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Enhancing geological interpretation with gravity; application to Permo-Carboniferious graben in Switzerland

Yassine Abdelfettah[1,2], Eva Schill[1], Olivier Zingg[3], Florentin Ladner[3] and Senecio Schefer[4]

1 Institut für Nukleare Entsorgung INE, Karlsruher Institut für Technologie (KIT), Karlsruher, Germany

2 Institut de Physique du Globe de Strasbourg, CNRS UMR7516, University of Strasbourg, Strasbourg, France

3 Geo-Energie Suisse AG, Reitergasse 11, CH-8004 Zürich, Switzerland

4 Geo Explorers, Wasserturmplatz 1, CH-4410 Liestal, Switzerland

yassine.abdelfettah@kit.edu, eva.schill@kit.edu, o.zingg@geo-energie.ch, f.ladner@geo-energie.ch, senecio.schefer@geo-ex.ch

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ABSTRACT

Understanding the geology is the first objective in exploration, either for geothermal or oil and gas projects. In Switzerland, the identification and characterization of Permo-carboniferous grabens represent an important exploration challenge. Reflection seismic often doesn't provide suitable imaging of the basement and reveals few places where these structures could be partially imaged. In this study, the application of high accuracy gravity forward modeling using finite element meshing and post-processing, mainly filtering of Bouguer anomaly, shows to be a robust technique to help understanding deep basement structures. To achieve this goal, two steps are taken: 1) identification of the gravity signature that would be arising from Permo-carboniferous grabens, 2) validation of the 3-D geological model based on geological and reflection seismic data. As a result, the geological model is modified to match the observation data.

1. INTRODUCTION

Geo-Energie Suisse is a company, which plans to produce electricity from geothermal energy in Switzerland. Their objective is to enhance natural permeability that may exist in the crystalline basement using EGS (Enhanced Geothermal Systems) to create and develop an economic geothermal reservoir. To achieve this aim, numerous points must be successfully achieved. Two points or scientific challenges mainly are concerned in this study; 1) the existing or the absence of the Permo-Carboniferous (PC) grabens at the selected site, and 2) enhancing geological interpretation of the selected geothermal site. These two points help to improve the final geological model and in the end enhance the success chance of the project.

These Permo-Carboniferous (PC) structures are complex grabens that extend over tens of kilometers in width. For example, the Northern Swiss trough striking approximately ENE-WSW and extending from E of Basel to the lake of Constance reveals Permian to Stephanian basin fills (Matter 1987, Abdelfettah et al., 2014) and a multiphase tectonic history (e.g. Diebold et al., 1991). A challenge on the localization of these structures using seismic reflection is well reported in Marchant et al., (2005). These difficulties are also documented in the Seismic Atlas of Swiss Molasse Basin (Sommaruga et al., 2012), where on 16 seismic lines across the entire Swiss molasses basin a total of about 465 km of the basement has been labelled "possible" PC trough identified by seismic reflection in the basement and a total of 995 km are labeled "uncertain extension", identified by intermediate reflection. A total of 100 km of PC trough is confirmed by the wells Entlebuch-1 and Weiach-1. Thus, these established criteria provide indication for PC, but need to be combined with further available information in order to establish whether or not PC deposits are present.

Gravity and magnetics have been successfully used to characterize the distribution of inhomogeneities in the crystalline basement in general (Edel 2004; Edel & Schulmann 2009) and information with respect to geothermal anomalies on regional (e.g. Baillieux et al. 2013) and local studies (e.g. Guglielmetti et al. 2013). In previous studies, gravity has been successfully applied according to the Permo-Carboniferous context to the northern Swiss trough (Klingelé & Schwendener 1984) and more recently to the northern part of Switzerland (Abdelfettah et al., 2014). Density measurements in deep boreholes (e.g. Weiach-1) show a mean density value of 2450 kg/m^3 whereas the mean density of the crystalline basement is about 2600-2700 kg m^3. This important density contrast increases the efficiency of the gravity method and makes it more suitable.

This study is achieved in two steps: one devoted to qualitative gravity interpretation, and the second for quantitative interpretation on the basis of an existing 3D geological model, which is derived mainly from seismic data and from available geological data. The main advantage of the proposed approach is that the study can be done only using available (free) gravity data. The acquisition and the processing costs (and time) can therefore be avoided. The objective of this paper is to show that using gravity method in geothermal exploration can give us an added value, helping in the understanding of the geology.

2. QUALITATIVE INTERPRETATION USING ONLY AVAILABLE GRAVITY DATA

This study can be considered as a reconnaissance step to identify potential regional density anomalies, which may exist and occur at depth. The scientific approach consists of analyzing the Bouguer anomaly existing in the Gravimetric Atlas of Switzerland, and build pseudo-tomography interpretation as showed in Abdelfettah et al. (2014).

The studied area is located in Lucerne and northeast of Lucerne in the central-eastern part of Switzerland. The potential geothermal sites are defined in Triengen and Pfaffnau area (Fig. 1). The sedimentary shallow basins can be mainly identified in Fig. 1b. Their orientations are mainly NNW-SSE (see dashed circles). This result is an agreement with available geological information on the quaternary filling sediment mainly their location and orientation.

Two representative pseudo-tomography examples are only presented here. The first one is presented in Figs. 1c-d. It shows the residual anomaly where the quaternary sedimentary gravity effect is strongly reduced (Fig. 1c). From this residual anomaly (ie. Fig. 1c), the big wavelength starts to be observed. The main negative anomaly observed in the central area in Fig. 1c is confirmed to be deeper and thicker by the second half part of this Pseudo-Tomography (Fig. 1d). Indeed, increasing the big wavelength cut-off from 30 to 60 km with fixing the small cut-off shows mainly the contribution of deep gravity (negative) effect.

The second Pseudo-Tomography is shown in Figs. 1e-f. The small wavelength is fixed at 20 km, which means that shallow gravity effects can be neglected. The central (big) negative anomaly is still observed (Fig. 1e). This second results shows also that this negative anomaly is deeper and thicker (Fig. 1f).

Several other Pseudo-Tomography results are an agreement with the discussed results above (not shown). Moreover, 2D cross-sections are also conducted to better analyze the progression of the negative anomalies with depth with results confirming the maps shown in Fig. 1. Finally, the main conclusion of this qualitative study is the presence of an important negative density contrast in the study area mainly under Triengen geothermal site, which may be the result of a Permo-Carboniferous graben.

3. QUANTITATIVE INTERPRETATION AND 3D GEOLOGICAL MODEL VALIDATION

The results obtained in the qualitative interpretation suggest the potential presence of the Permo-Carboniferious graben in the studied area under Triengen. To confirm this result and derive the dimensions of the potential PC trough, a quantitative interpretation was conducted. Therefore a 3D geological model is needed.

The geological model (Fig. 2) is based on the available wellbore data and the interpretation of 2D reflection seismic profiles. In total, seven geological units are modeled from top to bottom: 1) Tertiary, 2) Malm, 3) Dogger, 4) Keuper & Lias, 5) Buntsandstein & Muschelkalk, 6) Permo-Carboniferious and 7) Crystalline basement. A compilation of the density values derived mainly from borehole measurement is shown in Table 1. These densities are used to achieve the 3D gravity forward modeling. The model shown in Fig. 2 was meshed on tetrahedron shape to improve the accuracy of the gravity computation.

Sensitivity analysis has been conducted on the densities leading to the conclusion that the average density values best match the measured data from Fig. 1.

The comparison of the calculated and measured residual anomalies shows that the geological model reproduces only some gravity effects. Concerning the shallower effects (Figs. 3b), the geological model managed (overall) to reproduce some of them, such as for example the negative anomaly immediately to the south of Pfaffnau and the negative anomalies on both sides of Triengen (E and W). On the other hand, the model does not reproduce the negative anomaly SW of Triengen, and in that place we rather observe a positive anomaly.

The misfit between the measured and the modelled responses increases with longer wavelength corresponding to deeper structures. This discrepancy is in particular related to the negative anomaly probably generated by an important PC graben. On the observed data (Fig. 1), the progression of the pseudo-tomography indicates density reduction in the depth, because the negative anomaly increases according to the progression of the Pseudo-Tomography. The comparison of Figs. 3c-d with Fig. 1c-f shows clearly this behavior. On a deeper level immediately south of Triengen, the model shows a structure of an abnormally higher density in comparison with the real data.

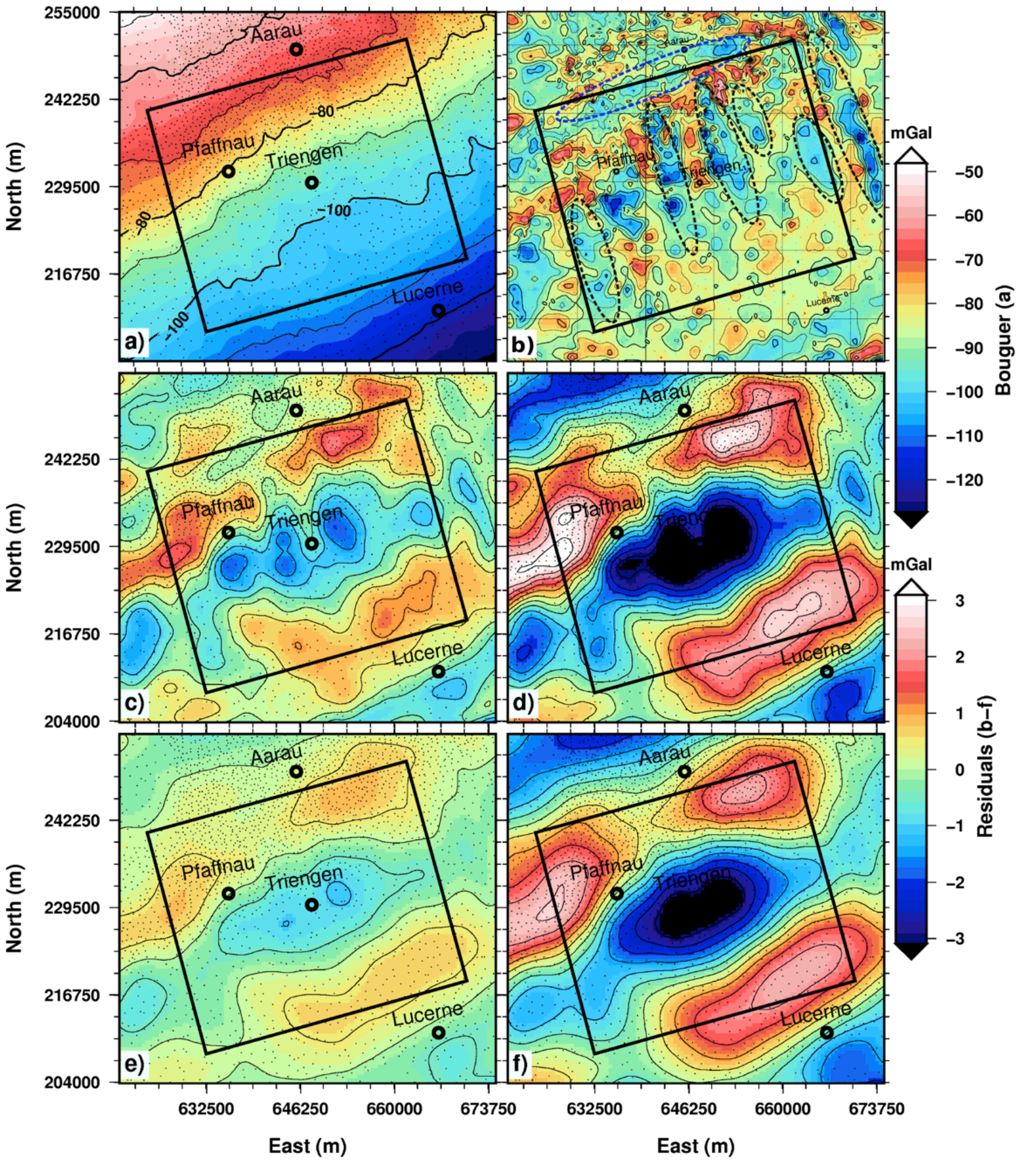

Figure 1: a) Bouguer anomaly for the studied area. b) residual anomaly obtained by 20 km high pass Butterworth filter. c) - d) residual anomalies obtained using 10-30 and 10-60 km band pass filter, respectively. e) – f) residual anomalies obtained by using 20-30 and 20-60 band pass filter, respectively. The box shows the limits of the 3D geological model.

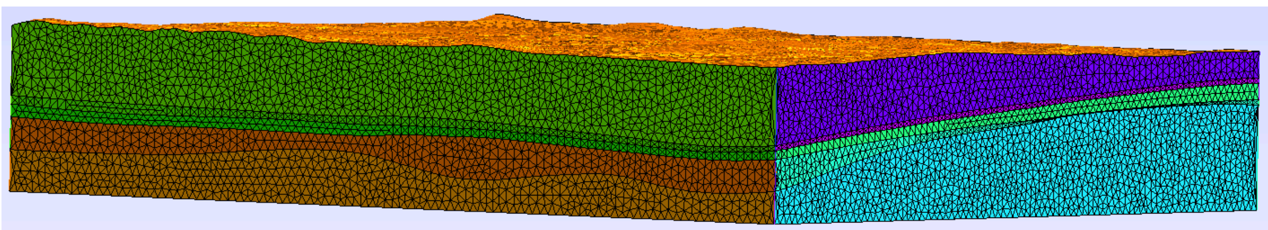

Figure 2: Southeast view of the 3D geological model of the studied area. Finite element meshing with tetrahedrons is also showed.

Geology vs. Density values	Min density (kg m-3)	Max density (kg m-3)	Avg. density (kg m-3)
Tertiary	2350	2650	2520
Malm	2400	2730	2640
Dogger	2270	2720	2530
Keuper & Lias	2400	2810	2610
BSST & Muschelkalk	2380	2850	2630
Permo-Carboniferious	2200	2750	2450
Crystalline basement	2330	2900	2670

Table 1: Minimum, maximum, and average density values compiled from boreholes logs.

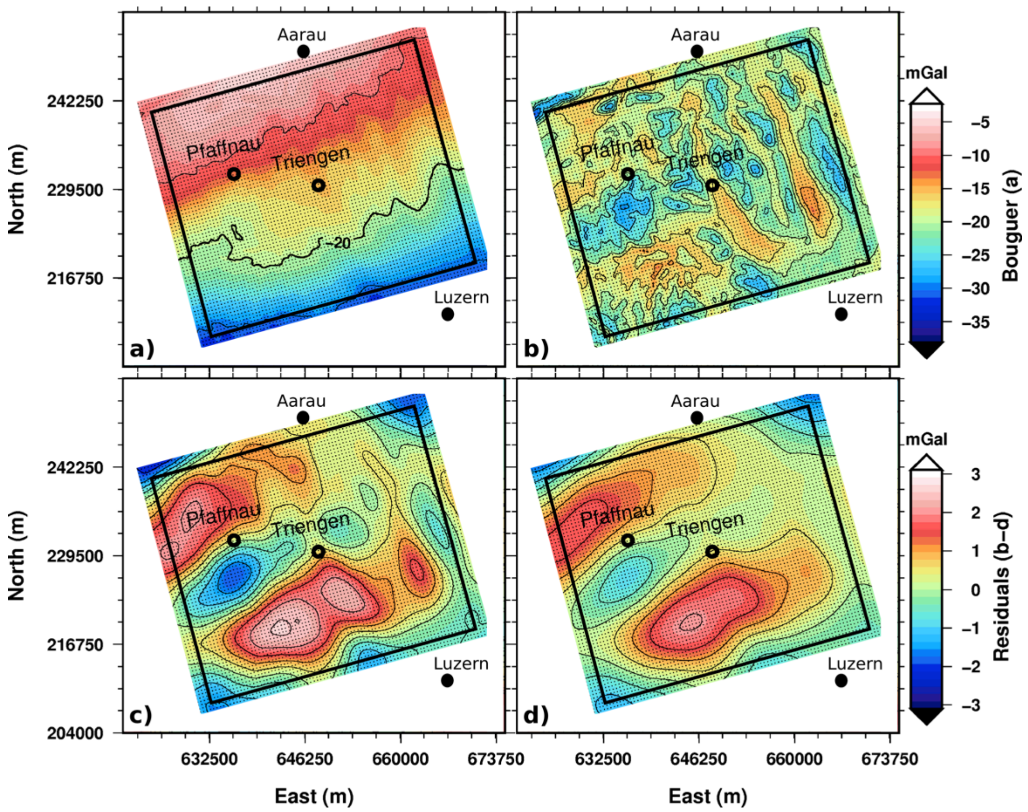

Figure 3: a) Computed Bouguer anomaly for the 3D geological model using average density values shown in Tab. 1. Residual anomalies obtained using 20 km high pass Butterworth filter (b), 10-60 km band pass Butterworth filter (c), and a 20-60 km band pass filter (d) are shown.

4. CONCLUSIONS

The gravity response of the 3D geological model shows a clear mismatch with the observed data. Several density values were tested to quantify the effect of their changes. The different tests carried out showed that the average densities reproduced the observations best. Consequently, these densities should be kept in the oncoming steps. The main challenge remaining now is to improve the adjustments between the real and the simulated data. For that purpose, it is necessary to modify the geometry of the P-C graben based on the geometry of the observed negative gravity anomaly.

The main conclusions of this study can be summarized: 1) presence of an important P-C graben at top of Crystalline basement, mainly at Triengen site. It seems to be a large and regional graben. 2) The geological model built on the basis of reflection seismic data does not explain several negative anomalies (mainly deeper ones). The gravity could assist in the construction of the final geological model for a better understanding of the basement structures.

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