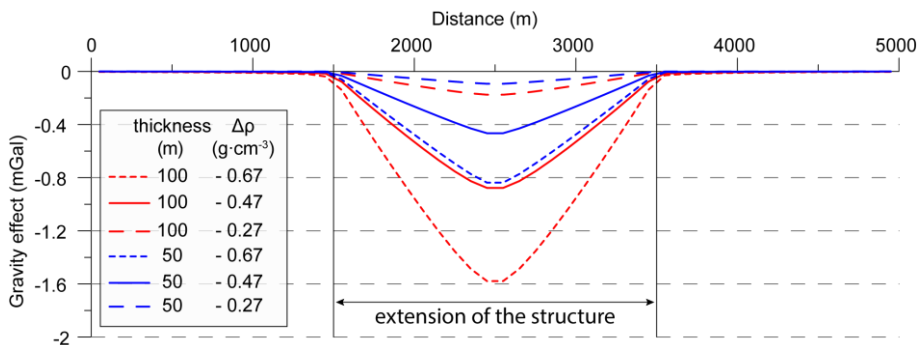


Figure 4.7: Anomaly due to a Quaternary structure of 2 km of length, thickness and  $\Delta\rho$  are specified in legend; distance (x axis) are related to the profile of Figure 4.6.

## Results

Looking at figure 4.7, we can see that the effect of a shallow Quaternary structure is only important right above the structure and becomes negligible as soon as we move a few tens of meters away from its limits. Considering that a CG5 Gravimeter has an accuracy of  $\pm 5 \mu\text{Gal}$ , a structure cannot be detected if its gravity effect is smaller than 0.1 mGal. In this respect, we consider that the distance from the borders of the structure to where its induced gravity effect is smaller than 0.1 mGal represents its detection limit. In all cases this distance is smaller than 100 m with the exception of the extreme case (100 m thickness and  $\Delta\rho$  of  $-670 \text{ g}\cdot\text{cm}^{-3}$ ) that we shall present in more detail. In this particular case the detection distance is roughly equal to 500 m. However at a distance of 50 m, the induced gravity effect is of only 0.038 mGal. Compared to the maximum intensity induced by this structure (table 4.2), this represents only 2.5 % on the maximum anomaly. The maximum intensity of the induced gravity effect for all cases is shown in table 4.2.

Table 4.2: Maximum intensity (in mGal) of an anomaly due to an important Quaternary structure with a length of 2 km and of infinite 3D extension.

| $\Delta\rho$<br>( $\text{g}\cdot\text{cm}^{-3}$ ) | maximum intensity |        |
|---------------------------------------------------|-------------------|--------|
|                                                   | 50 m              | 100 m  |
| -0.27                                             | -0.093            | -0.175 |
| -0.47                                             | -0.465            | -0.877 |
| -0.67                                             | -0.838            | -1.579 |

If we compare the modeled structures with the map of Quaternary thickness in the region of St. Gallen (figure 4.3), we can see that in most cases the expected structure will have a length of less than half a kilometer and is not infinite in the third dimension. Therefore, the following assumptions on anomalies due to Quaternary structures can be considered, and used for the analysis of field measurements:

1. Shape of the anomaly must be relatively steep and localized close to the assumed structure.
2. Wavelength of anomalies must be relatively low ( $< \frac{1}{2}$  km).
3. Maximum intensity should be  $< 0.5$  mGal.

We also see that  $\Delta\rho$  can be very close to the one of the molasse ( $-0.27 \text{ g}\cdot\text{cm}^{-3}$  for Quaternary and  $-0.22 \text{ g}\cdot\text{cm}^{-3}$  for molasse) and so it will be impossible to detect such a small and localized anomaly. This case can occur when Quaternary deposits are well consolidated and formed with a majority of clay, i.e. ground moraine. But in this case, the error will be localized and small enough to be negligible, as we are seeking deep structures (2.5-5 km).

#### 4.3.3 Change of density of the geological formations

This part of the synthetic case study helps us in the forward modeling phase. Indeed, by characterizing the change of shape and intensity due to changes of the bulk density of the different geological structures, we shall be able to understand more accurately the effect of these structures.

As the effect of Quaternary structures has already been quantified, only the regional structures of geological formations have been taken into account. In our model, it encompasses the Molasse series, the Mesozoic and the crustal basement. The synthetic model (figure 4.8) includes the following parameters:

- Mean altitude of Mesozoic at the middle of the profile is set to an average value of -3500 m.a.s.l.
- The crustal basement's density is constant and set to  $2.67 \text{ g}\cdot\text{cm}^{-3}$ .
- There is no topography.
- The dip of the Mesozoic is constant.
- Structures are considered to have an infinite extension in the third dimension.
- The range of the densities used is presented in table 4.1.

## Results

Figure 4.8 clearly shows that the influence on gravity of a bulk density change in Mesozoic sediments is almost negligible. On the contrary, a change in the Molasse sediments bulk density will have a major effect especially on the dip of the regional anomaly. This result is not surprising, as we increased (or reduced) a formation with a very important thickness. Indeed, as the thickness of the Molasse increases with the distance to the origin of the profile, the gravity effect due to a change of its density will also increase toward this direction.

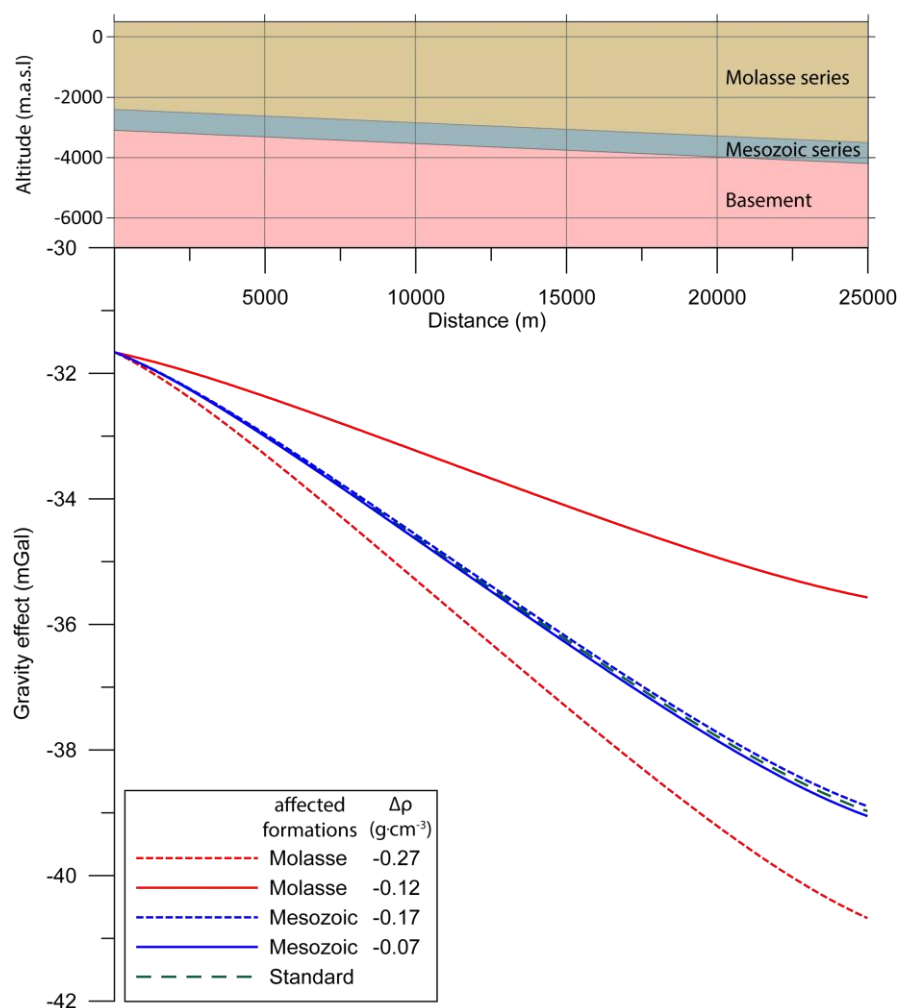


Figure 4.8: Influence on gravity of a bulk density change of the Molasse (red lines) and of the Mesozoic (blue lines) on a simplified model of the region of St. Gallen. The dashed green line represents the gravity effect of a model with the standard densities from table 4.1. Values have been shifted to have the same origin.

#### 4.3.4 Depth and thickness of Mesozoic

Mesozoic formations are the main target of the geothermal project of the city of St. Gallen. It is therefore important to establish the gravity influence of a change of burial (figure 4.9) and thickness (figure 4.10) of this formation. Moreover, these parameters are far from constant in the region. The depth especially will increase towards SE. The following parameters are considered in the model:

- Densities are constant and set in agreement with table 4.1.
- No topography.
- Constant dip of Mesozoic series.
- Structures are considered to have an infinite extension in the third dimension.
- Considered range for Mesozoic series depth change is +/- 1000 m.

#### **Results**

We can see on figure 4.9 that, in exception of a shift of almost 10 mGal, the effect on the anomaly concerns mainly its depth. Even if the effect on the dip is not very important, the change in shape of the anomaly differs slightly from that of the change in the Molasse series density (figure 4.8). Thus we think that we will be able to differentiate them in the forward modeling phase.

Figure 4.10 shows an example of the equivalence principle: as we thinned the Mesozoic by 200 m (red line), the gravity effect remained almost the same (green dashed line). The explanation is relatively simple: 100 m of Mesozoic rocks were replaced by crustal rocks with a density  $0.12 \text{ g}\cdot\text{cm}^{-3}$  higher than Mesozoic rocks and the other 100 m by a Molasse with a density  $0.1 \text{ g}\cdot\text{cm}^{-3}$  lower. As the difference of density of these two replacement layers is almost the same but with an opposite sign, each effect will be compensated by that of the other layer. Thus, the final gravity effect of the model remains almost unchanged.

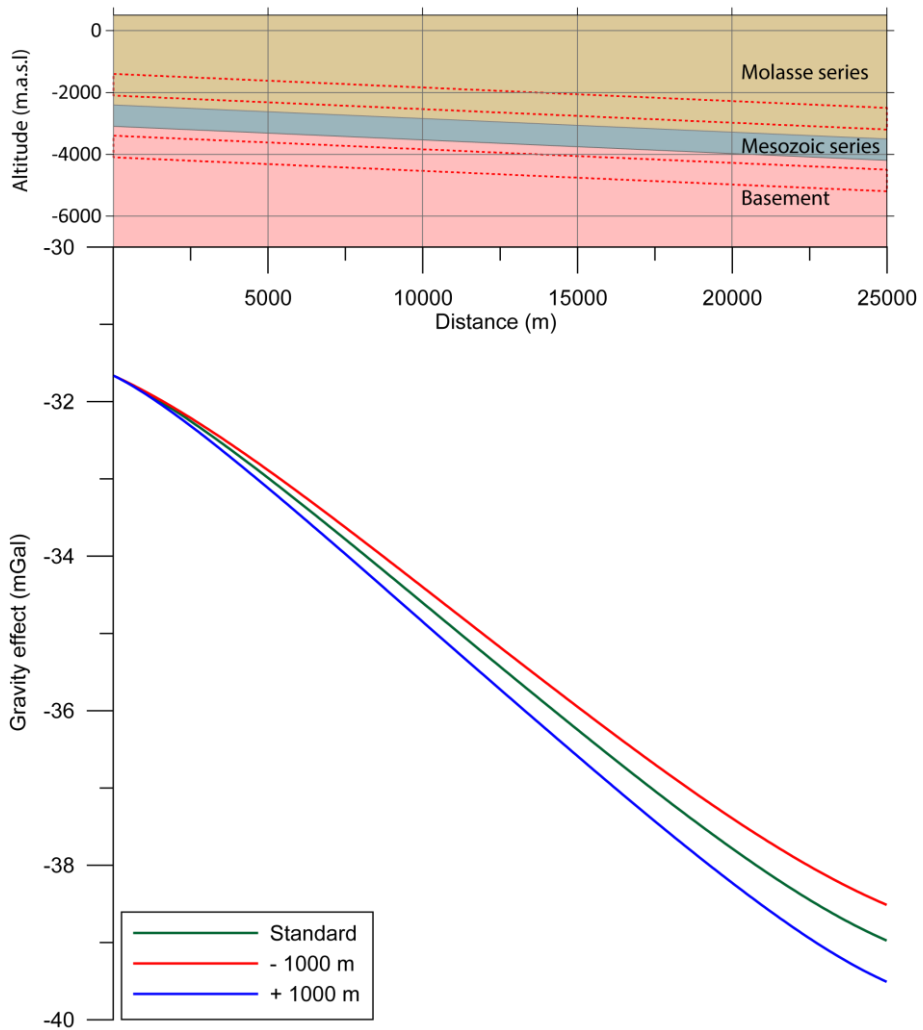


Figure 4.9: Influence on gravity of a change in depth (blue and red lines) of the Mesozoic (in blue) on a simplified model of the region of St. Gallen. The dashed red lines represent the Mesozoic place once shifted. The green line represents the gravity response of a model with the standard mean altitude of -3500 m.a.s.l. Values have been shifted to have the same origin.

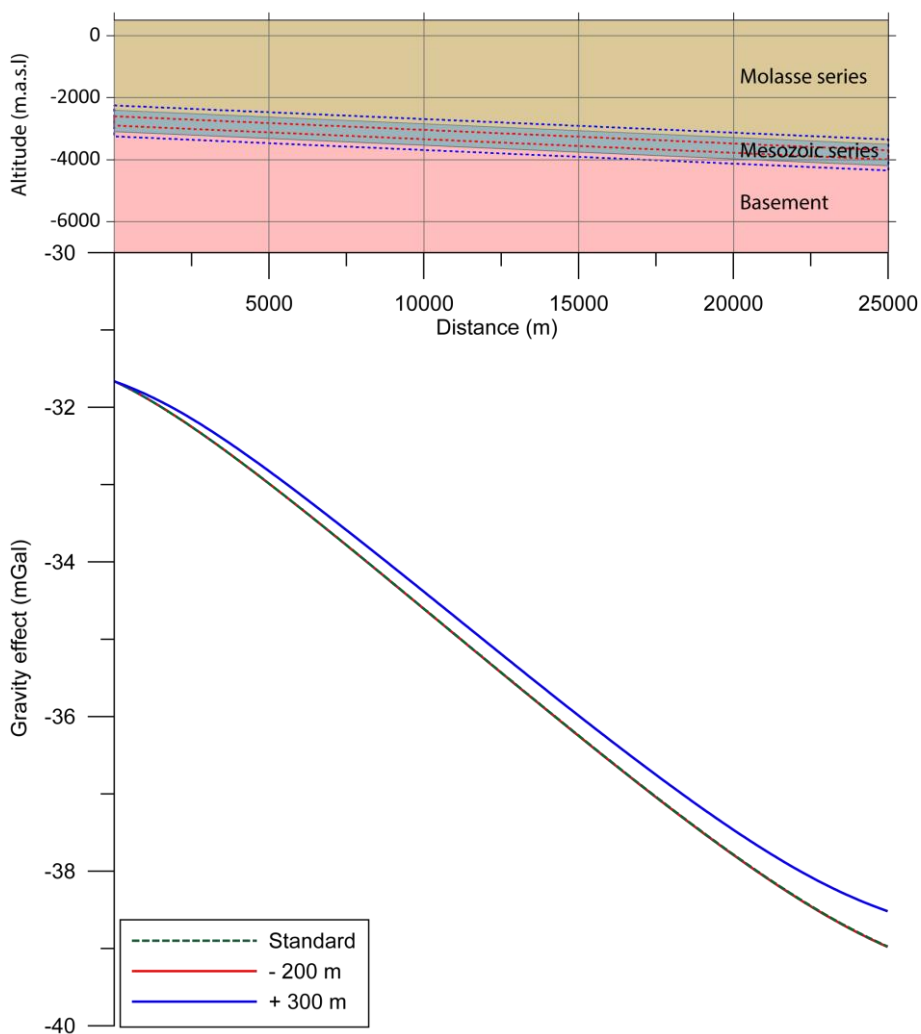


Figure 4.10: Influence on gravity of a change of thickness (blue and red lines) of the Mesozoic (in blue) on a simplified model of the region of St. Gallen. The dashed red lines represent the Mesozoic reduced by 200 m and the dashed blue lines Mesozoic increased by 300 m. The green dashed line represents the gravity response of a model with the standard thickness of 700 m. Values have been shifted to have the same origin.

### 4.3.5 Effect of a fault zone

The main target of the geothermal project of the city of St. Gallen was a fault in the Mesozoic formation. Thus it is important to quantify the effect of such a fault on the gravity measurements. We tested the following fault's parameters:

- shape (width, offset, orientation);
- amount of fracturing;
- extension in Molasse series and into basement;
- extension in the third dimension.

The range of variation of the selected parameters is presented in table 4.3, standard values where set using the geological profile of figure 4.2. To see the effect of the extension of the fault into the Molasse series and in the crustal basement, we considered that fracturing caused a change of density of 5 % referred to the standard density of table 4.1. The maximum, minimum and average values of density range were set in agreement with table 2.7 of the introduction.

*Table 4.3: Changing range of parameters used for the quantification of the gravity effect of a fault zone. The "standard" (highlighted in gray) represents the value used when nothing is specified. The standard model is presented in figure 4.11.*

| Parameter                      |             | Min. | Standard | Max. |
|--------------------------------|-------------|------|----------|------|
| Shape                          | Width (m)   | 200  | 500      | 1000 |
|                                | Offset. (m) | 100  | 250      | 500  |
|                                | Orient. (°) | -45  | 0        | 45   |
| Fracturing <sup>1</sup> (%)    |             | 2    | 5        | 10   |
| Extension (m)                  |             | 0    | 500      | 1000 |
| 3D extension <sup>2</sup> (km) |             | 5    | 30       | ∞    |

<sup>1</sup> The amount of fracturing is expressed as a change (reduction) of density of the affected formation in percent.

<sup>2</sup> For this parameter the standard value is not 30 km but infinite 3D extension. The extension in the two directions i.e. an extension of 5 km means a total extension of the structure of 10 km.

Table 4.4: Density Reduction of affected formations, induced by fracturing (reported to  $2.67 \text{ g}\cdot\text{cm}^{-3}$ ).

| Formation        | Density reduction ( $\text{g}\cdot\text{cm}^{-3}$ ) |       |       |
|------------------|-----------------------------------------------------|-------|-------|
|                  | 2 %                                                 | 5 %   | 10 %  |
| Molasse          | -0.27                                               | -0.34 | -0.47 |
| Mesozoic         | -0.17                                               | -0.25 | -0.38 |
| Crustal basement | -0.05                                               | -0.13 | -0.27 |

The following parameters are considered in the model:

- If not specified, densities are constant and set in agreement with table 4.1.
- The standard parameters for the fault zone are specified in table 4.3.
- There is no topography.
- Other structures have constant parameters.
- If not specified, structures are considered to have an infinite extension in the third dimension.
- Regional effect is calculated using a model without fault as presented in figure 4.11 by the dashed red line.

All the graphs presented below are residual anomalies: the regional anomaly values were subtracted to highlight the effect of the fault.

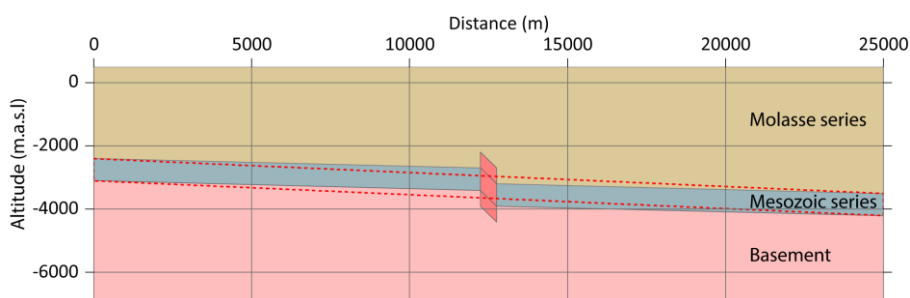


Figure 4.11: Model built with the standard parameters of table 4.1. The dashed red line represents the Mesozoic series without fault.

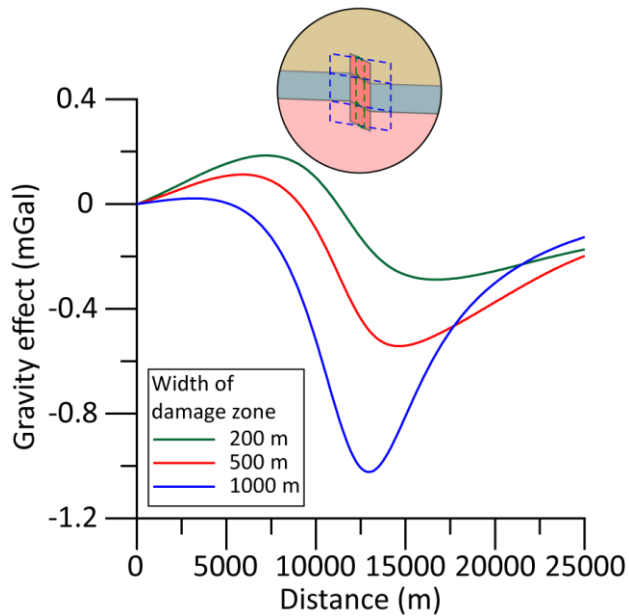


Figure 4.12: Residual anomaly representing the gravity effect of width change of the damage zone of the fault. The insert illustrates where the variation applies. Refer to table 4.3 p. 125 for other parameters of the fault zone.

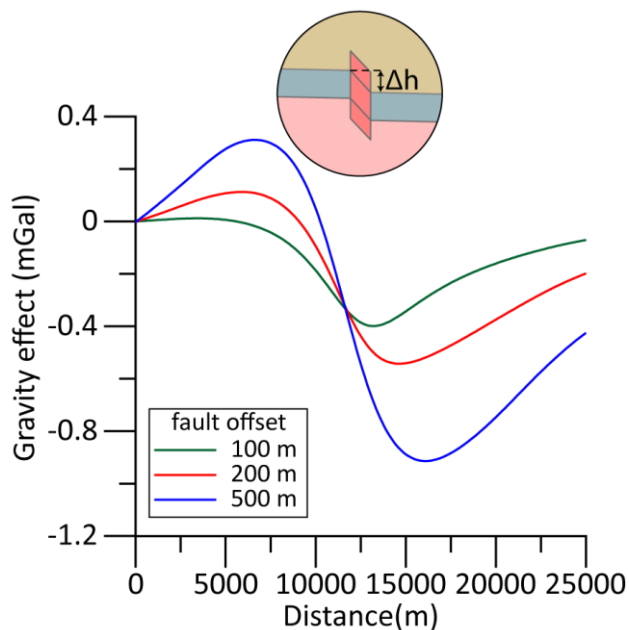


Figure 4.13: Residual anomaly representing the gravity effect of a change of vertical offset of the fault. The insert illustrates where the variation applies. Refer to table 4.3 p. 125 for other parameters of the fault zone.

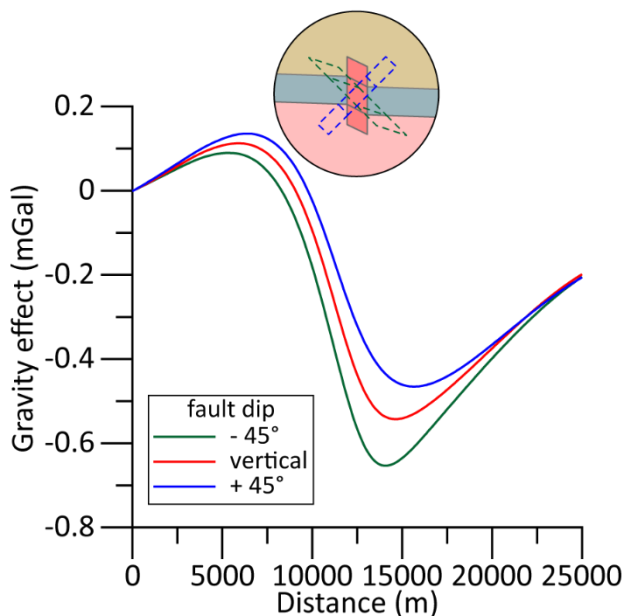


Figure 4.14: Residual anomaly representing the gravity effect of fault dip. The insert illustrates where the variation applies. Refer to table 4.3 p. 125 for other parameters of the fault zone.

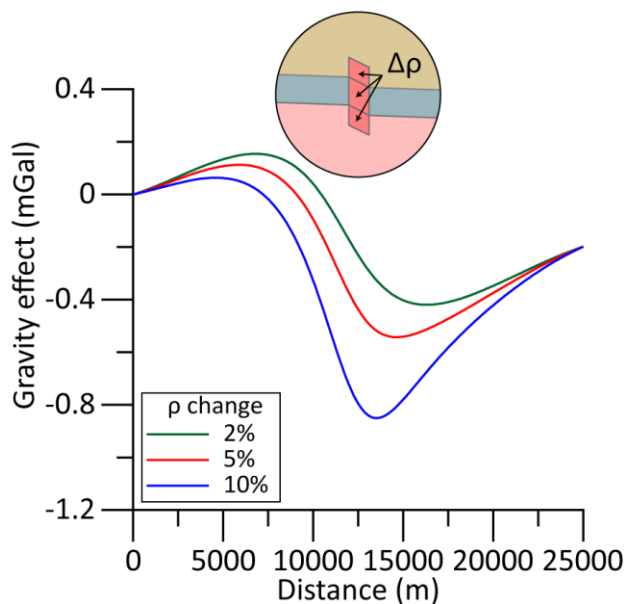


Figure 4.15: Residual anomaly representing the gravity effect of density change due to fracturing of the damage zone of the fault. The insert illustrates where the variation applies. Refer to table 4.3 p. 125 for other parameters of the fault zone.

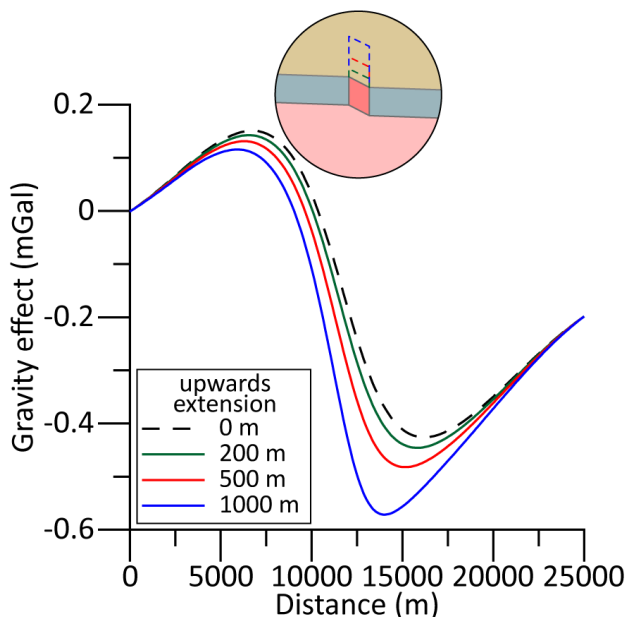


Figure 4.16: Residual anomaly representing the gravity effect of a change of the fault extension in the Molasse. The insert illustrates where the variation applies. Refer to table 4.3 p. 125 for other parameters of the fault zone.

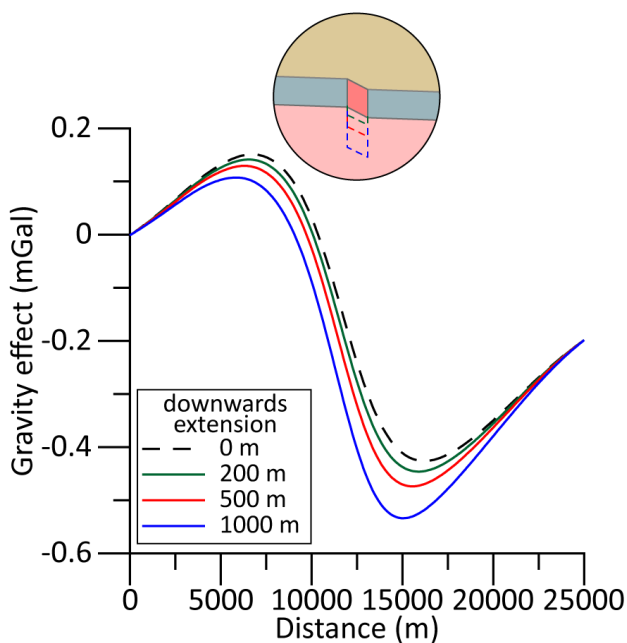


Figure 4.17: Residual anomaly representing the gravity effect of a change of the fault extension in the basement. The insert illustrates where the variation applies. Refer to table 4.3 p. 125 for other parameters of the fault zone.

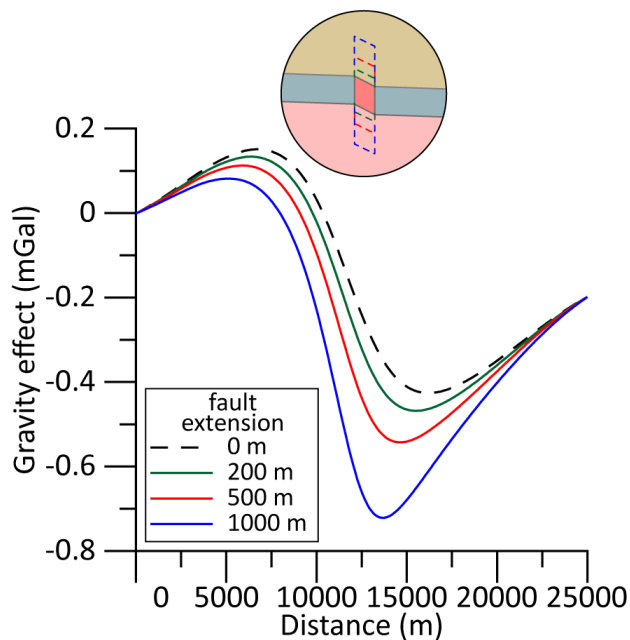


Figure 4.18: Residual anomaly representing the gravity effect of a change of the fault extension in the Molasse and in the crustal basement. The insert illustrates where the variation applies. Refer to table 4.3 p. 125 for other parameters of the fault zone.

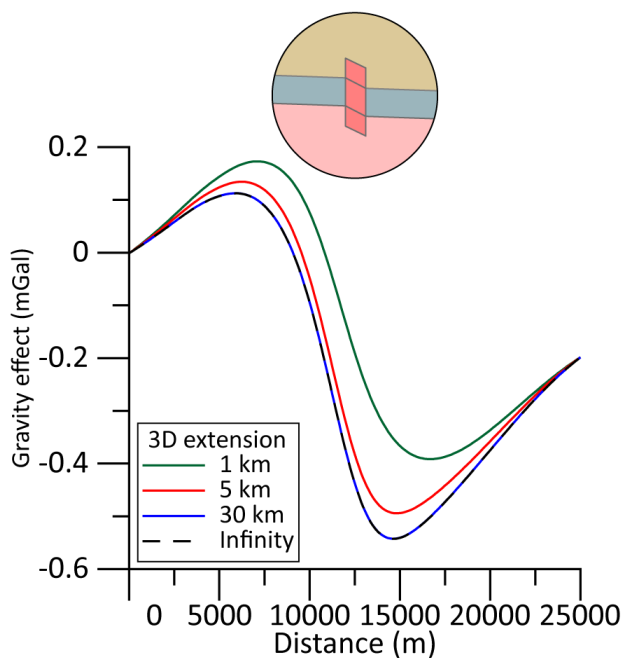


Figure 4.19: Residual anomaly representing the gravity effect of a change of the fault extension in the 3<sup>rd</sup> dimension. The insert illustrates where the variation applies. Refer to table 4.3 p. 125 for other parameters of the fault zone.

## Results

We can see on figures 4.12 to 4.19 the effect of the different parameters on the shape of the anomaly and the quantified results are summarized in table 4.5.

*Table 4.5: Summary of the effect on gravity of the fault parameters. All values are residual values (in mGal). Refer to table 4.3 p. 125 for fault zone parameter values.*

| Parameter    |          | Gravity effect (mGal) |        |            | Figure |
|--------------|----------|-----------------------|--------|------------|--------|
|              |          | Min.                  | Max.   | Difference |        |
| Shape        | Width    | -0.288                | -1.023 | 0.735      | 4.12   |
|              | Offset.  | -0.399                | -0.914 | 0.515      | 4.13   |
|              | Orient.  | -0.466                | -0.653 | 0.188      | 4.14   |
| Fracturing   |          | -0.420                | -0.851 | 0.431      | 4.15   |
| Extension    | Molasse  | -0.446                | -0.572 | 0.126      | 4.16   |
|              | Basement | -0.446                | -0.534 | 0.088      | 4.17   |
|              | Total    | -0.468                | -0.722 | 0.253      | 4.18   |
| 3D extension |          | -0.023                | -0.175 | 0.151      | 4.19   |

One important result concerns the third dimension extension of the fault. Indeed, we can observe on figure 4.19 and in table 4.5 that a fault with an extent of 30 km can be considered to be of infinite 3D extension and that the difference between 5 and 30 km remains limited. It is also important to notice that the difference of density due to fracturing has a major influence on the gravity effect of the fault. This anomaly has an average width of 10 – 15 km and an amplitude of almost 0.5 mGal. This suggests that we should be able to highlight it with precise gravity measurements.

#### 4.3.6 Effect of a Permo-Carboniferous graben

The seismic survey highlighted the likely presence of a Permo-carboniferous trough likely filled with detrital sediments in the region of St. Gallen. The density of these sediments is probably lower than that of the Mesozoic sediments and the crystalline basement. Thus, if the basement trough is rather large, a significant gravity effect should be observed.

Therefore a graben has been modeled in order to calculate, quantify and determine the shape of the gravity anomaly produced by such a structure. As the geometry of this structure remains highly uncertain, three cases have been modeled; thickness has been deduced from the first results of the 3D seismic:

- graben of 5 km length and a thickness of 1 km;
- graben of 10 km length and a thickness of 1 km;
- half-graben of 10 km length and a starting thickness of 1 km.

The following parameters are considered in the model:

- Densities are constant and set in agreement with table 4.1.
- There is no topography.
- Dip of the Mesozoic series is constant.
- Structures are considered to have an infinite extension in the third dimension.

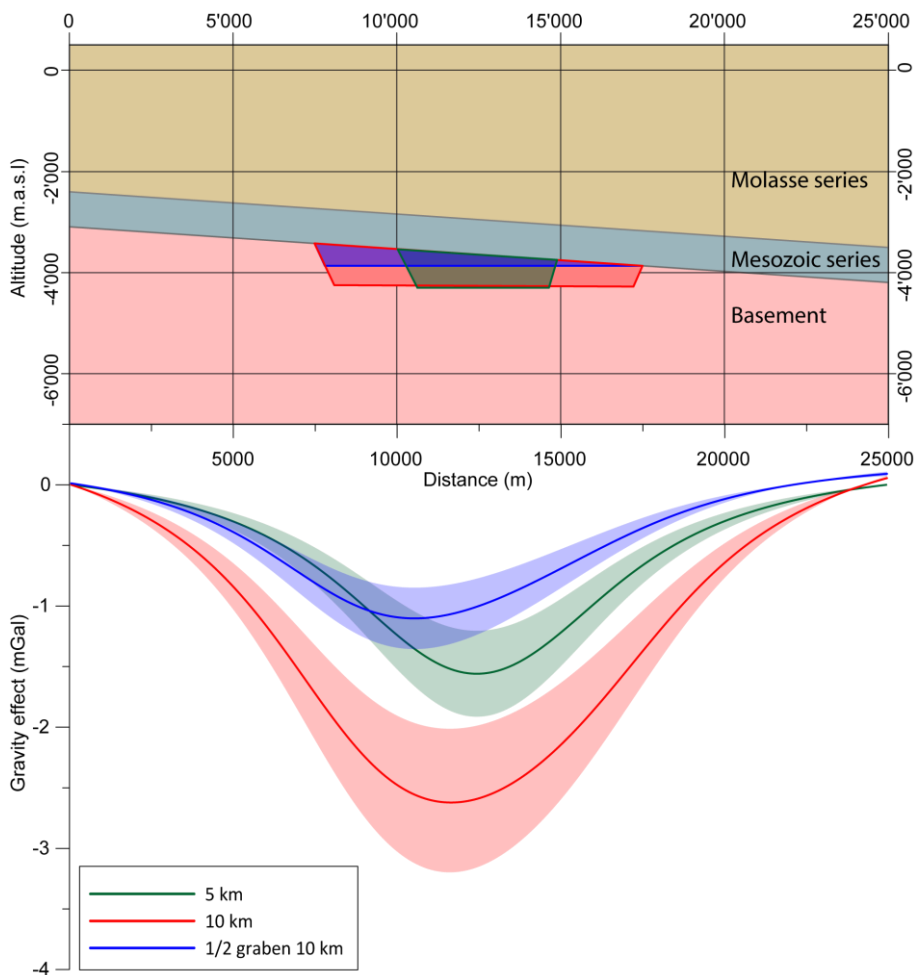


Figure 4.20: A simplified model of the region of Sankt Gallen with the three modeled cases is presented above. Gravity effects of the modeled Permo-Carboniferous grabens or half-graben. Other effects have been removed. The colored zones represent the effect of the density change of the grabens. The green line represents the effect of a graben with a width of 5 km, the red line for a 10 km wide and the blue line for a half graben of 10 km wide.

## Results

The modeled types of Permo-Carboniferous grabens on figure 4.20 show a major effect on gravity. This anomaly is 25 km wide and has an amplitude up to 3 mGal. The quantified results shown in table 4.6 mean that the effect of such a structure has a more important effect on gravity than the targeted fault and therefore should be modeled as precisely as possible.

*Table 4.6: Amplitude of the effect on gravity of three different Permo-Carboniferous graben (or half-graben). The value in the range column represents the difference of the anomaly amplitude due to density change of the graben. The average column represents the response of a model with the standard parameters of table 4.1; all the values are in mGal.*

| Graben case            | Range       | Average |
|------------------------|-------------|---------|
| 5 km wide, 1 km thick  | -1.2 – -1.9 | -1.55   |
| 10 km wide, 1 km thick | -2.0 – -3.2 | -2.6    |
| 1/2 graben 10 km wide  | -0.9 – -1.4 | -1.1    |

### 4.3.7 Conclusions

The sensitivity study has identified the structures influencing the gravity effect of a simplified model of the region of St-Gallen. Regarding Quaternary deposits, a maximum effect of gravity reduction up to -1.6 mGal can be observed across the lateral extension of the deposits. Outside of the area limited to the extension of the structure itself the influence is negligible (short wavelength, figure 4.7). Thus, using a detailed and independently acquired Quaternary deposition map should allow subtracting of this local effect from the anomalies by stripping.

Mesozoic sediments are gently dipping and have a relative uniform thickness across the investigation area and therefore variation of the thickness or of the uniform density do not create a local anomaly. Internal density variation was not taken into account, since there is no evidence of facies changes within the study area. In contrast, the density of the Tertiary sediments has a major influence on gravity effect of the model due to its important thickness and its thickening toward SE (figure 4.8). This can largely be taken into account by introducing different layers of the Molasse sediments in the 3D geological model as it will be shown later.

An important fault zone should result in a measurable anomaly ( $<0.5$  mGal). However, data on fracture porosity at 4500 m depth are scarce. Thus, in the present study, we assume that values taken from the Soultz EGS site are representative as they were the only data available at depth. In the upper reservoir at about 2000 m depth, porosity between 3 and 20 % has been observed for matrix and fracture porosity, respectively (Genter, 1990). A mean fracture porosity of about 8 % is estimated for the mean reservoir zone at about 5 km depth and appears also from gravity inversion (Schill et al., 2010). Thus, we have investigated porosities between 2 and 10 %. For the applied initial density distribution, this corresponds to density reduction of 27 and  $53 \text{ kg}\cdot\text{m}^{-3}$ , respectively. Assuming a lateral extension of about 500 m and a vertical extension of the fault zone of about 500 m into the Tertiary sediments and the basement, a minimum and maximum gravity reduction of about -0.3 to -0.7 mGal can be observed for respectively 2 and 10 % of fracture porosity (figure 4.15).

It should be noted here that these expected values are within the sensitivity range of the CG-5 gravimeter and the expected resolution including the uncertainty caused by station localization. Variation of the different parameters of the fault zone causes a sinusoidal signal with a minor positive and a major negative anomaly, and their effects on the residual gravity anomaly are of the same order of magnitude (figures 4.12 to 4.19). Following these observations, the 3D geometry of the fault zone must be known for determination of fracture porosity. This involved a major consequence on the applicability of our methodology, i.e. it may be applied only in combination with 3D seismic measurements.

As mentioned above, the vertical extension of the Permo-Carboniferous trough is unknown. As it was the only data available at this time, lateral extension in the sensitivity analysis has been estimated to about 5 km, from the mean extension of these structures given by Nagra (2008, figure 2.7 p. 27). Following depth estimates in the North Swiss trough of up to 3000 m with a lateral N-S extension of about 10 km (Klingelé and Schwendener, 1984; NAGRA, 2008), we assume a maximum vertical extension of 1000 m for the study area from the preliminary result of the 3D seismic survey. With this geometry and a density reduction of  $-200 \text{ kg}\cdot\text{m}^{-3}$  with respect to the crystalline basement, a Permo-Carboniferous graben causes a relatively broad anomaly of 25 km width (figure 4.20).

## 4.4 Geological 3D modeling

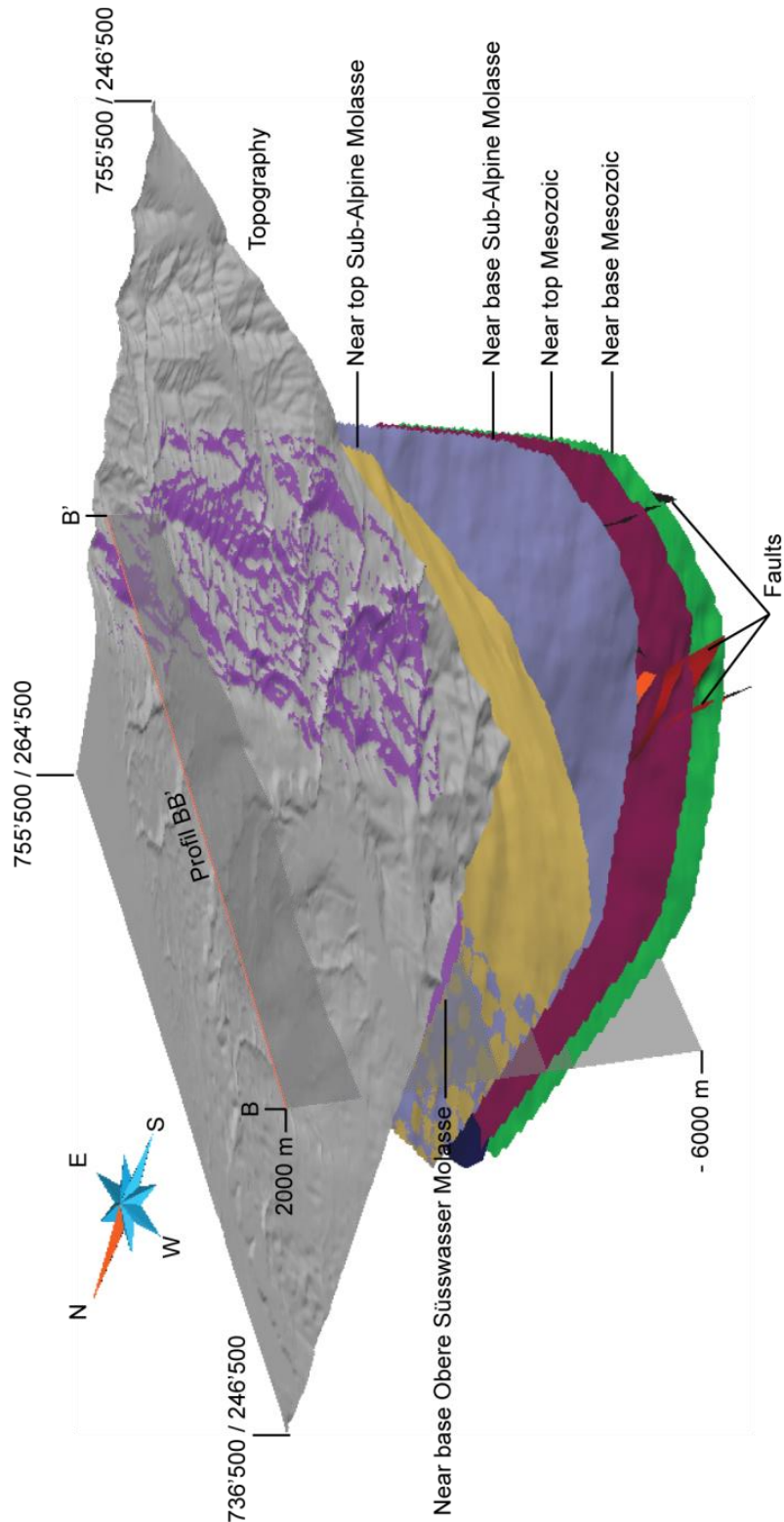
The 3D subsurface structures were obtained from a 3D seismic survey (e.g. figure 4.4) and extended to the limit of our geological model (Swiss coordinates CH1903 735'000/246'000 to 756'000/265'000). The model covers an area of 20 x 19 km and extends to a depth of -6000 m.a.s.l. (figure 4.21). The topography is obtained from two DEMs with a pixel size of 25 m (DHM25, Swisstopo, 2010b) and 2 m (SwissALTI3D, Swisstopo, 2010a).

With the exception of the Quaternary deposits and the Permo-Carboniferous graben, the layers were imported directly from the 3D seismic interpretation (Sankt Galler Stadtwerke, unpublished) into the 3D geological model using GOCAD (Paradigm Software, 2011; figure 4.5). The initial relative accuracy of the seismic interpretation is 10 m in all three directions. In the 3D geological model, the horizontal resolution of the geological layers was reduced to 100 m in order to approach the offset of the gravity stations. It should be mentioned here that in the absence of nearby wells, the seismic interpretation reveals an additional absolute uncertainty in depth of  $\pm 5\%$  (Sankt Galler Stadtwerke, unpublished), due to uncertain seismic velocity calibration. Nevertheless, since we are targeting lateral gravity variation this comparably large absolute uncertainty is negligible in our case. Mapped small-scale Quaternary structures (figure 4.4; Hofmann, 1973; Ludwig, 1930; Ludwig et al., 1949; Naeff, unpublished; Sankt Galler Stadtwerke, unpublished; Saxer, 1965) were implemented as a high-resolution grid using pixel size of 2 m.

As previously mentioned, no interpreted seismic horizon was available from the seismic survey for the Permo-Carboniferous graben. Therefore we deduced the limits of the graben from the depression in the near top Mesozoic horizon between the target fault zone and a second fault zone located to the East (figure 4.3 and 4.23). Although only limited information is provided by 3D seismic on the thickness of this structure, we assume it to be in first order linked to the possible penetration depth of the fault zone into the crystalline basement, i.e. about 900 m. The NNW-SSE orientation and the size of the graben may be astonishing compared with the North Swiss trough of WSW-ENE orientation. However other small sized Permo-Carboniferous troughs associated with strike-slip faults with such orientation exist,

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*Figure 4.21 (next page): Geological model of the Sankt Gallen region constructed on the basis of 3D seismic (data from Sankt Galler Stadtwerke). The topography is calculated using a DEM of 25 m (Swisstopo). Swiss coordinates (CH 1903) are used (from Altwegg et al., subm. to Geothermics).*



such as the Sillon Houiller in Massif Central, France (Faure, 1995; McCann, 2008; McCann et al., 2006) and some of the late Paleozoic basins of the Bohemian Massif in the Czech Republic (Brandmayr et al., 1995; McCann, 2008; McCann et al., 2006; Ulrych et al., 2006). We think that concerning the size and orientation, this latter case is the more emblematic as some analogy can be found with our case. Indeed, in both cases important basins are present in the north and comparatively smaller graben are associated with strike-slip faults like the Blanice and Boskovice troughs (figure 4.22). Therefore we assume that the N-S orientation of the Sankt Gallen graben is realistic, and to be consistent with the layers from the seismic survey, its resolution is set to 100 m.

Concerning the fault zone, the data available from the seismic interpretation are planar single fault sections indicated by offsets in the reflectors (figure 4.4 and 4.23). In order to determine the volume of the fault zone needed to compute its gravity effect (see previous chapter), we apply a conservative approach. Neglecting the fact that the damage zone is expected to extend on both sides of a fault zone (see section 3.4.3 p. 78), in our model the outermost fault segments define the boundary of the damage zone, i.e. a volume is considered to be inside the damage zone only, if it is located between two fault planes.

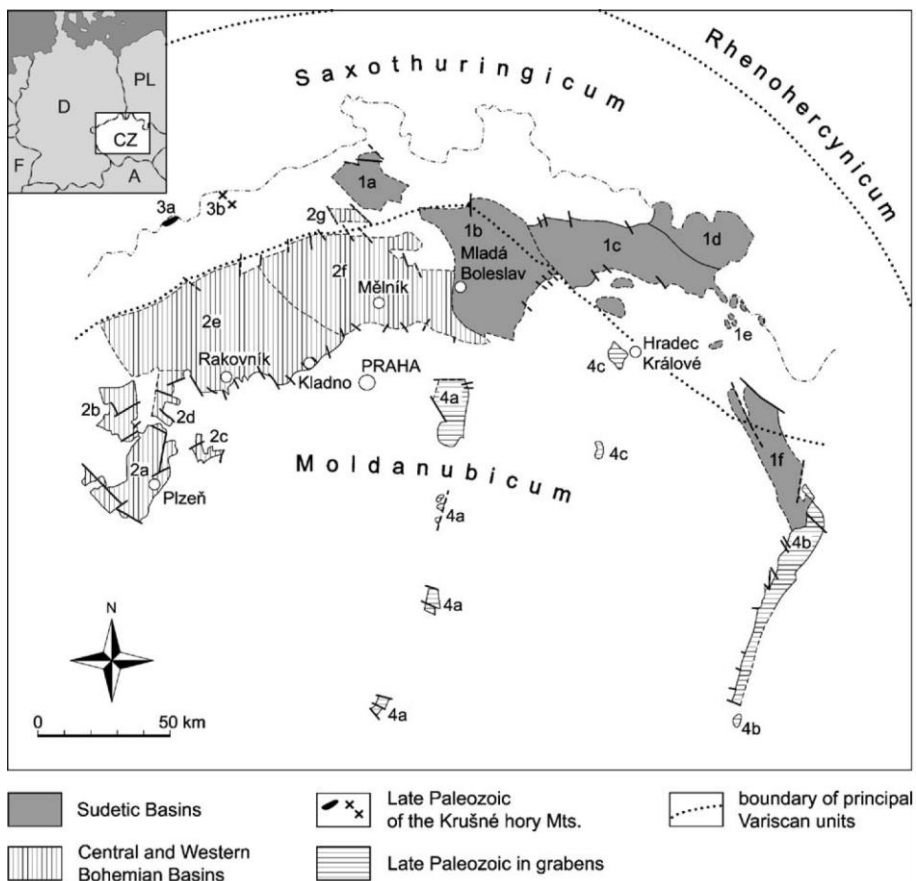


Figure 4.22: Late Paleozoic basins of the Bohemian Massif and their basement units (from Ulrych et al., 2006). 1: Sudetic Basins; 1a:Česká Kamenice, 1b:Mnichovo Hradiště, 1c: Krkonoše Piedmont, 1d: Intra-Sudetic (Czech part), 1e:Permian in the Orlické hory Mts., 1f: Orlice; 2: Central and Western Bohemian basins; 2a: Plzeň, 2b: Mělník, 2c: Radnice, 2d: Žihle, 2e—Kladno-Rakovník, 2f: Město-Roudnice, 2g: Kravčice occurrence; 3: Late Paleozoic of the Krušné hory Mts.; 3a: Brandov relic, 3b—Mikulov relics; 4: Late Paleozoic sediments of the graben structures; 4a: Blanice Graben, 4b: Boskovice Graben, 4c: Jihlava Graben.

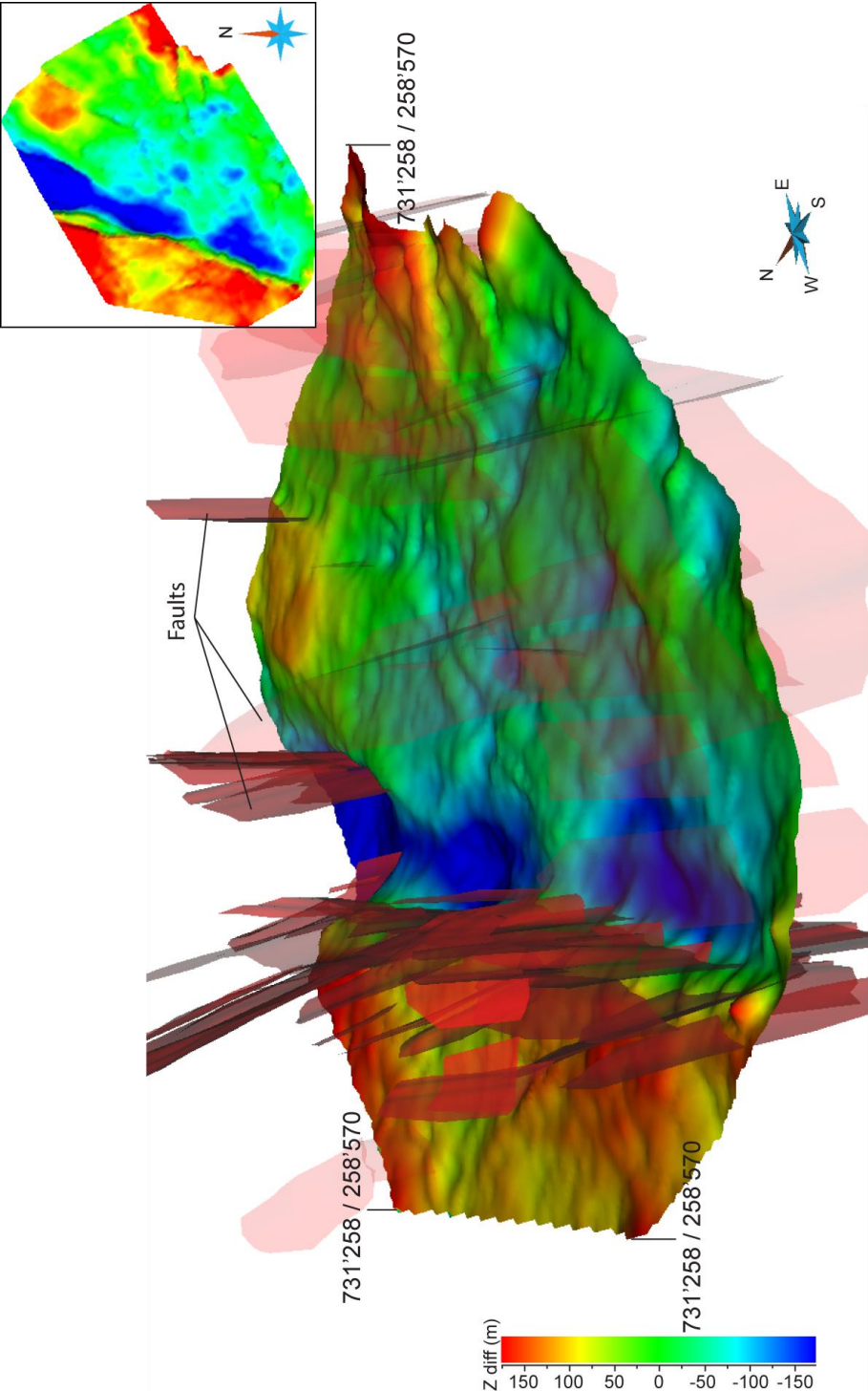


*Figure 4.23 (previous page): Representation of the basal (or nearby) seismic reflectors of the Mesozoic sediments and fault planes interpreted from the 3D seismic survey (data source: Sankt Galler Stadtwerke). The color scale represents the depth difference between this plane and the medium plane. The blue colored zone is assumed to overlie the Permo-Carboniferous graben; all mentioned coordinates are in Swiss coordinate (CH 1903)(from Altwegg et al., subm. to Geothermics).*

## 4.5 Gravity survey

The gravity measurements were carried out in 2011 and 2012 and cover an area of 20 x 10 km with about 700 measurement stations in the central part of the 3D seismic survey area (figure 4.24 and Appendix B). The offset of gravity stations of 200-250 m was obtained from the synthetic case study. In 2011, measurements were distributed along E-W profiles of 10 km length across the expected fault zone. Since our results indicated that the dominant local negative anomaly extends about 5-10 km to the East of the fault zone, in 2012 the profiles were prolonged across the expected extension of a possible Permo-Carboniferous trough that had been inferred from both the 3D seismic survey and the residual anomaly calculated from the Swiss Atlas of Gravity (Olivier et al., 2010). Geographic coordinates of the measurement stations were acquired using a Leica differential GPS (DGPS) GS 15 with an accuracy of 1-3 cm in vertical direction and gravity was measured using a CG-5 Autograv relative gravity meter (Scintrex, Canada) with an accuracy of 0.005 mGal. More than 20 % of the stations were re-measured to verify the quality of the dataset and to allow for uncertainty calculation. Following the individual uncertainties of the measurements (DGPS and gravimeter), a maximum uncertainty of about 0.03 mGal can be estimated. The uncertainty induced by the terrain correction is estimated from synthetic models to be < 0.1 mGal (see section 3.2.1 for details).

In addition to our own measurements 200 gravity stations from the Swiss Atlas of Gravity (Olivier et al., 2010) were added to the dataset to extend the data coverage to the entire area of the 3D seismic survey. In this respect, 30 of these additional gravity stations were re-measured in the field. The error induced by topographic correction for the Atlas data is 0.2 mGal and thus was too important for our purpose. Thus, the merging and standardization of the two data sets required the re-calculation of the terrain correction on the regional data from Olivier et al. (2010). This lead to a final mean difference between our measurements and the regional data of 0.12 mGal, which results mainly from uncertainties of station localizations in the regional dataset.

Complete Bouguer anomaly has been calculated with a reference density of  $2570 \text{ kg}\cdot\text{m}^{-3}$  for the topography (figure 4.24) following the methodology described in the previous section. This density value corresponds to the mean bulk density of the outcropping Molasse sediments. The most important error comes from topographic correction with 0.1 mGal and thus, the overall root mean square error is 0.1 mGal and as presented in the sensitivity study this value is five times smaller than the expected anomaly.

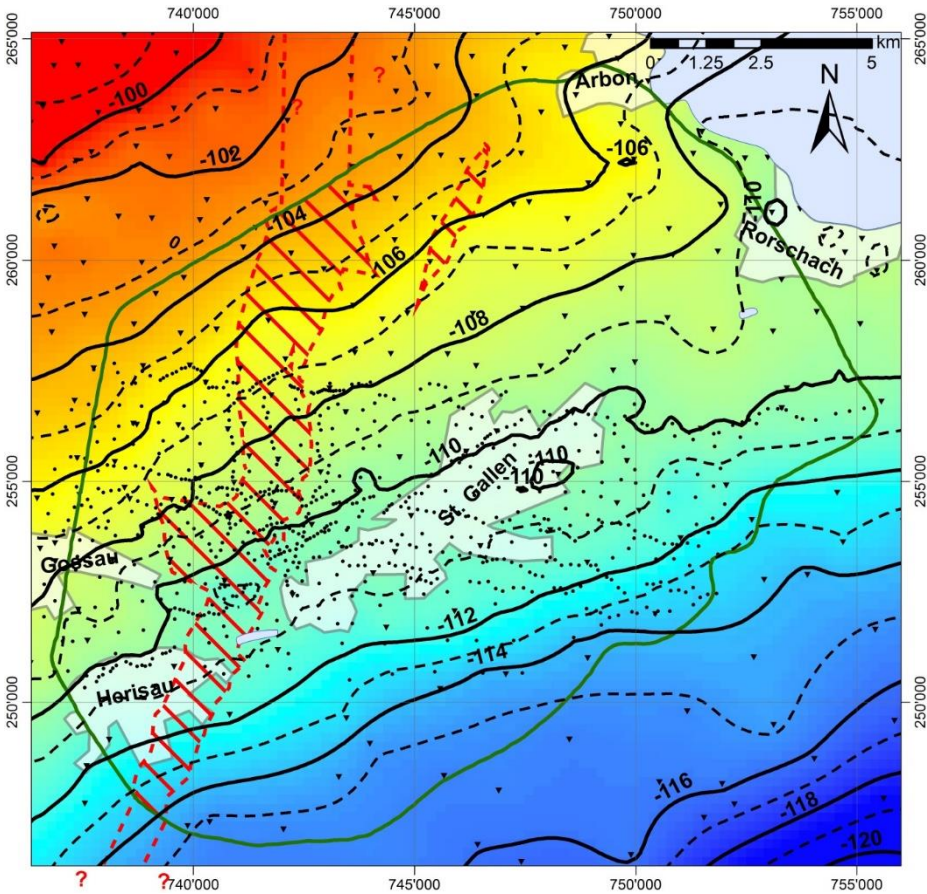


Figure 4.24: Bouguer anomaly map of the Sankt Gallen area calculated using a reference density of  $2570 \text{ kg}\cdot\text{m}^{-3}$ . Isogravity lines every 2 mGals. Dots indicate gravity measurements acquired during this study; black triangles are gravity stations from the Swiss Gravity atlas (Olivier et al., 2010). The green line shows the limit of the 3D seismic survey and the red area is the extent of the main fault zone inferred by the survey. Swiss coordinates (CH 1903) are used (from Altwegg et al., subm. to Geothermics).

#### 4.5.1 Forward modeling and stripping

Using GInGER (section 3.4), we calculated the gravity effect of every single structure of the above discussed 3D geological model individually using different densities and different resolutions, according to the depth of the respective geological units. Geological surfaces are transformed into continuous grids with the same cell size, extent and origin. Grids have a cell size of 100 m for the deep structures. Near-surface structures (above 0 m a.s.l.) such as Quaternary deposits were modeled with a cell size of 2 m in respect to the SwissAlti3D DEM (Swisstopo, 2010a).

In order to infer input values for forward modeling, density measurements were carried out on half a dozen samples from nearby outcrops of the different Molasses types. Others (essentially middle and upper Jurassic formations) were sampled from analog formations in the Swiss Jura Mountains (Altwegg et al., 2013). The method used for the determination of density in the laboratory is precisely described in Altwegg et al. (2013). The base principle is to use Archimedes's law in order to determine the volume of the sample, as its weight can be obtained easily.

It should be mentioned that in the latter case due to possible facies changes and fractures, real densities in the Sankt Gallen subsurface may differ from our measurements. Thus, measurements were cross-validated with available literature (e.g. Wagner et al., 1999). The measurements as well as the literature values are presented in figure 2.17 (p. 47). The resulting densities used for the calculation of the gravity effect of the model are presented in table 4.7.

*Table 4.7: Final density of the different formations used for the calculation of the gravity effect of the models.*

| Geological formations                | Density ( $\text{kg}\cdot\text{m}^{-3}$ ) |
|--------------------------------------|-------------------------------------------|
| Quaternary deposits                  | 2450                                      |
| OSM                                  | 2570                                      |
| OMM & USM                            | 2620                                      |
| Dreieckzone<br>(tectonized Molasses) | 2640                                      |
| Mesozoic                             | 2680                                      |
| Permo-carboniferous<br>graben        | 2620                                      |
| Basement s.s.                        | 2750                                      |

The density of the Permo-Carboniferous sediments was determined using the data of the Weiach borehole (Matter and Blüm, 1988) and a gravity exploration campaign (Klingelé and Schwendener, 1984). However, the Permo-Carboniferous graben of Sankt Gallen is located significantly deeper and thus, we slightly increased the density from  $2550 \text{ kg}\cdot\text{m}^{-3}$  (Klingelé and Schwendener, 1984) to  $2620 \text{ kg}\cdot\text{m}^{-3}$  for a final adjustment to best fit our profile.

The geometry of the modeled Permo-Carboniferous graben differs strongly from what was expected and thus modeled in the synthetic case study (section 4.3.6). Therefore, we established a new synthetic case, this time, by computing the effect of prisms whose tops are located on the bottom of Mesozoic of figure 4.2, and with dimensions and densities closer to what was expected (figure 4.25).

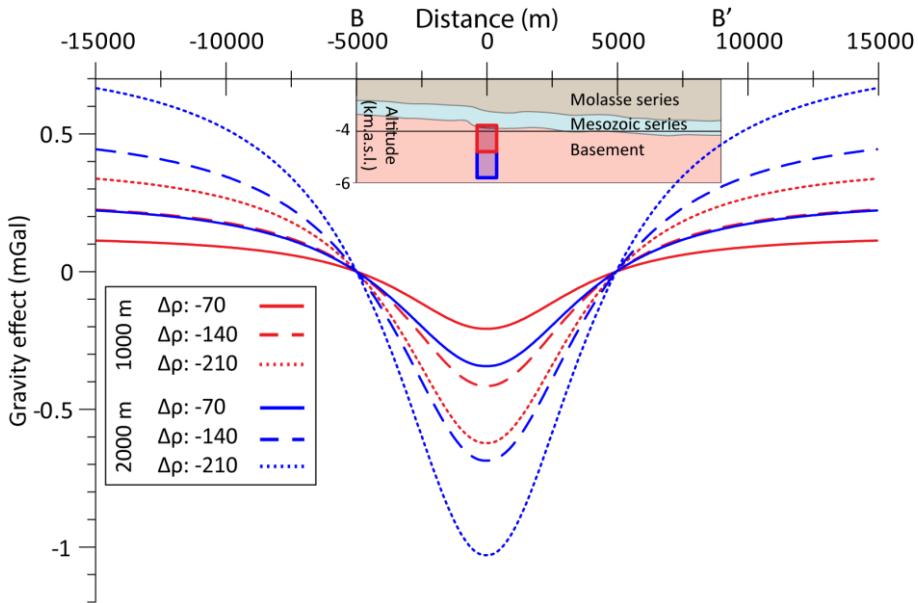


Figure 4.25: Synthetic residual anomaly calculated for possible geometries of a Permo-Carboniferous graben structure. The structure extends of 1000 or 2000 m into the crystalline basement with its top at the base of the Mesozoic sediments on profile BB' (see e.g. figure 4.1 for localization),  $\Delta\rho$  are in  $\text{kg}\cdot\text{m}^{-3}$ . The lateral extension is limited to 1000 m as observed in the 3D seismic survey (figure 4.23). The center of the structure is located at 0 m on the profile.

The 3D model allows us to apply an iterative stripping using GInGER. The contribution of a single structure on gravity is computed by assuming its bulk density value. This value is then modified until a best-fit between computed and measured gravity is obtained. This process is done for every geological structure present in the model in order to reduce the misfit between modeled and measured gravity. The order in which the structures' gravity effect is stripped is determined by the confidence and accuracy of their geometry. The gravity effect of the structures which we are confident in are the first to be removed, the order is the following: (1) Geological layers from the 3D seismic; (2) Quaternary structures; (3) Permo-Carboniferous graben; (4) Fault porosity.

## 4.6 Results

Reasonable quality of the corrections leading to the Bouguer anomaly can be deduced from the fact that no correlation or anti-correlation can be observed between local topography and Bouguer anomaly. The Bouguer anomaly shows a clear trend of decreasing gravity from NW to SE (figure 4.24). This regional trend of the Bouguer anomaly, well known in the Swiss Molasse basin (e.g. Kahle et al., 1976; Klingel , 2006; figure 3.8), represents the tectonic setting of the basin at orogenic scale and is irrelevant for geothermal reservoir exploration. It has been fitted using polynomial regression on stations from the Swiss Atlas of Gravity (Olivier et al., 2010) to a distance of 50 km from the survey area. As previously presented (section 3.2.2), the resulting regional anomaly is subtracted from the Bouguer anomaly, resulting in the residual anomaly emphasizing local gravity effects (figure 4.26).

The comparison of Bouguer and residual anomalies reveal that the regional effect is completely removed. In fact, this effect might have even been slightly overcorrected, since a slight trend of increasing positive anomaly towards SE is observed. In the vicinity of Lake Constance, Bouguer and residual anomaly suggest that up to a distance of about 2500 m from the shores of the lake, data are biased (figure 4.24 and 4.26 respectively). Since this area is located at the limit of the investigated zone and is not of interest for the geothermal project, the effect of the lake has not been taken into account during topographic correction. The negative anomalies in the southern part of the model, however, suggest a reasonable residual anomaly, as the found anomalies described hereafter correspond to what was expected from the sensitivity study.

It should be mentioned that the two northernmost anomalies are defined by one measurement only, but they fit within a more broadly defined trend following the -0.5 mGal line in figure 4.26. While directly to the South of Sankt Gallen and Herisau positive anomalies are observed, at the southernmost edge of the seismic survey, we observe two additional local minima; one of them is in the direct vicinity of the fault zone. These anomalies were not specifically studied for the following reasons: (1) the gravity data coverage was not sufficient in this area; it was not the target of the study and of the geothermal project; (2) they are located near the edge of the 3D seismic survey and thus of the model, and consequently border effects can be expected. However, the southernmost positive anomaly corresponds to the Subalpine Molasse Anticline Area (figure 4.2 south of the blue line) and may be linked to it. Concerning the negative anomaly South and East of Herisau we think it may be related to a density variation of the Molasse or of the “Rounded Overthrust” which outcrops in the vicinity (figure 4.2).

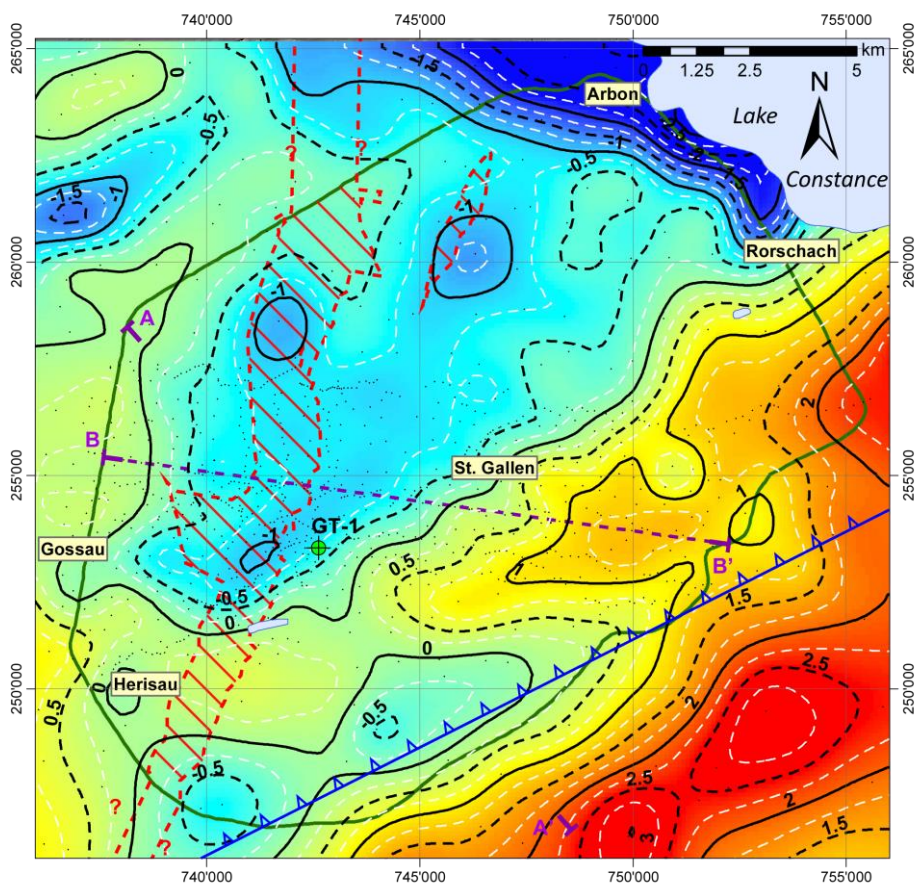


Figure 4.26: Residual anomaly of the Sankt Gallen area obtained from Bouguer anomaly (Figure 4.24), reference density of  $2570 \text{ kg}\cdot\text{m}^{-3}$ . Black lines every 1 mGal, dashed black lines every 0.5 mGal and white dashed line every 0.25 mGal. Red dashed area: extent of the modeled fault zone; dashed violet line: trace of profile BB' for which stripping is shown in figure 4.27. Trace of profile AA' of figure 4.2 is also shown, Blue line: approximate trace of the Rounded overthrust. Swiss coordinates (CH 1903) are used (from Altwegg et al., *subm. to Geothermics*).

To illustrate the applied stripping, a representative profile BB' (figure 4.1 and 4.27) across the central part of the target fracture zone, has been investigated for the different gravity effects (figure 4.27). The results of the different stripping steps (a) to (d) are compared to the residual anomaly and the geological features considered for each step as well as their densities, are indicated on the geological profile (figure 4.27 top). According to the synthetic case study, we must consider about  $\pm 0.1$  to  $0.25 \text{ mGal}$  of uncertainty due to density and geometry. Therefore, the overall error for the measurements is considered to be  $\pm 0.2 \text{ mGal}$  and is represented by the light blue area on figure 4.27. The important peak in gravity data near 9000 m has been neglected as it is caused by a single data point.

Stripping was executed in four steps following the order of confidence in the geometry of the geological units as indicated in section 4.5.1. The first forward model is calculated for the sedimentary layers obtained from the 3D seismic survey. The resulting gravity response shows that a large part of the gravity anomaly is linked to the general sedimentary sequences (figure 4.27, a). However, a maximum offset of about 0.5 mGal to the upper error limit of the regression remains at about  $x=4000$  m.

In the second step, the effect of the Quaternary sediments was added to the model (figure 4.27, b). It results in a short wavelength component, but does not reduce significantly the maximum offset with respect to the measured data. Introducing the previously described Permo-Carboniferous graben (figure 4.27, c) reduces the maximum offset by half to about 0.25 mGal. Considering the uncertainty introduced by the possible density ranges (table 4.1), we reach an overlap with the uncertainty of the measured data indicating that from this step, statistically, we fit the measured data.

Finally, an anomaly for the fault zone volume assuming fluid-filled fracture porosity of 5 % with a density of  $1000 \text{ kg} \cdot \text{m}^{-3}$  has been added (figure 4.27, d). This was done following the method presented in section 3.4.3 (p. 89). Although not significant regarding the  $R^2$  factor, the obtained curve fits completely (out of a shift) within the uncertainty of the polynomial regression introduced by measurements and their different corrections as presented here under.

Analyzing this trend further across the given profile by investigating the correlation between measured and modelled data, we find that our model fits preferentially well negative anomalies (figure 4.28), which was the target of the study. This indicates a well-defined model of the geothermally relevant area. The fit of the linear regression does not improve with respect to the root mean square  $R^2$  of 0.949 between the steps (c) including the Permo-Carboniferous Graben and (d) including the fracture porosity of the fault zone. However, the slope of the correlation reveals a trend from 0.75 to 1.0 for the negative anomalies by adding the fracture porosity to the modelled data (figure 4.28, b).

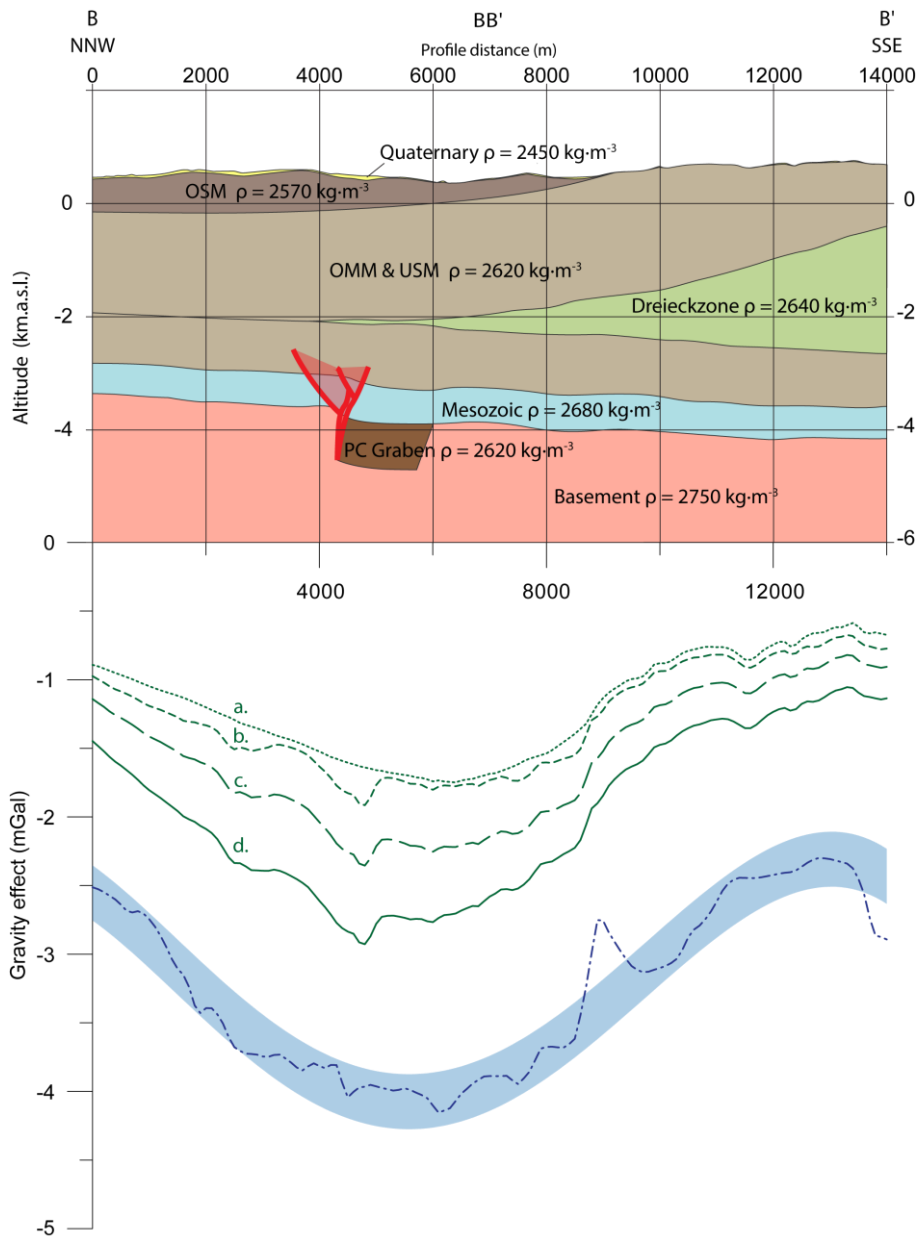


Figure 4.27: Stripping for different gravity effects applied on the geological profile obtained from the 3D geological model. Different steps of stripping: a. Effect of the geological model established using 3D seismic data. b. Quaternary deposits effect is added to (a). c. Effect of the Permo-Carboniferous graben is added to (b). d. Effect of the fault zone assuming a diminution of 5 % of the density due to fracturing is added to (c). The blue shaded area represents the error of the polynomial regression ( $R^2=0.979$ ) introduced by the uncertainty in the measurements, the blue line being the measured values (from Altwegg et al., *subm. to Geothermics*). Profile localization is presented on figure 4.26.

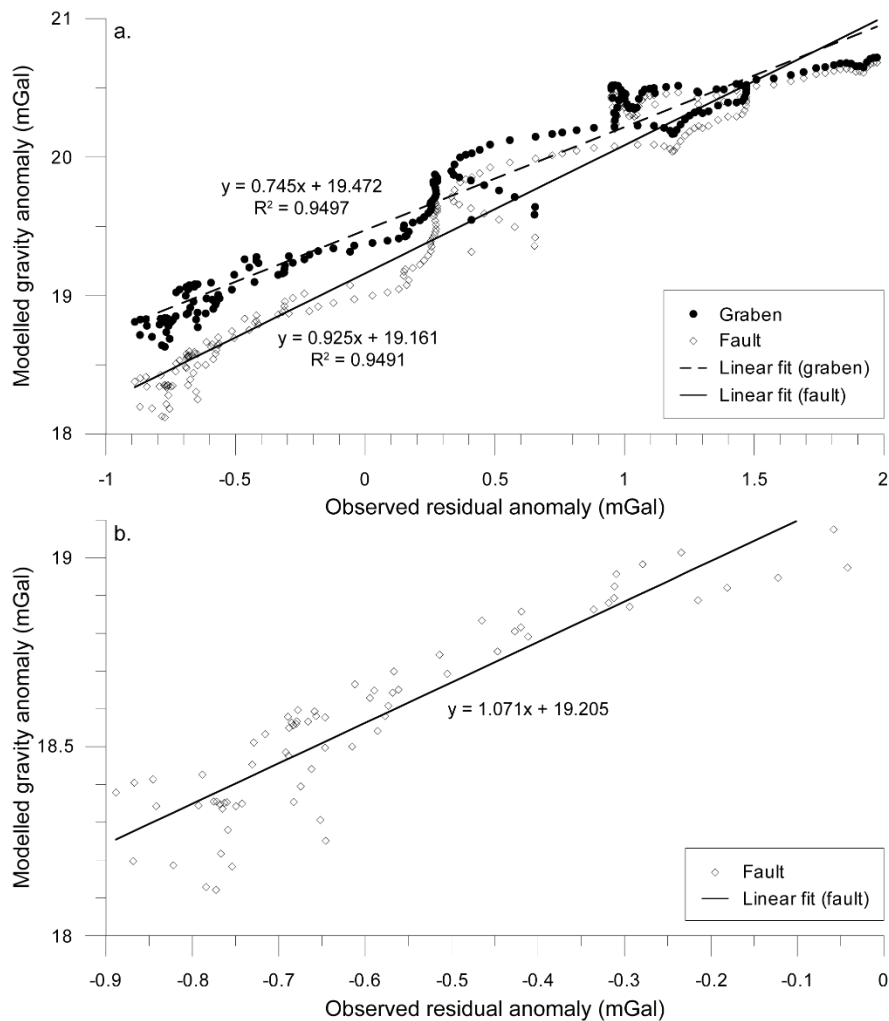


Figure 4.28: Comparison of measured and modelled gravity effects taking into account the sedimentary cover including Quaternary deposits and Permo-Carboniferous trough (dots and dashed line) and additionally the fracture porosity (diamonds and full line): a) across the entire profile B-B' (profile localization is presented on figure 4.26.) and b) across the negative anomalies on the same profile.

## 4.7 Discussion

Generally, our synthetic case study reveals that a number of geological features may cause amplitudes of the same order as of the gravity anomalies expected from fracture porosity in the target fault zone of the Sankt Gallen geothermal project. On the other hand, we have estimated the geometry of geological and tectonic units from independent measurements such as 3D seismics for the sedimentary units, orientation of the fracture zone, Permo-Carboniferous trough, and borehole information for the Quaternary sediments.

In the case of Quaternary sediments, we have observed that although the amplitude is in a range comparable to fracture porosity, the geometry of the anomaly, with a maximum half-wavelength  $\lambda_{1/2}$  of about  $>5$  km, is limited to the outline of the deposits at the surface, that are obtained from  $>1300$  shallow wells and additional geological information. The comparison between the model and the measured data reveals a misfit that is well in the range of the total measurement's error.

As shown in the synthetic case study for the fault zone, the geometry of the different subsurface structures is crucial for the determination of fracture porosity. This accounts in particular for the geometry of the Permo-Carboniferous trough. As it is often the case, this pre-requisite is fulfilled only to a certain extent in the Sankt Gallen area, where the Permo-Carboniferous trough cannot be traced directly in its full extension by 3D seismics. However, the lateral extension of its top is well expressed in the depression clearly visible on the near base Mesozoic horizon that was fully mapped using 3D seismics (figure 4.23). The boundary faults are equally well defined by the 3D seismic survey. Therefore only one degree of freedom remains: the vertical extension of the trough and even if all the prerequisites are not met. We would like to point out that the above discussion provides good indications from the geological considerations in order to interpret the 3D extension of the graben.

In the final gravity forward model, we were able to reproduce the densities of the single units that are published in Switzerland (e.g. Pfiffner et al., 1997; Schärli and Kohl, 2002; Wagner et al., 1999) or correspond to our own measurements. After stripping the geothermally irrelevant features, we have attributed the remaining part of the gravity anomaly to fracture porosity. This is confirmed by the results of figure 4.27, which show that the part of the anomaly interpreted as fracture porosity is shifted to the East with respect to the Permo-Carboniferous trough. It also shows that the maximum of its induced anomaly is located at the same place as the fault zone interpreted from the 3D seismic survey. Assuming that our model is correct, we may estimate

fracture porosity quantitatively. Following gravity analysis from the Geysers geothermal field (Denlinger et al., 1981), fracture porosity analysis depends on the type of fluid in the reservoir. At Sankt Gallen density variation of 4-6 % would translate in the case of fluid-filled fracture porosity with an approximate density of  $1000 \text{ kg}\cdot\text{m}^{-3}$  to a 6.5-9.5 % fracture porosity, while a gas-filled fracture porosity would reach 4-6 %. Although from the temperature at 4500 m depth of  $145^\circ\text{C}$  (SGSW, unpublished) steam is not expected in the reservoir, a considerable amount of methane was produced during the first production test (SGSW, unpublished). Thus, we expect the porosity to be between the two ranges. This porosity range is comparable to the one found in the reservoir zone at Soultz-sous-Forêts (Genter, 1990) and fits the measurements in the geothermal well GT-1 (SGSW, confidential).

## 4.8 Conclusions

The application of our methodology to the case study of Sankt Gallen brought highly valuable information for the geothermal project on the one hand and on the other hand to our methodology.

The synthetic case study firstly allowed us to determine if our methodology was applicable. This was done with little information only at the early stage of exploration, before the establishment of the 3D model based on 3D seismic data. This synthetic case study also allowed us to decipher the main parameters influencing gravity and therefore a better sizing of the gravity survey. Finally it showed that quantification of fracture porosity is possible on the condition that the 3D geometry of the sedimentary and structural setting is well defined.

The gravity data gathered with GInGER made possible the stripping of the gravity effects of the sedimentary and tectonic units. This led to a residual anomaly meant to only represent the effect of fracture porosity and this allowed a first estimation of the porosity of the damage zone. Depending on the amount of gas in the reservoir that may be considerable as indicated by the production test, the forecasted fracture porosity in the area of Sankt Gallen varies between 6.5-9.5 % (100 % of water) and 4- 6 % (100 % of gas).

The damage zone of the fault and Permo-Carboniferous graben are close to each other (figure 4.27) and their induced gravity anomalies are very similar in amplitude and wavelength. Furthermore, these two structures are the least constrained both in geometry and density, and therefore the results may seem equivocal. However, this ambiguity could be decreased by better constraining the different parameters. For example, the geometry of the two structures could be refined by carrying out a new interpretation of the 3D seismic focused on them. This is especially true for the Permo-Carboniferous graben. Indeed if its geometry can be inferred from the seismic data, its gravity effect could be better specified leading to an unambiguous interpretation concerning the damage zone.

To a certain extent, the remaining ambiguities on our results also bring ambiguity to the detection of fault porosity by gravity measurements, as only one of these structures was targeted. In the next chapter, we will show that faults of regional significance are almost systematically associated with negative anomalies and therefore can remove this doubt.



## Chapter 5

### Case study: Eclépens



## 5.1 Introduction

The geothermal project at Eclépens targets deep aquifers of the middle and lower Triassic units at a depth of about 2000 m as well as in deeper geological formations at the top of the crystalline basement and/or in Permo-Carboniferous sediments for electricity production and district heating. As it is presented hereafter, the project wants to benefit from the exceptional geothermal setting of the Eclépens area (e.g. Groupement PGV, 2003). Additionally, the region was intensively studied for oil exploration until the 1980s and revealed a major fault zone affecting at least the Cretaceous and Jurassic sediments.

The strike-slip faults affecting the Mesozoic formations of the Jura Mountains and which extend under the Swiss Molasse Basin (SMB) have been widely recognized as geothermal targets in the Western SMB (Baujard et al., 2007; Groupement PGV, 2003; Schnegg et al., 1986; Vuataz et al., 1999). Indeed as these faults affect the Mesozoic formations, the rocks are not only fractured but also subject to karstification, which can contribute to the infiltration and circulation of fluids down to considerable depths. In this context, the Vallorbe – Mormont fault is of special interest. Moreover, the oil exploration well Eclépens-1 and the geothermal well Yverdon F5 show an above average geothermal gradient of  $35 - 40 \text{ }^{\circ}\text{C}\cdot\text{km}^{-1}$  (figure 5.1 and 5.2). Due to the large number of deep wells in which temperature measurements were carried out, the region is considered to have abnormal positive geothermal gradient (Rybach, 1992).

The main aim of this case study is to test the methodology and tools presented in Chapter 3 in a different context to the Sankt Gallen project. Indeed, in Eclépens, the 3D model was established using 2D seismic, and there is more than one regionally significant fault. However, the model seems better constrained, compared to the case study of Sankt Gallen, as the area was extensively explored by the oil industry. Indeed, the seismic lines density is the highest in Switzerland and several deep boreholes also exist near the study area. In addition, Mesozoic units are much shallower compared to the first case study.

These differences between the two projects are one of the main motivations of selecting Eclépens as a second case study. The main objective is then to determine to what extent the tools developed in Sankt Gallen can be applied in a different situation and thus test its portability as well as better constrain its prerequisites. As in the first case study, the data used to create the 3D geological model are confidential and we have no access to them. Therefore

we will test the geological model without altering it. Moreover, as the available data are only 2D seismic profiles, the estimation of porosity will more likely be qualitative than quantitative, since the geometry of the faults remains poorly constrained.

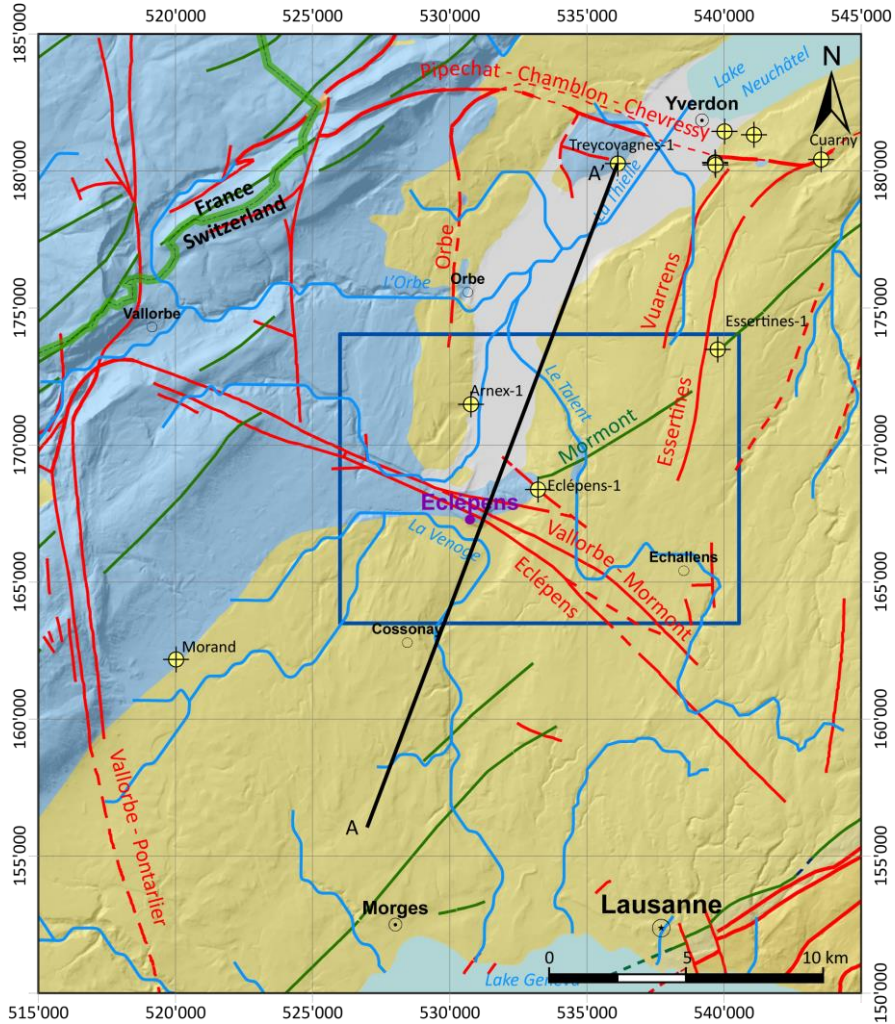


Figure 5.1 : Tectonic map of Eclépens and surrounding area. Red lines are major fault zones (dashed when uncertain); green lines correspond to anticline axis; the blue rectangle represents the limit of the 3D model; yellow circles indicate the deep boreholes. Blue areas represent Mesozoic sediments of the Jura fold and thrust belt, brown-yellow Tertiary and light gray major alluvial (Quaternary) deposits (after Swisstopo, 2005).

Concerning the geothermal project, we used the available 3D geological model, as mentioned previously, and GInGER in order to:

- establish a qualitative error map of the 3D model geometry;
- test geological assumptions on the model;
- detect and make a first estimation of the dimensions of a possible Permo-Carboniferous graben;
- detect major fault zones and estimate their porosity.

We also mention as a preliminary remark that for all figures, Swiss Coordinates (CH 1903) are used.

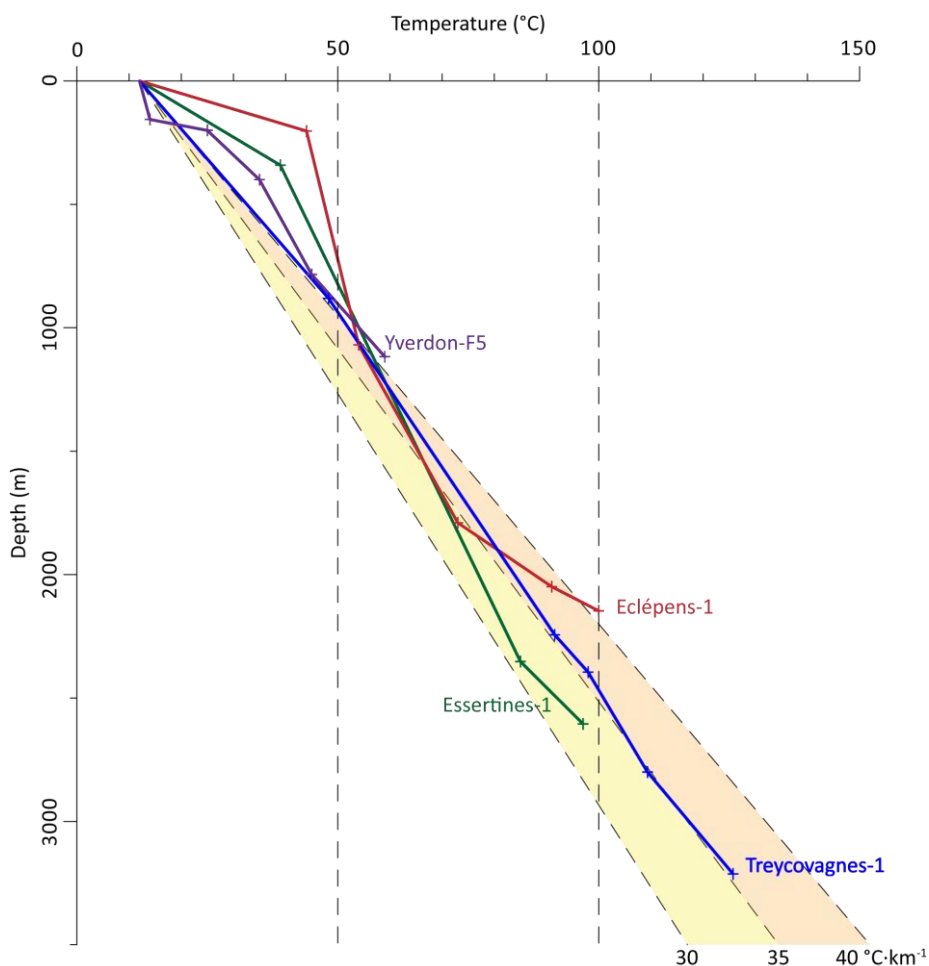


Figure 5.2: Temperature at depth from different deep wells in the vicinity of Eclépens. Different gradients are also shown (data from Vollmayr, 1983; Vuataz et al., 1999).

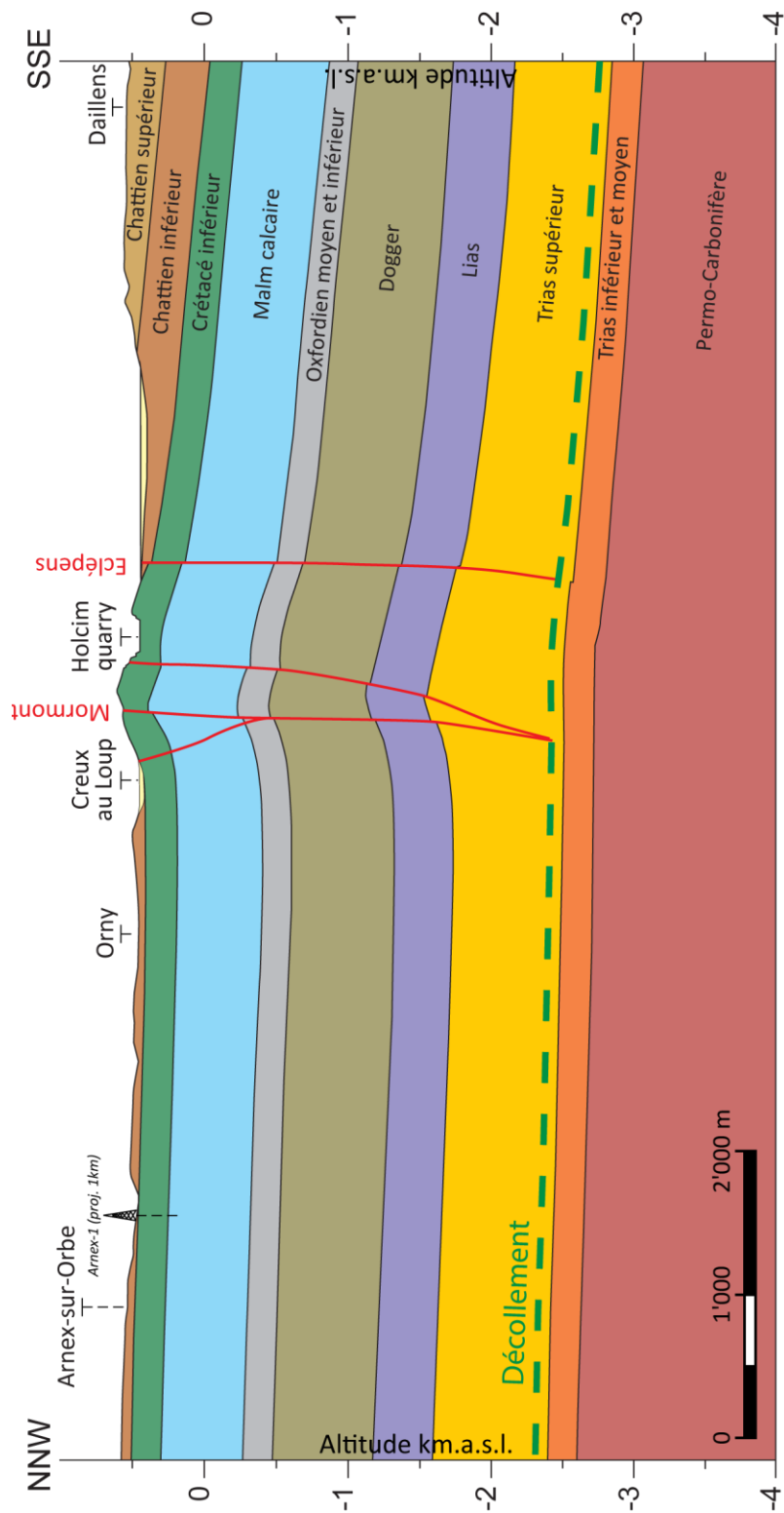
## 5.2 Geological setting

Eclépens is located at the northern edge of the Swiss Molasse Basin, at the foot of the Jura Mountains where a major strike-slip fault system, the Vallorbe-Mormont fault, affects an outcropping anticline of Mesozoic sediments forming a small hill of Cretaceous limestone called the Mormont, emerging from the surrounding Molasse sediments. Both structures are then hidden by the Molasse sediments (figure 5.1 and 5.3) to the East. This fault system is a dextral conjugate of the major sinistral fault zone of Vallorbe - Pontarlier. The geothermal potential of such a fault in the Jura foothills was already recognized (Burger and Gorhan, 1986; Groupe de travail PGN, 2008) and the Vallorbe – Mormont and its extension under the Molasse sediments specifically studied by magnetotelluric (Gex, 1997; Schnegg et al., 1986) and seismic methods (Sommaruga et al., 2012). The Vallorbe - Mormont fault zone also seems to form the limit between an area more affected by tectonics to the north and a relatively more intact area to the south. Indeed, as can be noticed on figure 5.1, the area between the Pipechat – Chamblon – Chevressy and the Vallorbe – Mormont faults is affected by several N - S faults, which is not the case further south. Regarding the Mormont anticline, it can be followed to the northeast as it outcrops in the valley of the Talent River at the location called “Le Bresil” and it was also drilled by the Essertines-1 borehole. However it cannot be linked with other structures to the south and is therefore considered to stop on the Vallorbe – Mormont fault system.

The Jura Mountains consist of a series of thrust-related folds and are divided into the external (or plateau) and internal (or folded) Jura. The region near Eclépens belongs to the latter, where large scale deformation is characterized by major folds, thrusts and tears faults (Sommaruga, 1997) resulting in topographic highs up to 1500 m. If the time of the deformation is widely accepted to have started in the Late Miocene (e.g. Mosar, 1999), discussion is ongoing concerning the mechanism of the deformation, for which two main hypotheses are considered (Gorin et al., 1993; Ibele, 2011; Madritsch et al., 2008; Rigassi and Jaccard, 1995; Sommaruga, 1997; Sommaruga et al., 2012).

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*Figure 5.3 (next page): Example of a typical NNW-SSE geological cross-section passing through the Holcim quarry (modified after R. Arn, unpublished in Vinard, 2012).*



The first hypothesis is the in-situ folding model in which the deformation of the Jura is the consequence of inversion of fault and thrusting in the basement (Pfiffner et al., 1997). The second is the distant push hypotheses (Fernschub hypothesis of Buxtorf, 1907; and Laubscher, 1961), in which the Mesozoic sediments of the Molasse Basin and of the future Jura mountains were detached from their basement at the level of the Triassic evaporites. These series were then pushed toward the North and Northwest (Affolter and Gratier, 2004; Hindle and Burkhard, 1999; Ibele, 2011; Tschanz, 1990). This active transport resulted in the so-called thin-skinned folding model of the Mesozoic in the Jura and in the Molasse Basin. In this model the difference of deformation between the Molasse Plateau and the Jura mountains is associated with the thickness and weight of the Molasse sediments that prevented more intensive deformation under the Molasse Basin (Sommaruga, 1997).

The important thickening of evaporites under the Jura Mountains (Sommaruga et al., 2012) corroborates this latter model and the distant-push hypothesis is widely accepted (Affolter and Gratier, 2004; Madritsch et al., 2008; Sommaruga et al., 2012; Valley et al., 2004). However debate is still ongoing as no indubitable evidence was found for the expected Triassic detachment level i.e. under the Molasse Basin of the Geneva region (Gorin et al., 1993; Groupe de travail PGG, 2011). Recently Madritsch et al. (2008) proposed that these two hypotheses should be seen as extreme cases and that both mechanisms were probably involved. Mosar (1999) also proposed that some structures, typically strike-slip faults, can be rooted in the crystalline basement or may be linked to Permo-Carboniferous troughs and can adapt small scale deformations (up to one km) in agreement with Donzeau et al. (1998). In this work we accept the distant-push hypotheses and thus we consider that major structures, such as faults and anticlines, are likely to stop in the Triassic layer and are no longer geographically linked with their possible counterparts in the basement.

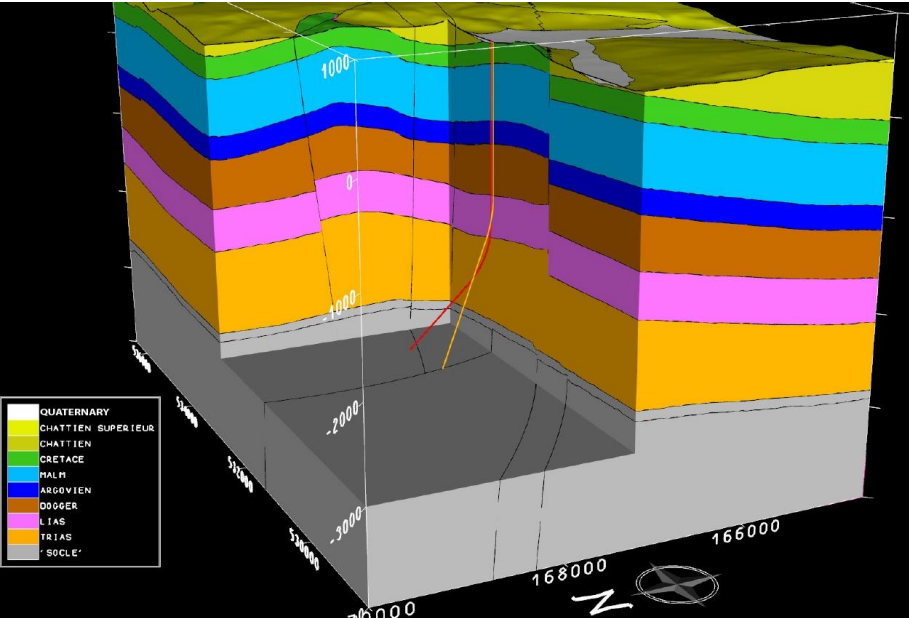


Figure 5.4: Structural geology of the 3D model of Eclépens (Vinard, 2012). The two lines (red and orange) represent the planned boreholes.

Table 5.1: Geological layer of the 3D geological model of the Eclépens geothermal project from the youngest to the oldest. The name used in this work is presented in the right column.

| Description                                                                            | Used name      |
|----------------------------------------------------------------------------------------|----------------|
| Quaternary deposits of the Orbe Plain and Venoge Valley                                | Quaternary     |
| Molasse deposits of the upper Chattian (USM)                                           | Upper Chattian |
| Molasse deposits of the lower Chattian (USM)                                           | Lower Chattian |
| Cretaceous series                                                                      | Cretaceous     |
| Calcareous formations of the Malm                                                      | Malm           |
| Oxfordian shales                                                                       | Argovian       |
| Dogger series                                                                          | Dogger         |
| Lias series                                                                            | Lias           |
| Upper and Middle Triassic series                                                       | Trias          |
| This layer include all formations between the Muschelkalk and Buntsandstein formations | Lower Trias    |
| Ante-Triassic crystalline rock of the basement and Permo-Carboniferous sediments       | Basement s.l.  |

The local geology is strongly influenced by the tectonic setting described previously. It will be described mostly with the support of a 3D geological model for deep structures (figure 5.4) established by L. Tacher & R. Arn, (pers. com). This model built for the BKW electric company, which leads the geothermal project, uses oil exploration 2D seismic and borehole data, as well as new seismic lines recently shot for the purpose of the geothermal project (figure 5.5). It is composed of ten geological layers which are described in table 5.1 together with the given name that is used in this work.

Locally, the most remarkable structure is the Mormont hill: *“A high calcareous hill, which abruptly closes the Orbe plain to the South. It rises as a transversal bar in the middle of the verdant country made of the smooth curves of Molasse and Quaternary”* (translated from Custer, 1928). This relief is made of two parts that can clearly be distinguished on figure 5.5. Its western part is linked with the Eclépens and Mormont faults, which form cliffs of a few tens of meters. Where these faults reach the anticline area near the Holcim cement factory, they form a topographic high culminating some 150 m above the Orbe and Venoge alluvial plains. This topographic high then gently dips toward the North-East and is then hidden by the Molasse sediments near the Eclépens-1 oil well (figure 5.5). The entire structure is affected by multiple fault zones forming little valleys, such as the Entreroche dry valley or the Cristallin River Valley. Regarding the faults zones, two orientations can be noticed: the WNW – ESE orientation with the Eclépens and Mormont faults and the N-S to NNW – SSE oriented set revealed by the Orbe, Talent and Essertines faults. These faults are represented on figure 5.5 as per their trace on top Triassic horizon in the 3D geological model (L. Tacher & R. Arn, pers. com).

The outcropping formations are Quaternary deposits, Molasse sediments and Cretaceous limestones (figure 5.5). The main Quaternary deposits are located in the Orbe plain and in the Venoge valley. In the Orbe plain, they can reach a maximum thickness of 150 m (Aubert, 1963; Custer, 1935; Jordi, 1995; Petch, 1970). These sediments are typically made of fluvio-glacial and alluvial deposits, but the Orbe plain was also known for its swamps and associated important peat deposits, even if the swamps are nowadays mostly dry. In the Venoge Valley, the river deposit thickness can reach 20 m (Custer, 1935) and the maximum thickness in all other areas should be under 10 m. Therefore they were neither represented on figure 5.5 nor integrated into the 3D model (R. Arn, pers. com, Aubert, 1963; Bersier, 1953; Custer, 1935; Jordi, 1995). In order to be able to quantify the gravity effect of peat, we added it to the 3D model using the data from Petch (1970) and from the boreholes of the geological cadaster of the Vaud Canton.

The Molasse deposits, as for the rest of the Swiss Molasse Basin, are gently thickening toward the Alps as the underlying Mesozoic formation gets deeper. In this respect, the geology of the model is relatively classical for the Swiss Molasse Basin (e.g. Sommaruga et al., 2012). Most of the faults are sub-vertical strike-slip and normal faults affecting the Mesozoic layers, which are gently dipping toward the Alps (ESE) by  $1 - 2^\circ$ . The Triassic layers are thickening toward the North-west and a local thickening is observed under the Mormont anticline.

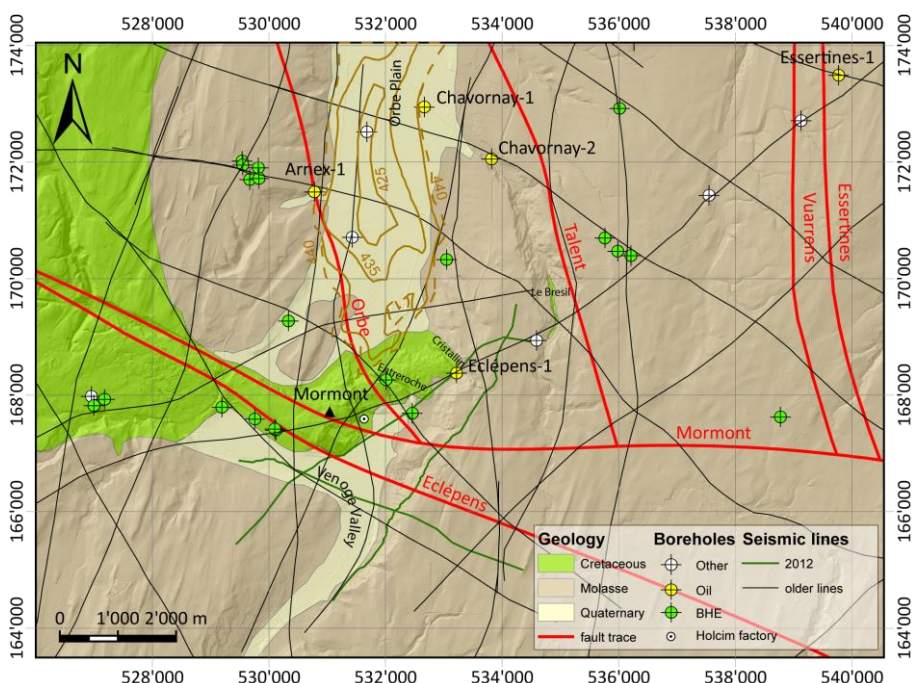


Figure 5.5: Geological map within the limit of the 3D geological model of the geothermal project Eclépens (L. Tacher & R. Arn, pers. com). Existing (old and recent) seismic lines and a selection of boreholes are also plotted. BHE: boreholes heat exchangers. Fault traces are the traces of the major faults at the top of the Triassic formations in the 3D model.

Structures below the Upper Triassic are relatively uncertain due the quality of the seismic data. However, they are considered to be parallel to the geometry of the basement s.l. composed of ante-Mesozoic formations. We must however highlight the fact that in the 3D model (figure 5.4), faults are going through the Triassic formations and continue to the ante Mesozoic formations of the basement, which is evenly considered as Permo-Carboniferous. This is in contradiction with the distant-push hypotheses, which was used by other authors (i.e. Sommaruga et al., 2012) and in this work. The effect of this contradiction and its consequence on our work is discussed later in this chapter.

Concerning the basement, there is regional evidence of the presence of Permo-Carboniferous sediments on some seismic lines, typically in the region of La Côte, where it may reach a thickness of 3 km (Sommaruga et al., 2012). In the Treycovagnes borehole (figure 5.1), 500 m of Permo-Carboniferous sediments were drilled and Rigassi (1995) also highlighted that Permo-Carboniferous deposits were drilled in the Essavilly and Laveron boreholes located respectively at 40 and 33 km to the West. The transect 14 Nyon - Romanshorn of the Swiss Seismic Atlas (Sommaruga et al., 2012) also suggests a continuous layer of Permo-Carboniferous in the area, but it seems to be considerably thinner near the Eclépens-1 well.

### 5.3 Preliminary study

The main aim of this part of the study is to collect existing gravity data to realize a first estimation of the size of the local anomaly linked with the targeted structures and to test the gravity effect of the different geological structures of the 3D geological model. This evaluation will also permit designing of the measurement campaigns by selecting the best locations for the future measurement stations, for better mapping of the detected anomalies. It also helps to determine the offset between stations and the extent of the survey. For this purpose, we used the Swiss Atlas of Gravity (Olivier et al., 2010) to establish the Bouguer anomaly over our study area, which corresponds to the limit of the 3D geological model (figure 5.6).

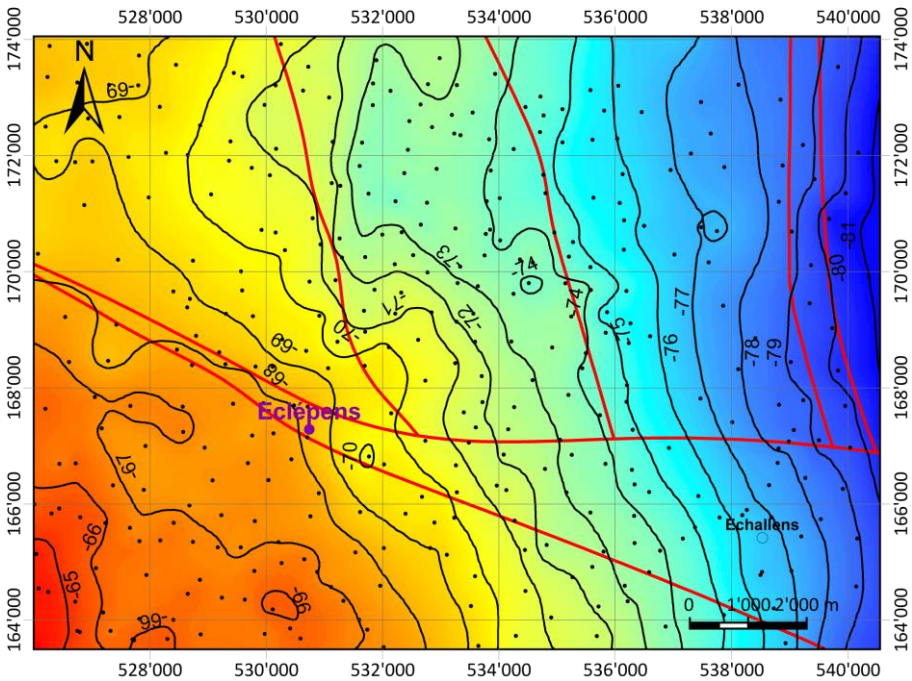


Figure 5.6: Bouguer anomaly map for a density of  $2670 \text{ kg}\cdot\text{m}^{-3}$  within the limit of the 3D model, computed with the data of the Swiss Atlas of Gravity (Olivier et al., 2010). Black dots are measurement stations, anomaly value are in mGal, fault traces (red lines) of the model are also displayed for localization purpose.

On this map a clear eastward trend is visible, as well as a strong negative anomaly to the North. This trend to the East is somehow abnormal, as the classical trend in the Swiss Molasse Basin is to the SE and is due to very deep structures. In order to remove the effect of these very deep structures, which is not the target of our study, we calculated a regional anomaly. For this purpose, we used the same methodology as our first case study of Sankt

Gallen. We calculated a plane using polynomial regression on the measurement stations of the Swiss Atlas of Gravity (Olivier et al., 2010) up to a distance of 50 km around the study area. The resulting residual anomaly map (figure 5.7) highlights two local anomalies. The first is located in the Orbe plain, east and south of Chavornay and thus must be related to the Quaternary deposits described earlier. The second is located east of the Mormont hill, in the Venoge River Valley south of Eclépens and therefore must also be induced by Quaternary deposits. Nevertheless, the residual anomaly also shows a clear and important negative trend to the north of 1 mGal·km<sup>-1</sup>.

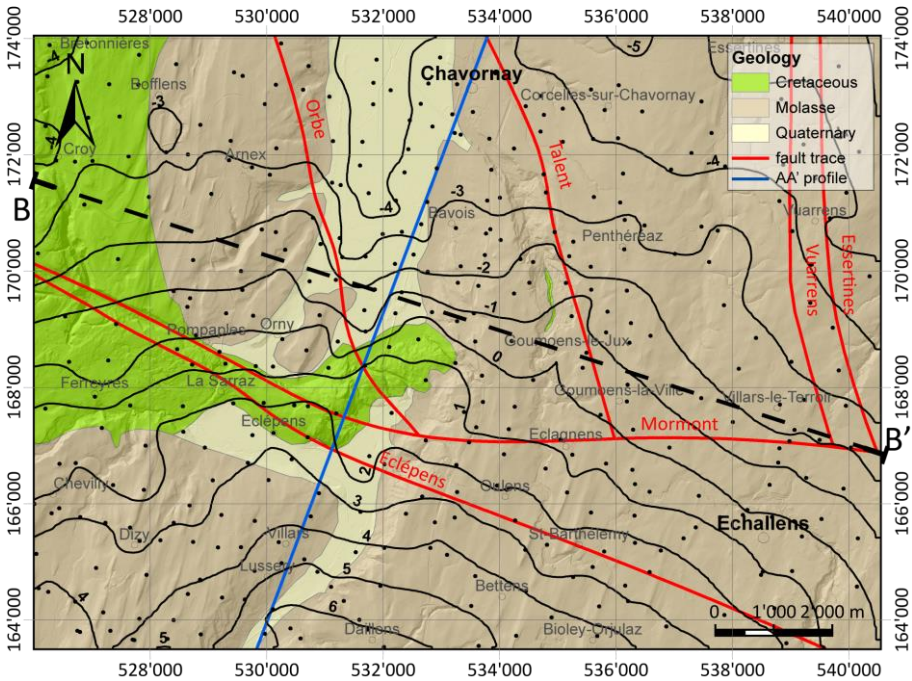


Figure 5.7: Residual anomaly map (in mGal) computed from the data of the Swiss Atlas of Gravity (dots, Olivier et al., 2010) and geology of the Eclépens region; the blue line is the AA' cross section of figure 5.1. Fault traces are the traces of the major faults at the top of the Triassic formations in the 3D model.

Before comparing the measured gravity with the gravity effect of the geological model, we computed the gravity effect of the 3D geological model using GInGER for a reference density of 2670 kg·m<sup>-3</sup> and tested the effect on the computed gravity of different parameters. As most of these effects can be computed routinely and instantly with GInGER, only a selection of the most relevant parameters will be presented. This sensitivity analysis is divided into two main topics: gravity effect of the geological layers and gravity effect of fault zones. As results are often more meaningful in profile than on a map, the different results will be presented on the BB' profile located on figure 5.7. The

geological cross-section of the BB' profile extracted from GInGER is presented on figure 5.8.

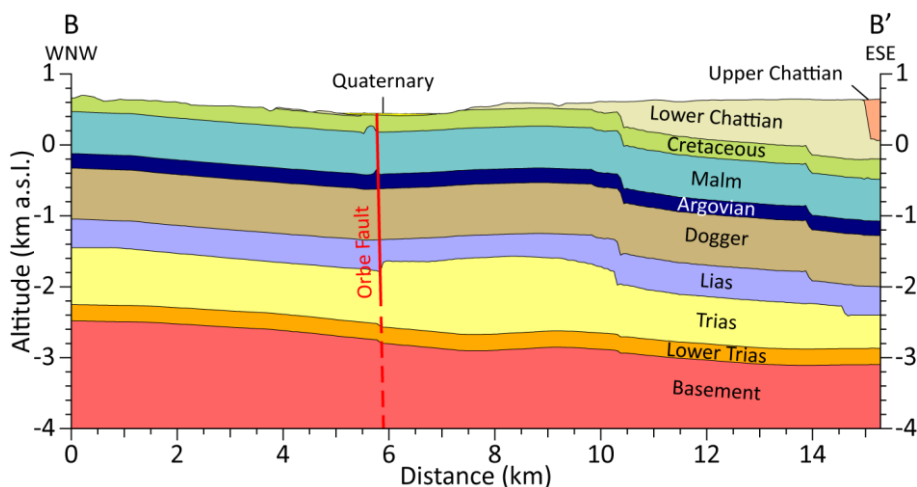


Figure 5.8: Geological profile of the 3D model of Eclépens made with GInGER. Trace of the Orbe fault has been added; localization of the profile on figure 5.7.

### 5.3.1 Gravity effect of the geological layers

The effects on gravity of the following parameters are presented regarding the geological layers:

- change of density;
- contribution of each layers;
- merging of two layers into one;
- effect of depth uncertainty.

In order to compute the effect on gravity of a change in density for each geological layer, end member values were set for each layer in agreement with their compositions and figure 2.17 p. 47. The lowest density for the Quaternary layer is represented by peat with a density of  $700 \text{ kg}\cdot\text{m}^{-3}$ . The maximum value was set to  $2600 \text{ kg}\cdot\text{m}^{-3}$  which is the maximum value for clays. The effect of the different values of density on gravity for the BB' profile (figure 5.8) is presented on figure 5.9.

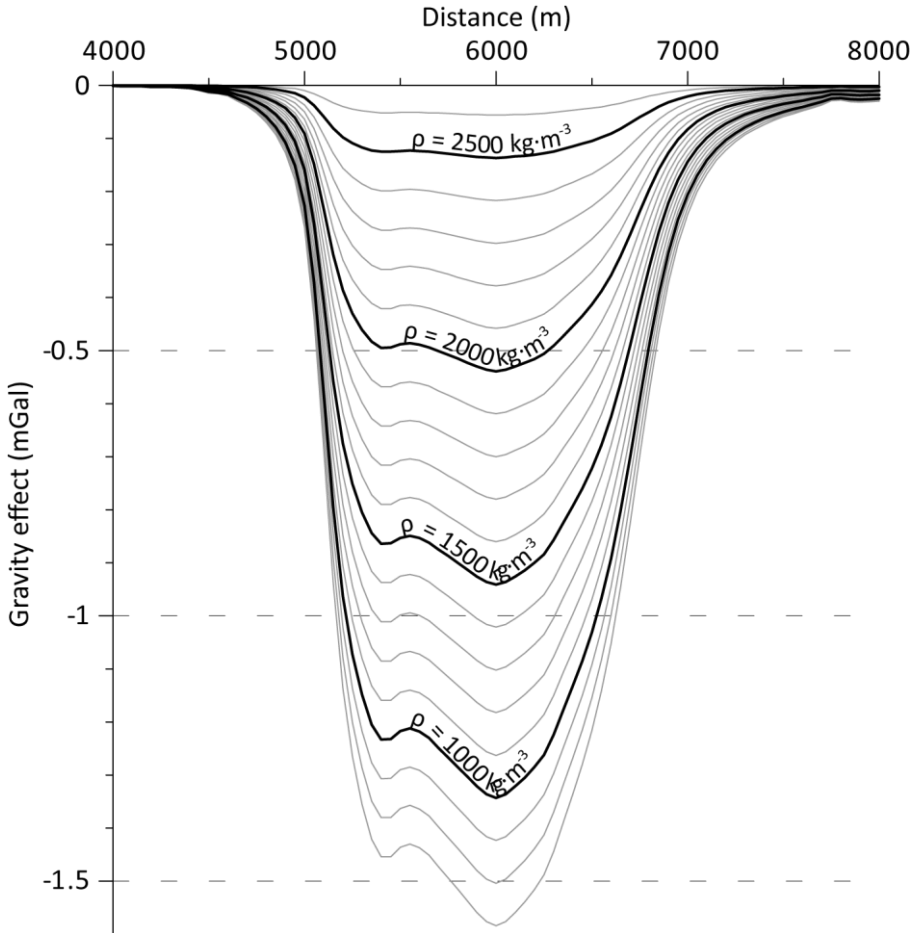


Figure 5.9: Gravity effect of a change of density of the Quaternary deposits shown on the BB' profile (report to figure 5.7 for localization). The gravity effect of these deposits was computed for the whole geological model between 700 and 2600  $\text{kg}\cdot\text{m}^{-3}$ . The thin lines represent a difference of density of 100  $\text{kg}\cdot\text{m}^{-3}$ . The distance corresponds to the distance on the geological profile of figure 5.8.

Concerning the density range of the Molasse layers (Lower and Upper Chattian), the density range of sandstone was used. The end-member values of all Mesozoic formations are considered to be the same even if the compositions vary widely. In this respect the minimum value was set to 1800  $\text{kg}\cdot\text{m}^{-3}$  which represents the average minimum value of the different rock types composing Mesozoic layers. The maximum value is set to the maximum density of limestone and dolomite. For the basement density values of gneiss and granite were used.

Finally the gravity effect of each layer was computed for a value which allows a best fit between the gravity effect of the model and the measured value of the Swiss Atlas of Gravity (Olivier et al., 2010) which were computed for a reference density of  $2670 \text{ kg}\cdot\text{m}^{-3}$ . To allow a comparison between the different cases, the effect on gravity is expressed in form of range in table 5.2. It corresponds to the difference between the maximum and minimum value of the gravity effect.

*Table 5.2: Range of gravity effect ( $\Delta g$ ) of the different geological layers of the 3D geological model for minimum ( $\rho_{\min}$ ) and maximum ( $\rho_{\max}$ ) density values as well as for the value for best fit ( $\rho_{\text{bfv}}$ ). See text for more details.*

| Geological layer | $\rho_{\min}$<br>( $\text{kg}\cdot\text{m}^{-3}$ ) | $\Delta g$<br>(mGal) | $\rho_{\max}$<br>( $\text{kg}\cdot\text{m}^{-3}$ ) | $\Delta g$<br>(mGal) | $\rho_{\text{bfv}}$<br>( $\text{kg}\cdot\text{m}^{-3}$ ) | $\Delta g$<br>(mGal) |
|------------------|----------------------------------------------------|----------------------|----------------------------------------------------|----------------------|----------------------------------------------------------|----------------------|
| Quaternary       | 700                                                | 2.74                 | 2600                                               | 0.09                 | 2170                                                     | 0.69                 |
| Upper Chattian   | 1800                                               | 25.89                | 3200                                               | 15.77                | 2570                                                     | 2.98                 |
| Lower Chattian   | 1800                                               | 28.14                | 3200                                               | 17.14                | 2570                                                     | 3.23                 |
| Cretaceous       | 1800                                               | 12.41                | 2900                                               | 3.28                 | 2680                                                     | 0.15                 |
| Malm             | 1800                                               | 8.31                 | 2900                                               | 2.2                  | 2680                                                     | 0.09                 |
| Argovian         | 1800                                               | 1.57                 | 2900                                               | 0.41                 | 2680                                                     | 0.02                 |
| Dogger           | 1800                                               | 4.17                 | 2900                                               | 1.11                 | 2680                                                     | 0.05                 |
| Lias             | 1800                                               | 3.55                 | 2900                                               | 0.94                 | 2680                                                     | 0.04                 |
| Trias            | 1800                                               | 12.32                | 2900                                               | 3.26                 | 2260                                                     | 5.81                 |
| Lower Trias      | 1800                                               | 0.46                 | 2900                                               | 0.12                 | 2260                                                     | 0.15                 |
| Basement         | 2500                                               | 2.99                 | 3000                                               | 5.81                 | 2670                                                     | 0                    |

These results show clearly that the layers with the predominant effect are the Molasse (Upper and Lower Chattian) and the Trias layers. They also show that the Quaternary layer also has an important effect. This is especially true for the rightmost column and is linked to the choice of the reference density.

To better illustrate these results, we computed the contribution of each geological layer using the densities of the  $\rho_{\text{bfv}}$  column of table 5.2 on the BB' profile (figure 5.10). As the densities of the Jurassic and Cretaceous layers are higher than the reference density used for the computation of the gravity effect of the model, they induce a positive gravity anomaly. On the contrary, the other geological layers have a lower density and therefore induce a negative gravity anomaly. The different effects have thus been separated on figure 5.10 for better visualization.

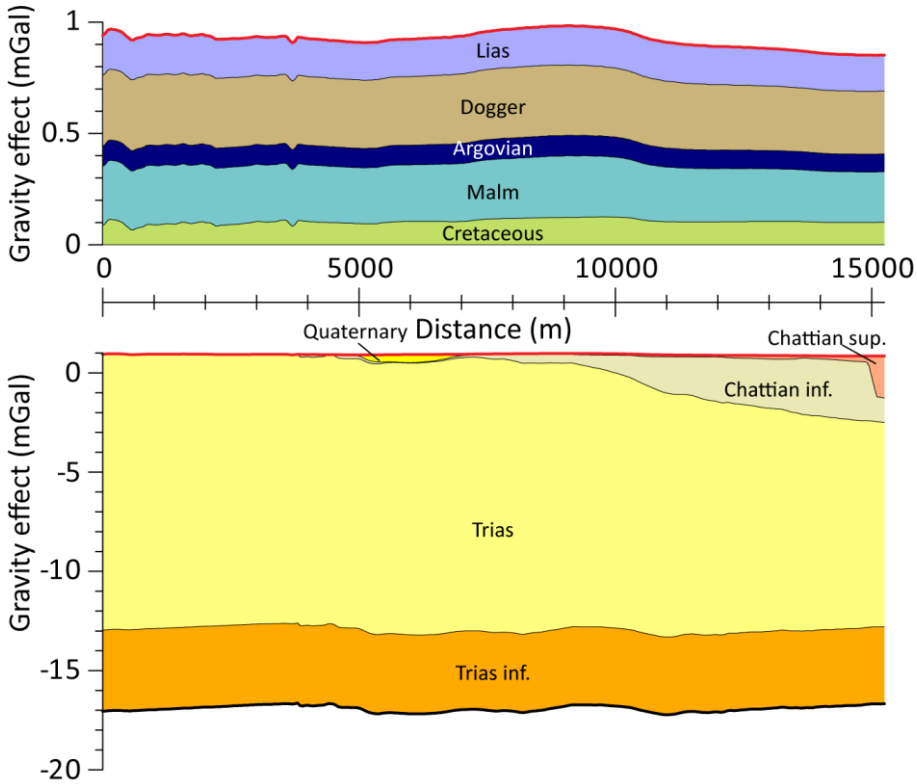


Figure 5.10: Gravity contribution of each geological layer on the gravity effect of the 3D geological model for the BB' profile (see figure 5.7 for localization). The effects of Jurassic and Cretaceous layers have been separated for better visualization. The red line represents the effect of these layers and the thick black line the total effect of the model.

It can be noted on figure 5.10 that except for the Cretaceous and Trias layers, the gravity effect of the Mesozoic layers seems constant. This is logical as these layers have an almost constant thickness and are parallel to each other (figure 5.8). We therefore wanted to test the effect of merging two layers into one. For that purpose, we computed the effect of the Malm and Argovian layers for a density of  $2700 \text{ kg}\cdot\text{m}^{-3}$  and  $2600 \text{ kg}\cdot\text{m}^{-3}$  respectively. We then merged these layers into a single one and used the inversion capability of GInGER to find the best density allowing us to reduce the difference induced by the merging. The resulting density for the merged layers is  $2679 \text{ kg}\cdot\text{m}^{-3}$ . This represents a change of density of less than 1 % compared to the initial density of the Malm layer and induces a maximum difference of 0.086 mGal on the gravity effect of the model.

The 3D geological model used for this case study is mostly based on 2D seismic data. As for all geophysical methods, this means that there is an uncertainty about the results and we wanted to quantify its effect on the gravity effect of the model. However, we don't have access to the data used for the determination of the model and the value of uncertainty. We will therefore use the values of Sommaruga et al. (2012) who estimate that the uncertainty on depth of the considered seismic lines is  $\pm 200$  m. For that purpose we used a model in which the Jurassic layers were merged together (further referred to as Jurassic layer) as well as the Chattian and the Triassic layers (further referred to as Trias layer). The densities used for the computation are presented in the  $\rho_{bfv}$  column of table 5.2. We tested the upper and bottom limits of the Trias layer and changed their depth by  $\pm 200$  m.

The resulting change on the model gravity effect is relatively small ranging from 0.2 to -0.15 mGal (figure 5.11 and 5.12). We then run inversion on the density of the Jurassic and Trias layers with the aim of compensating the gravity effect of depth change by changing the density of these layers. This was done for the case showing the biggest difference, which is when the depth of the upper limit of the Trias layer is increased by 200 m (figure 5.19). The result of the inversion showed that reducing the density of the Jurassic layer from 2680 to 2668  $\text{kg}\cdot\text{m}^{-3}$  and the density of the Trias layer from 2260 to 2242  $\text{kg}\cdot\text{m}^{-3}$ , less than 1 % of variation, allowed us to reduce the difference induced by the change of depth to  $\pm 0.06$  mGal.

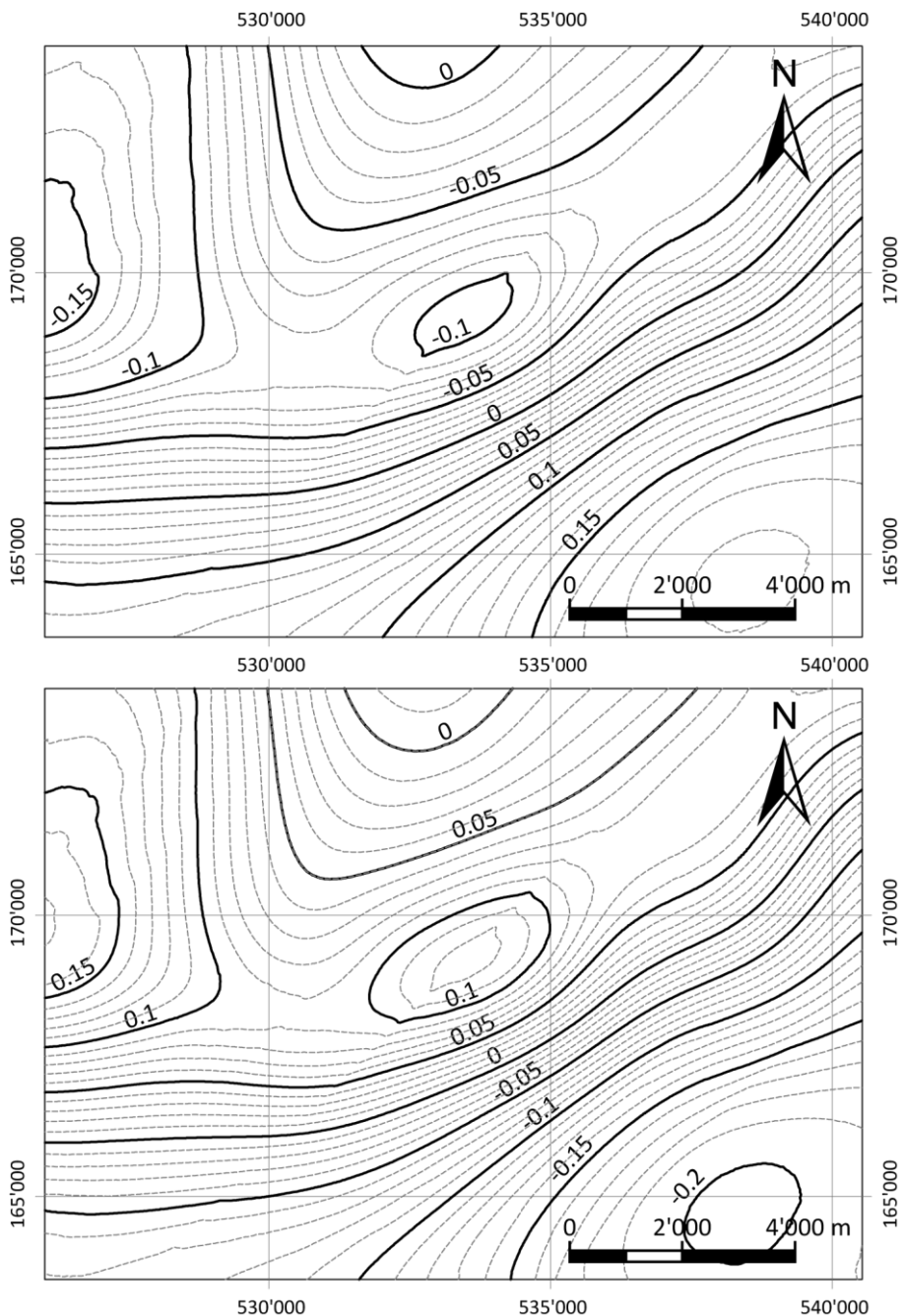


Figure 5.11: Effect on gravity of a change of depth of the upper limit of the Trias layer. Top: limit depth is reduced by 200 m. Bottom: limit depth is increased by 200 m. All values are in mGal.

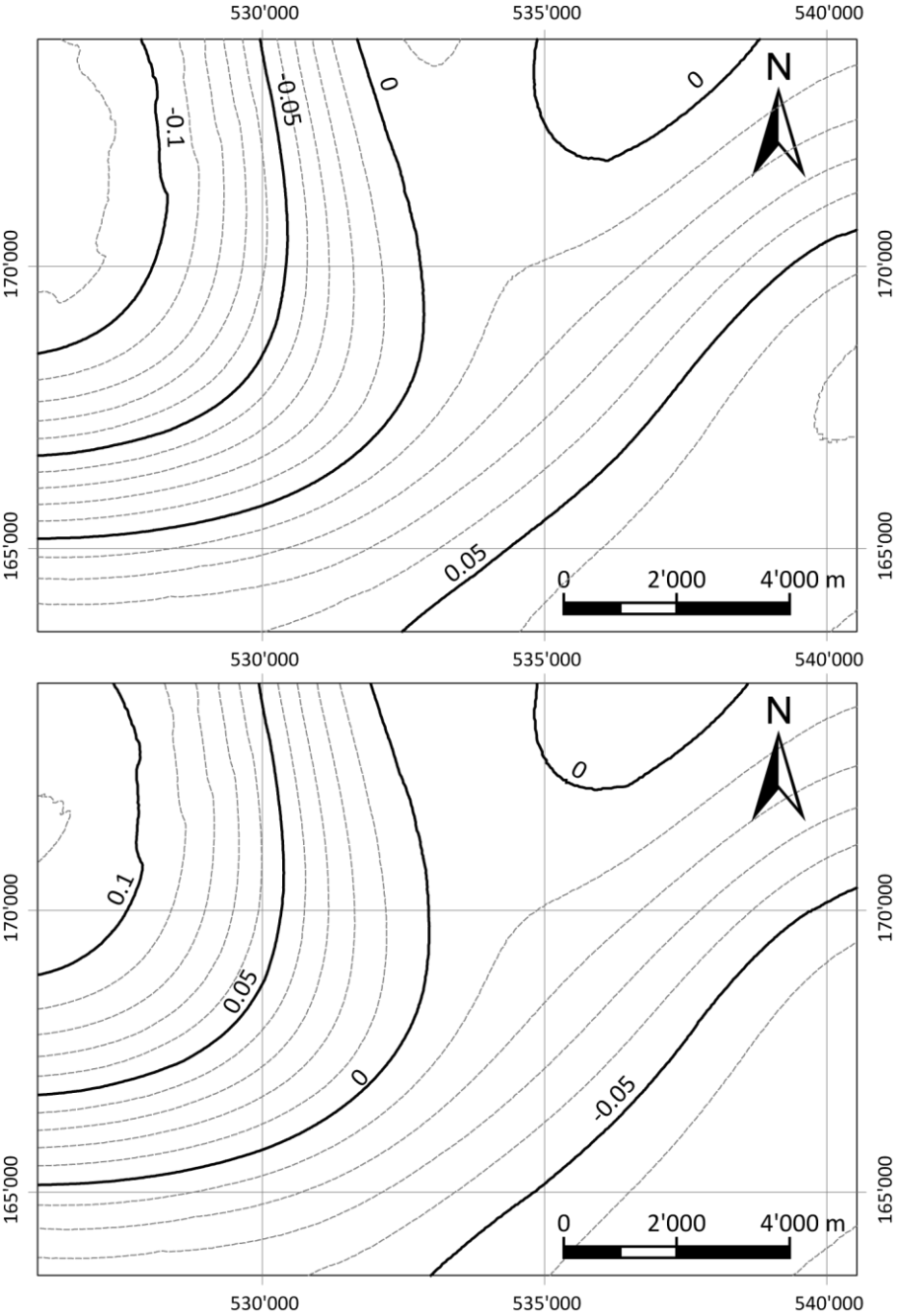


Figure 5.12: Effect on gravity of a change of depth of the lower limit of the Trias layer. Top: limit depth is reduced by 200 m. Bottom: limit depth is increased by 200 m. All values are in mGal.

### 5.3.2 Gravity effect of fault zones

Assuming that a fault zone has an effect on gravity other than the shift of the geological layers, this effect is determined by several inter-related parameters and the aim is to quantify their influence on gravity to determine which are predominant. We therefore computed the effect on gravity of:

- the width of the damage zone;
- a density change induced by fracture;
- the length of the fault and the contribution of each fault compartment;
- the dip angle;
- the strike angle between the fault zone and the profile.

In this respect, we chose the Orbe fault zone whose trace is visible on figure 5.7 and 5.8 to test the above specified parameters. The damage zone is determined following the methodology described in section 3.4.3 (p. 78) and its effect computed using GInGER. Results are presented on the BB' profile of figure 5.8, but were computed in 3D for the whole model. Nevertheless, in order to highlight the gravity effect of fault parameter, the other parameters must be fixed in a reference model. In this model geological layers of the Jurassic are merged into a single layer. The same was done for the Trias and Lower Trias layers. Densities of the different geological layers are set to the value of the  $\rho_{bfv}$  column of table 5.4. The fault is considered to affect Mesozoic formations only, to stop in the Trias layer and dip  $85^\circ$  towards  $63^\circ$ . Concerning the damage zone in the reference model, its width is fixed to 100 m and a decrease of density of 5 % is considered.

The first parameter tested is the influence on gravity of the width of the damage zone. This parameter is crucial as it controls the volume in which a density difference is applied. We tested four different values for the damage zone width 50, 100, 200 and 500 m. The lower value represents the present day detection limit of our methodology (see section 3.2 p. 55) and the maximum was fixed in agreement with Faulkner et al. (2011, figure 3.18 p. 79). The results, presented on figure 5.13 clearly show that this parameter has a predominant effect on the gravity and that, in a first approximation, the maximum gravity effect is directly proportional to the width of the damage zone (figure 5.14).

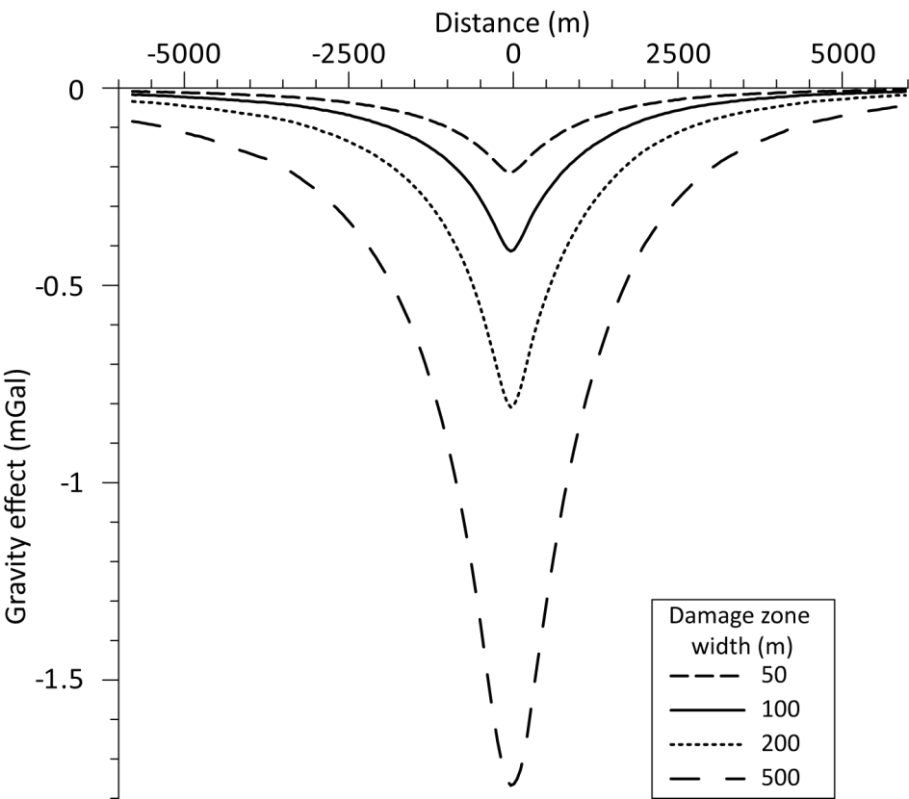


Figure 5.13: Gravity effect of the damage zone width of the Orbe fault zone on profile BB'. Refer to figure 5.8 for the geological profile. The profile is centered on the point where profile crosses the fault trace on figure 5.7.

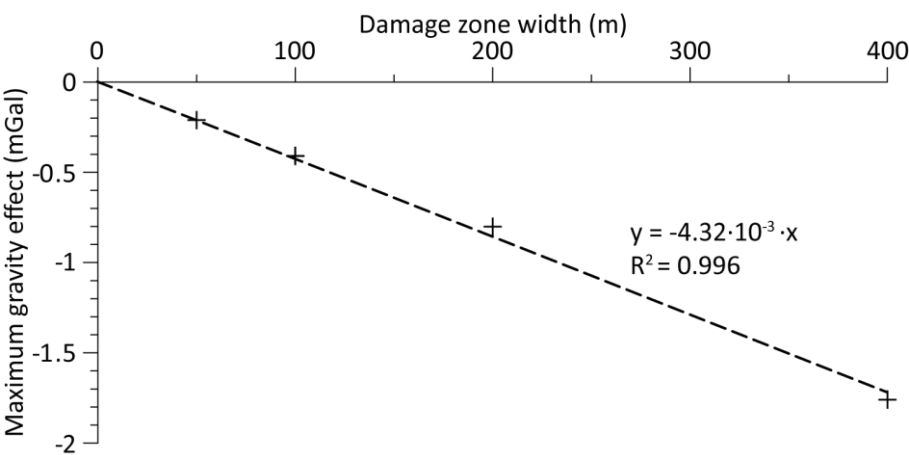


Figure 5.14: Maximum gravity effect versus damage zone width for the Orbe fault with data of figure 5.13.

As mentioned previously the aim is to compute the gravity effect induced by a change of density of the damage zone. Indeed, as presented in section 3.4.3 p. 78, fault zone increases locally the porosity of the rock and this can change the density of the rock. This change of density can be positive or negative depending on the material filling the pore. Therefore we tested density change between -2 and 10 % of the affected geological layers initial density of the reference model (figure 5.15).

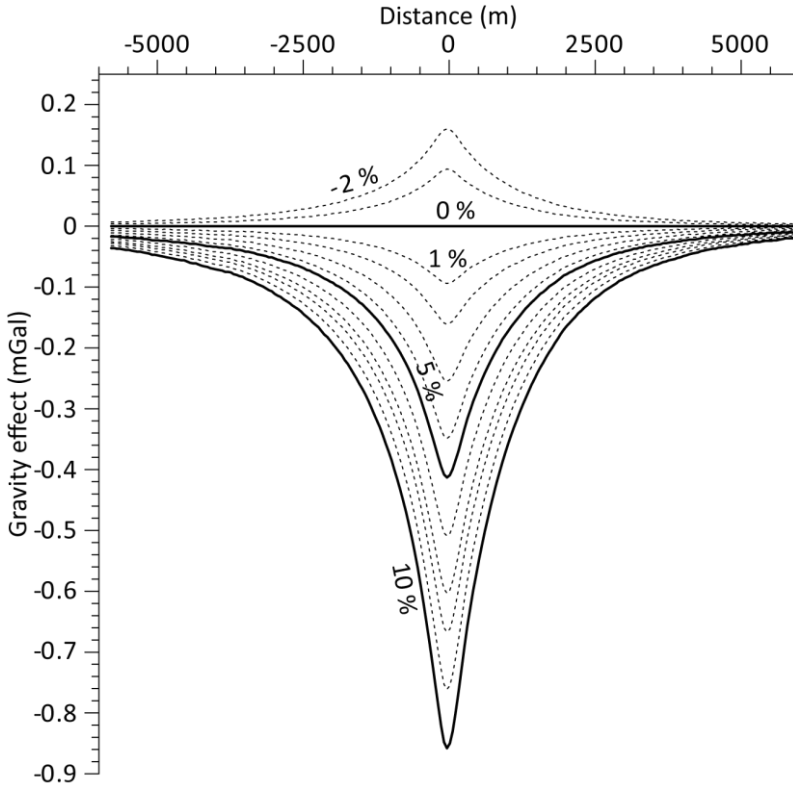


Figure 5.15: Gravity effect of the change of density induced by the Orbe fault zone on profile BB'. Curve every 1 % of density change; refer to figure 5.8 for the geological profile. The profile is centered on the point where profile crosses the fault trace on figure 5.7.

As for the width of the damage zone, the maximum gravity effect shows a linear relationship with the change of density induced by the fault zone. However, this ascertainment was expected as the geometry of the damage zone remains unchanged but it shows a good example of the use of the unitary gravity effect used in GInGER and described in section 3.4.2 p. 76. Indeed in GInGER the gravity effect of a structure is first computed for a density of  $1000 \text{ kg}\cdot\text{m}^{-3}$ . Its effect for any other density can then be obtained in real-time as the only computation that must be made is multiplying this effect by the ratio between the new density and  $1000 \text{ kg}\cdot\text{m}^{-3}$ .

In GInGER, the gravity effect of the damage zone of a fault is the sum of the effect of the different fault compartments (see section 3.4.3 p. 78). This allows us to determine the gravity effect of each of these compartments (figure 5.16). More specifically, in the case of the Orbe fault, we analyzed the difference of gravity induced by an extension of the fault into the basement (dashed red line of figure 5.8).

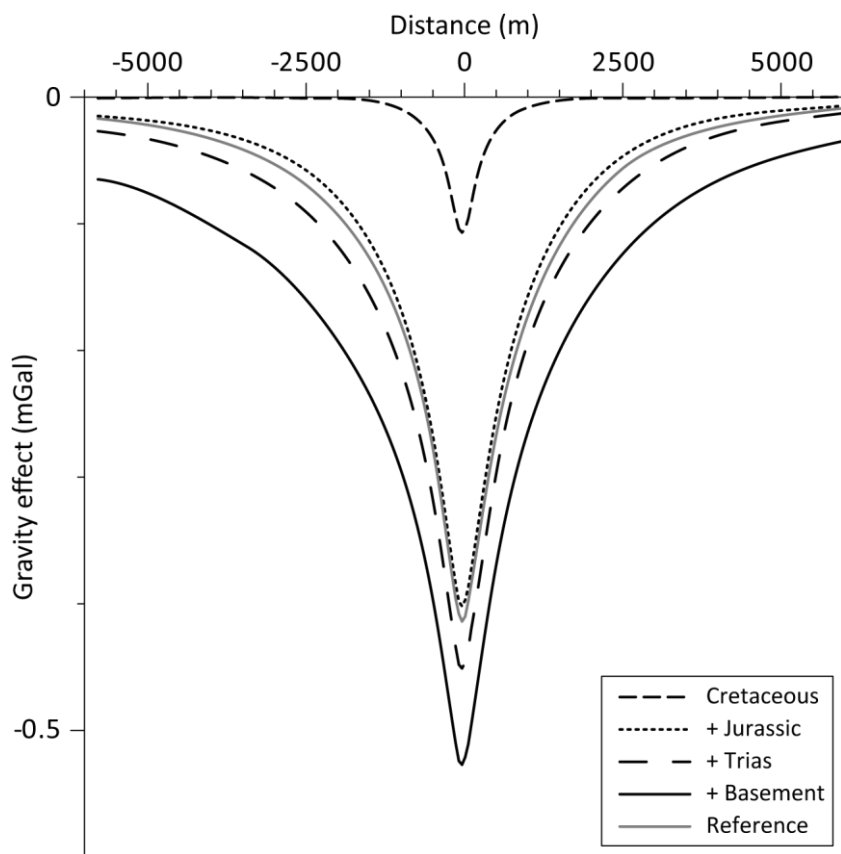


Figure 5.16: Gravity effect of each fault compartment of the Orbe fault zone on profile BB'. The gravity effects of each compartment are progressively added from the shallower to the deeper layer, the gray line is the effect of the reference model. Refer to figure 5.8 for the geological profile. The profile is centered on the point where the profile crosses the fault trace on figure 5.7.

The major observation that can be made on figure 5.16 is that a prolongation into the basement doesn't induce a very significant effect on the maximum anomaly induced by the damage zone (0.11 mGal). It has however a major impact on the shape of the anomaly by increasing its width.

In order to examine the change on gravity induced by a change of dip of the fault zone, we changed it by  $\pm 30^\circ$ . The fault trace on the top of the Cretaceous layer was kept as well as the other fault parameters. Results, presented here below (figure 5.17), show that the main effect on the induced anomaly affects its shapes by changing its width and symmetry. Concerning the maximum of the anomaly, the maximum value doesn't vary significantly (less than 0.1 mGal). However the localization of the maximum on the profile varies by more than 100 m.

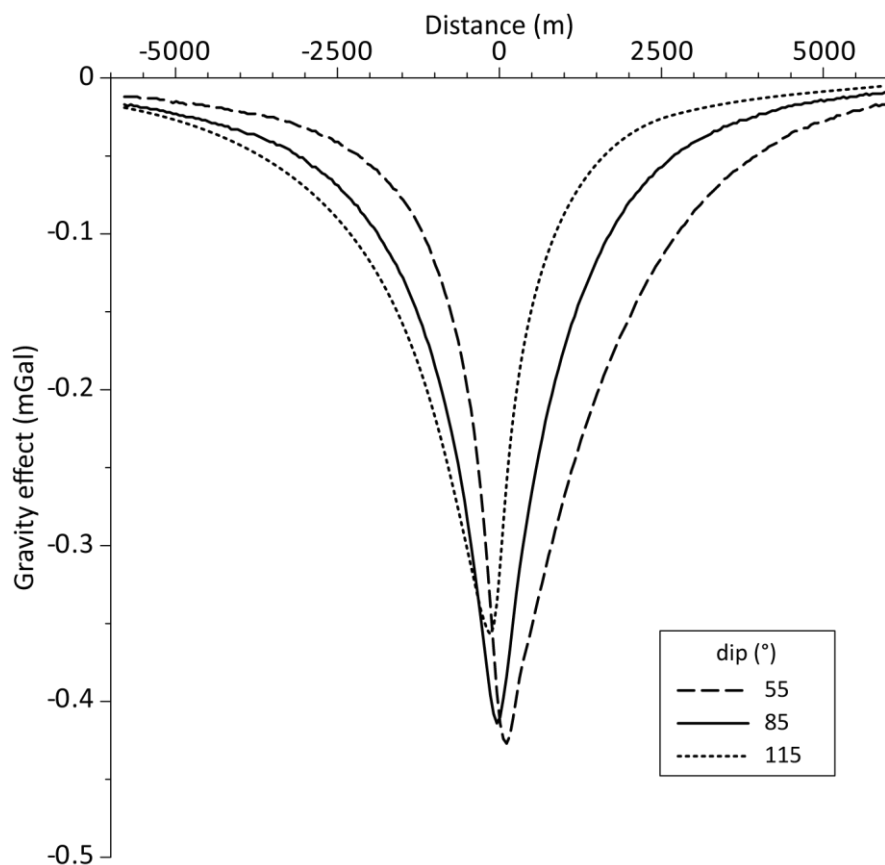


Figure 5.17: Gravity effect of a change of dip of the Orbe fault zone on profile BB'. The fault of the reference model has a dip of  $85^\circ$  toward  $63^\circ$  (continuous line). Refer to figure 5.8 for the geological profile. The profile is centered on the point where profile crosses the fault trace on figure 5.7.

The last parameter tested is the strike angle between the fault zone and the profile on which measurements are made. For that, we used the reference model and plotted five different profiles crossing the fault zone at the same point. This point is where Profile BB' crosses the fault zone trace on figure 5.7. Here we also would like mention that these results, shown on figure 5.18,

were obtained straightforwardly using GInGER. Indeed, the profile on which gravity and geology is shown is computed in real-time and can be changed by clicking two points on the map. Logically, the only effect concerns the shape of the anomaly as the strike angle controls the extent of the anomaly crossing the profile. However it can be noted that the induced anomaly is generally relatively steep but can be observed with measurement stations every 200 m as shown by the dotted gray lines of figure 5.18.

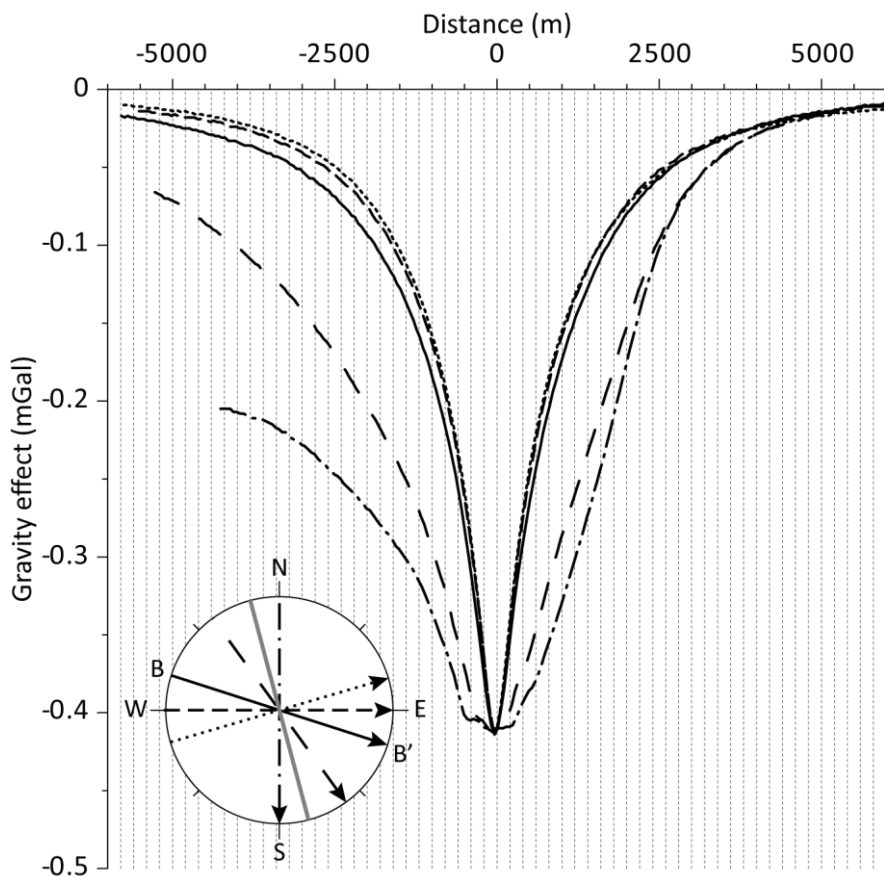


Figure 5.18: Gravity effect of a change of the strike angle between the Orbe fault zone and the measured profile. The fault of the reference model has a dip of  $85^\circ$  toward  $63^\circ$  (gray line), the orientation of the different profiles is shown in the insert at the bottom left, and arrows represent their directions. Refer to figure 5.8 for the geological profile. The profiles are centered on the point where the profile BB' crosses the fault trace on figure 5.7.

Following our methodology and the discussion that was presented in chapter 3, we consider that the uncertainty on gravity measurement is  $\pm 0.1$  mGal. Therefore, the sensitivity analysis shows that one should be able to measure the effect of a fault zone (gravity effect larger than 0.2 mGal) if it affect at least the whole Jurassic formations (figure 5.16), has a damage zone width of

more than 50 m (figure 5.16) and induce a density change of minimum 3 % (figure 5.16).

These analyses also show that the parameters that induce the more important effect are the width of the damage zone and the induced density change.

However, we can also notice on figure 5.13 and 5.15 that the width of the damage zone and the induced density change induce a similar anomaly in shape and intensity. It is therefore not possible to distinguish their effect using only gravity measurements. Therefore, to assess the increase of porosity induced by the fault zone, the width of the damage zone must be determined using another independent method.

### 5.3.3 Effect of a Permo-Carboniferous graben

We compared the gravity effect of the 3D geological model with the value of the Swiss Atlas of Gravity (Olivier et al., 2010) but it was not possible to reproduce the trend of the residual gravity map of figure 5.7. Since the effect of crustal scale structures has already been removed, we make the hypothesis that this trend is linked to the Permo-Carboniferous trough mentioned in the geological setting section (p. 160). To test this hypothesis, we used GInGERSP combined with GInGER on several SSW-NNE cross sections using simple geometrical shapes to reproduce the residual anomaly. The effect of the model is first calculated with GInGER using densities of the  $\rho_{bfv}$  column of table 5.2. This effect is then loaded into GInGERSP and basic geometrical shapes are iteratively added in order to reproduce the observed residual anomaly.

The residual anomaly was sampled for the whole profile in order to better see the effect of the suspected Permo-Carboniferous trough infill. A typical cross section is presented on figure 5.19, on which a horizontal slab with a density contrast of  $-90 \text{ kg}\cdot\text{m}^{-3}$  was added (green shape) in order to model the graben. However, this object, sitting at a depth of more than 3700 m, was not sufficient to reproduce the northward plunging slope of the residual anomaly of figure 5.7. Consequently, we added three vertical thin sheets with a density contrast of  $-135 \text{ kg}\cdot\text{m}^{-3}$ . These shapes are meant to model the damage zones of faults and induce smaller and more local anomalies.

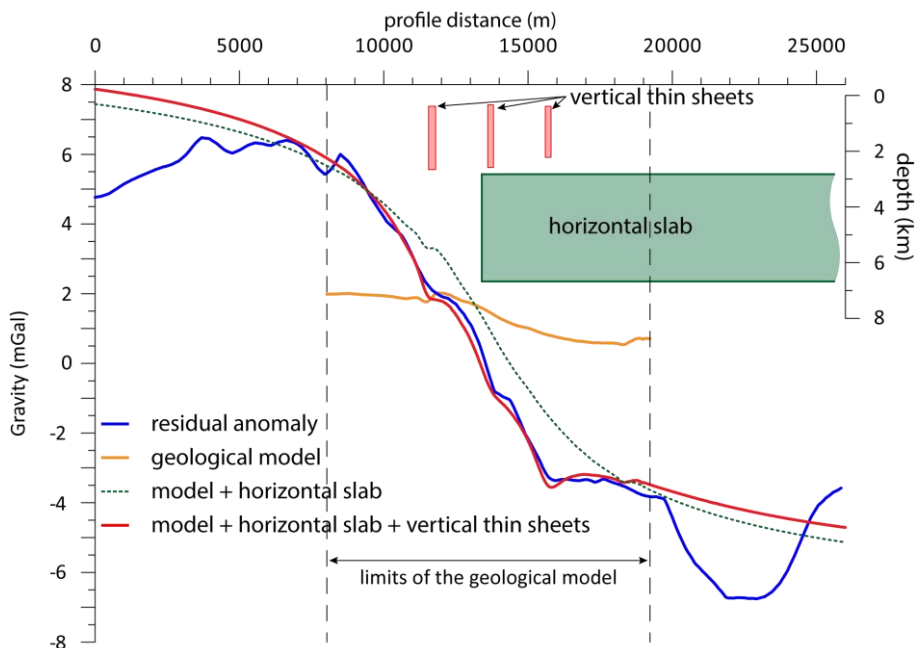


Figure 5.19: Typical SSW-NNE cross section (AA', figure 5.1) used to validate the hypothesis of the presence of a Permo-Carboniferous trough north of the Vallorbe – Mormont fault (see figure 5.1 for localization). Orange line: 3D effect of the 3D model; green dashed line: gravity effect of the horizontal slab has been added; red line: gravity effects of the three vertical thin sheets have been added; blue line: residual anomaly. Top right localization of the simple shapes with: green shape: horizontal slab with a density contrast of  $-90 \text{ kg}\cdot\text{m}^{-3}$ ; red shapes: vertical thin sheets with a density contrast of  $-135 \text{ kg}\cdot\text{m}^{-3}$  and a width of (from left to right): 300, 200, 200m respectively.

However, as illustrated on figure 2.8 (p. 28), the geometry of Permo-Carboniferous graben seems to be highly asymmetrical. We thus analyzed how this could affect the anomaly induced by such a structure. For that purpose, we reproduced the schematic illustration of figure 2.8 with GInGERSP using several horizontal slabs with a density contrast of  $-90 \text{ kg}\cdot\text{m}^{-3}$  (figure 5.20). The dip of the bottom of the Mesozoic formations was not modeled.

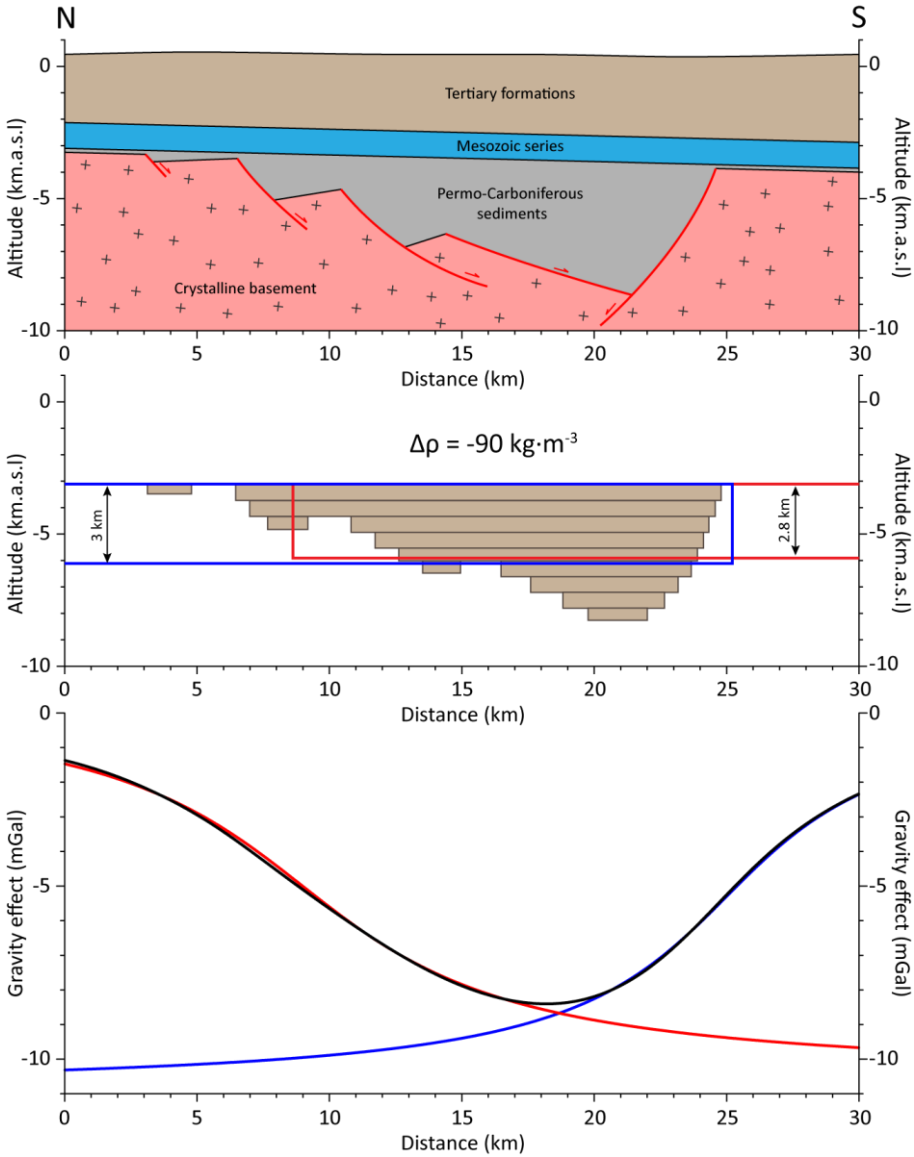


Figure 5.20: Effect of the geometry of a Permo-Carboniferous graben on gravity. Top: Schematic illustration of a Permo-Carboniferous graben in the Swiss Molasse Basin (figure 2.8). Red lines represent faults. Middle: Model used to compute its gravity effect in GInGERSP (brown shapes). Red and blue lines represent horizontal slabs used to reproduce the Southern, respectively Northern part of the anomaly. Bottom: Gravity effect of the shapes of the different model. Color code is the same as for the middle part with the exception of the brown shapes whose effect on gravity is represented by the black line.

The resulting anomaly shows a steeper slope to the south and this is clearly due to the geometry of the graben. We then reproduced half the effect of this model with a single shape. This was done in order to illustrate the effect of such approximation on the graben limit that can be deduced by gravity measurements. We also wanted to compute the effect of such structures in 3D. In this respect, we modeled a prism of 65 km in length and changed its density, depth of top, width and thickness. We defined a base prism with fixed parameters and then varied each parameter at a time to see their respective effect. It has its top at a depth of 3 km, a thickness of 3 km a width of 25 km and a  $\Delta\rho$  of  $80 \text{ kg}\cdot\text{m}^{-3}$ . Variation of top depth and thickness are presented in table 5.3. In addition, we modeled a prism of 65x35 km at a top depth of 4 km and a thickness of 5 km.

*Table 5.3: Maximum gravity anomaly (in mGal) induced by a prism of 25x65 km at different top depths for different thicknesses for a density contrast of  $80 \text{ kg}\cdot\text{m}^{-3}$ . The maximum anomaly induced by the above mentioned base parameters is highlighted in gray. \* For this case the prism has dimensions of 35x65 km.*

| Thickness | Depth of top |        |        |
|-----------|--------------|--------|--------|
|           | 2000 m       | 3000 m | 4000 m |
| 3000 m    | 8.20         | 7.70   | 7.22   |
| 3500 m    | 9.42         | 8.84   | 8.3    |
| 4000 m    | 10.60        | 9.95   | 9.33   |
| 5000 m    | 12.85        | 12.06  | 11.31  |
| 5000 m*   | -            | -      | 12.47  |

Varying the density contrast between 60 and  $100 \text{ kg}\cdot\text{m}^{-3}$  induced a maximum anomaly of 5.77 and 9.62 mGal respectively with geometry of the graben given by the base parameter. This represents a difference of 25 % as compared to the base parameters presented previously.

These results imply that the large negative anomaly visible on figure 5.19 can be induced by a Permo-Carboniferous graben of regional extent and a thickness of several kilometers (table 5.3). Due to the lack of precise information on the geometry and density of the infill of this structure and to the ambiguity of gravity data interpretation (see p. 45), our results implies that we will not be able to accurately model this structure and integrate it into the 3D geological model.

### 5.3.4 Conclusions

This preliminary study has shown how GInGER and GInGERSP can be used for sensitivity analysis. Using these tools, the user can quickly and easily analyse the effect of the different geological structures present in a 3D model. Moreover, the possibility of adding different types of objects and computing their gravity effect allows for testing assumptions as it was shown in the case of the possible Permo-Carboniferous trough.

Concerning the project, the initial calculation made with GInGER for the Eclépens project shows that the structures described in the existing 3D model are not sufficient to explain the different anomalies found in the residual. However, this preliminary study allowed us to identify the parameters (geometry, density, orientation, etc.) that have a preponderant effect on gravity. It also allowed quantifying their minimum values that allow the detection of a fault zone by gravity measurements as well as the determination of the offset between the gravity stations for planning the survey. It has also confirmed that due to the lack of information concerning the size of the damage zone, we will likely not be able to determine quantitatively the porosity of the different faults zones present in the 3D model.

In addition to these previous observations, the preliminary study showed that:

- The northward trend is likely induced by a very deep structure, which could be the Permo-Carboniferous trough that was drilled at Treycovagnes (figure 5.1). This object has a gravity effect of more than 10 mGal, which implies a large structure with a thickness of several kilometers (figure 5.19).
- Some limited and local anomalies may be related to some faults considered in the model, especially the Eclépens and Mormont faults (figure 5.19).
- Other anomalies essentially NNE – SSW may be induced by other faults such as the Orbe, Talent or Essertines faults (figure 5.7) or by Quaternary deposits.

Concerning the density distribution, the analysis showed that the model can be divided into six different layers without inducing significant errors:

- Quaternary deposits
- Molasse series
- Cretaceous and Jurassic formations
- Triassic series
- Permo-Carboniferous sediments
- Basement units

The two main targets of this study seem to induce very different anomalies: small steep sloped for faults zones and large and regional anomalies for the Permo-Carboniferous trough. Therefore, the trough will be studied in a more regional context, using the data from the Swiss Atlas of Gravity only whereas our gravity survey will target local structures.

## 5.4 Gravity survey

During this project, a gravity survey was carried out in May and July 2014 along five profiles representing a total length of 40 km and 239 measurement stations (figure 5.21, Appendix C). The offset of the gravity stations was 200 m, consistent with the preliminary study. The profiles were oriented perpendicular to the faults of the 3D model with one exception: the profile 25'000 was placed so as to follow the trace of one of the recent seismic lines (figure 5.21). Geographic coordinates of the measurement stations were acquired using a Leica differential GPS (RTK-DGPS) GS 15 with an accuracy of 1-3 cm in all directions. Gravity data were measured using a CG-5 Autograv relative gravity meter (Scintrex, Canada) with an accuracy of 0.005 mGal. More than 10 % of the gravity stations were re-measured to verify the quality of the dataset and allow for uncertainty calculation. As for the case study of Sankt Gallen, the individual uncertainties of the measurements (DGPS and gravimeter) have been estimated to a maximum of about 0.03 mGal. In addition, the uncertainty induced by the terrain correction is estimated from synthetic models to be  $< 0.1$  mGal (see methodology section for details). As presented on figure 5.21, a complete Bouguer anomaly map was calculated for a density of  $2670 \text{ kg}\cdot\text{m}^{-3}$  following the methodology presented previously (see chapter 3).

In addition to our measurements, 370 stations from the Swiss Atlas of Gravity (Olivier et al., 2010) were added in to the dataset. In order to avoid discrepancies between the two datasets, the gravity base used for our measurements was one of the second order bases of the Swiss Atlas of gravity (see appendix C for precise localization) and we re-measured 28 of these Swiss Atlas stations. Additionally, as for the case study of Sankt Gallen, we calculated the topographic correction again on the stations from the Swiss Atlas of Gravity following our methodology. This was done in order to reduce uncertainty and to obtain a consistent dataset. It must however be mentioned that several of these Swiss Atlas stations are poorly localized, with uncertainty in the order of 10 m in the x-y directions and 1 m in the z direction, which can induce a higher uncertainty. Therefore the uncertainty of the whole dataset is considered to be of 0.2 mGal, as mentioned by Olivier et al. (2010), which still remains five times smaller than the expected anomalies (see previous section).

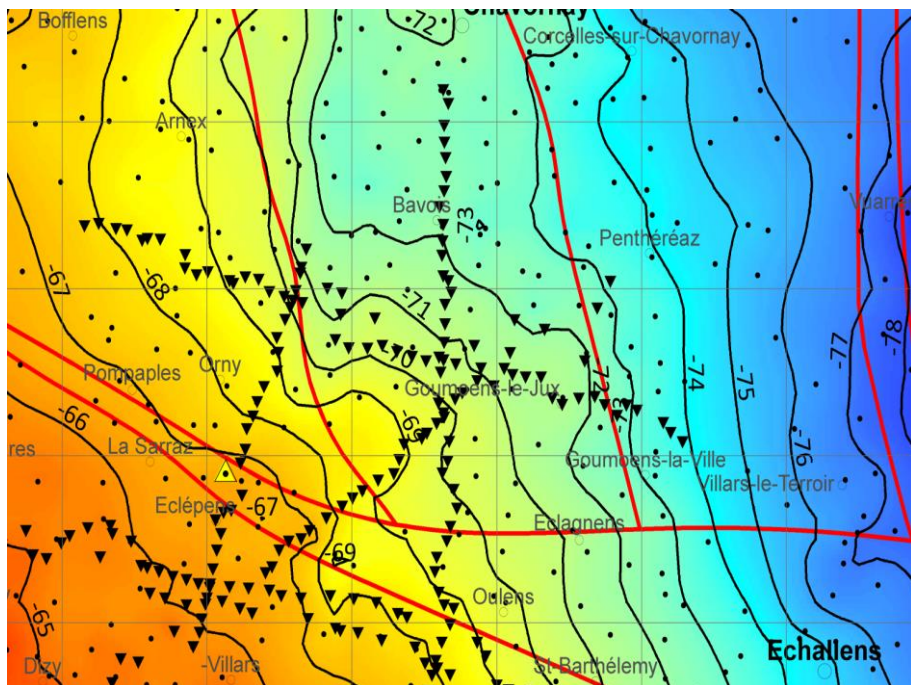


Figure 5.21: Bouguer anomaly map for a density of  $2670 \text{ kg}\cdot\text{m}^{-3}$  within the limit of the 3D model. Black triangles represent measurement stations of this study, black dots are measurements stations from Swiss Atlas of Gravity (Olivier et al., 2010), the yellow triangle is the base station used for the survey. Anomaly values are in mGal, fault traces (red lines) of the model are also kept for localization.

## 5.5 Gravity data treatment

The Bouguer Anomaly map obtained from the 639 gravity stations (data set from this study and from the Swiss Atlas) shows a clear trend of decreasing gravity from West to East (figure 5.21). The quality of the corrections leading to the Bouguer Anomaly can be deduced from the fact that this anomaly is very similar to the one obtained with gravity stations from the Swiss Gravity Atlas only (figure 5.6) and that no correlation or anti-correlation can be observed with topography. The regional trend of Bouguer Anomaly in the Swiss Molasse Basin is well known (e.g. Kahle et al., 1976; Klingelé, 2006) and gravity should decrease from NW to SE (figure 3.8). As mentioned in the previous case study of Sankt Gallen, this trend represents the tectonic setting of the basin at the orogenic scale and is irrelevant for geothermal exploration. The regional trend has been calculated using a quadratic polynomial regression to reproduce its effect.

After removing the orogenic trend, the residual gravity map shows a smaller trend with a deepening to the north similar to the one noticed in the preliminary study (figure 5.7). From the preliminary study, we know that the orientation of the trend on our measurements is induced by an important and deep structure to the north. However, due to its size and to its unknown geometry, this structure cannot be directly added to our model to calculate its gravity effect.

Therefore we calculated a second regional anomaly using the same gravity stations from the Swiss Atlas of Gravity (Olivier et al., 2010) to a distance up to 50 km away from the limit of our study area. This time we used minimum curvature with a cell size of 5 km to interpolate the regional anomaly using the same gravity stations. This use of minimum curvature with a broad cell size was already used on the data of the Swiss Atlas of Gravity for the determination of the bedrock of the Rhône Valley (Rosselli and Raymond, 2003) and is meant here to remove the effect of the suspected Permo-Carboniferous graben.

The difference of these two regional trends gives us a residual anomaly, which is only affected by very large structures (figure 5.22) and will be referred to hereafter as regional residual. Subtracting the regional anomaly obtained by minimum curvature to the Bouguer Anomaly gives another residual anomaly, which is only affected by local structures. This residual will be referred to hereafter as local residual.

## 5.6 Regional interpretation: Permo-Carboniferous graben

A clear and important WNW – ESE negative anomaly is present on the regional residual (figure 5.22) between Mouthe – Ste-Croix and Oron – Bulle with a maximum intensity in the region Moudon – Lucens. This anomaly was already recognized by Klingelé (1972), who suggested the presence of a Permo-Carboniferous trough in the region of Yverdon. This interpretation was confirmed by the Treycovagnes well in 1978, which encountered around 500 m of Permo-Carboniferous sediments without reaching the crystalline basement (e.g. Rigassi and Jaccard, 1995; Sommaruga et al., 2012). The presence of a negative anomaly in the Geneva region (figure 5.22) also supports this hypothesis. Indeed the well Humilly-2 located a few kilometers to the South East of Geneva encountered Permo-Carboniferous sediments at a depth of more than 3 km (Groupe de travail PGG, 2011; Marti, 1969) and their presence in the whole area was suggested by Gorin et al. (1993) from 2D seismic. Permo-Carboniferous troughs were also deduced by gravity surveys west of Neuchâtel (Kuhn, 2012) and in the Payerne area using existing data (Gangnant, 2012).

According to the results of the preliminary study, with such an anomaly, the graben should have a thickness of 3 – 3.5 km with a width of 25 km following the line Eclépens – Treycovagnes. In the region of Moudon, as explained below, the situation is not so clear; however a thickness of more than 4 km and a width of 35 km can be estimated for this object. A steeper slope between Eclépens and Lausanne can also be noticed on figure 5.22. According to the results of the preliminary study (section 5.3.3 p. 182), we interpret it as a near vertical limit of the graben. It can also be noticed that the anomaly minimum is located near Moudon and this could be induced by a thickening of the graben from WNW to ESE. However as the effect of shallower structures were removed by computation this increase toward SE could also be caused by large-scale structures in the Molasse sediment. Moreover, due to the important depth of the structure, the averaging effect of the gravity method and the method used to highlight this anomaly could be induced by several parallel graben of smaller scale and with a different orientation like the WSW – ENE orientation of the Entlebuch graben (e.g. McCann, 2008).

Nevertheless, as Permo-Carboniferous grabens are still largely unknown under the Swiss Molasse Basin, we tried to plot a plausible theoretical limit for a single graben on figure 5.22. However, due to the large uncertainty linked with the Permo-Carboniferous graben geometry this limit represents more an indication for further interpretation, modeling or study than the exact limit of the graben. For this purpose, we used the results of the preliminary study in

the investigated area. Indeed we were able to determine that this limit corresponds approximatively to the line of the 1 mGal of the residual map. The limit is then considered to be between the -1.5 and -0.5 mGal, represented by the hatched area of figure 5.22. In the region of Payerne the limit was extrapolated between the cities of Estavayer and Fribourg, as the dataset shows considerable discrepancies.

The Western limit of the anomaly must be taken with caution, as the effect of the thickening of Triassic evaporites (e.g. Sommaruga et al., 2012) was not taken into account, even if it should have been removed by the data treatment. In this region, there are also fewer gravity stations especially in France as we only used stations from the Swiss Atlas of gravity (Olivier et al., 2010). However, Permo-Carboniferous sediments were found in the Chatelblanc (Strobl, 2007) and Essavilly wells (Rigassi and Jaccard, 1995; Strobl, 2007), where it only shows a thickness of 60 m (figure 5.22).

The Eastern continuation is more doubtful especially east of the line Oron – Bulle. Indeed in this region close to the alpine front, the Molasse sediments were partly affected by the Alpine orogeny (e.g. Kuhlemann and Kempf, 2002). This region is very similar to the South East of our first case study, at Sankt Gallen, where large negative anomalies can be found. Moreover a large magnetic anomaly was found between Morges and Lausanne (Fischer and Le Quang, 1980; Meyer de Stadelhofen, C. et al., 1973; Wanner and Mercanton, 1945). This magnetic anomaly is considered to be a dyke of gabbro of a few kilometers width at a depth around 4 km with a direction of N 64° ending south of Romont (Meyer de Stadelhofen, C. et al., 1973) and this is not compatible with the presence of a Permo-Carboniferous graben at the same place and depth.

Four positive anomalies can also be noticed on figure 5.22, the first is located in the Lausanne - Rolle - Thonon area and most probably continues across Lake Geneva. A second positive anomaly is in the vicinity of Cossonay, a third one 10 km to the west, and the fourth one near Morat. In agreement with the hypothesis of the Permo-Carboniferous graben, we consider that these positive anomalies are related to areas where Permo-Carboniferous sediments thickness is minimal.

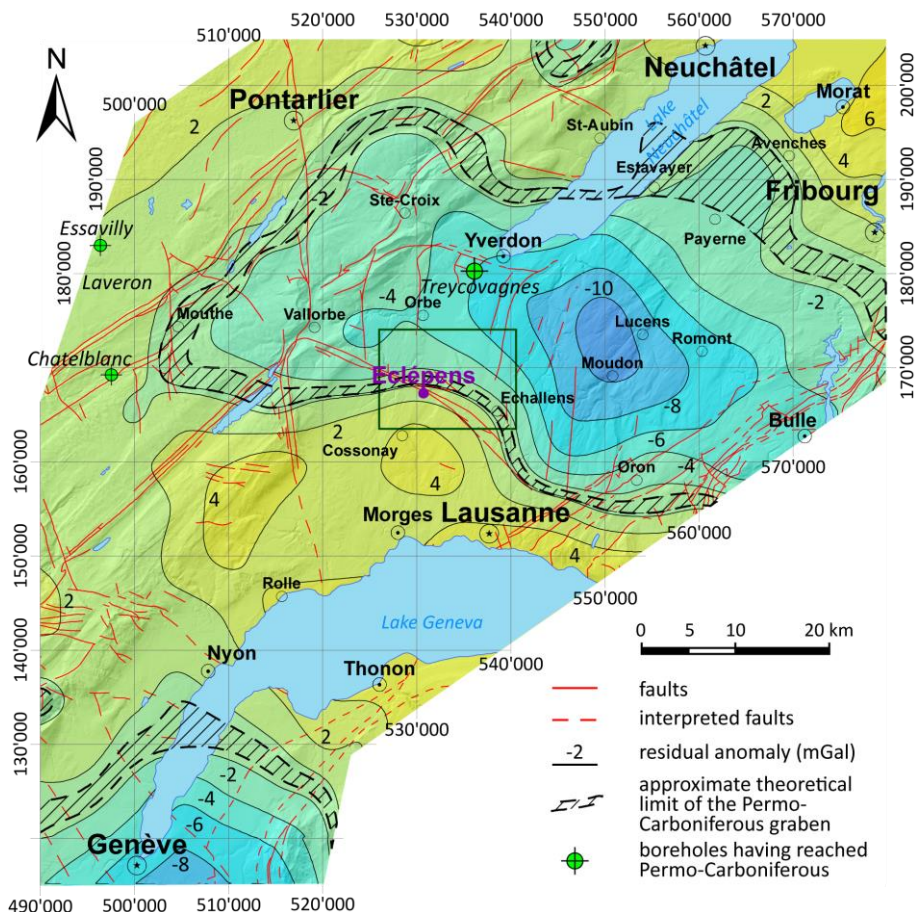


Figure 5.22: Map of residual anomaly obtained by subtracting two regional anomalies (see text for details) with the approximate theoretical limit of Permo-Carboniferous graben and major faults (from Tectonic Map of Switzerland 1:500000 Swisstopo, 2005). The rectangular limit of the 3D model is also plotted.

## 5.7 Local results

On a more local scale, we subtracted the regional anomaly obtained by minimum curvature to the Bouguer Anomaly of figure 5.21. The resulting residual anomaly (figure 5.23) shows no clear trend and thus we consider that the effect of the previously discussed Permo-Carboniferous graben has been totally removed and that the remaining anomalies are only linked with local and shallower geological structures.

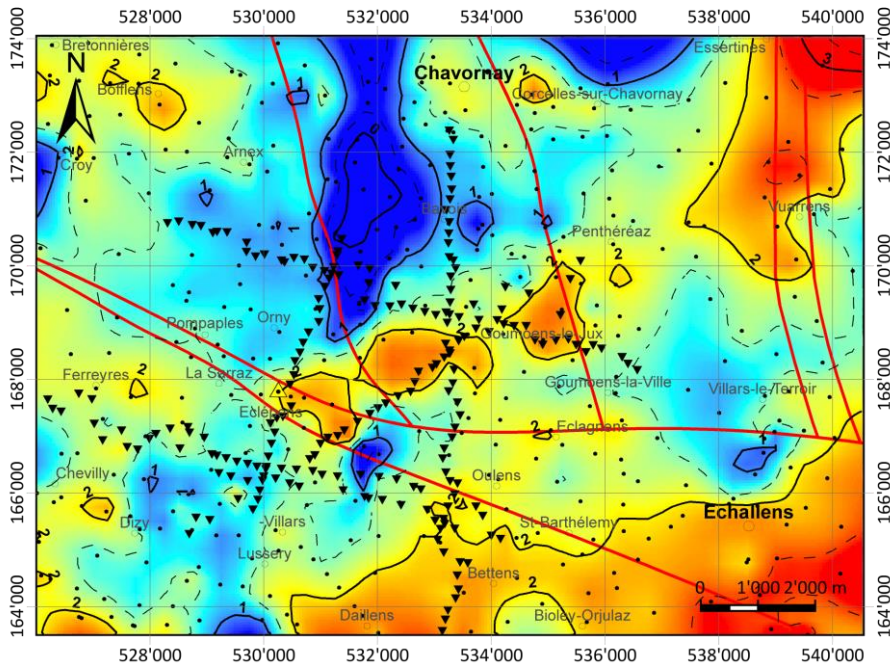


Figure 5.23: Residual anomaly within the range of the 3D geological model (see text for details): faults trace at top Argovian (red lines), measurement stations from this study (black triangles), measurement stations from the Swiss Atlas of Gravity (Olivier et al., 2010) (black dots), anomaly in mGal (black and dashed black lines), gravity base station (yellow triangle), Swiss Coordinates (CH 1903) are used.

On this residual anomaly map, a clear negative anomaly is present north of Eclépens between (531'000 / 169'000 – 533'000 / 174'000) and is likely linked with the Quaternary deposits of the Orbe plain. A positive anomaly with a maximum following the line Eclépens – Penthéréaz – Vuarrens is also present and follows the trace of the Mormont anticline. Other anomalies of smaller extent are also present and they will be discussed in more details hereafter.

This residual anomaly was compared to the gravity effect of the geological model calculated using GInGER for different densities. The first objective was to remove all the gravity effects of structures other than fault zones and especially the effect of Quaternary deposits. However, it was not possible to obtain a satisfying fit for the Quaternary deposits of the Orbe plain and we thus corrected the geological model for the bottom of the plain using the data from Petch (1970), which are more in agreement with boreholes from the geological cadaster of the canton of Vaud (“Cadastre géologique: Canton de Vaud: site officiel,” 2014). We used the same data in order to model peat present in this plain. Indeed, peat has a very low density, down to  $800 \text{ kg}\cdot\text{m}^{-3}$  (e.g. Hinze et al., 2013) and therefore a thickness of only a few meters may induce an important gravity effect and thus cannot be neglected. The gravity effect of this model was calculated with GInGER and compared with the residual anomaly of figure 5.23.

The difference between the model and the measured values (misfit) is presented on figure 5.24 for the densities of table 5.4. According to the result of the preliminary study, a single density was used for the Jurassic and Cretaceous formations as well as for the Triassic formations and Molasse sediments were considered as a single geological layer. These densities were obtained through inversion using prior values set to be common densities for the different geological formations (e.g. Altwegg et al., 2013; Wagner et al., 1999). This misfit ranges from -2.5 to 2.5 mGal and even less in the central part, which is the area of interest for the geothermal project. We consider that the two positives anomalies present to the north and north east are likely induced by border effect. Indeed, in order to compute the gravity effect of a geological model, geological layers are prolonged horizontally to infinity, which is far from reality. This is especially true for Quaternary sediments and peat present in the vicinity of the north anomaly, even if the thickness of peat may also be exaggerated. However, as previously mentioned these positive anomalies are far from the area of interest and were therefore not further investigated.

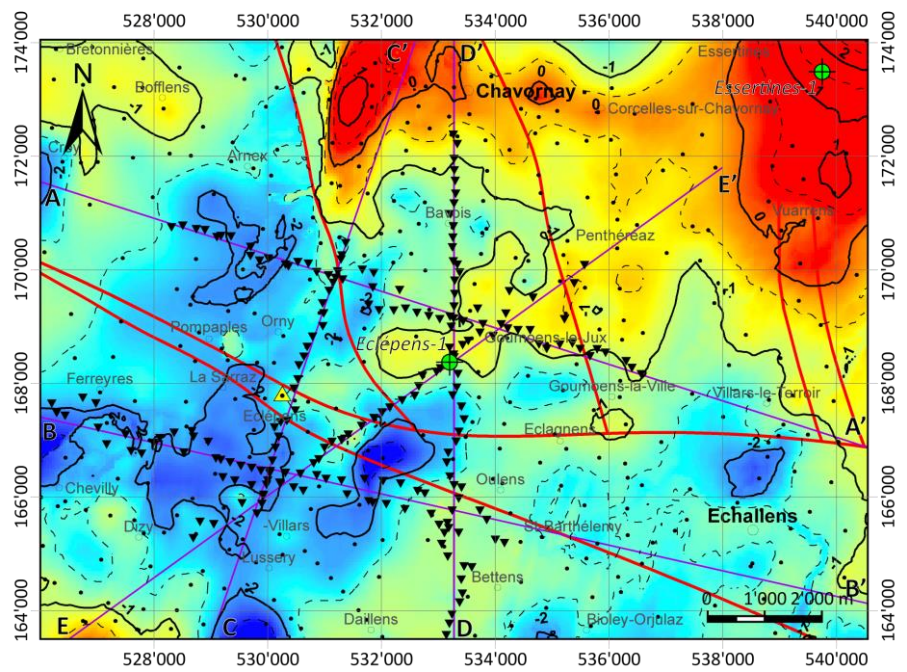


Figure 5.24: Misfit between residual anomaly and calculated gravity effect in mGal (black and dashed black lines) with gravity stations from this study (black triangles), from the Swiss Atlas of Gravity (Olivier et al., 2010)(black dots), gravity base station (yellow triangle). The purple lines show the profiles discussed in the text, green circles represent the deep oil exploration boreholes of Eclépens and Essertines; Swiss Coordinates (CH 1903) are used.

Table 5.4: Densities used to compute the gravity effects of the 3D geological model and legend for the different profile presented hereafter.

| Formation     | Density (kg·m <sup>-3</sup> ) | Color code                                                                          |
|---------------|-------------------------------|-------------------------------------------------------------------------------------|
| Peat          | 900                           |  |
| Quaternary    | 2000                          |  |
| Molasse       | 2550                          |  |
| Cretaceous    | 2680                          |  |
| Malm          | 2680                          |  |
| Argovian      | 2680                          |  |
| Dogger        | 2680                          |  |
| Lias          | 2680                          |  |
| Triassic      | 2200                          |  |
| Basement s.l. | 2670                          |  |

We will hereafter present our interpretation for each profile of figure 5.24. For these profiles a geological cross-section was obtained through GInGER, as well as the gravity effect of the model. This effect is then compared to the value of the residual anomaly (figure 5.23) with the measurement stations projected perpendicularly on the profiles. Gravity from the Swiss Atlas of Gravity (Olivier et al., 2010) located at less than 250 m from the profile were also added. We then use GInGERSP to add simple shapes in order adjust the model against the measured anomaly. As explained previously, we will not make change to the 3D geological model and we will rather try to explain the difference between modeled gravity and measurements. In this respect, we will propose hypotheses to explain the observed difference. However, these hypotheses should be considered more as reflections for further studies or for change in the model than real structures of the sub-surface.

With this in mind and considering that the 3D model is unchanged and that the effect of the Ante-Triassic formation has been completely removed, we will consider that the misfit is related to Quaternary deposits above the molasse, to local density change of the geological formation induced by facies change or to the damage zone of the faults and/or karstification. In this respect, we used horizontal slabs to model all these change except for damage zones and karstification for which vertical thin sheets are used. Concerning fault zones, we consider that:

- They mainly affect formations of the Jurassic and Cretaceous.
- They stop near the top of Cretaceous and in the Triassic.
- Their density contrast is  $-135 \text{ kg}\cdot\text{m}^{-3}$  in order to allow for qualitative comparison using dimensions of the vertical thin sheets.
- Vertical thin sheets should be placed near faults visible in the model by inducing a shift of geological layers on the cross sections.

Note that the interpretation was carried out for the whole length of the profiles. However, out of the central part of the profiles where our own measurements are located, it should be considered cautiously. Indeed, near the limit of the profiles anomalies are often determined by a few points only, as the data from the Swiss Atlas of Gravity were solely available. It is nevertheless presented as it can give indications for the continuation of the geothermal project, aimed at showing where the geological model can be improved.

### 5.7.1 Profile AA'

This WNW-ESE profile (figure 5.25) is located to the north of the Mormont hill and crosses the Orbe plain (figure 5.24). On figure 5.25, the effect of the Quaternary, before its modification, is plotted (green dashed line). We see that the deepening of the Quaternary sediments allowed a better fit between the model and the residual values, but without fully explaining the anomaly. We thus added a vertical thin sheet representing the damage zone of the Orbe fault visible on the profile. The dimensions of the considered damaged zone are presented on table 5.5, in which it can be seen that the Talent fault, even if they have an important geometrical effect, do not seem to have an important damaged zone. We interpreted the anomaly, for which the maximum intensity is located at 12'500 m, as the effect of a fault zone. However, this anomaly is determined by a few measurements only and thus its localization and dimensions should be better constrained before further interpretation. We associated this anomaly with the Vuarrens fault but as the profile is almost parallel to the Mormont fault, this anomaly may also be linked to it. These considerations are also true for the last damage zone, which is considered to represent the effect of the Essertines fault.

Between 0 and 2'500 m, we modeled 30 m of Quaternary sediments, but as Cretaceous limestones are almost outcropping, we think that it is likely not the case. Indeed, it may be related to a facies change, alteration or karstification in the Cretaceous formations, to border effect or to the presence of a negative anomaly induced by an important geological structure i.e. a fault further to the West. The modeled deposits between 2'500 and 5'000 m are more likely, even if their thickness is likely exaggerated. Indeed, in the area presence of Quaternary sediments is proven, but as there are also swamps, the density used may be too high and thus the thickness exaggerated. However another possible explanation can be found, if we consider the first anomaly to be linked with an important geological structure such as a fault to the West. This could explain the first anomaly and the overestimated thickness of Quaternary deposits for the second. In this respect, we consider that the thickness of Quaternary sediments in this area should not exceed 20 to 25 m.

The last anomaly considered to be induced by Quaternary sediments is located between the Orbe plain and the Talent River. In this region, Molasse sediment seems to have partially slipped into the Orbe plain forming an intermediate plateau clearly visible on the DEM and on the profile of figure 5.25. This comforts the presence of less dense deposits in this area, which may be Quaternary deposits and/or altered/slipped Molasse.

Table 5.5: Geometry of modeled vertical thin sheets of figure 5.25, all values are in meters, damage zone within the range of our measurements are highlighted in gray.

| Name          | Orbe | Talent (W) | Talent (E) | Vuarrens | Essertines |
|---------------|------|------------|------------|----------|------------|
| Mean position | 5950 | 10050      | 10400      | 12550    | 14250      |
| Depth of top  | 75   | 50         | 100        | 811      | 831        |
| Height        | 2700 | 1000       | 1500       | 2000     | 2000       |
| Width         | 130  | 30         | 30         | 230      | 140        |

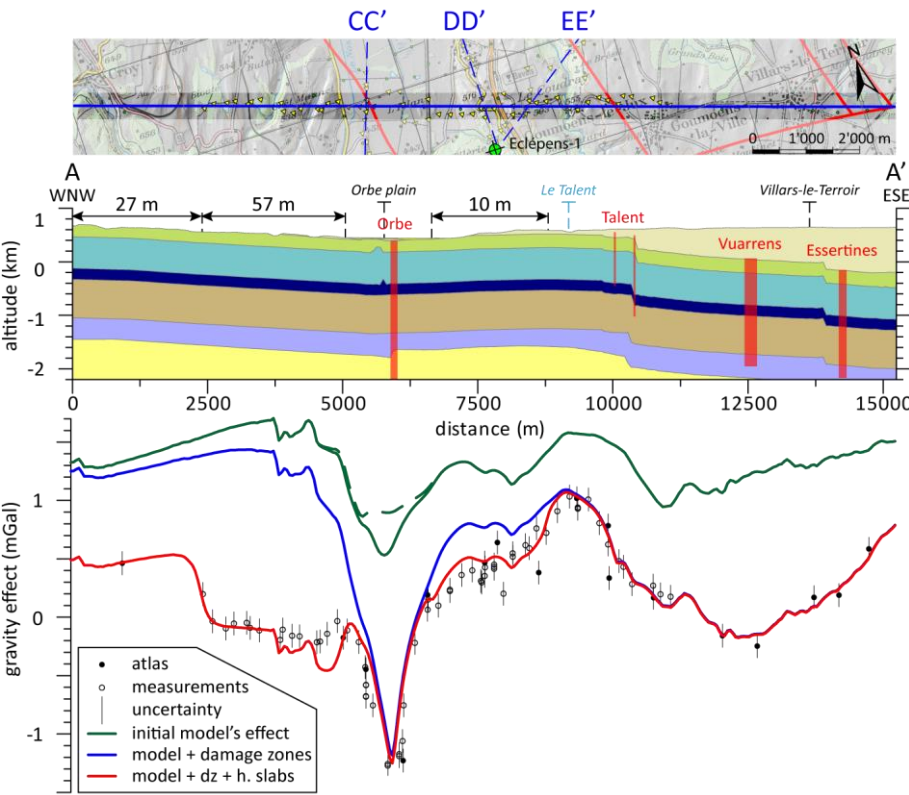


Figure 5.25: Residual anomaly at gravity stations from the Atlas and this study applied to geological cross section AA' of the 3D model (see table 5.4 for color description and figure 5.24 for localization) with modeled vertical thin sheets (red rectangle) and area where Quaternary deposits were considered (black arrow), considered thickness is specified. Uncertainty is represented by vertical bars. Green line is the effect of the model without the simple shapes; Blue line is the final gravity effect. Dashed green line is the effect of the model before the correction of the Quaternary thickness in the Orbe plain (see text for details).

### 5.7.2 Profile BB'

Profile BB' is a WNW-ESE profile (figure 5.26) located to the south of the Mormont hill and crosses the Venoge Valley (figure 5.24). The most remarkable anomaly on this profile is located at 5'800 m along the profile. This steep negative anomaly of more than 1 mGal is constrained by five measurement points. At this location, however, no particular geological structures are mentioned. We thus consider that this anomaly may be linked to a deepening of the Venoge Valley, to the presence of a fault at the Eastern border of the Valley, which has a compatible orientation with other N-S faults or to an important karst conduit. The shape of the anomaly seems to be more compatible with the fault hypothesis. An equivalent result can be obtained by modeling a horizontal cylinder meant to represent an important karst at a depth of 120 m (in the Cretaceous series) and a radius of 35 m. However, no evidence for a fault is visible on the recent seismic (confidential) and the vertical thin sheet was thus dashed on figure 5.24 and it was not possible to remove the ambiguity on the cause of this anomaly, which should therefore be further studied.

Two other damage zones were modeled at 10'450 and 14'000 m (table 5.6). The first one is located in the vicinity of the Eclépens fault and the second in the continuation of the Vuarrens fault to the south. However these structures and their linked anomalies are constrained by a few gravity stations from the Swiss Atlas of Gravity only, and thus are considered to be doubtful. This is especially true as our measurements were made on profile and it is not possible to follow the anomaly linked with a structure. In this respect the Vuarrens fault could be a local structure, a different fault or the continuation of the Vuarrens fault to the South.

Concerning Quaternary deposits modeled at the western part of the profile, they are in correlation with the geological map (Custer, 1935). However, the profile is parallel to the Eclépens fault zone and thus may be influenced by it. Therefore, as for the previous profile, the proposed Quaternary thickness is likely exaggerated; this is especially true for the first 2'500 m of the profile.

Table 5.6: Geometry of modeled vertical thin sheets of figure 5.26, all values are in meters, damage zone within the range of our measurements are highlighted in gray.

| Name          | Venoge | Eclépens | Vuarrens |
|---------------|--------|----------|----------|
| Mean position | 5800   | 10450    | 14000    |
| Depth of top  | 50     | 700      | 900      |
| Height        | 2250   | 2000     | 2000     |
| Width         | 120    | 100      | 320      |

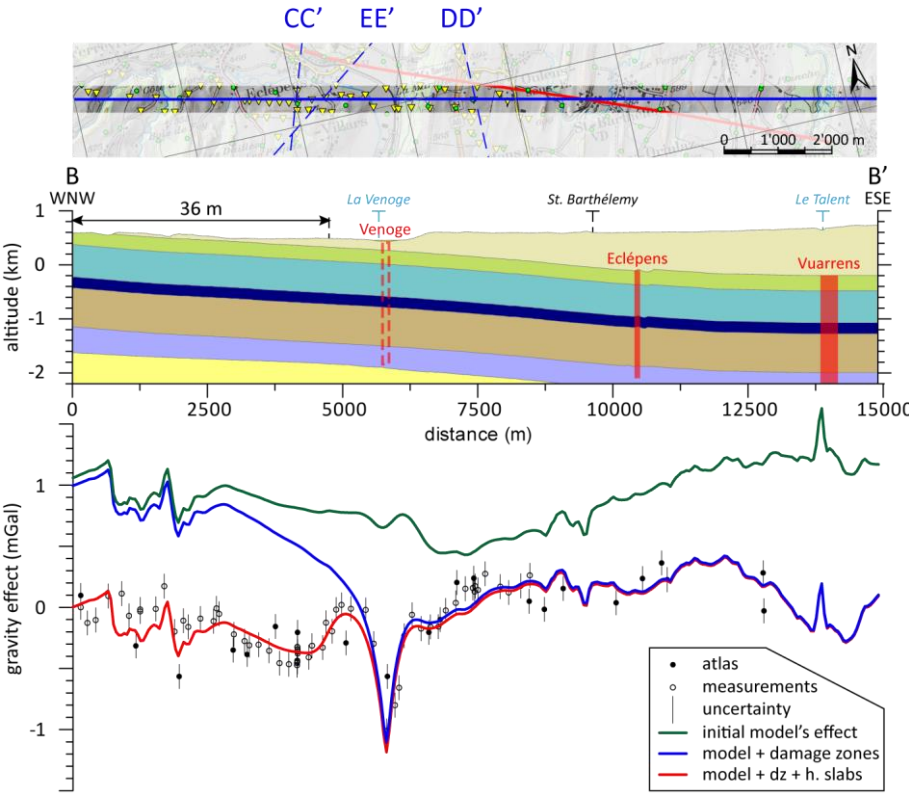


Figure 5.26: Residual anomaly at gravity stations from the Atlas and this study applied to geological cross section BB' of the 3D model (see table 5.4 for color description and figure 5.24 for localization) with modeled vertical thin sheets (red rectangle) and area where Quaternary deposits were considered (black arrow), considered thickness is specified. Uncertainty is represented by vertical bars. Green line is the effect of the model without the simple shapes; Blue line is the final gravity effect.

### 5.7.3 Profile CC'

This SSW – NNE profile starts a few hundred meters north of Cossonay, crosses the Mormont hill and ends in the Orbe plain near Chavornay. The section, between 3'700 and 5'250 m, follows the profile n° 2 of Boulaz (2014), who carried out a study of soil gas measurements (helium) to locate fault zones. Indeed fault zone are considered to be preferential flow path for Helium, which is produced by the natural nuclear decay of radioactive elements present in the geological formations and therefore can help to localize them. Five damage zones were modeled and their respective geometry is presented in table 5.7. It can be noticed that the Eclépens (S) fault is 150 – 200 m to the south to what can be observed on the geological cross section (figure 5.27). This shift was already observed by Boulaz (2014). The Eclépens (N) damage zone does not appear clearly on the geological cross section but its effect on gravity is clearer. We had to use two different shapes in order to model the Eclépens fault zone thus creating a secondary fault (Eclépens S). However, if we consider that this negative anomaly is linked to a single fault. An equivalent result can likely be obtained by considering that the Eclépens fault ends in a flower structure.

The Orbe (N) fault shows a shift as on the AA' profile, although we think that this shift is increased by the dip of the fault and the angle between the profile and the fault. This is also likely the reason why we had to use two different vertical thin sheets in order to reproduce the effect of the damage zone.

Table 5.7: Geometry of modeled vertical thin sheets of figure 5.27, all values are in meters, damage zone within the range of our measurements are highlighted in gray.

| Name          | Eclépens (S) | Eclépens (N) | Mormont | Orbe (S) | Orbe (N) |
|---------------|--------------|--------------|---------|----------|----------|
| Mean position | 3600         | 3950         | 5000    | 6750     | 7550     |
| Depth of top  | 80           | 50           | 150     | 75       | 175      |
| Height        | 540          | 2000         | 2000    | 1500     | 2700     |
| Width         | 140          | 90           | 130     | 70       | 150      |

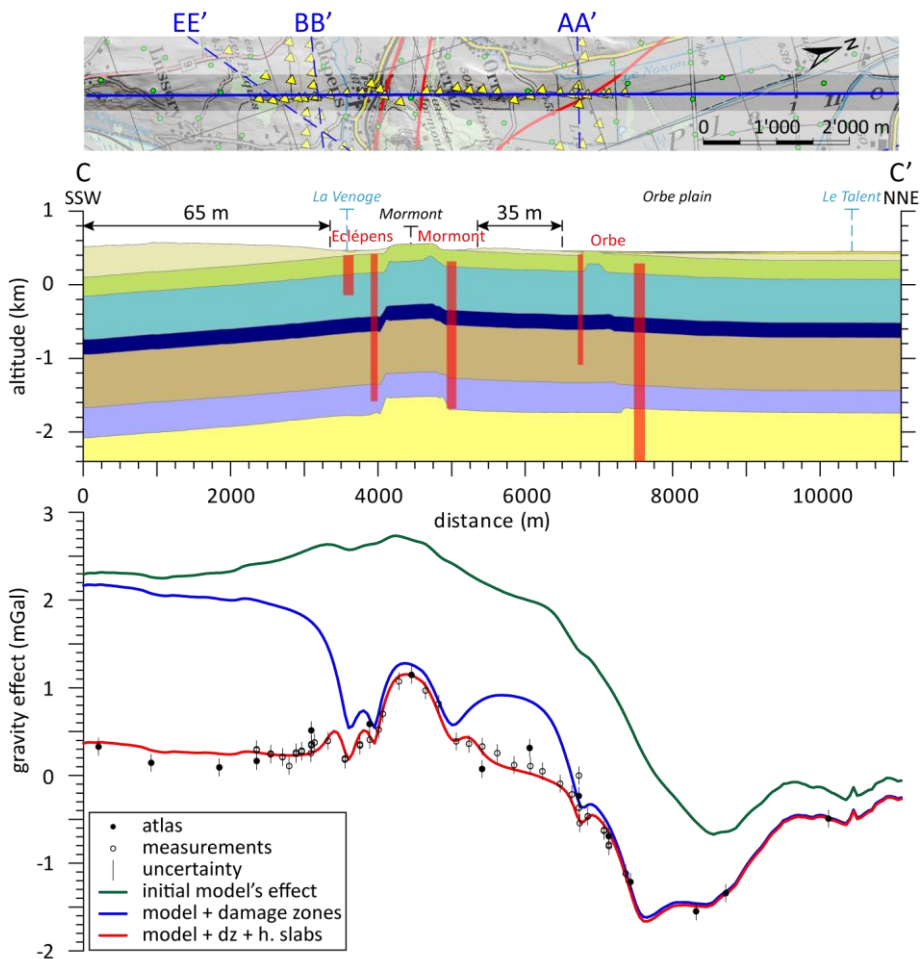


Figure 5.27: Residual anomaly at gravity stations from the Atlas and this study applied to geological cross section CC' of the 3D model (see table 5.4 for color description and figure 5.24 for localization) with modeled vertical thin sheets (red rectangle) and area where Quaternary deposits were considered (black arrow), considered thickness is specified. Uncertainty is represented by vertical bars. Green line is the effect of the model without the simple shapes; Blue line is the final gravity effect.

### 5.7.4 Profile DD'

This South-North profile shows a clear negative anomaly between 3'000 and 4'500 m, which is anti-correlated with the model. The minimum of this anomaly is located exactly where the Mormont fault is supposed to be. This anomaly shows three different minima each of them being interpreted as the effect of a fault zone. As for the Eclépens fault zone on the previous profile, we think that the Mormont fault on this profile presents a flower structure and, that at least, the Entreroche fault (named after the Entreroche dead valley, figure 5.5) is likely a secondary fault linked with the main fault.

The case of the Eclépens fault is different, as it is not clear if it is the continuation of this fault or a secondary fault of the Mormont fault zone. The second hypothesis seems more likely as the soil gas study by Boulaz (2014) located the Eclépens fault exactly where it is on the model (2'600 m, figure 5.28 ). We therefore consider that on this profile the Eclépens fault does not have an important damage zone and we are comforted in this hypothesis by Schnegg et al. (1986), who also did not find this fault with audio-magnetotelluric (AMT) method. Gex (1997) also attested to the presence of the "Cristallin" fault zone (named after the Cristallin dry valley, figure 5.5) a few meter north of the Eclépens-1 borehole. However, no evidence of this fault was found on our measurements.

*Table 5.8: Geometry of modeled vertical thin sheets of figure 5.25, all values are in meters, damage zone within the range of our measurements are highlighted in gray.*

| Name          | Eclépens | Mormont | Entreroche |
|---------------|----------|---------|------------|
| Mean position | 3050     | 3750    | 4300       |
| Depth of top  | 125      | 300     | 50         |
| Height        | 2000     | 2000    | 2000       |
| Width         | 90       | 170     | 60         |

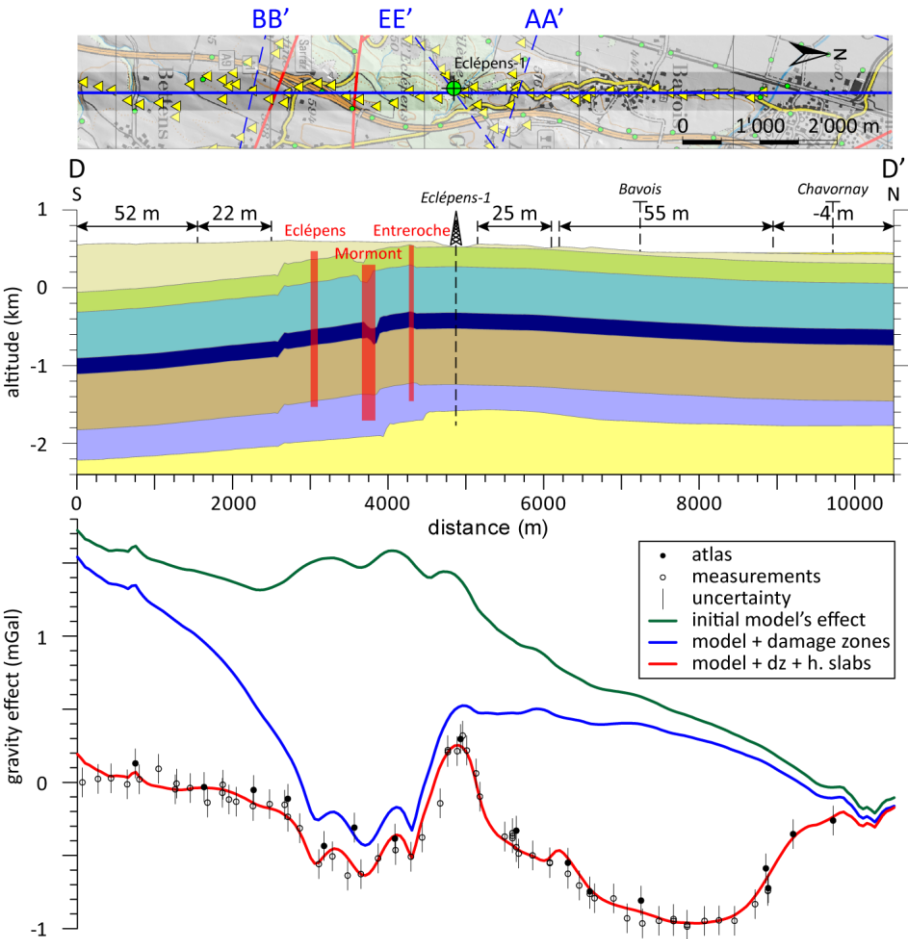


Figure 5.28: Residual anomaly at gravity stations from the Atlas and this study applied to geological cross section DD' of the 3D model (see table 5.4 for color description and figure 5.24 for localization) with modeled vertical thin sheets (red rectangle) and area where Quaternary deposits where considered (black arrow), considered thickness is specified. Uncertainty is represented by vertical bars. Green line is the effect of the model without the simple shapes; Blue line is the final gravity effect.

### 5.7.5 Profile EE'

The profile EE' is a SW-NE profile that follows approximatively the summit of the Mormont anticline and intersects all other profiles (figure 5.24). Where it crosses the Mormont fault a particularly important anomaly is visible (figure 5.29). Concerning the Eclépens fault, it seems more diffuse and a shift of 300 m with the model is observed. This shift is more important than the one highlighted on profile CC'. This increase may however be due to the orientation of the profile which is not perpendicular to the fault. On this profile, a negative gravity effect is visible where the Cristallin fault is supposed to be. However its localization is constrained by a few measurements points only and may also be induced by Quaternary deposits.

Three horizontal structures were added between 7'000 and 14'000 m (figure 5.29), the smallest is meant to represent a Quaternary structure with a thickness of 10 m. This structure, already modeled in profile AA' and DD', is likely due to a landslide highlighted on the 2m DEM (figure 5.30), which was drilled by several boreholes ("Cadastre géologique: Canton de Vaud : site officiel," 2014). The other body is highlighted in blue on figure 5.29 and is not supposed to be linked with Quaternary deposits as no such deposits are mentioned for most of its extent (Bersier, 1953; Custer, 1935). We suppose that it may be linked to a hydrocarbon-rich layer in the Cretaceous. We are comforted in this hypothesis as several boreholes drilled in the Mormont anticline between Eclépens and Essertines either present influxes of natural gas or found bituminous matter in cracks (figure 5.30). Moreover, oil venue in lower Cretaceous is attested in a well drilled for the installation of a borehole heat exchanger at Orny ("Cadastre géologique: Canton de Vaud : site officiel," 2014).

Table 5.9: Geometry of modeled vertical thin sheets of figure 5.29, all values are in meters, damage zone within the range of our measurements are highlighted in gray.

| Name          | Eclépens<br>(S) | Eclépens<br>(N) | Carrière | Mormont | Orbe | Cristallin | Talent | Vuarrens |
|---------------|-----------------|-----------------|----------|---------|------|------------|--------|----------|
| Mean position | 4450            | 5450            | 6500     | 6825    | 7300 | 8700       | 11400  | 12650    |
| Depth of top  | 500             | 100             | 20       | 80      | 150  | 70         | 811    | 350      |
| Height        | 1000            | 2000            | 1000     | 2000    | 2000 | 2000       | 2000   | 2200     |
| Width         | 90              | 110             | 70       | 120     | 60   | 80         | 250    | 80       |

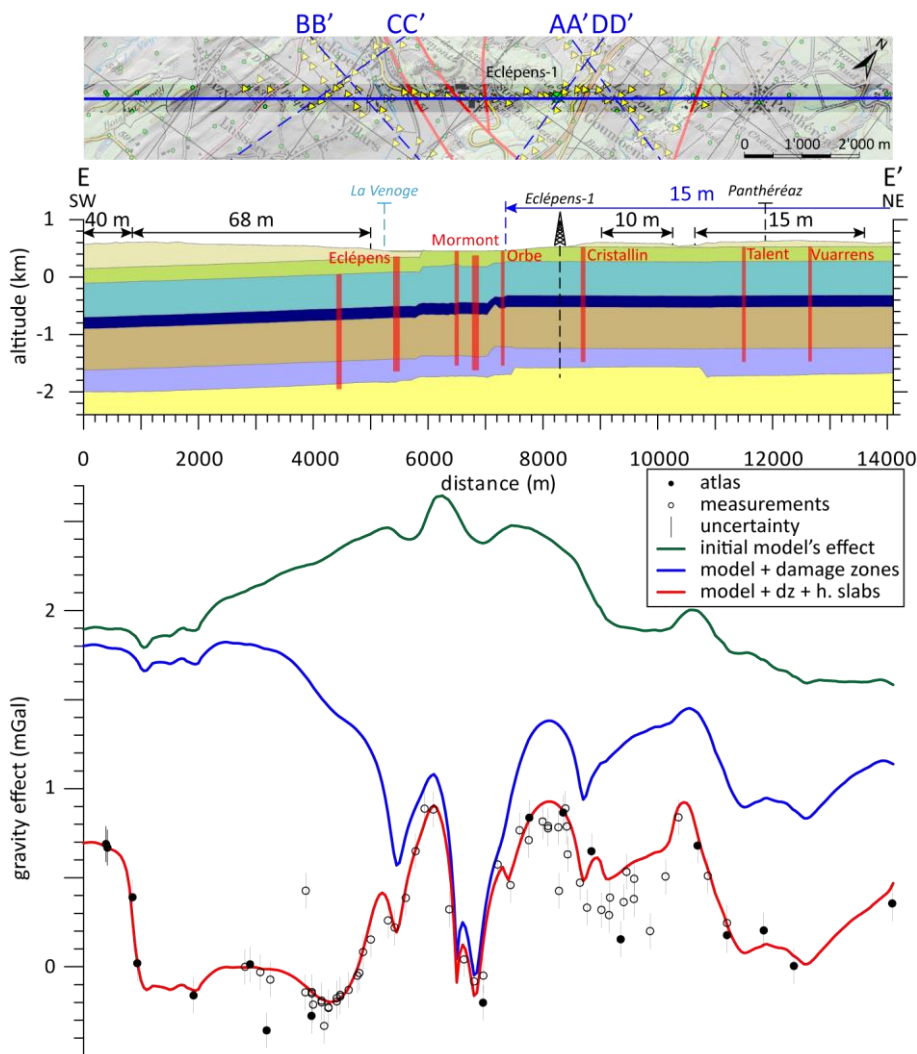


Figure 5.29: Residual anomaly at gravity stations from the Atlas and this study applied to geological cross section EE' of the 3D model (see table 5.4 for color description and figure 5.24 for localization) with modeled vertical thin sheets (red rectangle) and area where Quaternary deposits were considered (black arrow), considered thickness is specified. Uncertainty is represented by vertical bars. Green line is the effect of the model without the simple shapes; Blue line is the final gravity effect.

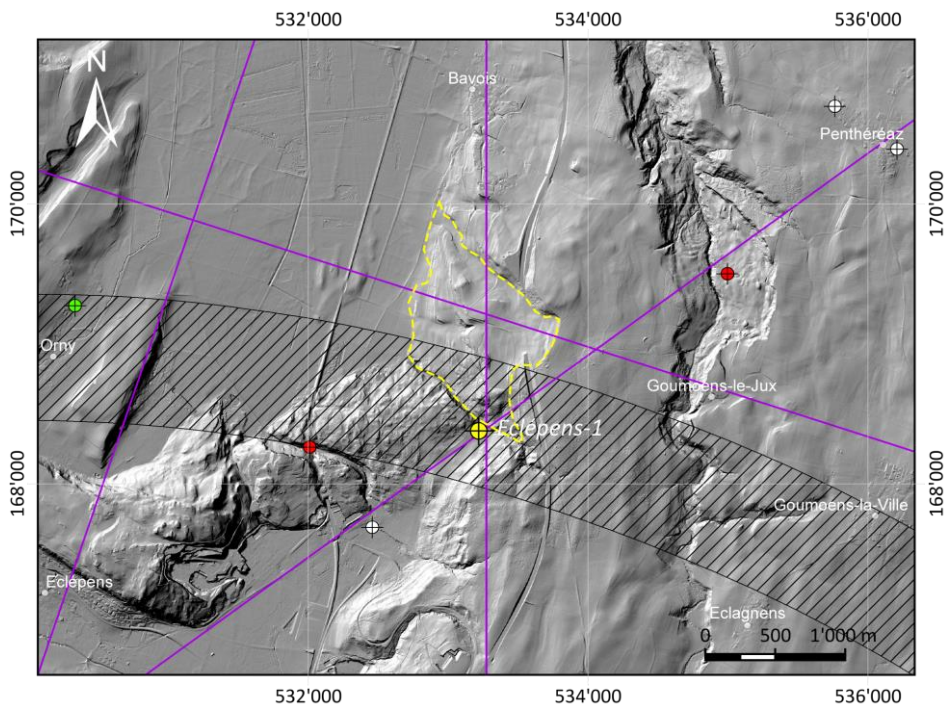


Figure 5.30: 2m DEM (Swisstopo, 2010a) in the vicinity of the Eclépens-1 oil prospection well (yellow circle); borehole with hydrocarbon indications (red circles), natural gas venues (white circles); oil venue (green circle); boreholes data are from ("Cadastre géologique: Canton de Vaud: site officiel," 2014). The area limited by the yellow dashed line is the considered landslide area (see text for detail); the hatched black zone shows the limit of the Permo-Carboniferous Graben as shown on figure 5.22. Purple lines remind the trace of profiles.

## 5.8 Discussion

In this section, we discuss first what the second case study has shown in terms of the evaluation of the proposed methodology. Then we discuss the validity of our results before presenting their significance both for regional exploration and for the geothermal project of Eclépens.

Concerning the methodology proposed in this thesis, this second case study brings useful information by showing some limits of its applicability. First, the simplification of faults geometry into single planes and uncertainty about their localizations prevented the use of the full possibilities of GInGER. Indeed, on most profiles, there was a shift between fault localization and the minimum of the gravity anomaly. This shift is likely related either to the fault geometry, or to its localization, and both are not well constrained in the present model. Moreover, in the framework of the present study, it was not feasible to re-analyze the original data and adapt the 3D model in order to fit all the available data. Therefore the quantification of the decrease of density induced by the damage zone of the faults could not be done using GInGER. To overcome this issue, it was decided to develop a simple extension of GInGER, allowing the used to study rapidly and iteratively in 2D the impact of simple shapes. This resulted in the development of a new tool, GInGERSP (section 3.5).

The combined use of these tools allowed better constraining of the possible localization, the volume, and the geometry of the different damage zones linked to the faults. They also made possible the comparison of these different damage zones qualitatively and the results may be used to adjust the model. GInGER was used for computing the 3D gravity effect of the geological model, thereby determining the density of the different geological formations and for establishing a map of the misfit (figure 5.24). This gravity effect was then used in GInGERSP as a base gravity effect before adding simple shapes and studying their impact.

Concerning the five gravity profiles presented in section 5.7 (p. 194), the effect of the different damaged zones of the faults shows a good fit between modeled and measured gravity. The regional correction used may have an impact on the amplitude of the different anomalies, but at this scale it will not have any impact on the qualitative comparison between different faulted zones. Moreover, the almost systematic correspondence of damage zone with negative gravity anomalies (e.g. figure 5.28) are correlated by the Helium gas measurements of Boulaz (2014). This provides evidence that damage zones can be highlighted by gravity measurements. However, as presented in the

section 5.7, a good fit cannot be obtained without the modeling of the different Quaternary deposits.

Nevertheless, the modeled thickness of Quaternary deposits seems exaggerated if compared with local geological information (section 5.2 and references herein), typically on the south of the model, on profiles CC' (figure 5.27), DD' (figure 5.28) and EE' (figure 5.29). This exaggeration may be induced by a difference of the density of the upper part of the Molasse or of one of the Mesozoic units caused by lithological variation or by alteration. It could also be induced by the extension of the different geological layers horizontally to infinity (section 3.4.2) and thus it may be a border effect.

For these reasons, the modeling of important Quaternary deposits, such as those of the Orbe plain or of the Venoge River, are not sufficient to remove all ambiguities on our results. However the amplitude of the anomaly induced by a damage zones is similar to those expected from Quaternary deposits. In the Eclépens region, fault zones superior extremities are often shallow and thus the anomaly induced by their damage zone is steep and of narrow width (see section 5.3.2 p. 176). This has a double effect: first they can be relatively easily distinguished from Quaternary deposits, but the narrow width also implies that they may not be clearly visible on gravity measurements if the distance between the gravity measurements stations is too important (figure 5.18).

A secondary result of this study is an estimation of the extension of the Permo-Carboniferous trough drilled at Treykovagnes-1 (figure 5.22). This result should be used with care as these limits were fixed using the results of the preliminary study. Thus, they represent more an indication for interpretation or for further modeling than the exact limit of the graben. This boundary, which should be associated with an important normal fault, especially in the Eclépens region, differs from the faults affecting the Mesozoic formations visible on figure 5.22, especially in the case of the Vallorbe - Mormont fault. We therefore think that there is no direct link between ante-Triassic and post-Triassic faults as proposed by Buxdorf (1961) near Eclépens and that the 3D geological model should be modified. The limit of this graben seems to be in the vicinity of the Eclépens-1 borehole (figure 5.22) and this may give an explanation for the observed thermal anomaly. Indeed, the border fault of the graben is likely to be a more permeable zone compared to the trough itself. It may trigger the ascent of deep fluids, consequently inducing the thermal anomaly. However such conceptual hypotheses should be confirmed by further detailed modeling of the Permo-Carboniferous graben and of deep fluid flows in such structures.

From the modeling of the different fault zones present within the limit of the geological model, we found that their respective dimensions are relatively constant and therefore allow for their qualitative comparisons. In this respect, the two major structures are clearly the Eclépens and Mormont faults, which induce a relatively clear gravity anomaly (e.g figure 5.28). The gravity effect is larger in the West for the Eclépens faults (Profile CC', figure 5.27) and to the East for the Mormont fault (profile DD', figure 5.28) and thus they must be modeled by more than one fault zone. We believe that the gravity decrease is the result of flower structures and it demonstrates the limit of modeling with simple shapes, which therefore do not represent precisely the geometry of the damage zone. However, on the profile EE', the two fault zones show a large anomaly and are therefore the more fractured zone as it can be seen on figure 5.29.

More information could be obtained using the proposed methodology for this project. First, a careful modeling of all the Quaternary deposits should be carried out using all the available data. In this respect a new model of the Orbe plain and of the Venoge Valley should be considered. Secondly, the damage zones could be modeled based on seismic data and then integrated in order to calculate their gravity effect. Due to the size of the anomaly linked with the Eclépens fault, we think that the model should be extended further to the south, in order to get rid of border effects. Finally, a new gravity measurement campaign should be considered. The main goal of the survey should be the mapping of the different anomalies and a precise localization of the minima associated with the damage zones. This survey should also be conducted following a grid layout to better localize and constrain the different gravity anomalies. If all these points could be fulfilled, we could adjust the 3D model and it should be possible to obtain quantitative results on the different damage zones.

## 5.9 Conclusion

This second case study clearly shows that the combined use of GInGER and GInGERSP allows testing of the plausibility of a 3D geological model by comparing its gravity effect with measurements. It also shows that the more precise the model is, the more we can obtain from our methodology. However, when the 3D model is not well constrained, the proposed methodology contributes to a better understanding of the local geological setting by highlighting areas where the model and measurements do not agree.

The preliminary study has shown how GInGER and GInGERSP can be used in order to conduct, quickly and easily, sensitivity analysis. Concerning the project it showed that the structures described in the existing 3D model are not sufficient to explain the different anomalies found in the residual. Nevertheless, it allowed identifying the parameters that have a preponderant effect on gravity to quantify their respective effect on gravity and to better size the gravity survey. It has also confirmed that it is not possible to determine quantitatively the porosity of the different faults zones present in the 3D model.

In addition to these previous results, the preliminary study showed that a very deep structure, which could be a Permo-Carboniferous trough is likely present in the Northern part of the model. That some limited and local anomalies are likely induced by some faults considered in the model. It also allowed determining that the model can be divided into six different layers without inducing significant errors. Finally it showed that the two main targets determined by the geothermal project (graben and faults) induce very different anomalies and must therefore be studied separately.

Concerning the geothermal project of Eclépens our methodology and the acquisition of new gravity revealed new features that were not present in the 3D geological model based on seismic data. It also permitted:

- The modeling of the damage zones associated with faults using GInGERSP which gave a qualitative comparison as well as indications on possible more complex geometry.
- It was also possible to highlight the area where, most probably, the Eclépens and Mormont fault zones present the largest damage zone.
- An important Permo-Carboniferous graben is likely present in the northern part of the 3D geological model and is most probably the same structure that was drilled at Treycovagnes. It was possible with the existing gravity data, to interpret its southern limit, which is

likely located in the vicinity of the Eclépens-1 oil prospection well (figure 5.22).

- Our investigation has shown that it was possible to highlight areas where Quaternary thickness should be modeled
- In addition, it was possible to highlight where a possible hydrocarbon reservoir could be present (figure 5.29).
- At a regional scale we were able to map the theoretical limits of the Permo-Carboniferous trough by interpreting the gravity data from the Swiss Atlas of Gravity in combination with modeling using GInGERSP.

We think that for these reasons our methodology brings useful information to the geothermal project that cannot be obtained by the other geophysical methods. The second case study also provided useful teaching concerning our methodology. Indeed, it allowed us to better determine the prerequisites for its applicability in 2D and 3D, especially regarding the qualitative/quantitative estimation of fault zone porosity.



## Chapter 6

# Conclusions



## 6.1 Main results

The main idea that we investigated in this thesis is whether gravimetry data can be of value during the exploration of deep geothermal projects. More precisely, the aim is to estimate the porosity of the damage zone of faults at depth that can be used as geothermal reservoirs. As gravity is a geophysical method that is known to integrate and then smooth out the variability of the underground, the aim of this research was particularly challenging. To overcome these difficulties, we propose a methodology that consists in five steps:

1. A sensitivity study is carried out to determine the shape, extent and intensity of the gravity anomalies linked to the different geological structures of the target area.
2. A gravity survey is carried out to obtain a precise Bouguer Anomaly of the region of investigation.
3. The regional anomaly linked with lithospheric scale structures is determined and then subtracted from the Bouguer anomaly.
4. The different geological structures are modelled in 3D and their respective effects on gravity are computed.
5. The final step is the stripping of all the known gravity effects so that the final residual (or misfit) highlights the gravity variation associated to the targeted structures.

To help the user to apply this methodology two computer programs, GInGER (GravImetry for Geothermal ExplRation) and GInGERSP (GInGER Synthetic Profile), have been developed. The main aim of GInGER is to provide a user-friendly and efficient way to compute the gravity effect of 3D geological model and the determination of the best densities for each geological element. In this respect, it can be used for preliminary or sensitivity study by determining the effect of each geological structures. It can also be used in combination with a gravity data. In this case the user can test the validity of 3D geological model, perform stripping and assess fracture porosity.

GInGERSP (GInGER Synthetic Profile) is a separate computer program that computes the gravity effect of simple shapes in 2D. The objective is to provide a simple and efficient tool to make quick preliminary or sensitivity studies. However, as the gravity profiles of GInGER can be directly imported in GInGERSP it also allows the testing of different hypotheses before modifying 3D geological models, which is often time-consuming and cannot be carried out routinely.

The methodology and the computer programs have been tested for two case studies that were ongoing geothermal projects in Switzerland. In Sankt Gallen, the synthetic case study allowed us to determine that our methodology was applicable with limited information. It also permitted the identification of the relevant major gravity parameters, which are in this specific case, the density of the molasse sediment, the geometry of the Quaternary deposits, the geometry and density of a Permo-Carboniferous graben, the geometry of the fault and its associated damage zone. Moreover, this synthetic case study allowed a better sizing of the gravity survey and confirmed that in order to quantify the porosity induced by the damage zone of a fault, its geometry must be well constrained.

Using existing and specifically acquired gravity data combined with a geological model based on 3D seismic data, we were able to make a first assessment of the porosity induced by a regional fault. We estimated that the porosity of the damage zone of the fault, which was the main target of the geothermal exploration, should be, depending of the fluid composition, between 4-6 %. We were also able to propose a first model of a Permo-Carboniferous graben located in the vicinity of the fault zone, even if all ambiguities linked with these results could not be removed.

In Eclépens, the preliminary study has shown that GInGER and GInGERSP can be used in order to conduct, quickly and easily, sensitivity analysis. Concerning the project itself, it showed that the structures described in the existing 3D model are not sufficient to explain the different anomalies found in the residual but allowed to identify the preponderant parameters for gravity and to quantify their effect. The preliminary study also showed that a very deep structure, which could be a Permo-Carboniferous trough is likely present in the Northern part of the model and therefore, as the two main targets of the case study (graben and faults) induce very different anomalies, they must be studied separately.

For this second case study, the gravity survey and the modeling of the different damage zones through GInGERSP allowed to perform a qualitative comparison between them and to highlight most suitable targets. Regarding local geology, it was also possible to localize areas where the model does not fit with the measurements and thus should be adjusted. The Eclépens case study revealed that a Permo-Carboniferous graben of regional extent crosses the northern part of the model. We were able to interpret and map its possible extension on a regional scale. More locally, as this limit is located in the vicinity of the Eclépens-1 oil prospection well, this may, to a certain extent, explain its high geothermal gradient.

The application of our methodology showed that strike-slip faults zones are, almost systematically, associated with measurable negative gravity anomalies in the two study areas. The main differences between these two case studies are that in Sankt Gallen, fault geometry and the uncertainty of the model were known. This difference allowed us to determine that in order to quantitatively assess the porosity of a damage zone:

- The gravity measurements must be precise enough, typically with accuracy of  $\pm 0.1$  mGal.
- The different structures of the model must be well constrained especially the geometry of near surface structures such as the structures filled by Quaternary sediments.
- The geometry of the fault must be well constrained.

However, when these prerequisites are not met, a qualitative assessment of the porosity is still possible.

For our two case studies, it allowed us to test the validity of the 3D geological model and to highlight where these models could be adjusted. We were also able, in both cases, to identify and model two Permo-Carboniferous troughs which was not possible using seismic data.

In conclusion our methodology combined with GInGER proved to be useful for geothermal exploration and could also be applied to other fields as it is presented in the next section.

### 6.1.1 Limitations

The two case studies allowed determining the main limitations of our methodology. Indeed, the presence of non-modeled/identified geological structures which may have a significant gravity effect led to ambiguities in the final interpretation of the gravity data. This consideration is especially true for deep structures, such as the damage zones of the faults and for Permo-Carboniferous grabens, which both can have an important, even regional, gravity effect. Indeed, in our two case studies, Permo-Carboniferous structures were not present in the initial model. Moreover, in both cases no geometrical model of reservoir was available for the damage zone of the faults, even if it was the main target of the geothermal exploration. The presence of such structures increases the overall uncertainty of the gravity model by increasing the number of unconstrained parameters. This leads to an equivocal interpretation especially for the quantitative assessment of porosity induced by fault zones.

This ambiguity can be significantly reduced if GInGER is used in an iterative process. In this process, as it is the case for our two case studies, the initial 3D geological model would be first established with seismic data and then compared with gravity data. Then the model would be adjusted to fit the two datasets, i.e. using gravity to help a seismic interpretation of a Permo-Carboniferous graben or to better constrain the reservoir. Following this process, it should be possible to have a geological model, which has only reservoir porosity as unconstrained parameter and thus allows for non-equivocal quantitative assessments of the reservoir porosity. This iterative, multidisciplinary, approach should allow decreasing the inherent equivocal interpretation of the different methods and their associated uncertainties.

Despite these limitations, in all cases, our methodology provides complementary information on the validity of the 3D geological model. It also allows identifying structures that are important for the understanding of the reservoir and its exploitation and that can hardly be detected using seismic method.

## **6.2 Outlook**

### **6.2.1 Potential new applications**

The proposed methodology and the corresponding computer programs were developed specifically for geothermal exploration in the context of sedimentary basins. We think, however, that it could also be used for other purposes, such as the detection of Permo-Carboniferous graben.

Regarding geothermal EGS projects, the methodology could be used in order to monitor and quantify the induced fracturing by measuring the same gravity stations before and after hydraulic fracturing. Doing so, the gravity difference between the two surveys will only be related to the created porosity and this should allow for its mapping and/or its quantification. This time-lapse approach is of course also applicable to the oil and gas industries that use fracking technology. Regarding these fossil resources, as one also searches for areas of “high” porosity, we think that our methodology is directly applicable, as it was proven by our two case studies.

It should also be possible to apply our methodology to the mining industry, especially for mineral deposits linked with hydrothermal systems. In this case, the material filling the cavities will not be water or gas but the secondary mineral (ore). Therefore their density will be much higher and we will be able to identify and study these positive anomalies.

Finally, application for micro-gravity surveys can be considered for civil engineering purpose, such as validation of the limit of the bedrock or the identification of possible landslides.

## 6.2.2 Further software development

First concerning GInGER the time needed to compute the gravity effect of the model could be reduced by using Graphical Processor Unit (GPU) and/or spectral domain computation for the model calculation. Border effects could also be reduced using regional, broad scale 3D models, like the forthcoming model from the GeoMol project or, if not available by improving the way geological structures are prolonged outside the extension of the 3D geological model. Concerning topography, this prolongation likely creates border effects which could become problematic in rugged areas like the Alps. This can however be avoided if a topographical correction is carried out for every cell of the grid, as it was done for the measurements. The test of geological hypotheses can also be facilitated if the user can directly add shapes with simple geometry directly in 3D. It should also be possible to propose a user-friendly manner to allow the integration of more complex structures in the model like inverse fault or heterogeneities in the densities of formations.

For GInGERSP, the integration of more geometrical shapes with more complex geometries i.e. inclined thin sheets, non-perpendicular shapes or the possibility to create shapes with arbitrary geometry could greatly improve its usefulness. This last possibility would even allow the creation of 2D or 2.5D profile that can be used to modify the 3D geological model.

Finally and for both computer programs an important improvement would be to allow the geometrical inversion using the misfit on a single geological structure.

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# Appendices



# Appendix A

## GBOX algorithm

```
1 void gravi_cal::gbox(double &pdG, double &pt_x,
2 double &pt_y, double &pt_z, double &x1, double &x2,
3 double &y1, double &y2, double &z1, double &z2)
4 {
5     double rijk, ijk, arg1, arg2, arg3;
6     double dx [2], dy [2], dz [2];
7     int i, j, k;
8     double sign [2] = {-1,1};
9     const double km2m = 1000;
10    const double twopi = 2 * M_PI;
11    QString text;
12
13    // Hereafter a transcription of Blakely 1996
14    // gbox, m are converted to km
15
16    dx[0] = (pt_x - x1)/km2m;
17    dy[0] = (pt_y - y1)/km2m;
18    dz[0] = (pt_z - z1)/km2m;
19    dx[1] = (pt_x - x2)/km2m;
20    dy[1] = (pt_y - y2)/km2m;
21    dz[1] = (pt_z - z2)/km2m;
22
23    pdG =0;
24    for (i=0;i<2;i++)
25    {
```

```

26         for (j=0;j<2;j++)
27         {
28             for (k=0;k<2;k++)
29             {
30                 rijk=sqrt( (dx[i]*dx[i]) +
31                     (dy[j]*dy[j]) + (dz[k]*dz[k]));
32
33                 ijk=sign[i]*sign[j]*sign[k];
34
35                 arg1=atan2( (dx[i]*dy[j]),
36                     (dz[k]*rij));
37
38                 if (arg1 < 0)
39                 {
40                     arg1 = arg1 + twopi;
41                 }
42
43                 arg2 = rijk + dy[j];
44                 arg3 = rijk + dx[i];
45
46                 if (arg2 <= 0)
47                 {
48                     text = "An error occured!\n";
49                     text += "pt_x: " +
50 QString("%1\npt_y: %2\npt_z: %3\nx1:    %4\nx2:
51 %5\ny1:    %5\ny2:    %6\nz1:    %z\nz2:
52 %7\n").arg(pt_x,0,'f',3).arg(pt_y,0,'f',3).arg(pt_z
53 ,0,'f',3).arg(x1,0,'f',3).arg(x2,0,'f',3).arg(y1,0,
54 'f',3).arg(y2,0,'f',3).arg(z1,0,'f',3).arg(z2,0,'f'
55 ,3)+ "\n";
56
57                     QMessageBox::critical(NULL,
58                         "Error", text);
59                     exit(0);
60                 }
61                 if (arg3 <= 0)
62                 {
63                     text = "An error occured!\n";
64                     text += "pt_x: " +
65 QString("%1\npt_y: %2\npt_z: %3\nx1:    %4\nx2:
66 %5\ny1:    %5\ny2:    %6\nz1:    %z\nz2:
67 %7\n").arg(pt_x,0,'f',3).arg(pt_y,0,'f',3).arg(pt_z
68 ,0,'f',3).arg(x1,0,'f',3).arg(x2,0,'f',3).arg(y1,0,
69 'f',3).arg(y2,0,'f',3).arg(z1,0,'f',3).arg(z2,0,'f'
70 ,3)+ "\n";

```

```
71
72         QMessageBox::critical(NULL,
73         "Error", text);
74         exit(0);
75     }
76     arg2 = log(arg2);
77     arg3 = log(arg3);
78     pdG += ijk*(dz[k]*arg1-dx[i]*arg2-
79     dy[j]*arg3);
80     }
81     }
82     }
83 }
```



## Appendix B

### Sankt Gallen gravity measurements

This appendix includes all the gravity measurements used in chapter 4. X, Y, and Z value are in CH 1903, the uncertainty is considered to be  $\pm 0.02$  m in all directions. Raw values are reported to the Swiss Atlas of Gravity Value (Olivier et al., 2010) following the methodology of chapter 4 and reported to the base station localized here below; the considered uncertainty on measurement is  $\pm 0.01$  mGal. The Bouguer Anomaly is computed for a mean density of  $2570 \text{ kg}\cdot\text{m}^{-3}$  and its considered uncertainty is  $\pm 0.1$  mGal.

#### **Base station**

Base station:

X: 742'971.54

Y: 253'932.20

Z: 632.48

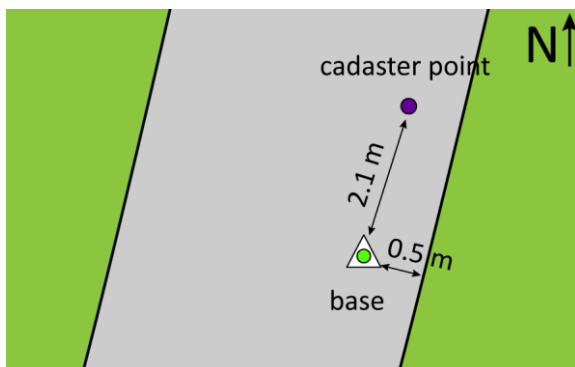
g: 980600.159 mGal

Cadaster point:

X: 742972.13

Y: 253934.24

Z: 632.52



| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 103  | 740186.72 | 255360.45 | 766.65 | 980577.626 | -111.125 |
| 105  | 741915.34 | 255480.80 | 878.48 | 980551.550 | -112.720 |
| 107  | 741846.12 | 254491.28 | 670.44 | 980593.951 | -113.033 |
| 109  | 740709.63 | 252741.08 | 648.88 | 980595.826 | -114.542 |
| 119  | 746489.60 | 253534.38 | 760.02 | 980573.671 | -114.516 |
| 123  | 750443.10 | 251993.68 | 916.88 | 980537.875 | -117.253 |
| 125  | 753305.78 | 256650.74 | 825.51 | 980562.526 | -114.087 |
| 150  | 739918.33 | 257612.18 | 781.06 | 980578.519 | -109.200 |
| 151  | 740280.22 | 257223.18 | 793.50 | 980575.042 | -109.910 |
| 152  | 740779.99 | 256173.00 | 788.06 | 980574.042 | -111.340 |
| 999  | 740800.10 | 257515.89 | 868.40 | 980558.480 | -110.414 |
| 1000 | 737548.03 | 250334.61 | 777.44 | 980568.226 | -114.379 |
| 1002 | 737486.14 | 250537.88 | 764.12 | 980571.289 | -113.651 |
| 1004 | 737593.77 | 250602.65 | 748.23 | 980574.389 | -113.915 |
| 1006 | 737814.02 | 250469.88 | 742.00 | 980575.362 | -114.416 |
| 1008 | 737866.99 | 250574.57 | 726.09 | 980578.656 | -114.466 |
| 1010 | 737958.28 | 250625.44 | 714.37 | 980580.980 | -114.483 |
| 1012 | 737971.54 | 250766.41 | 701.76 | 980583.920 | -113.887 |
| 1014 | 738133.99 | 250700.59 | 707.90 | 980582.512 | -114.148 |
| 1016 | 738183.06 | 250772.01 | 720.31 | 980579.952 | -114.190 |
| 1018 | 738262.44 | 250835.59 | 751.69 | 980573.804 | -113.773 |
| 1020 | 738242.42 | 251103.60 | 772.07 | 980570.593 | -113.610 |
| 1022 | 738483.45 | 250917.64 | 781.40 | 980568.031 | -114.157 |
| 1024 | 738586.12 | 250867.11 | 778.50 | 980568.652 | -113.939 |
| 1026 | 738729.65 | 250816.73 | 758.95 | 980572.250 | -114.087 |
| 1030 | 738843.05 | 250839.59 | 768.99 | 980570.268 | -114.096 |
| 1032 | 738918.78 | 250821.97 | 778.17 | 980568.383 | -114.213 |
| 1034 | 739021.49 | 250849.38 | 791.12 | 980565.563 | -114.216 |
| 1036 | 739075.11 | 250984.07 | 817.02 | 980560.247 | -114.183 |
| 1038 | 739168.94 | 251014.12 | 826.61 | 980557.414 | -114.739 |
| 1040 | 739213.80 | 251037.03 | 827.22 | 980556.734 | -115.293 |
| 1042 | 739304.11 | 251103.07 | 819.96 | 980559.515 | -113.908 |
| 1044 | 739385.41 | 251116.35 | 813.69 | 980560.685 | -114.154 |

| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 1046 | 739475.56 | 251159.97 | 812.60 | 980560.709 | -114.394 |
| 1048 | 739580.86 | 251246.58 | 801.20 | 980563.156 | -114.385 |
| 1050 | 739670.56 | 251497.29 | 737.99 | 980576.450 | -114.717 |
| 1052 | 739521.90 | 251504.92 | 741.38 | 980576.267 | -114.222 |
| 1054 | 739589.94 | 252127.90 | 653.90 | 980594.622 | -114.198 |
| 1056 | 739699.42 | 252098.62 | 654.64 | 980594.489 | -114.312 |
| 1058 | 739789.86 | 252087.22 | 655.40 | 980594.214 | -113.941 |
| 1060 | 739889.61 | 252043.47 | 655.58 | 980594.060 | -114.335 |
| 1062 | 739992.07 | 252004.48 | 659.76 | 980593.194 | -114.283 |
| 1064 | 740095.77 | 251966.18 | 663.21 | 980592.463 | -114.362 |
| 1066 | 740171.99 | 251952.88 | 662.88 | 980592.450 | -114.392 |
| 1068 | 740246.85 | 251973.40 | 661.00 | 980592.905 | -114.361 |
| 1070 | 740357.09 | 252032.33 | 655.24 | 980594.152 | -114.264 |
| 1072 | 740472.08 | 251999.46 | 655.89 | 980593.932 | -114.368 |
| 1074 | 740579.18 | 251991.20 | 655.25 | 980594.014 | -114.466 |
| 1076 | 740689.21 | 252054.06 | 654.94 | 980594.023 | -114.532 |
| 1078 | 740751.98 | 252135.98 | 654.41 | 980594.237 | -114.578 |
| 1084 | 740839.87 | 252250.57 | 653.70 | 980594.431 | -114.644 |
| 1088 | 740896.35 | 252400.43 | 652.99 | 980594.544 | -114.835 |
| 1090 | 740979.49 | 252399.01 | 652.38 | 980594.658 | -114.843 |
| 1092 | 741118.53 | 252487.31 | 651.88 | 980594.816 | -114.774 |
| 1096 | 741155.92 | 252582.90 | 652.48 | 980594.828 | -114.675 |
| 1098 | 741210.83 | 252655.04 | 650.08 | 980595.418 | -114.710 |
| 1100 | 741299.98 | 252673.58 | 648.15 | 980596.011 | -114.745 |
| 1104 | 741420.20 | 252727.32 | 651.26 | 980595.614 | -114.361 |
| 1106 | 741539.56 | 252787.59 | 653.54 | 980595.165 | -114.059 |
| 1108 | 741631.93 | 252852.35 | 647.76 | 980596.384 | -114.339 |
| 1110 | 741664.99 | 252987.92 | 640.88 | 980597.529 | -114.481 |
| 1112 | 741691.93 | 253132.64 | 642.49 | 980597.191 | -114.805 |
| 1114 | 741745.28 | 253243.06 | 639.95 | 980597.918 | -114.635 |
| 1116 | 741846.61 | 253303.05 | 639.40 | 980598.169 | -114.547 |
| 1118 | 741929.00 | 253342.99 | 640.31 | 980598.197 | -114.341 |
| 1120 | 742059.92 | 253400.72 | 644.54 | 980597.563 | -114.100 |

| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 1122 | 742183.29 | 253436.79 | 644.92 | 980597.433 | -113.979 |
| 1124 | 742364.50 | 253479.26 | 647.02 | 980596.536 | -114.307 |
| 1126 | 742348.04 | 253586.79 | 640.53 | 980598.443 | -114.166 |
| 1128 | 742439.37 | 253615.01 | 638.47 | 980598.933 | -113.896 |
| 1132 | 742551.97 | 253662.83 | 636.64 | 980599.366 | -114.081 |
| 1134 | 742730.22 | 253758.69 | 633.21 | 980599.762 | -114.177 |
| 1136 | 742643.59 | 253710.82 | 632.80 | 980599.949 | -114.368 |
| 1138 | 742813.89 | 253813.02 | 632.71 | 980600.107 | -113.781 |
| 1140 | 742896.92 | 253868.84 | 632.13 | 980600.279 | -114.077 |
| 1142 | 742972.13 | 253934.24 | 632.87 | 980600.157 | -114.095 |
| 1144 | 743024.23 | 253987.30 | 634.32 | 980599.786 | -114.185 |
| 1146 | 743110.79 | 254033.86 | 634.72 | 980599.669 | -113.966 |
| 1148 | 743225.68 | 254071.20 | 628.26 | 980600.881 | -114.081 |
| 1150 | 743471.45 | 253896.28 | 582.79 | 980609.562 | -114.377 |
| 1152 | 743503.15 | 253950.62 | 574.72 | 980611.123 | -114.260 |
| 1154 | 743593.98 | 254043.31 | 570.32 | 980611.854 | -114.139 |
| 1156 | 743618.03 | 254143.19 | 590.91 | 980607.784 | -114.169 |
| 1158 | 743745.60 | 254200.49 | 607.81 | 980604.912 | -114.169 |
| 1160 | 743802.24 | 254248.96 | 607.63 | 980604.891 | -114.194 |
| 1162 | 743836.70 | 254335.00 | 603.87 | 980605.989 | -113.718 |
| 1164 | 743941.30 | 254361.93 | 607.61 | 980605.073 | -113.928 |
| 1166 | 744033.02 | 254344.22 | 611.63 | 980604.119 | -114.047 |
| 1170 | 744314.30 | 254285.14 | 663.14 | 980594.131 | -114.005 |
| 1172 | 744378.82 | 254352.39 | 654.58 | 980595.956 | -114.099 |
| 1174 | 744430.45 | 254441.18 | 648.12 | 980597.124 | -114.141 |
| 1176 | 744493.83 | 254482.17 | 640.97 | 980598.651 | -113.930 |
| 1178 | 744585.83 | 254583.24 | 623.35 | 980602.189 | -113.936 |
| 1180 | 744658.09 | 254669.87 | 615.29 | 980603.892 | -113.800 |
| 1182 | 744751.22 | 254751.44 | 614.36 | 980604.148 | -113.778 |
| 1184 | 744760.31 | 254833.56 | 613.36 | 980604.979 | -112.974 |
| 1186 | 744878.74 | 254905.09 | 616.15 | 980603.548 | -114.666 |
| 1188 | 744964.31 | 254910.04 | 627.90 | 980601.590 | -113.774 |
| 1190 | 745044.16 | 254989.14 | 636.75 | 980599.546 | -114.619 |

| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 1192 | 745064.48 | 255107.94 | 625.37 | 980602.492 | -113.607 |
| 1194 | 745185.98 | 255123.43 | 635.81 | 980601.963 | -111.487 |
| 1196 | 745355.98 | 255135.51 | 645.06 | 980598.362 | -113.617 |
| 1197 | 745384.86 | 255153.47 | 646.87 | 980597.920 | -113.633 |
| 1198 | 745387.26 | 255208.72 | 655.74 | 980596.237 | -113.780 |
| 1200 | 745483.17 | 255276.51 | 678.65 | 980592.089 | -113.454 |
| 1202 | 745577.32 | 255351.44 | 689.09 | 980589.726 | -114.361 |
| 1204 | 745662.63 | 255384.67 | 702.17 | 980587.998 | -112.775 |
| 1206 | 745773.34 | 255432.54 | 711.16 | 980585.795 | -113.756 |
| 1208 | 745843.27 | 255456.57 | 720.85 | 980583.912 | -113.707 |
| 1210 | 746018.48 | 255422.17 | 742.12 | 980579.575 | -113.818 |
| 1212 | 746058.81 | 255497.01 | 742.22 | 980579.744 | -113.656 |
| 1214 | 746107.52 | 255587.60 | 742.32 | 980579.904 | -113.567 |
| 1216 | 746153.48 | 255671.77 | 742.37 | 980580.051 | -113.549 |
| 1218 | 746330.18 | 255592.57 | 719.91 | 980584.540 | -113.658 |
| 1220 | 746375.41 | 255686.55 | 718.31 | 980584.893 | -113.916 |
| 1222 | 746426.76 | 255792.96 | 718.72 | 980584.954 | -113.618 |
| 1224 | 746535.17 | 255853.81 | 710.39 | 980586.750 | -113.650 |
| 1226 | 746596.51 | 255968.88 | 713.46 | 980586.207 | -113.647 |
| 1228 | 746655.39 | 256016.71 | 712.69 | 980586.335 | -113.648 |
| 1230 | 746719.39 | 256065.96 | 714.14 | 980586.144 | -113.589 |
| 1232 | 746893.02 | 256137.17 | 709.06 | 980587.300 | -113.404 |
| 1236 | 747087.45 | 256223.52 | 694.03 | 980590.447 | -113.496 |
| 1240 | 747272.82 | 256281.26 | 681.67 | 980592.873 | -113.482 |
| 1244 | 747419.57 | 256392.34 | 668.70 | 980595.669 | -113.368 |
| 1500 | 743825.81 | 254330.06 | 603.68 | 980605.920 | -114.038 |
| 1600 | 742972.14 | 253934.22 | 632.86 | 980600.149 | -114.077 |
| 1800 | 745309.52 | 254881.75 | 694.50 | 980588.380 | -113.918 |
| 1804 | 745166.04 | 254723.76 | 688.04 | 980589.605 | -114.032 |
| 1808 | 745023.15 | 254723.77 | 673.32 | 980592.525 | -114.049 |
| 1812 | 744883.88 | 254639.08 | 664.02 | 980594.289 | -113.883 |
| 1816 | 744807.24 | 254534.81 | 668.25 | 980593.359 | -113.981 |
| 2002 | 739326.98 | 257334.50 | 784.53 | 980577.274 | -109.448 |

| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 2004 | 739407.12 | 257386.40 | 781.90 | 980577.968 | -109.367 |
| 2006 | 739532.29 | 257431.38 | 780.11 | 980578.465 | -109.270 |
| 2008 | 739618.41 | 257477.10 | 776.14 | 980579.424 | -109.293 |
| 2010 | 739735.26 | 257549.61 | 774.13 | 980579.959 | -109.337 |
| 2012 | 739822.49 | 257567.05 | 778.47 | 980579.058 | -109.205 |
| 2014 | 740013.50 | 257568.40 | 781.69 | 980578.216 | -109.435 |
| 2016 | 740096.31 | 257529.88 | 782.11 | 980577.902 | -109.648 |
| 2018 | 740179.03 | 257493.08 | 782.88 | 980577.584 | -109.730 |
| 2020 | 740278.01 | 257264.24 | 791.67 | 980575.440 | -109.949 |
| 2024 | 740351.38 | 257112.64 | 801.94 | 980572.938 | -110.185 |
| 2026 | 740435.80 | 257129.00 | 814.26 | 980570.262 | -110.067 |
| 2028 | 740529.67 | 257117.14 | 827.55 | 980567.362 | -110.168 |
| 2030 | 740685.70 | 257115.29 | 841.81 | 980564.182 | -110.334 |
| 2031 | 740754.53 | 257260.40 | 853.27 | 980561.796 | -110.369 |
| 2032 | 740757.75 | 257254.46 | 853.38 | 980561.746 | -110.359 |
| 2034 | 740903.94 | 257228.80 | 853.27 | 980561.586 | -110.687 |
| 2036 | 740985.51 | 257218.24 | 849.18 | 980562.511 | -110.546 |
| 2040 | 741049.99 | 257006.39 | 825.41 | 980567.329 | -110.730 |
| 2042 | 741122.30 | 257041.31 | 818.37 | 980568.885 | -110.599 |
| 2044 | 741276.42 | 257058.91 | 809.38 | 980570.755 | -110.693 |
| 2046 | 741349.32 | 257129.08 | 811.47 | 980570.361 | -110.697 |
| 2048 | 741429.02 | 257206.51 | 815.15 | 980569.683 | -110.613 |
| 2049 | 741438.58 | 257188.16 | 816.87 | 980569.288 | -110.372 |
| 2050 | 741527.59 | 257249.61 | 817.96 | 980569.113 | -110.698 |
| 2052 | 741615.46 | 257294.81 | 820.11 | 980568.637 | -110.653 |
| 2054 | 741711.47 | 257343.96 | 821.66 | 980568.261 | -110.746 |
| 2055 | 741663.51 | 257104.36 | 834.35 | 980565.242 | -110.927 |
| 2056 | 741810.47 | 257394.63 | 822.68 | 980568.028 | -110.744 |
| 2057 | 742090.35 | 257188.91 | 825.75 | 980566.836 | -110.832 |
| 2058 | 741894.99 | 257437.71 | 823.42 | 980567.839 | -110.722 |
| 2060 | 742004.43 | 257492.13 | 824.42 | 980567.608 | -110.678 |
| 2061 | 742086.68 | 257541.50 | 825.51 | 980567.412 | -110.520 |
| 2062 | 742196.70 | 257165.17 | 812.08 | 980569.624 | -111.019 |

| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 2063 | 742179.56 | 257175.97 | 812.39 | 980569.628 | -111.038 |
| 2064 | 742235.52 | 257133.51 | 807.77 | 980570.342 | -111.034 |
| 2065 | 742230.43 | 257141.53 | 808.71 | 980570.194 | -111.023 |
| 2066 | 742287.30 | 257123.27 | 796.94 | 980572.587 | -111.219 |
| 2068 | 742371.88 | 257088.69 | 782.49 | 980575.523 | -111.259 |
| 2069 | 742456.82 | 257040.02 | 770.36 | 980578.005 | -111.098 |
| 2070 | 742454.13 | 257040.00 | 769.61 | 980578.124 | -111.230 |
| 2072 | 742506.00 | 257065.90 | 763.30 | 980579.364 | -111.180 |
| 2074 | 742589.06 | 257033.54 | 748.61 | 980580.860 | -112.464 |
| 2076 | 742619.17 | 257004.32 | 747.55 | 980582.910 | -110.565 |
| 2078 | 742672.68 | 257011.07 | 743.16 | 980583.299 | -111.446 |
| 2080 | 742718.09 | 256980.98 | 745.63 | 980582.748 | -111.394 |
| 2082 | 742817.66 | 257007.53 | 743.81 | 980583.112 | -111.527 |
| 2084 | 742862.65 | 257028.98 | 742.65 | 980583.404 | -111.537 |
| 2086 | 742908.16 | 257050.75 | 741.27 | 980583.797 | -111.437 |
| 2088 | 742954.11 | 257072.57 | 740.38 | 980584.066 | -111.309 |
| 2090 | 743003.28 | 257061.75 | 741.15 | 980583.883 | -111.487 |
| 2092 | 743062.89 | 257046.61 | 743.43 | 980583.343 | -111.526 |
| 2094 | 743111.73 | 257042.62 | 740.03 | 980584.012 | -111.427 |
| 2096 | 743168.22 | 257036.85 | 739.25 | 980584.132 | -111.484 |
| 2098 | 743228.28 | 257048.78 | 735.05 | 980584.927 | -111.531 |
| 2100 | 743228.19 | 257050.73 | 735.12 | 980584.903 | -111.560 |
| 2102 | 743278.98 | 257047.64 | 730.30 | 980585.852 | -111.514 |
| 2104 | 743312.60 | 257051.11 | 725.97 | 980586.726 | -111.634 |
| 2106 | 743404.25 | 257051.78 | 716.75 | 980588.514 | -111.627 |
| 2108 | 743525.60 | 257053.35 | 701.62 | 980591.476 | -111.827 |
| 2109 | 743525.24 | 257048.48 | 701.50 | 980591.494 | -112.037 |
| 2110 | 743586.06 | 257190.44 | 699.31 | 980591.859 | -111.687 |
| 2112 | 743664.33 | 256966.49 | 688.93 | 980593.860 | -111.859 |
| 2113 | 743743.66 | 257208.55 | 685.32 | 980594.809 | -111.760 |
| 2114 | 743818.96 | 257170.71 | 680.08 | 980595.947 | -111.749 |
| 2115 | 743758.12 | 256989.83 | 682.06 | 980595.198 | -111.955 |
| 2116 | 743845.87 | 257002.96 | 681.55 | 980595.250 | -112.077 |

| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 2118 | 743918.70 | 257179.96 | 669.93 | 980598.051 | -111.678 |
| 2119 | 743988.66 | 257088.08 | 671.20 | 980597.553 | -111.583 |
| 2120 | 744004.16 | 257239.09 | 662.33 | 980599.635 | -111.671 |
| 2122 | 744216.87 | 256950.45 | 662.88 | 980598.909 | -112.164 |
| 2124 | 744345.72 | 256936.35 | 663.85 | 980598.504 | -112.206 |
| 2126 | 744538.77 | 256855.87 | 649.29 | 980600.859 | -112.599 |
| 2128 | 744854.94 | 256905.08 | 586.75 | 980613.105 | -112.401 |
| 2132 | 745143.36 | 257081.36 | 563.84 | 980617.941 | -112.170 |
| 2136 | 745347.07 | 257202.92 | 598.34 | 980611.437 | -112.284 |
| 2140 | 745546.61 | 257179.36 | 619.94 | 980607.021 | -112.492 |
| 2144 | 745703.73 | 257127.74 | 637.36 | 980603.332 | -112.577 |
| 2148 | 745823.01 | 256836.04 | 663.89 | 980597.641 | -112.705 |
| 2152 | 745997.95 | 256681.13 | 693.13 | 980591.393 | -112.825 |
| 2156 | 746106.32 | 256649.49 | 710.95 | 980587.623 | -112.887 |
| 2160 | 746299.00 | 256511.61 | 741.62 | 980581.203 | -113.186 |
| 2164 | 746526.95 | 256459.79 | 759.88 | 980577.248 | -113.287 |
| 2168 | 746769.75 | 256801.03 | 787.05 | 980571.687 | -113.031 |
| 2172 | 746961.00 | 256950.17 | 788.02 | 980571.433 | -113.180 |
| 2176 | 747067.39 | 257025.81 | 781.64 | 980572.702 | -113.010 |
| 2186 | 747600.48 | 256579.83 | 665.39 | 980596.373 | -113.343 |
| 2190 | 747929.35 | 256574.15 | 656.98 | 980598.235 | -113.400 |
| 2194 | 748063.89 | 256503.18 | 657.24 | 980598.177 | -113.482 |
| 2198 | 748284.51 | 256422.00 | 674.55 | 980594.534 | -113.529 |
| 2202 | 748449.42 | 256592.30 | 679.96 | 980593.624 | -113.544 |
| 2206 | 748807.28 | 256582.99 | 660.92 | 980597.206 | -113.617 |
| 2210 | 748933.78 | 256512.21 | 655.21 | 980597.841 | -113.983 |
| 2214 | 749095.07 | 256518.18 | 640.09 | 980600.770 | -113.963 |
| 2218 | 749366.77 | 256446.41 | 651.62 | 980598.258 | -114.001 |
| 2222 | 749530.17 | 256278.54 | 646.95 | 980599.146 | -113.964 |
| 2226 | 749756.36 | 256467.44 | 637.35 | 980601.300 | -113.639 |
| 2230 | 749977.18 | 256742.80 | 619.98 | 980604.445 | -113.810 |
| 2234 | 750146.49 | 256301.65 | 571.85 | 980612.761 | -113.571 |
| 2238 | 750265.60 | 256265.42 | 575.80 | 980612.086 | -113.461 |

| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 2242 | 750382.69 | 256166.26 | 622.33 | 980602.850 | -113.590 |
| 2246 | 750584.23 | 256206.50 | 638.28 | 980599.868 | -113.644 |
| 2250 | 750836.82 | 256302.76 | 658.79 | 980596.056 | -113.797 |
| 2254 | 750888.83 | 256023.43 | 723.77 | 980582.105 | -113.888 |
| 2258 | 751211.92 | 256087.10 | 764.14 | 980574.201 | -113.494 |
| 2262 | 751301.60 | 255941.30 | 756.81 | 980575.136 | -114.130 |
| 2270 | 751769.10 | 256076.91 | 793.24 | 980567.920 | -113.872 |
| 2274 | 751887.30 | 256099.45 | 795.19 | 980567.334 | -113.997 |
| 2278 | 752197.70 | 256269.40 | 809.68 | 980565.013 | -113.780 |
| 2282 | 752411.38 | 256338.56 | 812.83 | 980564.634 | -113.285 |
| 2286 | 752571.22 | 256386.22 | 818.74 | 980563.468 | -113.800 |
| 2290 | 752797.43 | 256525.22 | 822.71 | 980562.857 | -113.799 |
| 2294 | 752994.15 | 256638.37 | 820.38 | 980563.475 | -113.862 |
| 2298 | 753218.12 | 256638.06 | 822.24 | 980563.209 | -114.010 |
| 2302 | 753405.80 | 256611.84 | 828.29 | 980561.975 | -114.038 |
| 2306 | 753640.29 | 256452.97 | 831.70 | 980561.362 | -113.775 |
| 2310 | 753777.51 | 256407.97 | 833.49 | 980560.582 | -113.965 |
| 2316 | 754072.43 | 256385.83 | 838.28 | 980559.259 | -114.176 |
| 2326 | 754527.81 | 256526.39 | 842.63 | 980558.286 | -114.217 |
| 2332 | 754838.40 | 256586.15 | 849.66 | 980556.837 | -113.872 |
| 2336 | 755168.94 | 256651.13 | 864.40 | 980554.096 | -113.913 |
| 2342 | 755400.16 | 256726.68 | 871.58 | 980552.705 | -114.110 |
| 2500 | 737752.71 | 257523.80 | 634.13 | 980609.684 | -107.806 |
| 2504 | 737959.60 | 257576.48 | 658.91 | 980604.556 | -107.925 |
| 2508 | 738217.20 | 257667.00 | 680.11 | 980600.102 | -108.064 |
| 2512 | 738295.34 | 257459.48 | 690.60 | 980597.763 | -108.192 |
| 2516 | 738412.25 | 257224.67 | 702.63 | 980594.902 | -108.632 |
| 2520 | 738693.86 | 257217.28 | 731.46 | 980588.690 | -108.689 |
| 2524 | 738850.12 | 257486.35 | 731.97 | 980588.841 | -108.856 |
| 2528 | 739026.92 | 257383.35 | 760.93 | 980582.334 | -109.055 |
| 2532 | 739258.41 | 257288.58 | 789.88 | 980576.031 | -109.342 |
| 3000 | 739425.70 | 255148.52 | 794.20 | 980571.882 | -111.422 |
| 3002 | 739496.42 | 255119.28 | 788.47 | 980573.036 | -111.251 |

| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 3004 | 739602.85 | 255085.69 | 777.12 | 980575.347 | -111.332 |
| 3006 | 739735.68 | 255048.32 | 766.88 | 980577.362 | -111.470 |
| 3008 | 739825.43 | 255045.31 | 765.06 | 980577.656 | -111.496 |
| 3010 | 739915.63 | 255024.67 | 769.18 | 980576.605 | -111.746 |
| 3012 | 740045.35 | 255084.95 | 767.71 | 980576.782 | -111.770 |
| 3014 | 740142.16 | 255058.11 | 746.67 | 980580.825 | -111.822 |
| 3016 | 740169.15 | 254878.71 | 759.79 | 980577.799 | -112.114 |
| 3018 | 740361.45 | 254733.46 | 783.32 | 980572.825 | -112.171 |
| 3023 | 740531.21 | 254816.36 | 794.42 | 980570.524 | -112.269 |
| 3024 | 740575.75 | 254857.02 | 794.02 | 980570.688 | -112.276 |
| 3026 | 740654.46 | 254857.55 | 791.11 | 980571.351 | -112.206 |
| 3028 | 740768.38 | 254840.78 | 788.24 | 980571.826 | -112.246 |
| 3030 | 740894.36 | 254820.33 | 786.36 | 980572.064 | -112.267 |
| 3032 | 740996.86 | 254809.80 | 783.65 | 980572.437 | -112.287 |
| 3036 | 741088.34 | 254724.69 | 773.99 | 980574.139 | -112.716 |
| 3038 | 741186.77 | 254583.40 | 766.95 | 980574.856 | -112.619 |
| 3040 | 741305.79 | 254644.19 | 756.73 | 980576.899 | -112.577 |
| 3042 | 741417.64 | 254712.94 | 746.93 | 980578.803 | -112.620 |
| 3044 | 741515.26 | 254755.27 | 739.08 | 980580.297 | -112.614 |
| 3046 | 741619.57 | 254765.49 | 732.45 | 980581.634 | -112.735 |
| 3048 | 741716.53 | 254816.82 | 725.16 | 980583.151 | -112.685 |
| 3050 | 741812.35 | 254764.81 | 717.09 | 980584.612 | -112.698 |
| 3052 | 741912.04 | 254786.85 | 710.62 | 980585.974 | -112.683 |
| 3054 | 742001.93 | 254788.62 | 705.18 | 980587.065 | -113.152 |
| 3056 | 742104.95 | 254782.19 | 698.36 | 980588.529 | -113.026 |
| 3058 | 742239.54 | 254838.79 | 702.85 | 980587.772 | -112.816 |
| 3060 | 742288.96 | 254695.09 | 685.32 | 980591.175 | -113.258 |
| 3062 | 742376.04 | 254642.11 | 676.67 | 980592.901 | -113.288 |
| 3064 | 742456.27 | 254593.85 | 667.38 | 980594.758 | -113.164 |
| 3066 | 742460.74 | 254438.75 | 657.66 | 980596.542 | -113.086 |
| 3068 | 742554.63 | 254444.31 | 653.64 | 980597.283 | -113.388 |
| 3070 | 742669.55 | 254513.94 | 661.10 | 980595.901 | -113.350 |
| 3072 | 742782.75 | 254573.84 | 666.18 | 980594.835 | -113.445 |

| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 3074 | 742909.65 | 254638.64 | 664.18 | 980595.149 | -113.307 |
| 3076 | 743009.28 | 254696.45 | 665.76 | 980594.739 | -113.570 |
| 3078 | 743161.77 | 254782.45 | 664.37 | 980594.937 | -113.507 |
| 3080 | 743169.18 | 254480.70 | 613.06 | 980604.745 | -113.496 |
| 3082 | 743232.23 | 254499.41 | 610.08 | 980605.186 | -113.715 |
| 3084 | 743307.15 | 254524.87 | 601.44 | 980606.483 | -113.827 |
| 3086 | 743464.05 | 254535.53 | 585.51 | 980609.611 | -113.671 |
| 3088 | 743599.93 | 254492.12 | 567.71 | 980612.860 | -114.053 |
| 3090 | 743700.45 | 254513.16 | 565.05 | 980613.127 | -113.990 |
| 3092 | 743860.71 | 254600.54 | 567.72 | 980612.398 | -113.940 |
| 3094 | 743996.47 | 254638.24 | 564.70 | 980613.151 | -113.852 |
| 3096 | 744076.91 | 254658.92 | 563.27 | 980613.598 | -113.847 |
| 3104 | 744699.49 | 254423.07 | 666.08 | 980593.785 | -114.169 |
| 3108 | 744875.34 | 254396.06 | 690.87 | 980588.763 | -114.121 |
| 3112 | 745075.17 | 254358.58 | 728.77 | 980580.540 | -114.415 |
| 3116 | 745272.70 | 254324.85 | 710.43 | 980584.463 | -114.248 |
| 3120 | 745445.92 | 254294.71 | 678.94 | 980590.820 | -114.190 |
| 3124 | 745638.89 | 254318.63 | 670.93 | 980592.458 | -114.386 |
| 3128 | 745824.63 | 254262.09 | 670.72 | 980592.501 | -114.479 |
| 3132 | 746000.09 | 254299.00 | 673.24 | 980591.857 | -114.678 |
| 3134 | 746161.59 | 254204.65 | 675.58 | 980591.355 | -114.163 |
| 3136 | 746223.64 | 254212.68 | 676.52 | 980591.207 | -114.172 |
| 3140 | 746388.95 | 254160.94 | 706.16 | 980584.998 | -113.671 |
| 3144 | 746557.18 | 254056.85 | 747.01 | 980576.946 | -113.993 |
| 3148 | 746853.63 | 254179.05 | 753.67 | 980575.331 | -114.142 |
| 3152 | 746992.95 | 254077.48 | 774.60 | 980570.857 | -114.423 |
| 3156 | 747155.12 | 254119.33 | 777.56 | 980570.071 | -114.464 |
| 3160 | 747342.29 | 254299.46 | 774.98 | 980571.135 | -114.269 |
| 3164 | 747707.32 | 254211.62 | 804.59 | 980564.704 | -114.513 |
| 3168 | 747936.05 | 254149.32 | 832.00 | 980558.996 | -114.600 |
| 3172 | 748030.17 | 254133.68 | 841.99 | 980556.982 | -114.420 |
| 3174 | 747852.95 | 253890.75 | 898.22 | 980544.385 | -114.713 |
| 3178 | 748079.26 | 253900.25 | 892.04 | 980546.316 | -114.582 |

| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 3182 | 748275.48 | 253924.04 | 903.78 | 980543.707 | -114.705 |
| 3186 | 748522.32 | 254000.93 | 922.42 | 980539.506 | -114.443 |
| 3190 | 748633.36 | 253650.25 | 825.04 | 980559.998 | -114.673 |
| 3194 | 748928.82 | 253840.72 | 842.12 | 980556.757 | -114.662 |
| 3198 | 749171.12 | 254124.86 | 855.26 | 980554.665 | -114.413 |
| 3206 | 749246.64 | 254070.17 | 855.81 | 980554.196 | -114.642 |
| 3210 | 749468.69 | 254046.72 | 858.04 | 980553.596 | -114.623 |
| 3214 | 749658.95 | 254035.25 | 860.25 | 980552.979 | -114.672 |
| 3220 | 749839.27 | 254008.91 | 866.39 | 980551.480 | -114.895 |
| 3224 | 749985.65 | 253880.90 | 880.34 | 980548.126 | -115.102 |
| 3228 | 750205.97 | 253767.02 | 898.24 | 980544.300 | -115.039 |
| 3232 | 749967.29 | 253713.90 | 907.68 | 980542.617 | -114.931 |
| 3236 | 750336.84 | 253734.13 | 908.26 | 980542.153 | -115.074 |
| 3240 | 750468.05 | 253662.46 | 938.78 | 980535.645 | -115.184 |
| 3244 | 750647.03 | 253584.21 | 938.83 | 980535.739 | -115.335 |
| 3248 | 750831.97 | 253583.12 | 961.10 | 980530.740 | -115.377 |
| 3250 | 750936.14 | 253568.40 | 937.80 | 980535.639 | -115.524 |
| 3254 | 751175.13 | 253599.43 | 898.77 | 980543.752 | -116.063 |
| 3258 | 751425.61 | 253534.71 | 891.29 | 980545.123 | -116.190 |
| 3266 | 751861.79 | 253345.84 | 885.93 | 980545.420 | -116.606 |
| 3500 | 737379.29 | 255522.45 | 661.43 | 980601.240 | -109.337 |
| 3504 | 737555.01 | 255515.62 | 664.87 | 980600.391 | -109.425 |
| 3508 | 737685.31 | 255430.84 | 676.12 | 980598.009 | -109.489 |
| 3516 | 738057.67 | 255370.53 | 696.95 | 980593.443 | -109.797 |
| 3520 | 738205.22 | 255343.21 | 706.66 | 980591.287 | -109.992 |
| 3528 | 738470.87 | 255302.21 | 703.73 | 980591.744 | -110.006 |
| 3536 | 738697.16 | 255343.37 | 717.98 | 980588.583 | -110.266 |
| 3540 | 738867.94 | 255297.61 | 742.17 | 980583.309 | -110.433 |
| 3544 | 739039.47 | 255250.87 | 775.54 | 980576.109 | -110.764 |
| 3548 | 739222.69 | 255158.54 | 789.66 | 980573.026 | -110.873 |
| 4024 | 739445.21 | 254092.13 | 732.33 | 980582.640 | -112.198 |
| 4026 | 739649.06 | 254317.37 | 723.96 | 980584.446 | -112.217 |
| 4028 | 739689.65 | 254365.62 | 726.35 | 980584.099 | -112.081 |

| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 4030 | 739828.60 | 254524.24 | 751.97 | 980580.290 | -110.220 |
| 4032 | 739923.77 | 254441.35 | 770.83 | 980574.796 | -112.396 |
| 4034 | 740080.46 | 254625.91 | 765.28 | 980576.493 | -112.338 |
| 4036 | 740178.66 | 254560.13 | 766.91 | 980576.164 | -112.215 |
| 4038 | 740258.23 | 254451.71 | 775.52 | 980574.148 | -112.240 |
| 4040 | 740353.20 | 254418.51 | 775.53 | 980574.084 | -112.291 |
| 4042 | 740459.01 | 254361.07 | 779.49 | 980573.090 | -112.328 |
| 4044 | 740528.13 | 254302.26 | 784.62 | 980571.778 | -112.458 |
| 4046 | 740607.95 | 254248.34 | 786.96 | 980571.009 | -112.710 |
| 4048 | 740767.09 | 254179.38 | 785.08 | 980570.828 | -112.946 |
| 4050 | 740843.15 | 254213.93 | 777.42 | 980572.566 | -112.798 |
| 4052 | 740841.20 | 253940.18 | 753.94 | 980576.787 | -113.034 |
| 4054 | 740958.36 | 254025.93 | 750.23 | 980577.429 | -113.101 |
| 4056 | 741072.55 | 254110.18 | 739.08 | 980579.537 | -113.075 |
| 4058 | 741211.39 | 254275.47 | 719.53 | 980584.042 | -112.949 |
| 4060 | 741240.25 | 253850.63 | 663.99 | 980594.405 | -113.447 |
| 4062 | 741371.00 | 253831.53 | 653.11 | 980596.591 | -113.580 |
| 4064 | 741501.16 | 253894.68 | 647.20 | 980597.808 | -113.658 |
| 4066 | 741584.62 | 253907.08 | 648.79 | 980598.310 | -112.402 |
| 4068 | 741666.85 | 253989.19 | 645.67 | 980598.304 | -113.539 |
| 4070 | 741763.81 | 254023.68 | 644.61 | 980598.594 | -113.681 |
| 4072 | 741892.32 | 254055.86 | 649.25 | 980597.781 | -113.447 |
| 4074 | 742005.50 | 254068.39 | 655.40 | 980596.568 | -113.484 |
| 4076 | 742090.68 | 253992.56 | 645.85 | 980598.200 | -113.670 |
| 4078 | 742177.61 | 253927.46 | 639.41 | 980599.197 | -113.948 |
| 4080 | 742258.54 | 253866.10 | 636.76 | 980599.506 | -114.104 |
| 4082 | 742382.55 | 253811.46 | 637.26 | 980599.402 | -114.108 |
| 4084 | 742481.34 | 253745.81 | 629.22 | 980600.989 | -114.009 |
| 4088 | 742643.24 | 253710.75 | 634.36 | 980599.761 | -114.044 |
| 4098 | 742975.54 | 253848.51 | 632.91 | 980599.843 | -114.351 |
| 4100 | 743063.98 | 253891.24 | 631.45 | 980599.728 | -114.128 |
| 4104 | 743285.00 | 253621.99 | 575.96 | 980610.462 | -114.376 |
| 4106 | 743384.44 | 253529.26 | 588.38 | 980607.911 | -114.309 |

| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 4108 | 743465.02 | 253510.11 | 593.55 | 980606.737 | -114.167 |
| 4110 | 743566.79 | 253535.75 | 604.39 | 980604.686 | -114.257 |
| 4114 | 743807.09 | 253577.77 | 629.52 | 980600.078 | -114.298 |
| 4116 | 743982.93 | 253590.87 | 648.53 | 980596.429 | -114.398 |
| 4118 | 744049.29 | 253576.78 | 650.15 | 980596.146 | -114.521 |
| 4120 | 744135.30 | 253657.48 | 651.60 | 980595.978 | -114.366 |
| 4122 | 744273.60 | 253612.23 | 658.92 | 980594.485 | -114.498 |
| 4124 | 744475.61 | 253653.15 | 670.58 | 980592.296 | -114.301 |
| 4128 | 744617.26 | 253567.68 | 678.60 | 980590.502 | -114.370 |
| 4132 | 744898.36 | 253561.84 | 686.96 | 980588.719 | -114.511 |
| 4136 | 745036.50 | 253507.44 | 676.94 | 980590.504 | -114.306 |
| 4140 | 745352.00 | 253562.00 | 695.58 | 980586.616 | -114.394 |
| 4146 | 745359.87 | 253406.85 | 725.22 | 980580.387 | -114.413 |
| 4150 | 745640.95 | 253396.06 | 787.71 | 980567.577 | -114.309 |
| 4158 | 746021.39 | 253321.70 | 758.83 | 980573.242 | -114.611 |
| 4162 | 746258.73 | 253375.71 | 757.85 | 980573.764 | -114.612 |
| 4166 | 746548.86 | 253161.32 | 804.74 | 980563.980 | -114.779 |
| 4170 | 746643.23 | 253191.71 | 803.58 | 980564.286 | -114.605 |
| 4174 | 746765.92 | 253226.26 | 800.52 | 980564.931 | -114.720 |
| 4178 | 746865.81 | 253233.41 | 794.14 | 980566.177 | -114.686 |
| 4182 | 747032.08 | 253238.97 | 817.03 | 980561.379 | -114.869 |
| 4186 | 747199.04 | 253167.27 | 828.99 | 980558.970 | -114.919 |
| 4190 | 747406.32 | 253082.84 | 842.97 | 980556.205 | -114.710 |
| 4194 | 747612.60 | 252943.28 | 845.10 | 980555.392 | -115.032 |
| 4198 | 747737.09 | 252877.57 | 863.17 | 980551.719 | -115.140 |
| 4200 | 747895.34 | 252847.22 | 880.20 | 980548.116 | -115.123 |
| 4202 | 747990.36 | 253183.91 | 833.62 | 980557.898 | -114.877 |
| 4206 | 748066.92 | 253277.57 | 819.12 | 980560.932 | -114.752 |
| 4210 | 748184.73 | 253219.75 | 850.02 | 980554.815 | -114.762 |
| 4214 | 748323.75 | 253098.79 | 878.38 | 980548.814 | -115.112 |
| 4218 | 748533.26 | 253118.71 | 897.32 | 980544.890 | -114.964 |
| 4222 | 748721.31 | 253097.84 | 915.33 | 980540.931 | -115.106 |
| 4226 | 748989.88 | 253095.68 | 929.37 | 980538.064 | -115.168 |

| Name | X         | Y         | Z       | Raw        | AB       |
|------|-----------|-----------|---------|------------|----------|
| 4230 | 749104.72 | 253105.57 | 931.72  | 980537.499 | -115.212 |
| 4232 | 749149.12 | 252992.28 | 930.33  | 980537.504 | -115.446 |
| 4236 | 749348.34 | 252831.66 | 945.42  | 980533.794 | -115.755 |
| 4240 | 749457.88 | 252772.00 | 947.80  | 980533.194 | -115.877 |
| 4244 | 749611.53 | 252591.30 | 962.20  | 980529.692 | -115.982 |
| 4248 | 749753.19 | 252474.40 | 985.09  | 980524.517 | -116.289 |
| 4256 | 750259.48 | 252676.72 | 1017.61 | 980517.194 | -116.207 |
| 4260 | 750400.82 | 252673.45 | 1004.28 | 980519.902 | -116.558 |
| 4264 | 750573.33 | 252718.30 | 998.22  | 980521.407 | -116.487 |
| 4270 | 750795.06 | 252523.04 | 945.87  | 980532.622 | -116.898 |
| 4274 | 750976.74 | 252538.75 | 944.35  | 980532.968 | -117.059 |
| 4278 | 751138.07 | 252487.80 | 922.49  | 980537.208 | -116.734 |
| 4282 | 751301.78 | 252597.05 | 916.35  | 980538.654 | -116.996 |
| 4286 | 751463.98 | 252373.76 | 955.82  | 980530.016 | -117.333 |
| 4290 | 751634.50 | 252442.09 | 953.91  | 980530.403 | -117.032 |
| 4294 | 751834.69 | 252461.58 | 939.25  | 980533.461 | -117.008 |
| 4500 | 737363.27 | 254873.07 | 681.59  | 980595.979 | -110.100 |
| 4504 | 737609.92 | 254589.22 | 692.92  | 980593.230 | -110.126 |
| 4508 | 737853.33 | 254833.46 | 712.12  | 980589.415 | -110.293 |
| 4512 | 737968.80 | 254747.07 | 711.06  | 980589.504 | -110.435 |
| 4516 | 738141.89 | 254791.30 | 696.27  | 980592.633 | -110.305 |
| 4520 | 738329.21 | 254801.43 | 693.21  | 980593.106 | -110.433 |
| 4524 | 738515.02 | 254685.11 | 700.09  | 980591.463 | -110.481 |
| 4528 | 738747.49 | 254549.24 | 710.53  | 980588.923 | -110.975 |
| 4532 | 738951.57 | 254466.98 | 720.90  | 980586.470 | -111.212 |
| 4536 | 739154.62 | 254400.53 | 729.44  | 980584.420 | -111.462 |
| 4540 | 739274.42 | 254477.75 | 737.66  | 980582.798 | -111.476 |
| 5500 | 737311.89 | 254412.28 | 678.94  | 980595.901 | -109.993 |
| 5504 | 737478.73 | 254457.90 | 685.06  | 980594.686 | -110.229 |
| 5508 | 737688.35 | 254420.88 | 696.83  | 980592.124 | -110.398 |
| 5512 | 737857.27 | 253960.75 | 688.48  | 980592.824 | -110.926 |
| 5516 | 738028.27 | 253939.23 | 675.70  | 980595.331 | -111.029 |
| 5520 | 738239.87 | 253772.05 | 680.42  | 980593.745 | -111.490 |

| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 5528 | 738744.63 | 253787.12 | 711.60 | 980587.183 | -111.409 |
| 5532 | 738872.15 | 253972.06 | 725.18 | 980584.433 | -111.945 |
| 5536 | 738891.64 | 254036.89 | 726.34 | 980584.372 | -111.763 |
| 5538 | 739078.29 | 254158.74 | 726.21 | 980584.778 | -111.564 |
| 5540 | 739204.83 | 254256.80 | 729.23 | 980584.202 | -111.557 |
| 5542 | 739345.47 | 254325.24 | 727.60 | 980584.515 | -111.628 |
| 5544 | 739234.31 | 253538.48 | 724.45 | 980583.410 | -112.514 |
| 5548 | 739499.60 | 253739.05 | 739.75 | 980580.492 | -112.778 |
| 5552 | 739682.58 | 253907.60 | 741.85 | 980580.463 | -112.459 |
| 5556 | 739877.43 | 254056.01 | 751.36 | 980578.781 | -112.270 |
| 5560 | 740015.74 | 253925.60 | 761.49 | 980576.443 | -112.449 |
| 5564 | 740188.23 | 253743.55 | 760.32 | 980575.908 | -112.792 |
| 5568 | 740360.97 | 253578.75 | 740.43 | 980579.339 | -113.124 |
| 5576 | 740935.13 | 253444.79 | 665.88 | 980593.591 | -113.464 |
| 5580 | 741121.77 | 253621.15 | 660.54 | 980594.843 | -113.523 |
| 5584 | 741243.99 | 253371.52 | 634.44 | 980599.430 | -114.174 |
| 5588 | 741387.86 | 253213.64 | 635.47 | 980599.157 | -114.006 |
| 5592 | 741561.23 | 253315.38 | 633.73 | 980599.535 | -114.144 |
| 5596 | 741734.82 | 253415.82 | 633.99 | 980599.413 | -114.350 |
| 5604 | 742119.15 | 253519.77 | 637.11 | 980599.148 | -114.081 |
| 5608 | 742324.81 | 253461.89 | 646.69 | 980596.753 | -114.312 |
| 5612 | 742392.32 | 253154.94 | 581.19 | 980609.249 | -114.232 |
| 5616 | 742720.70 | 253276.42 | 584.77 | 980608.570 | -114.293 |
| 5620 | 742853.95 | 253290.46 | 584.75 | 980608.536 | -114.315 |
| 5624 | 743100.47 | 253390.89 | 588.46 | 980607.800 | -114.393 |
| 5628 | 743352.76 | 253522.13 | 589.31 | 980607.830 | -114.299 |
| 5632 | 743383.95 | 253190.95 | 633.65 | 980599.022 | -114.347 |
| 5636 | 743531.46 | 253089.82 | 634.07 | 980598.607 | -114.588 |
| 5640 | 743730.70 | 253095.28 | 636.87 | 980598.112 | -114.381 |
| 5644 | 743885.12 | 253095.49 | 649.86 | 980595.374 | -114.373 |
| 5648 | 744202.88 | 253084.17 | 674.07 | 980590.438 | -114.338 |
| 5652 | 744431.20 | 253145.93 | 683.26 | 980588.608 | -114.372 |
| 5656 | 744570.91 | 253087.91 | 698.87 | 980585.168 | -114.384 |

| Name | X         | Y         | Z      | Raw        | AB       |
|------|-----------|-----------|--------|------------|----------|
| 5660 | 744779.33 | 253108.19 | 716.01 | 980581.538 | -114.430 |
| 5664 | 744841.17 | 252959.72 | 767.17 | 980570.937 | -114.316 |
| 5668 | 744957.06 | 253042.55 | 760.09 | 980572.516 | -114.443 |
| 5672 | 745137.30 | 253004.98 | 770.58 | 980570.829 | -114.584 |
| 5676 | 745139.99 | 252776.12 | 787.12 | 980567.396 | -114.798 |
| 5680 | 745258.06 | 252742.79 | 782.99 | 980568.236 | -114.759 |
| 5684 | 745377.89 | 252692.47 | 783.08 | 980568.079 | -114.742 |
| 5688 | 745517.50 | 252796.11 | 746.57 | 980575.478 | -114.737 |
| 5698 | 746262.25 | 252733.33 | 843.19 | 980555.287 | -114.921 |
| 5702 | 746463.42 | 252702.68 | 828.55 | 980558.714 | -115.043 |
| 5706 | 746672.54 | 252734.33 | 827.28 | 980559.018 | -114.987 |
| 5710 | 746843.11 | 252570.91 | 875.02 | 980548.698 | -114.981 |
| 5714 | 746996.34 | 252516.04 | 888.72 | 980545.854 | -115.065 |
| 5718 | 747237.94 | 252590.41 | 900.03 | 980543.783 | -114.867 |
| 5722 | 747466.86 | 252589.87 | 918.08 | 980539.707 | -115.021 |
| 5726 | 747663.89 | 252499.26 | 921.00 | 980539.109 | -115.457 |
| 5734 | 748159.18 | 252589.86 | 885.33 | 980546.313 | -115.542 |
| 5738 | 748308.14 | 252588.20 | 904.80 | 980542.299 | -115.494 |
| 5742 | 748428.16 | 252462.61 | 916.16 | 980539.699 | -115.908 |
| 5746 | 748582.41 | 252512.26 | 912.34 | 980540.350 | -115.826 |
| 5750 | 748761.71 | 252619.91 | 917.58 | 980539.466 | -115.768 |
| 5758 | 748891.07 | 252118.52 | 984.98 | 980524.154 | -116.291 |
| 5762 | 748979.36 | 252001.94 | 965.37 | 980527.453 | -116.633 |
| 5764 | 749116.07 | 252069.43 | 941.72 | 980532.686 | -116.570 |
| 5766 | 749207.94 | 252026.24 | 929.11 | 980535.156 | -116.840 |
| 5770 | 749412.93 | 251922.38 | 914.55 | 980538.342 | -117.282 |
| 5774 | 749611.42 | 251966.79 | 896.58 | 980541.961 | -117.167 |
| 5778 | 749920.49 | 252048.78 | 901.51 | 980540.979 | -117.171 |
| 5782 | 750031.84 | 252011.99 | 903.42 | 980540.627 | -117.202 |
| 5786 | 750252.42 | 252147.51 | 907.43 | 980539.910 | -117.145 |
| 5792 | 750510.49 | 252062.17 | 913.67 | 980538.682 | -116.931 |
| 5798 | 750777.74 | 252059.81 | 914.69 | 980538.273 | -117.326 |
| 5808 | 751305.59 | 252209.66 | 952.28 | 980530.746 | -117.129 |

| Name  | X         | Y         | Z      | Raw        | AB       |
|-------|-----------|-----------|--------|------------|----------|
| 35500 | 740796.52 | 256945.06 | 837.54 | 980564.894 | -110.495 |
| 35504 | 740924.76 | 256766.33 | 805.54 | 980571.396 | -110.738 |
| 35508 | 740807.60 | 256588.60 | 796.26 | 980573.099 | -110.726 |
| 35512 | 740808.87 | 256383.46 | 790.05 | 980574.030 | -110.928 |
| 35514 | 740780.12 | 256166.83 | 788.33 | 980573.959 | -111.181 |
| 35516 | 740868.94 | 255999.83 | 793.62 | 980572.663 | -111.310 |
| 35520 | 740891.86 | 255855.58 | 800.38 | 980570.968 | -111.290 |
| 35524 | 740998.00 | 255651.06 | 819.30 | 980566.491 | -111.649 |
| 35528 | 740930.77 | 255463.95 | 815.61 | 980566.940 | -111.812 |
| 35532 | 740911.01 | 255216.35 | 828.90 | 980563.665 | -111.880 |
| 35534 | 740889.58 | 255095.83 | 816.41 | 980566.242 | -112.001 |
| 35538 | 740779.48 | 254687.49 | 777.31 | 980573.933 | -112.277 |
| 35542 | 740718.17 | 254494.98 | 771.71 | 980574.849 | -112.298 |
| 35546 | 740789.19 | 254295.90 | 777.80 | 980572.920 | -112.635 |
| 35550 | 740814.05 | 254045.10 | 767.16 | 980574.244 | -113.048 |
| 35554 | 740789.01 | 253809.01 | 747.33 | 980577.999 | -113.017 |
| 35558 | 740658.97 | 253609.95 | 731.45 | 980581.059 | -113.147 |
| 35562 | 740619.92 | 253439.81 | 712.19 | 980584.803 | -113.200 |
| 35566 | 740511.88 | 253290.35 | 691.19 | 980588.717 | -113.285 |
| 35570 | 740470.80 | 253053.32 | 659.32 | 980594.802 | -113.696 |
| 35574 | 740537.98 | 252822.20 | 648.60 | 980596.281 | -114.372 |
| 35578 | 740716.60 | 252618.39 | 650.10 | 980595.339 | -114.745 |
| 35580 | 740599.41 | 252588.22 | 650.80 | 980595.246 | -114.839 |
| 35582 | 740698.53 | 252335.13 | 653.22 | 980594.566 | -114.744 |
| 37504 | 741608.73 | 256895.25 | 835.31 | 980564.830 | -110.957 |
| 37508 | 741586.55 | 256688.60 | 838.05 | 980563.968 | -110.814 |
| 37512 | 741687.38 | 256553.24 | 847.03 | 980561.758 | -111.423 |
| 37516 | 741658.16 | 256430.08 | 846.33 | 980561.745 | -111.292 |
| 37520 | 741740.85 | 256228.84 | 852.85 | 980559.914 | -111.530 |
| 37524 | 741788.42 | 256093.04 | 857.93 | 980558.377 | -111.698 |
| 37528 | 741780.91 | 255888.40 | 866.00 | 980556.334 | -111.777 |
| 37530 | 741819.45 | 255742.93 | 869.90 | 980554.998 | -111.961 |
| 37536 | 741885.27 | 255377.51 | 867.80 | 980553.987 | -112.569 |

| Name  | X         | Y         | Z      | Raw        | AB       |
|-------|-----------|-----------|--------|------------|----------|
| 37544 | 741767.70 | 254978.35 | 767.91 | 980574.480 | -112.471 |
| 37548 | 741719.48 | 254708.11 | 707.26 | 980586.733 | -112.732 |
| 37552 | 741774.41 | 254560.45 | 680.41 | 980592.040 | -112.986 |
| 37558 | 741811.41 | 254402.40 | 663.99 | 980595.153 | -113.287 |
| 37560 | 741739.23 | 254165.27 | 648.26 | 980597.921 | -113.357 |
| 37564 | 741795.09 | 253919.01 | 642.42 | 980598.835 | -113.656 |
| 37568 | 741839.78 | 253782.11 | 638.66 | 980598.930 | -114.236 |
| 37572 | 741895.74 | 253609.83 | 633.86 | 980599.593 | -114.463 |
| 37574 | 741949.80 | 253451.83 | 635.33 | 980599.410 | -114.298 |
| 37576 | 741984.08 | 253360.95 | 641.00 | 980598.228 | -114.078 |
| 37580 | 742088.33 | 253208.45 | 621.81 | 980601.654 | -114.232 |
| 37584 | 742142.54 | 252983.27 | 591.44 | 980606.644 | -114.414 |
| 37586 | 742081.97 | 252870.62 | 587.17 | 980607.322 | -114.443 |
| 37590 | 742114.59 | 252736.97 | 585.53 | 980607.753 | -114.126 |
| 37594 | 742129.49 | 252645.39 | 588.81 | 980606.923 | -114.490 |
| 37598 | 742236.98 | 252502.25 | 600.04 | 980604.630 | -114.547 |
| 40500 | 743090.20 | 257213.41 | 751.20 | 980581.997 | -110.922 |
| 40504 | 743177.76 | 256923.42 | 735.61 | 980584.725 | -111.556 |
| 40508 | 743268.31 | 256740.02 | 736.99 | 980583.665 | -112.064 |
| 40512 | 743054.94 | 256653.66 | 709.32 | 980589.372 | -111.980 |
| 40516 | 742870.55 | 256486.02 | 709.43 | 980589.257 | -111.846 |
| 40520 | 742842.05 | 256297.87 | 723.36 | 980586.077 | -112.007 |
| 40524 | 742887.24 | 256156.98 | 735.96 | 980583.431 | -112.035 |
| 40528 | 742807.15 | 255851.85 | 752.98 | 980579.641 | -112.193 |
| 40532 | 742819.77 | 255691.90 | 759.84 | 980577.828 | -112.349 |
| 40536 | 742863.54 | 255567.67 | 745.66 | 980580.454 | -112.554 |
| 40540 | 743072.92 | 255360.00 | 724.84 | 980584.218 | -112.981 |
| 40544 | 743046.38 | 255187.89 | 720.12 | 980584.816 | -113.141 |
| 40548 | 743009.50 | 254992.20 | 708.78 | 980586.721 | -113.147 |
| 40552 | 742863.21 | 254861.28 | 690.73 | 980590.128 | -113.145 |
| 40556 | 742764.19 | 254783.36 | 680.18 | 980592.325 | -113.222 |
| 40560 | 742711.70 | 254652.71 | 670.67 | 980594.157 | -113.381 |
| 40564 | 742606.87 | 254270.10 | 640.40 | 980599.672 | -113.467 |

| Name  | X         | Y         | Z      | Raw        | AB       |
|-------|-----------|-----------|--------|------------|----------|
| 40568 | 742554.54 | 254192.04 | 638.63 | 980599.760 | -113.657 |
| 40572 | 742494.77 | 253992.57 | 646.78 | 980598.065 | -113.624 |
| 40576 | 742504.87 | 253848.30 | 637.78 | 980599.397 | -114.002 |
| 40580 | 742579.58 | 253677.28 | 636.09 | 980599.522 | -113.941 |
| 40584 | 742463.99 | 253535.27 | 651.16 | 980595.660 | -113.934 |
| 40588 | 742312.04 | 253303.83 | 599.34 | 980605.619 | -114.354 |
| 40592 | 742261.02 | 253168.90 | 593.19 | 980606.840 | -114.310 |
| 40596 | 742359.61 | 253048.82 | 586.36 | 980608.168 | -114.384 |
| 40600 | 742554.15 | 252976.69 | 579.75 | 980609.228 | -114.322 |
| 40604 | 742462.54 | 252745.22 | 581.19 | 980608.589 | -114.454 |

## Appendix C

### Eclépens gravity measurements

This appendix includes all the gravity measurements used in chapter 5. X, Y, and Z value are in CH 1903, the uncertainty is considered to be  $\pm 0.02$  m in all directions. Raw values are reported to the Swiss Atlas of Gravity values (Olivier et al., 2010) using the base of second order of La Sarraz, localized here below and the considered uncertainty on measurement is  $\pm 0.01$  mGal. The Bouguer Anomaly is computed for a mean density of  $2670 \text{ kg}\cdot\text{m}^{-3}$  and its considered uncertainty is  $\pm 0.1$  mGal.

**Base station:**

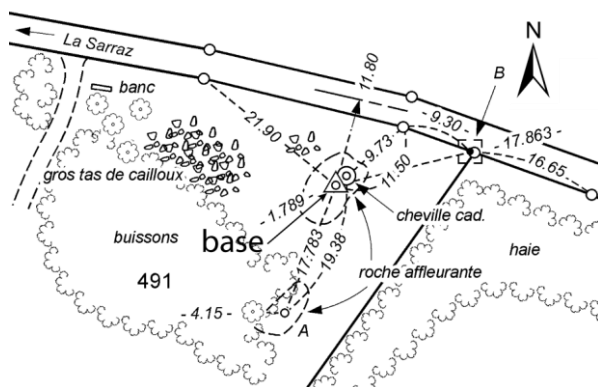
La Sarraz station:

X: 530'238.421

Y: 167'167.010

Z: 535.82

g: 980595.596 mGal



| Name | X         | Y         | Z      | Raw        | AB      |
|------|-----------|-----------|--------|------------|---------|
| 3500 | 528306.78 | 170743.96 | 554.24 | 980593.152 | -67.596 |
| 3504 | 528503.00 | 170772.94 | 551.20 | 980593.481 | -67.961 |
| 3508 | 528743.75 | 170713.39 | 549.08 | 980593.730 | -68.148 |
| 3512 | 528895.43 | 170695.68 | 550.05 | 980593.491 | -68.192 |
| 3516 | 529103.70 | 170572.54 | 535.13 | 980596.230 | -68.264 |
| 3518 | 529178.14 | 170595.55 | 532.60 | 980596.708 | -68.362 |
| 3524 | 529352.51 | 170584.34 | 535.08 | 980595.937 | -68.486 |
| 3528 | 529700.66 | 170402.73 | 530.20 | 980596.284 | -68.703 |
| 3530 | 529696.92 | 170239.73 | 528.09 | 980596.976 | -68.543 |
| 3532 | 529853.17 | 170159.72 | 510.49 | 980600.440 | -68.655 |
| 3536 | 530010.60 | 170193.84 | 496.80 | 980603.006 | -68.798 |
| 3540 | 530311.87 | 170090.81 | 484.47 | 980605.041 | -69.085 |
| 3542 | 530365.08 | 170057.51 | 484.06 | 980605.181 | -69.115 |
| 3544 | 530526.43 | 170133.03 | 477.48 | 980606.392 | -69.256 |
| 3548 | 530714.72 | 170106.77 | 451.84 | 980611.234 | -69.327 |
| 3552 | 530858.95 | 169956.48 | 448.38 | 980611.775 | -69.472 |
| 3556 | 531065.08 | 169898.24 | 447.84 | 980611.645 | -69.752 |
| 3559 | 531192.16 | 169855.64 | 447.83 | 980611.170 | -70.225 |
| 3562 | 531316.13 | 169824.78 | 445.76 | 980611.286 | -70.505 |
| 3566 | 531660.41 | 169997.35 | 440.88 | 980611.406 | -71.471 |
| 3570 | 531862.68 | 169940.18 | 439.84 | 980611.475 | -71.565 |
| 3572 | 531848.18 | 169686.88 | 439.23 | 980611.684 | -71.261 |
| 3574 | 531771.82 | 169383.38 | 439.42 | 980611.986 | -70.665 |
| 3578 | 531957.31 | 169283.03 | 438.64 | 980612.429 | -70.249 |
| 3582 | 532214.96 | 169280.05 | 441.99 | 980611.890 | -70.138 |
| 3584 | 532319.98 | 169640.03 | 439.80 | 980612.094 | -70.587 |
| 3588 | 532423.06 | 169311.30 | 440.97 | 980611.748 | -70.422 |
| 3592 | 532623.92 | 169239.18 | 445.18 | 980610.758 | -70.434 |
| 3596 | 532833.31 | 169181.00 | 467.06 | 980606.273 | -70.451 |
| 3600 | 533023.00 | 169128.53 | 488.61 | 980601.816 | -70.550 |
| 3604 | 533206.23 | 169172.76 | 536.32 | 980592.197 | -70.836 |
| 3606 | 533268.41 | 169141.72 | 538.92 | 980591.868 | -70.830 |
| 3610 | 533436.79 | 169092.63 | 546.49 | 980590.339 | -70.875 |

| Name | X         | Y         | Z      | Raw        | AB      |
|------|-----------|-----------|--------|------------|---------|
| 3614 | 533689.61 | 169314.79 | 593.40 | 980580.109 | -71.467 |
| 3618 | 533783.30 | 169043.47 | 594.01 | 980580.586 | -71.079 |
| 3622 | 533960.42 | 168828.21 | 595.43 | 980580.496 | -71.025 |
| 3626 | 534217.69 | 168962.84 | 590.64 | 980581.472 | -71.195 |
| 3630 | 534400.94 | 168936.12 | 585.60 | 980582.325 | -71.391 |
| 3634 | 534613.91 | 168936.73 | 576.23 | 980584.028 | -71.404 |
| 3638 | 534771.40 | 168683.89 | 557.82 | 980587.318 | -71.308 |
| 3642 | 534906.39 | 168608.24 | 583.27 | 980582.406 | -71.504 |
| 3646 | 535134.84 | 168682.36 | 589.73 | 980581.039 | -71.695 |
| 3650 | 535357.26 | 168702.60 | 605.08 | 980577.542 | -72.142 |
| 3654 | 535493.19 | 168602.63 | 614.04 | 980575.434 | -72.426 |
| 3658 | 535664.05 | 168476.20 | 611.45 | 980575.685 | -72.697 |
| 3662 | 535790.68 | 168597.04 | 611.09 | 980575.583 | -72.931 |
| 3666 | 535939.03 | 168537.02 | 608.26 | 980575.808 | -73.212 |
| 3670 | 536300.67 | 168390.95 | 626.32 | 980571.740 | -73.553 |
| 3674 | 536403.74 | 168268.45 | 633.35 | 980570.117 | -73.690 |
| 3678 | 536566.51 | 168161.00 | 631.83 | 980570.164 | -73.845 |
| 6502 | 526199.99 | 167639.99 | 572.21 | 980589.826 | -64.630 |
| 6504 | 526288.82 | 167477.18 | 585.50 | 980587.035 | -64.729 |
| 6508 | 526435.19 | 167427.85 | 565.86 | 980590.707 | -64.773 |
| 6512 | 526745.85 | 167743.53 | 562.92 | 980591.487 | -64.936 |
| 6516 | 526979.04 | 167646.96 | 545.33 | 980594.752 | -65.002 |
| 6520 | 527019.14 | 167215.36 | 579.34 | 980587.858 | -65.024 |
| 6526 | 527164.82 | 166921.97 | 557.19 | 980592.136 | -64.961 |
| 6530 | 527498.90 | 167094.97 | 545.62 | 980594.302 | -65.203 |
| 6534 | 527595.12 | 166803.68 | 509.66 | 980600.988 | -64.948 |
| 6538 | 527779.79 | 166759.59 | 562.01 | 980590.523 | -65.369 |
| 6540 | 527988.64 | 166948.56 | 551.15 | 980592.950 | -65.432 |
| 6542 | 528101.22 | 167033.78 | 540.58 | 980594.982 | -65.560 |
| 6546 | 528353.94 | 167130.52 | 511.96 | 980600.586 | -65.626 |
| 6550 | 528664.55 | 167158.01 | 477.68 | 980607.231 | -65.669 |
| 6552 | 528692.06 | 167056.84 | 479.58 | 980606.780 | -65.678 |
| 6554 | 528524.53 | 166780.20 | 506.10 | 980601.608 | -65.552 |

| Name  | X         | Y         | Z      | Raw        | AB      |
|-------|-----------|-----------|--------|------------|---------|
| 6558  | 528952.00 | 166966.69 | 466.79 | 980609.139 | -65.897 |
| 6562  | 529089.40 | 166677.57 | 483.55 | 980605.756 | -65.862 |
| 6566  | 529173.71 | 166654.15 | 479.06 | 980606.588 | -65.914 |
| 6570  | 529338.76 | 166608.46 | 473.68 | 980607.519 | -65.943 |
| 6574  | 529525.15 | 166545.28 | 478.82 | 980606.394 | -66.024 |
| 6578  | 529713.47 | 166507.22 | 482.23 | 980605.577 | -66.169 |
| 6580  | 529880.52 | 166459.46 | 484.21 | 980605.156 | -66.210 |
| 6582  | 530036.32 | 166413.92 | 481.99 | 980605.619 | -66.185 |
| 6586  | 530208.44 | 166248.87 | 498.86 | 980602.176 | -66.269 |
| 6590  | 530454.39 | 166164.81 | 505.11 | 980600.749 | -66.365 |
| 6594  | 530620.85 | 166106.91 | 493.72 | 980603.036 | -66.349 |
| 6598  | 530859.56 | 166379.72 | 460.26 | 980609.504 | -66.507 |
| 6602  | 531024.11 | 166315.70 | 460.40 | 980609.336 | -66.651 |
| 6606  | 531297.47 | 166287.23 | 451.64 | 980610.740 | -66.892 |
| 6610  | 531394.00 | 166039.37 | 446.61 | 980611.312 | -67.102 |
| 6614  | 531700.62 | 166313.91 | 445.96 | 980610.456 | -68.267 |
| 6618  | 531773.06 | 165930.21 | 444.75 | 980610.505 | -67.873 |
| 6620  | 531842.05 | 165896.85 | 445.62 | 980610.230 | -67.769 |
| 6622  | 532026.16 | 166279.71 | 455.57 | 980608.568 | -67.761 |
| 6624  | 532082.63 | 165871.93 | 489.30 | 980601.612 | -67.368 |
| 6626  | 532335.87 | 166231.72 | 542.62 | 980590.853 | -67.951 |
| 6630  | 532411.78 | 165780.93 | 590.44 | 980581.582 | -67.701 |
| 6634  | 532634.42 | 166102.86 | 601.55 | 980579.355 | -68.156 |
| 6636  | 532763.23 | 166055.50 | 600.31 | 980579.881 | -68.147 |
| 6640  | 532873.07 | 165698.29 | 579.48 | 980584.223 | -67.980 |
| 6644  | 533011.77 | 165505.54 | 581.92 | 980583.714 | -67.910 |
| 6648  | 533182.25 | 165448.08 | 579.90 | 980584.003 | -68.066 |
| 6652  | 533357.22 | 165368.36 | 573.73 | 980585.100 | -68.136 |
| 6656  | 533729.82 | 165756.32 | 579.94 | 980583.433 | -68.944 |
| 6660  | 533851.74 | 165593.96 | 583.58 | 980582.488 | -69.047 |
| 6664  | 534000.03 | 165245.51 | 578.74 | 980583.288 | -68.979 |
| 6668  | 534161.10 | 165188.35 | 580.62 | 980582.729 | -69.067 |
| 13500 | 529810.16 | 165705.54 | 517.43 | 980598.602 | -65.753 |

| Name  | X         | Y         | Z      | Raw        | AB      |
|-------|-----------|-----------|--------|------------|---------|
| 13504 | 529895.18 | 165878.47 | 514.28 | 980599.206 | -65.923 |
| 13508 | 529928.74 | 166035.97 | 512.31 | 980599.599 | -66.060 |
| 13512 | 530000.28 | 166287.09 | 495.47 | 980602.944 | -66.170 |
| 13516 | 530044.05 | 166456.25 | 476.76 | 980606.678 | -66.190 |
| 13520 | 530080.63 | 166635.82 | 461.12 | 980609.744 | -66.289 |
| 13524 | 530134.65 | 166860.75 | 454.53 | 980610.814 | -66.654 |
| 13528 | 530193.20 | 167056.93 | 455.01 | 980610.805 | -66.656 |
| 13532 | 530229.07 | 167313.08 | 471.39 | 980607.522 | -66.655 |
| 13533 | 530117.72 | 167223.10 | 462.06 | 980609.551 | -66.616 |
| 13534 | 530333.45 | 167337.29 | 481.57 | 980605.021 | -66.591 |
| 13538 | 530482.36 | 167516.85 | 560.24 | 980589.966 | -66.475 |
| 13546 | 530462.46 | 167904.23 | 536.79 | 980594.808 | -66.816 |
| 13550 | 530530.35 | 168069.66 | 462.18 | 980608.886 | -67.148 |
| 13554 | 530550.79 | 168314.93 | 496.27 | 980602.367 | -67.762 |
| 13558 | 530636.40 | 168468.72 | 500.34 | 980601.469 | -67.980 |
| 13562 | 530691.86 | 168640.25 | 501.97 | 980601.100 | -68.184 |
| 13566 | 530789.08 | 168821.74 | 492.16 | 980602.964 | -68.481 |
| 13570 | 530968.22 | 169003.27 | 449.14 | 980611.231 | -68.923 |
| 13574 | 530985.60 | 169229.49 | 456.41 | 980609.882 | -69.107 |
| 13578 | 530965.14 | 169408.92 | 455.08 | 980610.272 | -69.269 |
| 13582 | 531077.95 | 169626.03 | 449.05 | 980611.318 | -69.674 |
| 13586 | 531150.30 | 169769.75 | 448.36 | 980611.260 | -69.969 |
| 13590 | 531227.85 | 169970.37 | 446.32 | 980611.361 | -70.425 |
| 13594 | 531288.67 | 170181.01 | 443.43 | 980611.719 | -70.756 |
| 13596 | 531305.96 | 170247.15 | 442.63 | 980611.747 | -70.972 |
| 13600 | 531371.70 | 170465.35 | 440.30 | 980611.879 | -71.450 |
| 16500 | 533138.33 | 163563.81 | 550.04 | 980589.265 | -67.140 |
| 16504 | 533192.93 | 163764.62 | 556.38 | 980588.082 | -67.250 |
| 16508 | 533239.56 | 163931.60 | 561.39 | 980587.143 | -67.359 |
| 16512 | 533374.07 | 164140.80 | 564.12 | 980586.526 | -67.640 |
| 16516 | 533423.06 | 164297.28 | 570.25 | 980585.343 | -67.720 |
| 16520 | 533401.02 | 164543.45 | 563.68 | 980586.876 | -67.702 |
| 16524 | 533450.57 | 164774.61 | 566.99 | 980586.200 | -67.944 |

| Name  | X         | Y         | Z      | Raw        | AB      |
|-------|-----------|-----------|--------|------------|---------|
| 16526 | 533585.77 | 164758.17 | 571.90 | 980585.008 | -68.152 |
| 16530 | 533163.19 | 164948.14 | 565.20 | 980586.909 | -67.671 |
| 16534 | 533055.69 | 165171.69 | 576.44 | 980584.757 | -67.748 |
| 16538 | 533105.42 | 165363.66 | 580.06 | 980584.054 | -67.869 |
| 16542 | 533160.74 | 165541.10 | 582.61 | 980583.411 | -68.114 |
| 16546 | 533243.07 | 165757.11 | 590.62 | 980581.712 | -68.384 |
| 16550 | 533355.27 | 165971.11 | 593.41 | 980581.087 | -68.643 |
| 16554 | 533404.95 | 166164.17 | 599.18 | 980579.886 | -68.828 |
| 16556 | 533274.97 | 166205.00 | 606.05 | 980578.459 | -68.780 |
| 16560 | 533199.71 | 166358.53 | 595.09 | 980580.744 | -68.866 |
| 16564 | 533148.45 | 166603.23 | 587.26 | 980582.120 | -69.208 |
| 16568 | 533173.53 | 166777.53 | 576.45 | 980584.287 | -69.296 |
| 16572 | 533311.59 | 166973.46 | 596.79 | 980579.807 | -69.709 |
| 16576 | 533360.23 | 167144.23 | 599.05 | 980579.324 | -69.861 |
| 16580 | 533451.95 | 167364.57 | 601.72 | 980578.922 | -69.992 |
| 16584 | 533405.59 | 167588.90 | 592.41 | 980580.883 | -70.023 |
| 16588 | 533249.40 | 167786.61 | 588.07 | 980581.602 | -70.024 |
| 16592 | 533325.79 | 167930.78 | 590.76 | 980581.246 | -70.063 |
| 16597 | 533344.22 | 168163.70 | 558.95 | 980587.632 | -69.993 |
| 16598 | 533037.77 | 168261.40 | 516.28 | 980597.139 | -69.388 |
| 16600 | 533172.69 | 168382.55 | 521.11 | 980596.046 | -69.601 |
| 16602 | 533273.76 | 168453.50 | 518.59 | 980596.283 | -69.640 |
| 16604 | 533265.47 | 168505.63 | 523.47 | 980595.167 | -69.766 |
| 16608 | 533197.21 | 168624.45 | 527.34 | 980594.281 | -69.931 |
| 16612 | 533227.17 | 168992.78 | 541.60 | 980591.280 | -70.625 |
| 16620 | 533276.56 | 169350.81 | 524.47 | 980594.677 | -71.024 |
| 16624 | 533288.88 | 169572.38 | 515.25 | 980596.186 | -71.224 |
| 16628 | 533285.98 | 169805.02 | 515.77 | 980596.269 | -71.442 |
| 16632 | 533371.91 | 169950.32 | 512.34 | 980596.965 | -71.673 |
| 16635 | 533332.97 | 170086.97 | 516.77 | 980596.037 | -71.763 |
| 16636 | 533261.45 | 170147.72 | 509.44 | 980597.452 | -71.760 |
| 16638 | 533245.33 | 170391.48 | 483.41 | 980602.799 | -71.829 |
| 16642 | 533253.43 | 170565.66 | 473.11 | 980604.829 | -72.029 |

| Name  | X         | Y         | Z      | Raw        | AB      |
|-------|-----------|-----------|--------|------------|---------|
| 16646 | 533264.11 | 170762.20 | 455.18 | 980608.439 | -72.137 |
| 16650 | 533215.38 | 170974.92 | 448.45 | 980609.939 | -72.153 |
| 16654 | 533275.24 | 171162.94 | 449.83 | 980609.696 | -72.254 |
| 16658 | 533304.89 | 171337.79 | 451.02 | 980609.536 | -72.371 |
| 16662 | 533295.05 | 171561.49 | 451.31 | 980609.636 | -72.405 |
| 16666 | 533280.90 | 171746.99 | 450.24 | 980609.976 | -72.452 |
| 16670 | 533276.89 | 171946.56 | 448.52 | 980610.450 | -72.518 |
| 16674 | 533334.35 | 172210.90 | 446.47 | 980611.046 | -72.528 |
| 16678 | 533261.98 | 172375.88 | 444.40 | 980611.739 | -72.444 |
| 25500 | 528687.38 | 165273.98 | 553.62 | 980591.827 | -65.082 |
| 25504 | 528807.63 | 165561.28 | 551.28 | 980592.258 | -65.278 |
| 25508 | 529051.03 | 165521.36 | 540.46 | 980594.301 | -65.370 |
| 25516 | 529210.13 | 166343.62 | 504.42 | 980601.424 | -65.887 |
| 25518 | 529546.18 | 165889.09 | 537.73 | 980595.013 | -65.196 |
| 25522 | 529419.47 | 166285.81 | 510.15 | 980600.145 | -65.995 |
| 25526 | 529715.91 | 166203.71 | 510.87 | 980599.856 | -66.168 |
| 25530 | 529978.88 | 166212.22 | 502.07 | 980601.635 | -66.140 |
| 25538 | 530311.64 | 166423.80 | 482.99 | 980605.284 | -66.364 |
| 25542 | 530572.13 | 166404.48 | 475.29 | 980606.738 | -66.404 |
| 25546 | 530806.99 | 166590.58 | 450.75 | 980611.382 | -66.621 |
| 25550 | 530897.96 | 166662.52 | 450.20 | 980611.444 | -66.788 |
| 25554 | 530994.80 | 166860.04 | 449.97 | 980611.385 | -66.830 |
| 25558 | 531128.37 | 166967.71 | 450.52 | 980610.892 | -66.759 |
| 25562 | 531298.75 | 166998.18 | 450.40 | 980611.327 | -66.702 |
| 25566 | 531416.04 | 167094.72 | 450.09 | 980611.402 | -66.879 |
| 25570 | 531648.37 | 167248.24 | 447.94 | 980611.240 | -67.762 |
| 25574 | 531864.93 | 167386.75 | 447.34 | 980610.882 | -68.345 |
| 25578 | 532011.09 | 167485.12 | 447.88 | 980610.514 | -68.679 |
| 25582 | 532147.59 | 167570.51 | 448.07 | 980610.386 | -68.840 |
| 25586 | 532362.79 | 167699.54 | 452.54 | 980609.902 | -68.520 |
| 25590 | 532581.07 | 167776.52 | 456.69 | 980608.643 | -68.914 |
| 25594 | 532654.59 | 167947.08 | 478.34 | 980604.818 | -68.801 |
| 25598 | 532719.84 | 168130.57 | 494.29 | 980601.712 | -69.050 |

| Name  | X         | Y         | Z      | Raw        | AB      |
|-------|-----------|-----------|--------|------------|---------|
| 25602 | 532965.27 | 168200.39 | 512.86 | 980597.883 | -69.242 |
| 25614 | 533426.60 | 168673.27 | 565.67 | 980586.686 | -70.342 |
| 25618 | 533526.61 | 168744.66 | 581.36 | 980583.197 | -70.621 |
| 25622 | 533731.62 | 168889.34 | 594.26 | 980580.615 | -70.913 |
| 25630 | 534102.90 | 169037.82 | 587.76 | 980581.974 | -71.298 |
| 25634 | 534186.85 | 169224.72 | 587.31 | 980582.055 | -71.457 |
| 25638 | 534249.16 | 169620.00 | 578.35 | 980583.714 | -71.900 |
| 25646 | 534663.38 | 169504.76 | 560.89 | 980586.989 | -71.895 |
| 25650 | 535216.44 | 169126.13 | 578.13 | 980583.122 | -71.915 |
| 25658 | 535389.95 | 169759.62 | 604.93 | 980577.643 | -72.694 |
| 25666 | 535569.99 | 170080.01 | 605.79 | 980577.401 | -73.252 |