Delineation of geothermally relevant Paleozoic graben structures in the crystalline basement of Switzerland using gravity

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Summary

Although many are suspected from seismic observations, few and far between Permo-Carboniferous (PC) troughs at the top of the Variscian basement in Switzerland are confirmed by wells. The well-known and geothermally relevant Northern Swiss trough with its top in a depth of about 1.5 km has been first identified in its spatial extension by gravity measurements revealing its smaller density with respect to the crystalline basement. Further south, towards the Alps, paleo-graben structures are expected to occur with a top depth down to about 5 km following the deepening of the top crystalline basement. A sensitivity study using Butterworth filter of different wavelengths applied to realistic 2D and 3D geological models was conducted in order to understand the gravity variation with increasing depth of the top of the troughs. It reveals high potential in the delimitation of the PC troughs at significant depth as well as in tracing their vertical geometry using the different wavelengths. Application on the real data confirms the interpretation of negative anomalies in terms of PC troughs.

Introduction

Major heat flow anomalies in central Europe are located in the Upper Rhine Graben (URG) and are found to be linked to hydrothermal convection in strongly fractured rocks including the basement (e.g. Kohl et al. 2000; Pribnow and Schellschmidt 2000; Bächler 2003). Kohl et al. (2000) and Bächler (2003) have shown that the convection occurs along fault zones related to the tectonics of the URG. This convection accounts to a large part for the temperature anomalies of these geothermal fields. In a similar way, several structural elements in the basement of the Swiss Molasse basin revealing naturally enhanced permeability may contribute to a comparable surface heat flux anomaly. A 2D thermo-hydraulic modeling for the area of Bad Zurzach (Rybach et al. 1987) has shown a strong influence of deep thermal water up-flow along the Northern boundary fault of late-Variscian graben structures, Permo-Carboniferous (PC) troughs, in the granitic basement. Thus, the authors concluded that the heat flux anomaly is related to the occurrence of such Permo-Carboniferous troughs.
Challenges in localization of PC troughs using seismic data include (Marchant et al., 2005): (1) Uncertainty in the origin of the characteristically weak reflections below the Mesozoic in the absence of boreholes. (2) Where PC deposits are present, the little expressed base Mesozoic reflection can be mistaken for an internal PC reflection, and (3) the structural interpretation is often uncertain, as faults below the Mesozoic cannot be traced along marker horizons on the seismic sections.

In an attempt to better identify reflections originating from PC troughs, a number of criteria were established on the basis of seismic sections (Marchant et al., 2005). The remaining difficulties are obvious in the new "Seismic atlas of the Swiss Molasse Basin" (Sommaruga et al., 2012).

The best investigated trough in Switzerland is the North Swiss trough (Sprecher and Müller, 1986). In this region, the thickness of Permian sediments in the Upper Rhine Graben was first estimated using seismic and well information as well as paleogeographic considerations (e.g. Boigk and Schöneich, 1974). A first interpretation of a regional negative residual anomaly has interpreted as depth of the top crystalline basement, i.e. the base of the PC troughs (Klingelé and Schwendener, 1984). The residual had been obtained using a polynomial of third order and fitting their coefficients by least-square. For the interpretation in terms of depth of the top crystalline, the reduction density of 2400 kg m^{-3} had been chosen due to overlying Quaternary sediments with a density close to that value. Modeling the geometry of the PC troughs has been carried out on the bases of measured densities in different wells, e.g. from gamma-gamma logs (mean density of 2550 kg m^{-3}). This value has led to a density contrast of -100 kg m^{-3} between the PC troughs and the crystalline basement (Klingelé and Schwendener, 1984).

Further interpretations have improved the localization of the PC trough mainly using seismic investigation calibrated by well data. The most complete compilation of PC graben structures in northern Switzerland is given in the technical report of Nagra (NAGRA, 2008). A more regional interpretation has been compiled (Ustazewski, 2004).

Geophysical approaches

Regardless, gravity has been proven to be a good exploration tool for the investigation of PC troughs in Switzerland, it was not used for further understanding their distribution. In the present study, we have investigated systematically the application of Butterworth filter with different wavelengths to 2D and 3D gravity forward models based on realistic geology as well as on real measurements on an area of 55 x 40 km around the city of Biel/Bienne.

Gravity modeling

In order to systematically assess the potential of the gravity data to detect and characterize PC troughs in the Molasse basins, 2D and 3D conceptual models were set up. Synthetic gravity data sets were generated for these models using a homogenous basement density of 2670 kg m^{-3}. According to different types of measurements a range of density for the PC troughs is obtained (Klingelé and Schwendener, 1984), resulting in the 3 scenarios: (1) an extreme density contrast of -220 kg m^{-3} (PC density ρ_{PC} = 2450 kg m^{-3}), which is slightly smaller than the value obtained from gamma-gamma ray density logs in the wells of Böttstein and Weiach, (2) an intermediate density contrast of -

100 kg m^{-3} (ρ_{PC} = 2570 kg m^{-3}) obtained from gravity measurement (BHGM) in the same wells, and (3) a small density contrast of -50 kg m^{-3} (ρ_{PC} =2620 kg m^{-3}) is assumed as worst case scenario.

The forward modeling is carried out using a Finite Element FE code (Abdelfettah, unpublished) that is based on Pohanka's algorithm (Pohanka, 1988). The vertical gravity attraction is computed by

$$g(r,\varepsilon) = -G\delta \sum_{k=1}^{K} n_k \sum_{l=1}^{L(k)} \Phi_{k,l}$$, where

$$\Phi_{k,l} = \phi(u_{k,l}(r), v_{k,l}(r), w_{k,l}(r), z_k(r), \varepsilon)$$

and r is the distance between the gravity station and the body. For further details see Pohanka (1988).

FE meshing was carried out in 2D and 3D using the gmsh's software (Geuzaine and Remacle, 2009). This meshing allows for approaching the geological geometry using tetrahedrons. Gravity stations are located on the topography. An example for the simulation of a complete Bouguer anomaly in 2D is shown in Fig. 1c. This approximate N-S section presents the typical geological setting of the Swiss Molasse basin, where the slightly bended Mesozoic sediments are inclined by about 2-5 ° towards the Alps and the Tertiary filling of the molasses basin is deepening following this geometry. It should be noted that in our model the thickness of the PC trough PC1 decreases from N (x=7 km) to S (x=12 km) by 750 m. The minimum thickness is located at about x=8 km.

As expected from geology, the computed Bouguer anomaly is strongly dominated by the gravity effect of the Tertiary fillings of the Molasse basin (Fig. 1a). It should be noted that the residual anomaly has been calculated using the data inside the model only and thus, the borders of the model are not representative.

The Butterworth filter and applications

Since the Bouguer anomaly is strongly dominated by the gravity effect of the Molasse sediments deepening towards the Alps, a code using Butterworth filter was developed and applied on the complete Bouguer anomaly to eliminate this trend (Butterworth, 1930). This filter is characterized and controlled mainly by two parameters: (1) cut-off frequency or wavelength and (2) the filter order. The advantage of the Butterworth filter is that we can easily use different wavelength to i) delineate and characterize different negative anomalies at depth, and ii) to choose an adequate residual anomaly which provides the comparable gravity response with the conceptual model. Depth and size of the origin of the anomalies are indicated among others by the wavelength of the filter. With increasing wavelength, we are able to visualize increasing larger or deeper structures until approaching the Bouguer anomaly (see Fig. 4). Moreover, the filter order parameter can be also changed to delineate a very small variation, for instance, in the case of low density contrast between the PC trough and the basement. With increasing filter order the horizontal density contrast is emphasized.

A residual anomaly obtained using high-pass Butterworth filter with wavelengths of λ = 30, 50 and 80 km applied to the Bouguer anomaly obtained from the 2D synthetic model using the density distribution of scenario 1 is shown in Fig. 1b. Since the regional trend is constrained only in the model, our discussion excludes effects observed at the borders of the model (km 0-2 and km 26-27 in Fig.1-3). In this example, the regional trend is best eliminated using a wavelength of λ = 80 km. Both wavelengths λ = 30 km and λ = 50 km overestimate it. The synthetic model shows that even so the regional trend obtained using a highpass filter with a wavelength of < 50 km is overestimated, the signature of both PC troughs can be observed in all three residual anomalies.
In the following, we will discuss features in the residual anomalies related to PC1 (see Fig. 1). It can be observed that the local minimum follows approximately the thickness of the PC filling, which has its maximum thickness at about x= 8 km. Using a wavelength of λ= 30 or 50 km, the minimum residual anomaly is located at around x=7 km, whereas when increasing the wavelength to λ=80 km, we observed best fit of the residual anomaly and the geometry of the trough structure. Furthermore, we observed that at this wavelength the residual anomaly is smaller in lateral extension compared to λ < 50 km and follows approximately the topography of the bottom of the trough. This may in comparison indicate that the top lateral extension is broader than the one at the bottom as provided in the synthetic model.
For the second scenario, the results of the sensitivity study are qualitatively similar (Fig. 2). The signatures of the residuals are very close to those obtained for the first scenario in terms of the shape and off course, its amplitudes are slightly smaller, since the density contrast between the PC trough and the basement (-100 kg m^{-3}) is smaller.

In the third scenario the density contrast between the PC troughs and the basement is set to -50 kg m^{-3}. As shown in Fig. 3b, both, PC1 and PC2 troughs are also identified by the residual anomalies. This implies that the chance to detect and delineate the PC troughs in Switzerland by gravity measurements in the real case study is given for deep seated troughs as PC2 as well as for low density contrasts as shown in scenario 3.

Real data application

A Butterworth filter with different wavelengths was applied to a low-enthalpy geothermal area near the city of Biel/Bienne in NW Switzerland. This area is well-known for complex structured PC troughs linked to the distribution of synclines and anticlines in the overlying sediments (A. Pfiffner, pers. comm.). Furthermore, a hot spring is located in the center of the anomalies. An interpretation of seismic section is provided (Fig. 4). Residual anomalies have been calculated for wavelengths between λ = 50 and 120 km. The filter with a wavelength of λ = 120 km reveals the minimum value of -6 mgal that can be related to the occurrence of the hot spring. With decreasing wavelength a major negative anomaly striking NE-SW persists indicating according to our sensitivity analysis a PC trough structure. Furthermore, in the center of the area of investigation a second E-W striking anomaly also persist through all filters. This structure

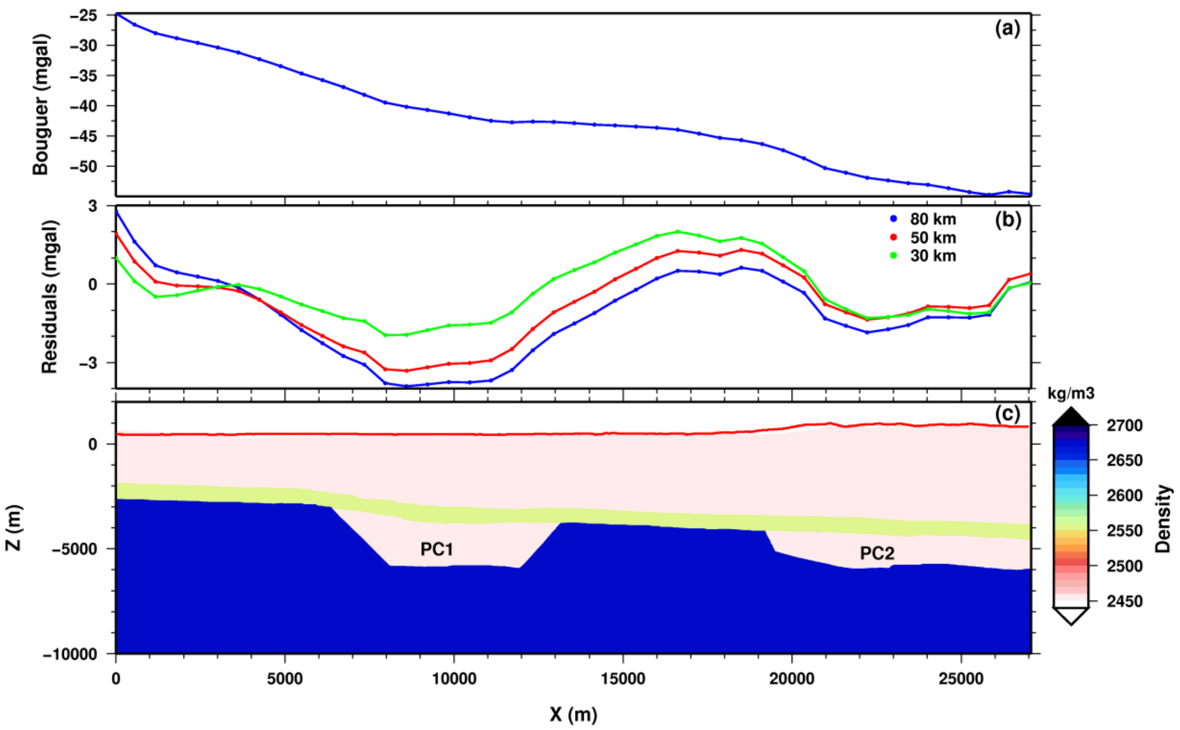

Fig. 1: a) Computed Bouguer anomaly. b) Residuals anomalies obtained using the Butterworth filter with wavelengths of 30, 50 and 80 km applied on the Bouguer anomaly shown in (a). c) The conceptual 2D geological model used to assess the possibilities for the gravity to characterize the PC troughs. This model presents the first scenario (further explanation see text), where the density of the PC troughs was set to 2450 kg m^{-3}.

coincides with one of the PC troughs in the interpreted seismic section.

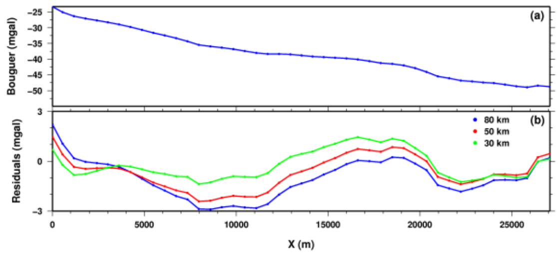

Fig. 2: The gravity response for the sensitivity study of the second scenario. a) The computed Bouguer anomaly, and b) residuals anomalies obtained using a high-pass Butterworth filter with 30, 50 and 80 km wavelength. PC1 and PC2 density is 2570 kg m^{-3}.

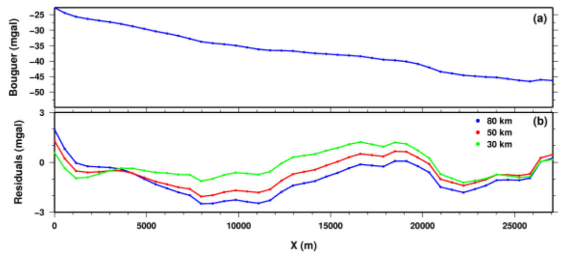

Fig. 3: The gravity response obtained from the model of the third scenario. a) The computed Bouguer anomaly, and b) residuals anomalies obtained using a high-pass Butterworth filter with 30, 50 and 80 km wavelength. PC1 and PC2 density is 2620 kg m^{-3}.

Conclusions

A very high potential for a gravity data to delineate the PC troughs in Swiss Molasse basin is shown and discussed. Filtered Bouguer anomaly using Butterworth filter with different wavelengths is an essential tool to detect and trace the horizontal and vertical extension of the PC troughs. The sensitivity studies on the conceptual geological models reveal that the negative anomaly related to PC troughs persists through the different steps of Butterworth filter with varying wavelength. The different wavelengths provide insight into different vertical levels of the trough and thus, allow describing 2½ D geometry of the graben structures. Finally, the application of the filters to real measurements reveals the distribution of the PC troughs in the area of Biel/Bienne in Switzerland. It, however, shows that the tracing of the geometry is more complex, since long wavelengths risk to take up also other more regional structures, such as in this case the deepening of the Molasse basin, which introduces a broader negative anomaly overlying the expected narrowing of the PC trough at depth.

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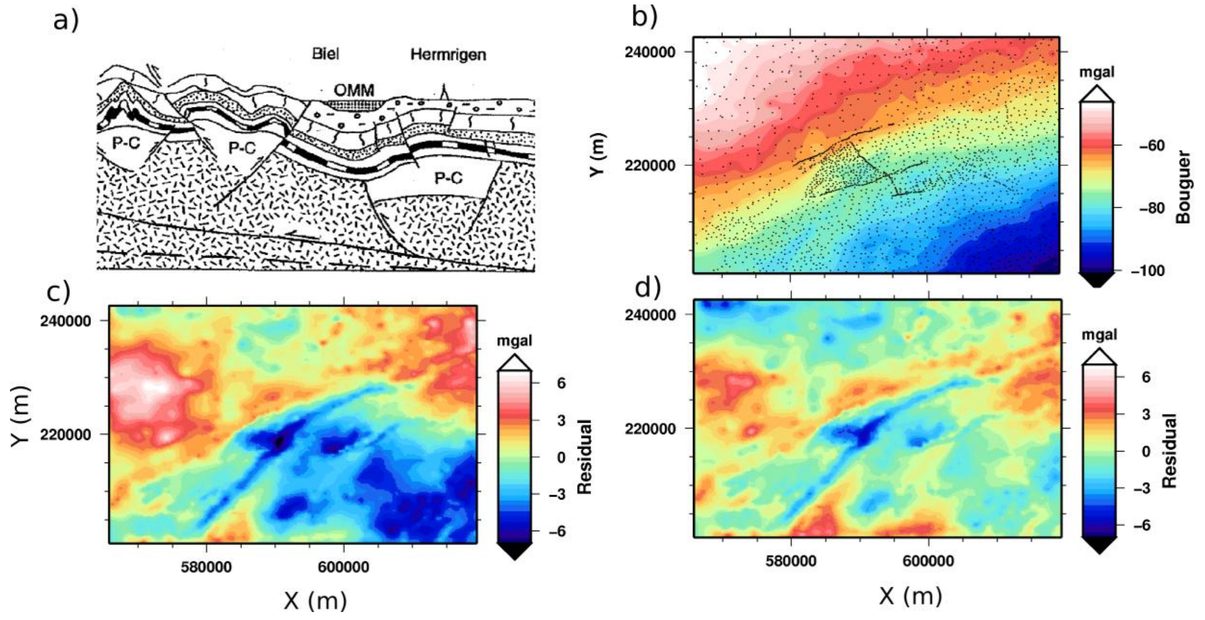

Fig. 4: a) Geological N-S section at about x=590000 across the city of Biel/Bienne (Pfiffner,pers. comm.). b) Bouguer anomaly for a reduction density of 2670 kg m^{-3}. c) Residual anomaly obtained using a Butterworth filter with λ= 120 km. d) Residual anomaly obtained using a Butterworth filter with λ= 50 km.

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