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GInGER (GravImetry for Geothermal ExploRation): A New Tool for Geothermal Exploration Using Gravity and 3D Modelling Software

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ABSTRACT

With the aim to determine fracture porosity in geothermal reservoirs associated with fault zones, GInGER was developed for computing gravity effects of 3D geological units using high resolution DEM. Since the code builds up on seismic data, i.e. on fix distribution of geological structures, it allows for changing interactively the density of every structure, calculating the new gravity effect of the model in real time and comparing it with field measurements. The software was developed to sustain fracture porosity determination using micro-gravity measurements, i.e. based on an accurate geological model to characterize areas with a significant misfit between the model's gravity effect and measurements. However this misfit can also be interpreted for other purposes such as reservoirs characterization, error map of the model, first modelling of geological structures which were not highlighted by other methods.

In this paper, we will present the methodology and the capability of the software on two geothermal projects located in the Swiss Molasse Basin of Switzerland: the projects of Sankt Gallen and Eclépens. Both projects are targeting deep faults affecting sub-horizontal aquifers at a few kilometers of depth. In both cases a 3D geological model was established for the project and then used for our studies. In Sankt Gallen, we were able to determine fracture porosity due to a fault system at a depth of > 4 km based on a 3D seismic survey. The study in Eclépens focuses on sensitivity analyses investigating to which extend our method is applicable to less constrained 3D geological models.

1. INTRODUCTION

The concept of geothermal exploration of low-temperature, hydrothermal systems, bases on the assessment of aquifers. Geothermal wells are typically connected via fault zones to the regional flow field charging the system. Such exploration nowadays typically includes 3D geological modelling (e.g. Milicich et al., 2010) to assess the depth and extension of the potential aquifer and to best target the fault zones. 3D geological models are usually built on geological and geophysical data (e.g. Jolie et al., 2012; Calcagno et al., 2008). In sedimentary basins such as the Swiss Molasse Basin, models are generally based on seismic measurements. They provide an image of the subsurface geology, but little information on the porosity or permeability of the geological units and their lateral variation. In the entire North Alpine Foreland Molasse Basin, most geothermal projects target steeply dipping faults zones in deep aquifers. They are expected to provide preferential flow pathways when orientated favorably to the recent stress field (Baillieux et al., 2013). Steep dipping faults zones in sedimentary environment are typically identified by offsets in the seismic reflectors and thus, difficult to characterize physically from seismic data acquired from the surface. Local increase of porosity due to the occurrence of fractures results in a local decrease of the affected geological formation bulk density and can be assessed by gravity measurements (Guglielmetti et al., 2013). The determination of porosity in geothermal systems by means of gravity measurements has been applied. For example, the Geysers field, where according the phase of the fluid porosity changes in the order of 0.5 to 1.6% have been attributed to density changes of 40 to 60 kg·m^{-3} for reservoir zones of an extension of several kilometers (Denlinger and Kovach, 1981). In this case, density changes were related to porosity through measurements of the interconnected porosity on samples. In a similar approach, first estimates on porosity by gravity in the European EGS reservoir area in Soultz-sous-Forêts reproduce the order of magnitude obtained from logging data (Schill et al., 2010). Based on the sub-horizontally layered geology of the North Alpine Foreland Molasse Basin, we have developed GInGER (GravImetry for Geothermal ExploRation) using Blakely's algorithm for gravity forward modelling computing the effect of a rectangular prism (Blakely, 1996). In the present paper, we show the results of two test sites in Switzerland: the projects of Sankt Gallen and of Eclépens (Figure 1). Both projects target fault zones in a deep aquifer. However the knowledge on the 3D distribution of geological units in the subsurface differs significantly. In the case of Sankt Gallen, the provided 3D geological model (SGSW, pers. comm.) is based on a 3D seismic survey, whereas in the case of Eclépens the provided 3D model (BKW, pers. comm.) only 2D seismic data were used.

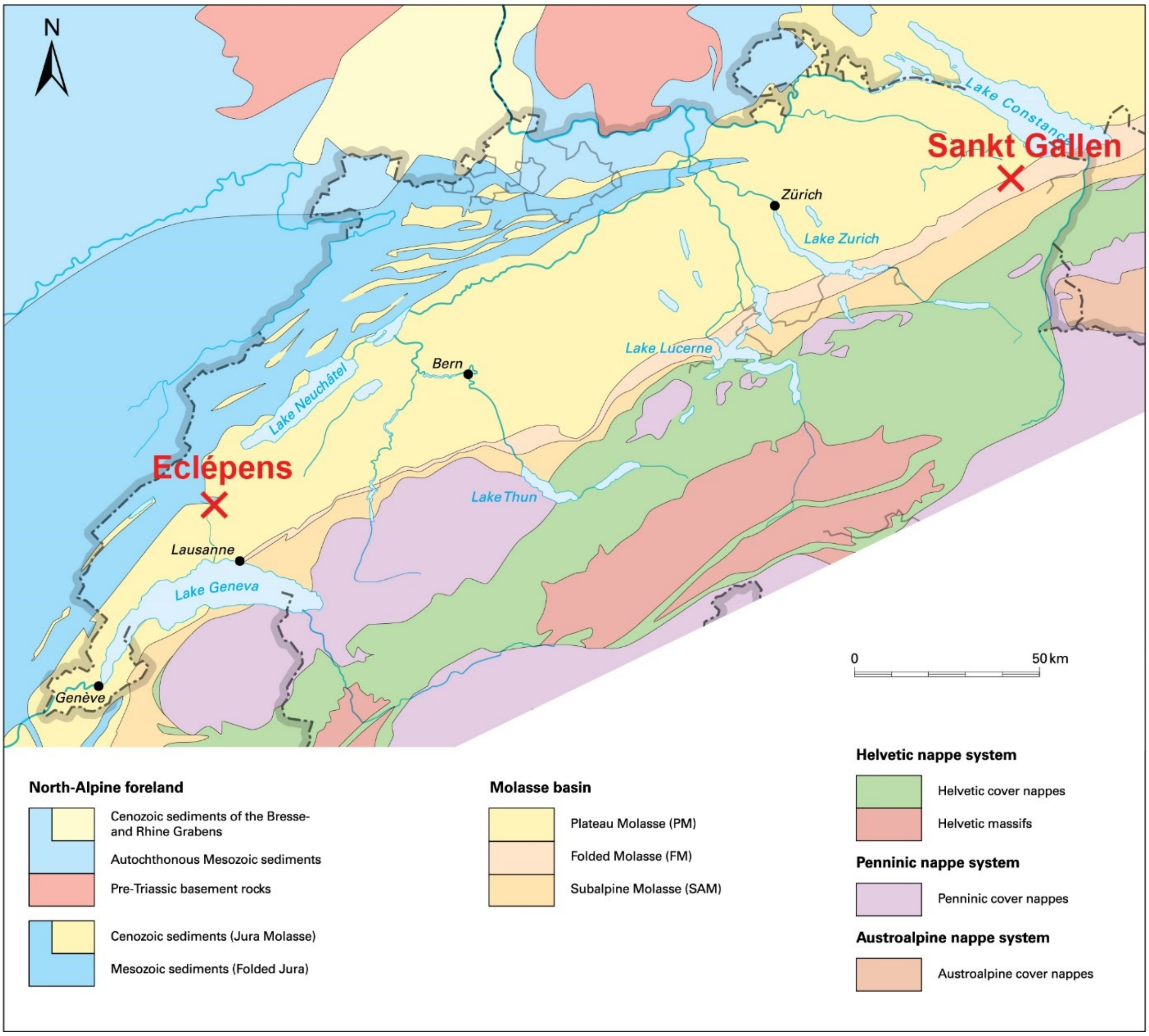

Figure 1: Main tectonic units of the Swiss Molasse Basin and surrounding areas (after Sommaruga et al., 2012) with geothermal projects of Eclépens and Sankt Gallen (red crosses).

2. SOFTWARE SPECIFICS

A major aim of GInGER is to provide a user-friendly tool allowing for the computation of the precise gravity effects of the different geological structures of a 3D model at the topography. To achieve this goal, GInGER was written in C++ using the QT framework (Digia plc) and Qwt – Qt Widgets for Technical Application (Rathmann and Wilgen, 2013) to allow for efficient computation of the gravity effects and an easy-to-use GUI (Graphical User Interface) (Figure 2).

Models are uploaded in the software by considering horizontal geological limits represented by uniform depth grids. The software accepts ASCII and ESRI binary grid formats, as well as a special binary format created for the software itself. Geological layers are then created in-between those limits. Each of their gravity effect is computed using Blakely gbox-algorithm (1996) translated into C++ and parallelized. Two cell sizes are accepted for grids: one of comparatively lower resolution used for ordinary geological limits and another one of higher resolution for near surface limits such as topography (mandatory) and Quaternary structures. This allows for efficient and precise calculus of the gravity effect.

With respect to fracture porosity, special attention is given to the gravity effect of fault zones. Since in geological models faults are typically represented by planar surfaces, they represent neither volume, nor a gravity effect. However, faults, or more precisely damage zones around faults, that are of interest to geothermal exploration may be described by an envelope enclosing the related fractures. This envelop can be represented graphically by an upper and lower grid that is either uploaded or generated by GInGER from faults planes uploaded as DXF. In the latter case, the user needs to choose the normal (perpendicular) distance to the fault plane that is considered to be fractured to allow the generation of the envelope.

In GInGER, the GUI is separated in five parts (Figure 2): (1) toolboxes, (2) a table with all geological objects in which density can be modified, (3) 2D geological and (4) 2D gravity section, which can be chosen by clicking on (5) the gravity anomaly map (e.g. misfit, measured gravity or model gravity). Once a geological limit or object is inserted and its gravity effect calculated based on a chosen density the results can be displayed in real time on the gravity profile.

Fault zones are physically treated as zones of porosity change, i.e. the gravity effect of each formation that is cross-cut by the fault zone is reduced by the percentage of porosity of the fault zone. Therefore, throughout the different formations the fault zone is separated in fault compartments, one for each geological formations affected by a fault. The density of each compartment is then determined by the original layer density, fracture porosity, and fluid density according to the following formula.

$$\rho_{bulk} = \left(1 - \phi_{frac}\right)\rho_{gl} + \phi_{frac} \cdot \rho_{fluid} \qquad \text{(eq. 1)}$$

where ρ_{bulk}, ϕ_{frac}, ρ_{gl}, ρ_{fluid} are bulk density, fracture porosity in percent, geological formation density, fluid density, respectively.

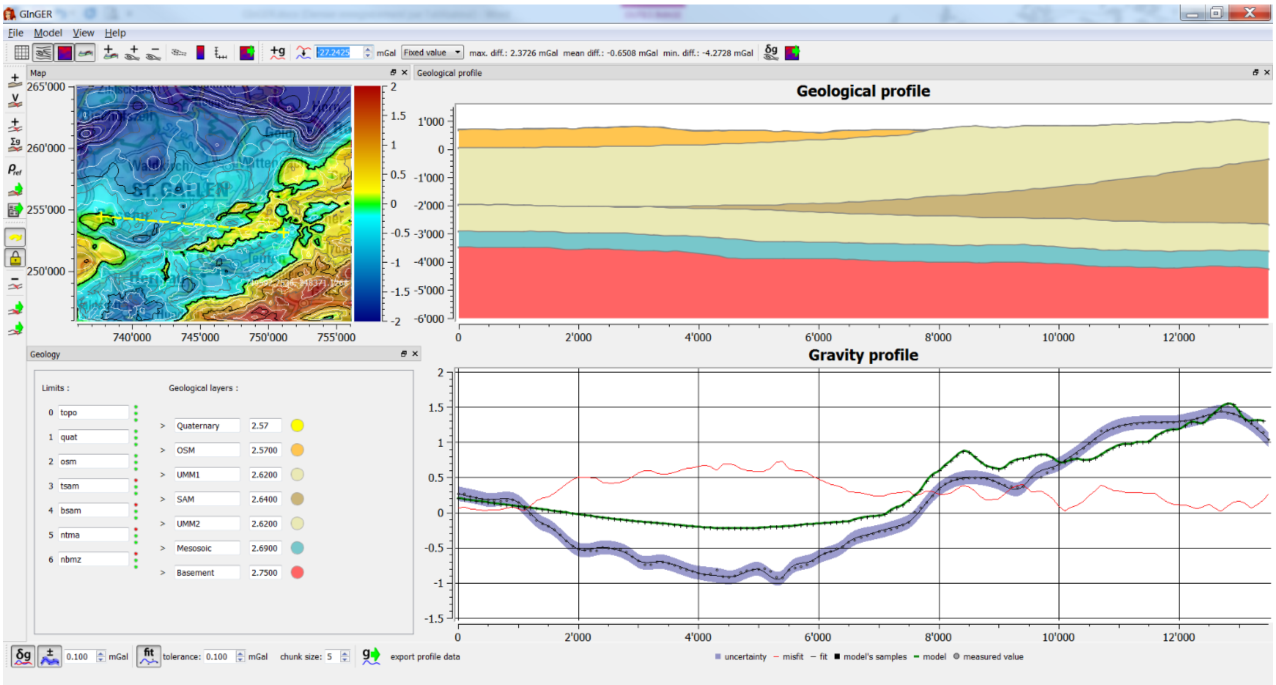

Figure 2: Example of the user interface of GInGER.

Additionally, the software provides a tool for 2D forward modelling called GInGER Synthetic Profile (GInGERSP) with the aim of being able to calculate the gravity effects of classical shapes like sphere, cylinder, etc. in 2D. When used in combination with GInGER it allows to add shapes to the model and thus, to test hypotheses.

3. APPLICATION TO GEOTHERMAL EXPLORATION

GInGER was tested in two different geothermal projects in the North Alpine Foreland Molasse Basins of Switzerland: the projects of Sankt Gallen and Eclépens (Figure 1). This basin formed during Tertiary extends laterally from the region of Aix-les-Bains in France to Brno in the Czech Republic. It is build up on the Variscian crystalline basement (including Permo-Carboniferous graben structures) and its overlying Mesozoic sediments that dip with about 5° towards the Alpine chain. It is filled with Tertiary Molasse sediments locally overprinted by Quaternary deposits. Both projects targets deep aquifers in Mesozoic formations.

The gravity surveys 2011/2012 in Sankt Gallen cover an area of 20 x 10 km with about 700 measurement stations. Geographic coordinates of the measurement stations were acquired using a Leica differential GPS (DGPS) GS-15 with an error of 1-3 cm in vertical direction. Gravity was measured using a relative CG-5 Autograv gravity meter (Scintrex, Canada) with an accuracy of 0.005 mgal. About 200 gravity measurements from the Swiss Atlas of Gravity (Olivier et al., 2010) were added to the measured datasets of Sankt Gallen to extend the data coverage of the study area. In Eclépens, more than 400 measurements stations are planned covering an area of 10 x 10 km. However as the measurements are on-going in this paper only existing data from Olivier et al. (2010) are used.

Complete Bouguer anomaly has been calculated assuming a mean bulk density of the Molasse sediments of 2570 kg·m^{-3} to the topography in Sankt Gallen. In Eclépens, the upper crust density of 2670 kg·m^{-3} was used. The topography is described using a digital elevation model DEM (Swisstopo, 2010). In both case, residual anomaly used is obtained by using a regional anomaly calculated by polynomial regression on the data of Olivier et al. (2010) to a distance of 50 km from the border of the models.

3.1 Sankt Gallen Geothermal Project

The general geological setting of the Sankt Gallen project is shown in Figure 3. At the surface, we can distinguish the Molasse basin from the folded sub-alpine Molasse sediments. The target fault zone of the geothermal project is observed in the Mesozoic sediments.

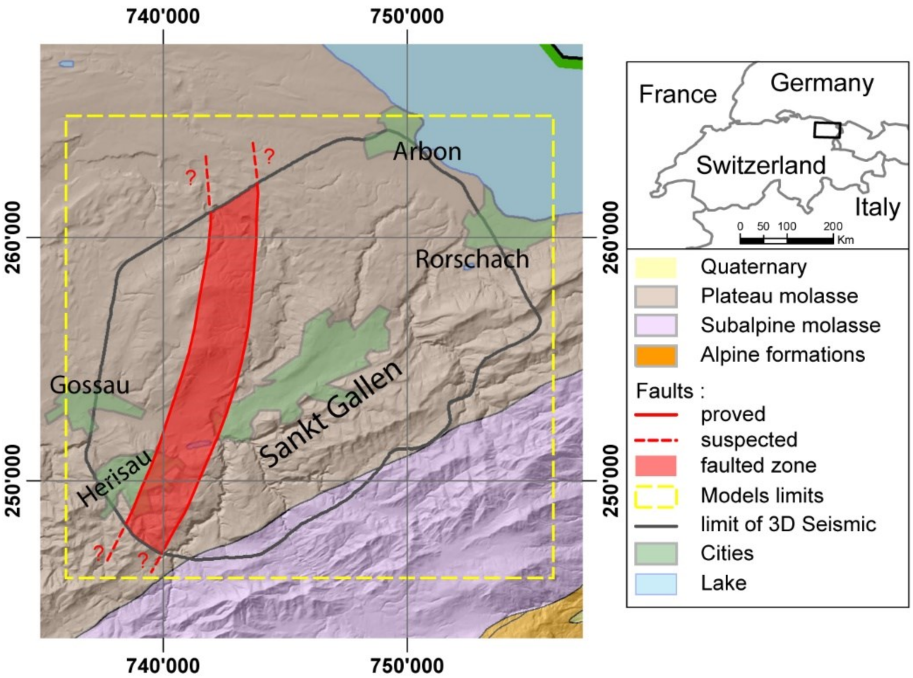

Figure 3: Localization and simplified tectonic map of Sankt Gallen geothermal project (Swiss coordinate system: CH 1903). The fault zone observed in the Mesozoic sediments by seismic data is outlined in red.

In the final forward modeling, we were able to reproduce the densities of the single units that are published from Switzerland (e.g. Schärli & Kohl, 2002) or correspond to our own measurements. It should be mentioned that even if the 3D geometry is not fully described by 3D seismics, due to unknown vertical extension of a Permo-Carboniferous trough within the top of the crystalline basement, we were able to attribute part of the gravity anomaly to fracture porosity. This was done by creating a volume considered to be fractured and thus which density is lowered due to an increased porosity (Figure 4, Altwegg et al., subm.). The final density of this damaged zone is then calculated using eq 1.

As shown also in the Geysers field (Denlinger and Kovach, 1981), depending on the type of fluid the forecasted fracture porosity in the area of Sankt Gallen varies between 6.5-9.5% for water and 4- 6% for gas. Although from the temperature at 4000 m depth of 140 °C (SGSW, pers. comm.) steam is not expected in the reservoir, a considerable amount of methane has been produced in the first production test (SGSW, pers. comm.). Thus, we expect the porosity to be between the two values. This porosity is comparable to the one found in the reservoir zone at Soultz-sous-Forêts representing the intermediate reservoir, which is located at comparable depth with the Sankt Gallen site.

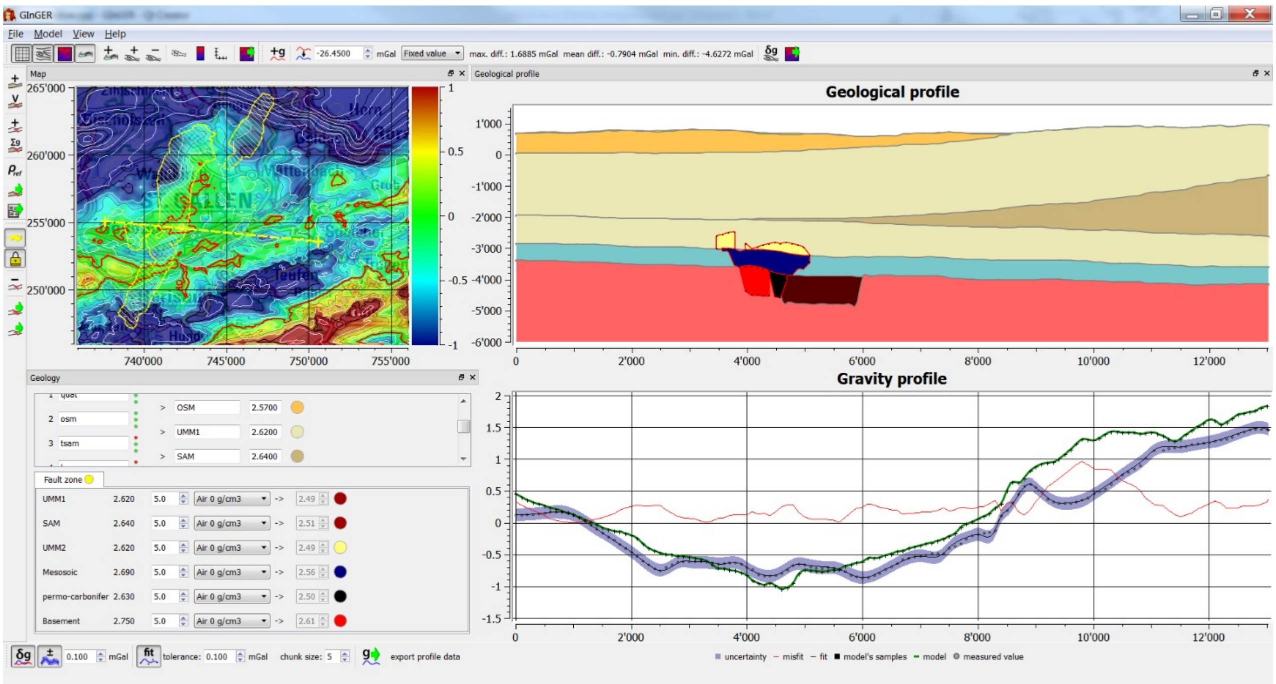

Figure 4: Print screen of GInGER made with Quaternary structures, Permo-Carboniferous graben and fractured zone added. On gravity profile, blue line: measured gravity with uncertainty, green line: model's gravity effect, red line: misfit.

3.2 Eclépens Geothermal Project

The Mesozoic sediments in the area of Eclépens are characterized by an anticline with a fold axis trending in NE-SW direction and its crest located underneath the wells of Eclépens-1 and Essertines-1 (Figure 5). The anticline is crosscut by a major strike-slip fault. As in Sankt Gallen, the target of the project is the fault zone within the Mesozoic sediments, in this case the Muschelkalk and Buntsandstein formations. In this respect, a 3D geological model was established using 2D seismic lines and borehole information (Figure 5).

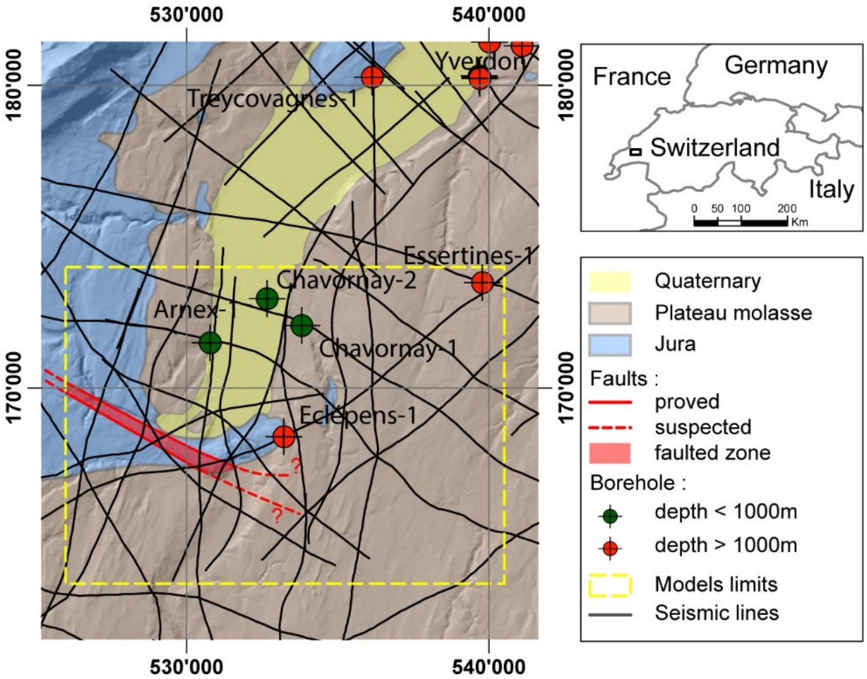

Figure 5: Localization and simplified tectonic map of Eclépens geothermal project (Swiss coordinates: CH 1903). The fault zone observed in the Mesozoic sediments by seismic data is outlined in red

Applying the above mentioned corrections to the existing gravity data of the Swiss Atlas of Gravity (Olivier et al., 2010), we obtain a prominent negative anomaly extending over more than 50% of the study area (Figure 6). This negative residual anomaly was already discussed by Klingelé (1972) who proposed three hypotheses: (1) a collapsed Mesozoic compartment between Eclépens and Treycovagnes, (2) an increased thickness of the Triassic formation including an evaporitic series or (3) the presence of a Permo-Carboniferous graben. At its bottom the Treycovagnes-1 borehole reveals nearly 500 m of Permian sediments. This is in favor of the third hypothesis.

The second major observation is that the target fault zone is located at the transition between the negative and the positive residual anomaly. Assuming that the third hypothesis best describes the large negative anomaly, the tectonic setting of Eclépens is comparable to the one in Sankt Gallen, where we also observe the fault zone affecting the Mesozoic sediments and originating from a boundary fault of a Permo-Carboniferous graben (Altwegg et al., subm).

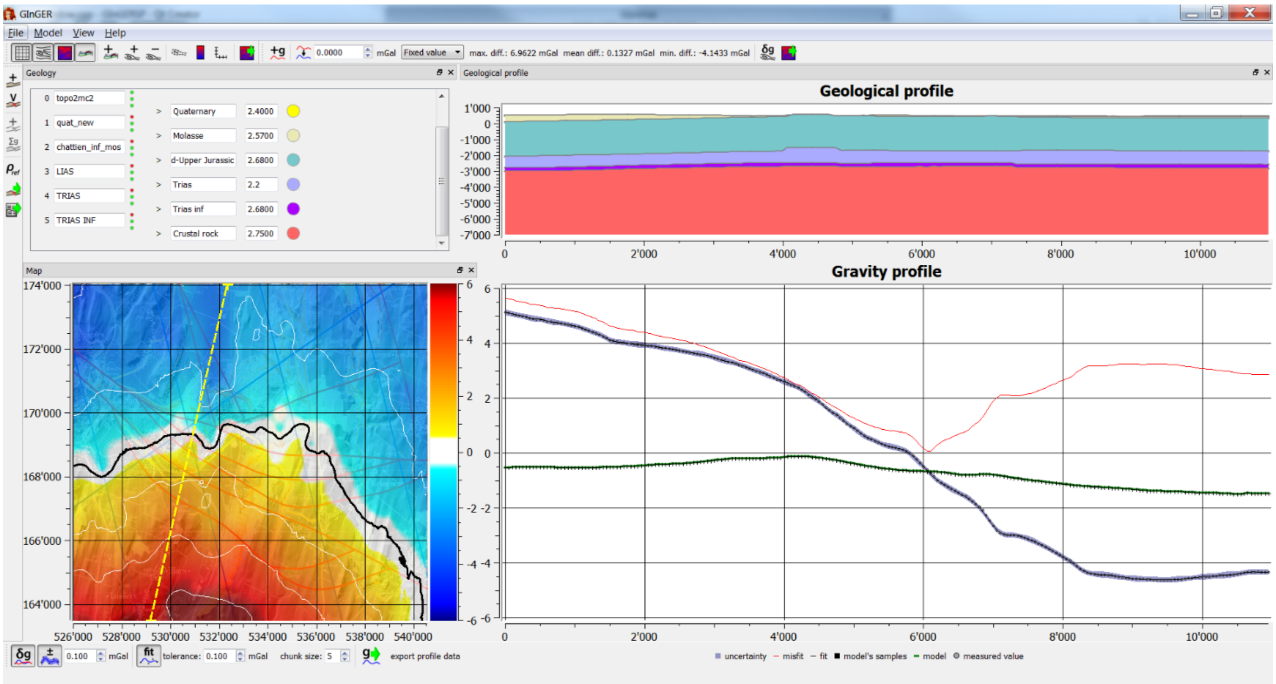

Figure 6: Print screen of GInGER made while Eclépens 3D model is used.

In order to test this hypothesis, we imported the representative profile shown in Figure 6 directly into GInGERSP and added measurement of Olivier et al. (2010) further to the north and the south of our area of investigation (Figure 7). In order to obtain a satisfying fit with realistic geometry and difference of density, we had to add two horizontal bodies: one representing the suspected Permo-Carboniferous graben at a depth of about 3200 m (Figure 7, brown), a thickness of 960 m and a density contrast of -120 kg·m^{-3} and a second body at a shallower depth of 2000 m (Figure 7, blue), a thickness of 400 m and a density contrast of -470 kg·m^{-3} and to represent an increased thickness of Triassic evaporites. The chosen profile is roughly south to north and due to the local shape of the Jura Mountains (Figure 5), it nears the foot of the Jura Mountains where evaporites thickness can reach 1000m (Sommaruga et al., 2012). We also added four vertical dykes with a width between 100 and 150m to take into account the possible effect of regional faults zones (Figure 7, orange, red, yellow and green).

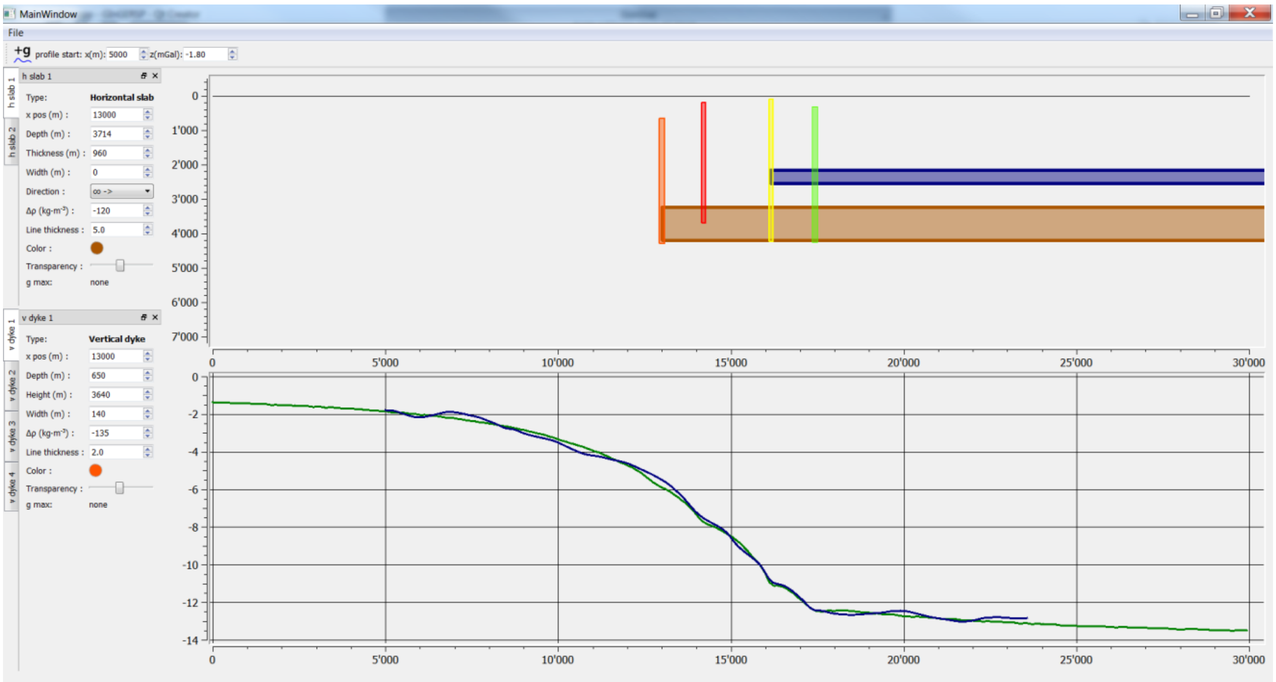

Figure 7: Print Screen of GInGERSP with the profile of Figure 6, the upper part represent the modeled shapes, and the lower part the gravity effect, the blue line is measurements and the green line model plus the gravity effect of the shapes.

4. CONCLUSIONS AND FURTHER DEVLOPMENTS

The use of 3D models combined with gravity data and GInGER allows the stripping of gravity effects of sedimentary and structural units. Additionally to the 3D seismic survey across the Sankt Gallen region, residual anomalies across the target fault zone reveal the sedimentary and structural elements. The top and lateral boundary faults of the Permo-Carboniferous graben have been inferred from 3D seismic data. Their vertical extension of about 900 m is deduced from forward modelling of gravity data. Fault zones have been mapped in detail using 3D seismics. Stripping of the gravity effects of the single sedimentary and tectonic units lead to a residual anomaly representing the fracture porosity only. Due to important amount of gas presents in the reservoir the forecasted fracture porosity in the area of Sankt Gallen varies between 6.5-9.5% for 100% water and 4- 6% for 100% gas. In Eclépens a very similar structural setting has been found and fracture porosity determination will be presented in a forthcoming paper.

Three main topics are currently under development, the first is the inversion on density and the calculation of the statistics of the fit to allow an insight on the quality of the gravity modelling. The second is to allow the user to add simple shapes like plan, cylinder, etc. directly in 3D for GInGER. The third topic is concerning GInGERSP in which we want to add the possibility to have shapes with a strike different from 90°.

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