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THE ROLE OF STRUCTURAL CHANGES FOR GEOTHERMAL PROJECTS IN THE AREA OF BASEL

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ABSTRACT

A refined structural model of the area of the two geothermal sites of Basel and Riehen has been developed. In particular, gravity data have been analyzed for the structural setting in the crystalline basement and for zones of high fracturation in the investigation area.

The thermally relevant Permo-Carboniferous graben structures could be relocated. As a consequence of this, the geothermal wells of Basel and Riehen appear now to occur in a supposed hydraulically favorable situation at the rim of the trough structure.

The comparison of temperature and hydraulic conditions with further major heat flux anomalies in Switzerland reveal similar conditions for an enhanced thermal gradient of about 40 °C km^{-1}. The hydraulic field, however, seems to be mainly influence by Rhenian and re-activated Hercynian structures. This is shown by the permeability and tracer test analysis at Riehen, as well as the indication of high porosity along these types of structures.

A compilation of the structures in the areas of major positive heat flux anomalies in Switzerland shows that not only the Permo-Carboniferous troughs, but also the Hercynian structures are present in these areas.

INTRODUCTION

Along the German-Swiss border, on a length of about 350 km, the heat flux distribution (Figure 1) reveals several positive anomalies (Basel, Bad Zurzach and St. Gallen) in the same order as the one observed at the European EGS site at Soultz-sous- Forêts (>160 mW m^{-2}).

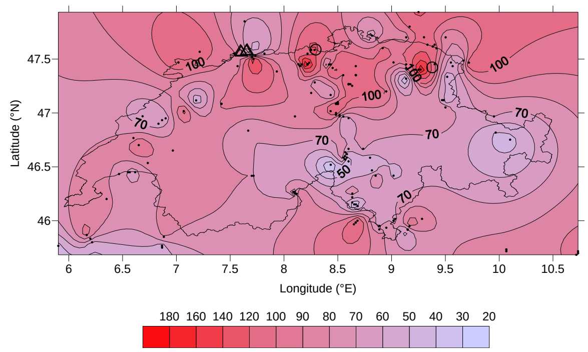


Figure 1: Heat flux map of Switzerland (after http://www.heatflow.und.edu) in mW m^{-2}. Small black dots: measurement points; open triangles: locations of geothermal wells Otterbach-2, Basel-1, Riehen-1 and Riehen-2; open dots: locations of Bad Zurzach and St. Gallen; black line: outline of the Swiss border.

The major heat flow anomalies in the Upper Rhine Graben at Soultz and Landau are found to be linked to hydrothermal convection in strongly fractured rocks including the basement (Bächler, 2003; Illies and Greiner, 1979; Kohl et al., 2000; Pribnow and Schellschmidt, 2000). Kohl et al. (2000) and Bächler (2003) have shown that the convection occurs along fault zones related to the tectonics of the Upper Rhine valley. This convection accounts to a large part for the temperature anomalies of these geothermal fields. The origin of the heat flow anomalies at the Swiss German border has been investigated by thermo-hydraulic modeling (Rybach et al., 1987) for the area of Bad Zurzach taking into account one of the main geological features, the Northern Swiss Permo-Carboniferous trough.

Structurally and geologically, however, two common regional features have been identified in the three areas, approximately ESE-WNW to SE-NW striking fault zones and Permo-Carboniferous graben systems in the crystalline basement. Both may have an important influence on the thermal field of these areas since they may account for deep fluid circulation.

The aim of this project is to characterize the geological and hydraulic conditions at the Basel site with and to set it into relation with the observations from the thermal anomalies at Bad Zurzach (Rybach et al., 1987; Schill et al., 2011) and St. Gallen.

REGIONAL GEOLOGICAL SETTING

The tectonic setting of the Basel area itself is dominated by being the southern edge of the Upper Rhine valley. The geothermal sites of Basel and Riehen are located at the Eastern boundary of the Upper Rhine valley with SSW-NNE-striking boundary fault. The main development of the Upper Rhine graben, a lithospheric extension taking place from the end of the Oligocene to that of the Eocene (Villemin et al., 1986),caused the formation of many small tectonic units. It is assumed that the Mesozoic sediments with the geothermally relevant Upper Muschelkalk in this area are highly fractured.

Towards the East of Basel a series of fault systems striking ESE-WNW to SE-NW propagates to the St. Gallen area. For example, the 20km long Vorwald fault (Figure 2) is assumed to be of Pre-Variscian age (Wirth, 1984). During the Variscian orogeny and Permian times the main fault systems such as the Vorwald, Wehr, Zeininger and Eggberg faults were active. After a period of inactivity during the Mesozoic, the faults restarted their activity.

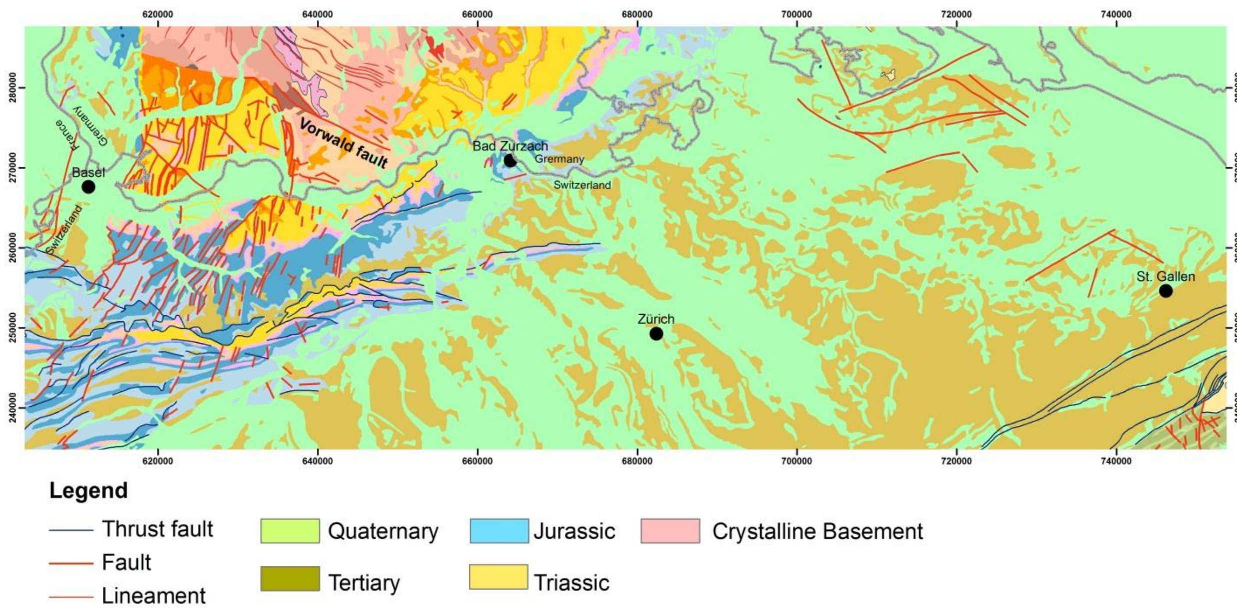


Figure 2: Geological map of northern Switzerland (Swisstopo, 2004).

Recent displacements are, however, observed at a prolongation of the Vorwald fault (5.5.2009 M 4.5 Schopfheim earthquake). This fault belongs to the same system as the Zurzach fault, which is known only from seismics and thus, its activity history is unknown.

The areas of thermal anomaly are characterized by another significant common tectonic feature: Permo-Carboniferous graben systems at the top of the crystalline basement. The relation between this type of trough structure and the thermal anomaly has been discussed on the basis of a coupled thermo-hydraulic model for the area of the Bad Zurzach anomaly (Rybach et al., 1987). They observe that the center of the thermal anomaly correlates with the center of the trough structure. Numerical modeling indicates that up-rising deep thermal water favors the creation of the thermal anomaly and that boundary faults of the through have a draining effect. The high basal heat flux indicates however that high permeability is necessary to several kilometers of depth. One of the open questions remains the role of the Vorwald fault, which could also account for the vertical up-flow of thermal water. The trough structures are complex grabens that extend over tens of kilometers in width. For example, the Northern Swiss trough reveals Permian to Stephanian basin fill (Matter et al., 1987) and a multiphase tectonic history (Diebold, 1989; Diebold and Noack, 1997): The subsidence in the

Stephanian to lower Permian goes along with the deposition of coal beds and bituminous shale in a WSW-ENE striking, probably transtensional, intermountain basin. Strong dextral transpressive deformation in the lower Permian involves major oblique fault systems (e.g. Vorwald fault). During subsidence at the end of the Variscian cycle Upper Permian sediments were deposited within and overlapping these structures. Reactivation occurred during Paleogene and early Miocene in relation with the opening of the Rhine graben and the subsidence of the Molasse basin. The extension of the Permo-Carboniferous graben in the area of Basel and Riehen will be discussed in the following. In the area of St. Gallen such a structure has been determined in the 3D seismic survey.

3D GEOLOGICAL MODEL

On the basis of an implicit approach, geology can be modeled using the location of the geological interfaces and orientation data from structural field and 2D cross-sections. Both types of data are co-kriged to interpolate a continuous 3D potential-field function describing the geometry of the geology (Calcagno et al., 2008; Lajaunie et al., 1997), in which the dip of the layers represents the gradient of the field. This approach is implemented in 3DGeomodeller (BRGM, Intrepid Geophysics).

In a first step, a 3-D geological model has been established on the basis of seismic section and borehole information. A number of 18 wells were used to constrain the model. In the area of the reservoir the existing 3D geological model of Dresmann (2010) has been modified according to the boundary conditions. Since only a few wells provide information on the extent of the Permo-Carboniferous graben systems in the crystalline basement, we did not include those structures in the geological model. The area was subjected to an E-W striking extensional tectonics and thus, major fault zones (Figure 2; Figure 3Figure 3) such as the Rheintal boundary fault of the graben, the Allschwiler fault zone and the broad Zeininger fault area are oriented approximately N-S (Laubscher, 2001; Laubscher, 2004). Along the Rheintal fault vertical offset of the Mesozoic sediments of about 1000 m starts and propagates towards the West over several fault zones, where these sediments are overlain by Tertiary filling of the graben (Gürler et al., 1987; Hauber, 1989). The fault reveals a dip of about 70° to the West. Details of the internal structure of the fault are unknown. The Allschwiler fault zone (to the West of the Rheintal fault) incorporates different faults dipping with 65 to 70° to the West with offsets in the order of 150 to 300 m. To the East of the Rheintal fault the Zeininger fault area is limited by the Zeininger fault dipping with 70° to the NW with a vertical offset of 400 to 500 m. Between this fault zone and the Bloond fault numerous parallel faults are observed.

There are different Hercynian faults revealing a WNW-ESE orientation comparable to the system including the Vorwald fault, such as Sierentz, Weil am Rhein, Rheinfelder fault. They are reactivated during Eocene to Miocene times.

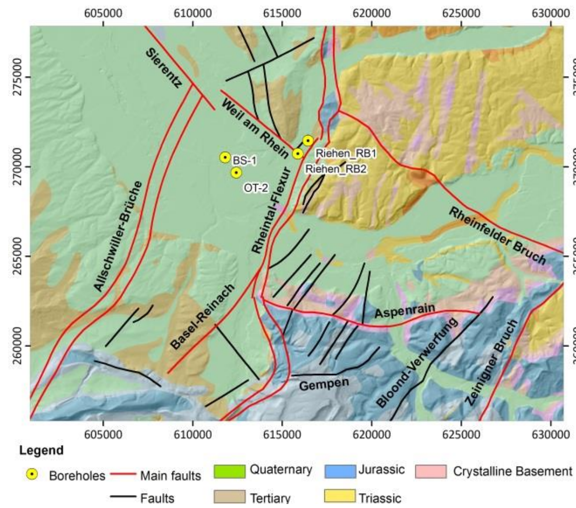


Figure 3: Geological map of the area of the geothermal sites of Riehen with the wells RB1 and RB2 and Basel with the wells BS-1 and OT-2. The fault zones are compiled from different studies (Delacou et al., 2009). Red: major fault zones modeled as fault zones cutting the entire geological model; black: minor fault zones modeled with finite depth extension.

The realization of the fault zones in the model is different for major (red: Figure 3) and minor faults (black: Figure 3). Major faults are represented as infinite structures with a constant mean offset. Such type of faults can only come to an end at another fault (Figure 4). Minor faults are represented using finite ellipses with a defined horizontal and vertical extension where the offset is a function of the fault geometry.

The stratigraphic pile was simplified. The modeled horizons are: Tertiary, Malm, Keuper, Upper Muschelkalk, Sulfate zone (Lower Muschelkalk and Buntsandstein), and the Basement including possible Permo-Carboniferous sediments.

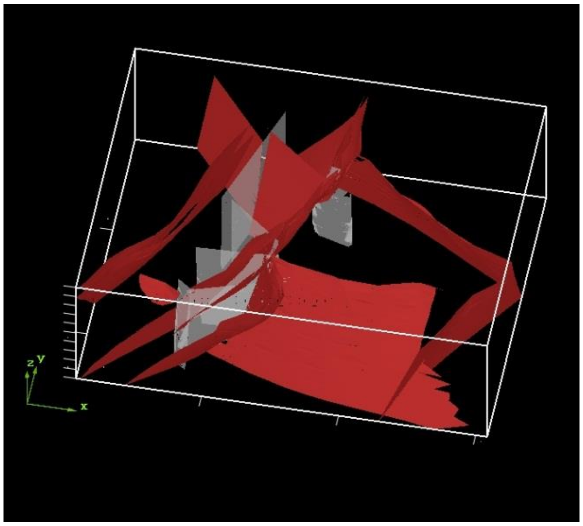


Figure 4: Fault model of the major faults represented in red as infinite faults with constant offset. White planes are used to increase the accuracy of the model. They do not appear in the final model.

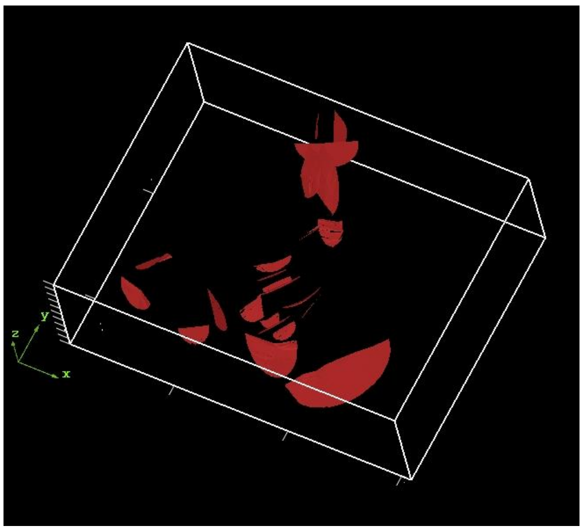


Figure 5: Fault model of the minor faults represented in red as finite ellipses.

VALIDATION OF THE MODEL USING GRAVITY

Determination of residual Bouguer anomaly

The data are compiled from three different sources. The Swiss data were obtained from the Gravimetric Altas of Switzerland (Dumont et al., 1994). This dataset has been used as a reference. Due to wrong coordinate transformation the French and German measurement points had to be relocated. A selection of 565 data points was used from the compilation of the Upper Rhine valley (Rotstein et al., 2006). A set of data was remeasured revealing differences for the different data sets of 1.69 mgal, -1.75 mgal and -1.82 mgal, which were corrected. A selection of 56 data points were taken from the LIAG database (FIS Geophysik). Those revealed a difference of 0.29 (±0.04) mgal, which was also corrected.

The Bouguer anomaly was obtained using the GraviFor3D code (Abdelfettah and Schill, subm.). A total of 1303 gravity measurements were treated to achieve the complete Bouguer anomaly. The data corrections applied to the observed gravity data is: free air correction, latitude correction, topographic and terrain corrections. The topography and terrain corrections were achieved using a digital elevation model with a resolution of 25 m applied to a radial distance of 1.5 arc degrees (~167 km) from the gravity stations. The topography was considered homogeneous with a density set to 2670 kg m^{-3}. To increase the accuracy, the exact formula, which allows computing the gravity effect of the prism, are used in the inner and near zones. The GRS80 (Geodetic Reference System, 1980) was used to carry out latitude correction (Moritz, 1980). The complete Bouguer anomaly is shown in Figure 6. Since the Bouguer anomaly is dominated by the regional effects of the Molasse basin and the Alps, the regional trend was eliminated from the complete Bouguer using a Butterworth filter (Butterworth, 1930). From a selection of wavelengths a residual of 100 km filter wavelength was chosen for further interpretation, since it reveals a dynamic and structures closest to the results from the gravity forward modeling of the 3D geological model. Both, gravity forward modeling of the 3D geological model and the residual anomaly are shown in Figure 7. The *densities used to complete gravity forward modeling are displayed in*

Table 1. The values were obtained from density logs of the boreholes Basel-1 and others in the vicinity of the area of investigation.

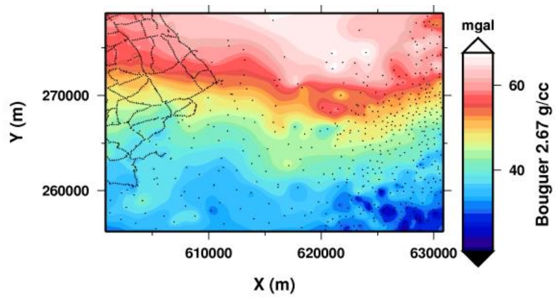
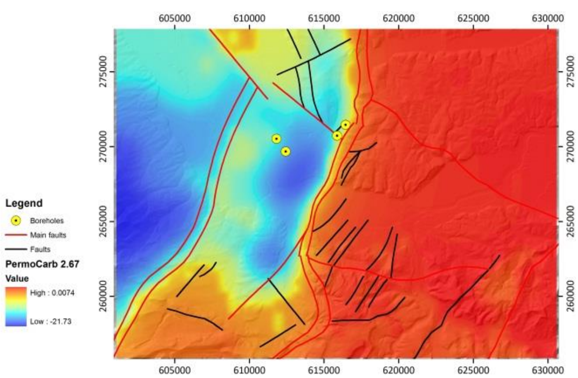


Figure 6: Complete Bouguer anomaly of the area of investigation obtained using GraviFor3D (Abdelfettah and Schill, subm.).

A)



B)

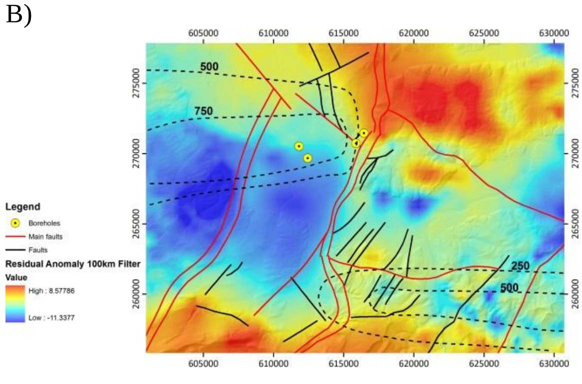


Figure 7: A) Gravity forward modeling of the 3D geological model without including the Permo-Carboniferous sediments. B)

Residual Bouguer anomaly with a Butterworth filter with a wavelength of 100 km. Black dashed lines: Thickness of the Permo-Carboniferous sediments below the base of the Mesozoic sediments (Ustaszewski, 2004).

Table 1: Density values used for gravity forward modeling.

Formation	Density (kg/m^3)
Tertiary	2050
Malm	2570
Keuper	2580
Muschelkalk	2670
Sulfate Zone	2580
Crystalline basement	2670

Interpretations of gravity

A large misfit between the gravity forward modeling and the residual anomaly becomes obvious already form qualitative comparison of the results displayed in Figure 7.

Two major observations can be made in Figure 7 B:

1) In the SE part of the area of investigation a series of small local negative anomalies can be observed between the Zeininger and Bloond faults, as well as E of the Rheintal fault between the Aspenrain and Rheinfelder fault.
2) The interpretation of the Permo-Carboniferous graben structures (Ustaszewski, 2004) shown in Figure 7 B, which is not included in the gravity forward modeling, do not correspond to the negative anomalies as expected from earlier studies (Klingelé and Olivier, 1980).

Both observations may be related to two different structural changes. First of all, we have integrated the Permo-Carboniferous sediments according to earlier interpretations (Ustaszewski, 2004) into the 3D geological model. This type of sediments is very little known in terms of lithology and petrophyiscal properties. In the area of Bad Zurzach, logs a mean density of 2300 kg m^{-3} and 2550 kg m^{-3} has been obtained from gamma-gamma logs and borehole gravimeter (BHGM), respectively, in the wells of Weiach and Böttstein for the Permo-Carboniferous sediments. This value has been confirmed by well gravity measurements and leaded to a density contrast of < -100 kg m^{-3} between the Permo-Carboniferous troughs and the crystalline basement (Klingelé and Schwendener, 1984).

A significant decrease of the misfit between gravity forward modeling and the residual anomaly can be obtained by attributing a density < 2300 kg m^{-3} to the Permo-Carboniferous sediments as observed in the gamma-gamma logs as shown in Figure 8. Our results reveal, however, that center of the Western part of the Permo-Carboniferous part (W of the Rheintal boundary fault) is located further to the South compared to the earlier interpretation (Ustaszewski, 2004). This is in agreement with the findings in the Basel-1 well, where no Carboniferous sediments have been encountered, and thus, it is likely that the well is located rather at the rim of such a graben structure and not in the center.

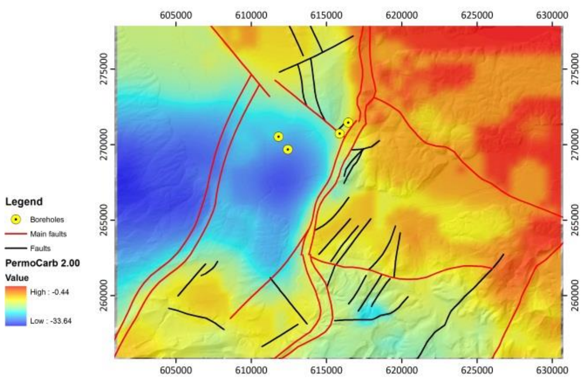


Figure 8: Gravity forward modeling of the 3D geological model including the Permo-Carboniferous sediments below the base of the Mesozoic sediments (Ustaszewski, 2004) with an attributed density of 2000 kg m^{-3}.

The more local anomalies, for examples between the Zeininger and Bloonds faults, may be related to the high degree of fracturation in this area. A simple relation between bulk and matrix density indicates the influence of porosity on the gravity changes in fractured environment (Figure 9). In the Soultz site inversion of gravity data has confirmed the approximately 8% of porosity in the reservoir zone by a reduction of density of about 250 kg m^{-3} (Schill et al., 2010).

Differences in gravity of about 10-20 mgal at a rather superficial level (in the first few hundred meters of depth) may correspond to a density change from about 2600 kg m-3 for the Mesozoic sediments down to in the order 2400-2500 kg m^{-3}. This corresponds to porosity in the order of 5-12%.

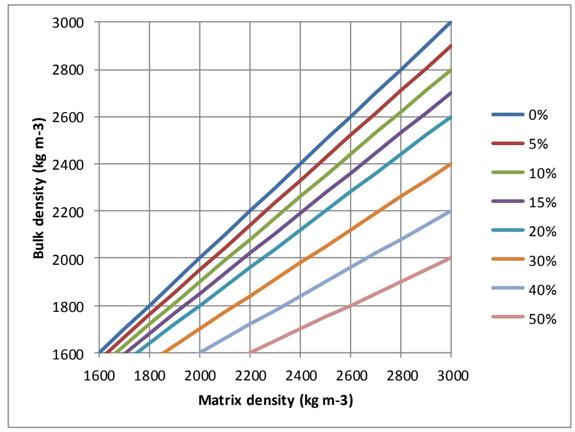


Figure 9: Influence of porosity on the bulk density of a rock. Legend shows the porosity change in percent.

TEMPERATURE AND HYDRAULIC PROPERTIES IN THE EXISTING WELLS

According to the findings in the coupled thermo-hydraulic models, the Permo-Carboniferous trough structures should have a strong influence on the heat flux distribution as well as on the hydraulic field (Rybach et al., 1987). In the area of Riehen and Basel the presence of a Permo-Carboniferous trough seems evident on both sides of the Rheintal boundary fault from both, borehole data and gravity. The center of the Western graben, however, seems to be more in the South of the previously predicted outline (Ustaszewski, 2004). This would lead to the fact that the existing wells Riehen 1 and 2 as well as Basel-1 and Otterbach-2 are located in the vicinity of the rim of the graben with rather permeable boundary faults (Rybach et al., 1987).

The thermal gradient in the wells is in the sediments in the order of 36-37 °C km-1 at Riehen and 41 °C km-1 at Basel-1 (Ladner and Häring, 2009). In the basement the gradient reduces to 27 °C km^{-1}. The temperature gradient in the sediments is comparable to the one observed in the well of Riniken and Weiach, which are located on top of the center of the Permo-Carboniferous trough, which is interpreted to be responsible for the heat flux anomaly in the area of Bad Zurzach.

A sequence of venting and injection tests (Figure 10) was performed in Basel-1 prior to the main stimulation exercise in December 2006. The main objective was to determine the undisturbed conditions of the system and its hydraulic parameters, the reservoir type, the formation pressure and to detect the presence of significant boundary conditions at the vicinity of the well (e.g., pre-existent fractures). The open borehole section represents a several meter thick cataclastic fracture zone at 4'691m and a further zone at 4'826m below surface. Both zones are affected by argillic alteration. In the fracture zone at 4'826m cataclasticly deformed anhydrite was observed with argillic altered plagioclase. These are interpreted by standard techniques. First, diagnostic plots are evaluated to ascertain the best possible conceptual model. Once this has been decided, hydraulic parameters are interpreted by fitting analytical solutions (e.g., Jacob, Papadopoulos-Cooper, etc.). Häring et al. (2008) report that, under the assumption of radial flow conditions, an average transmissibility of $\sim 5 \cdot 10^{-15}$ m^3 and an effective (intrinsic) permeability of $\sim 1 \cdot 10^{-17}$ m^2 were interpreted for the open hole section.

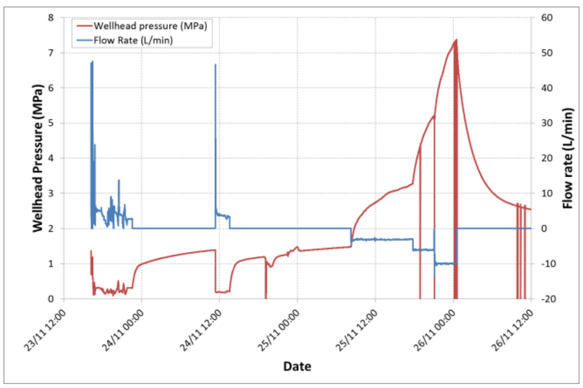


Figure 10: Hydraulic test in the open hole section of the Basel-1 well. The open hole section is located entirely in the crystalline basement over a depth of the open hole section (4629–5000m below surface) containing two major fractures zones.

Estimated hydraulic conductivity of about $5 \cdot 10^{-13}$ m s^{-1} are by 1 ½ orders of magnitude lower than expected for the deep crystalline in earlier thermo-hydraulic simulations. The hydraulic conductivities in the wells Riehen 1 and 2, $9 \cdot 10^{-5}$ m s^{-1} and $1 \cdot 10^{-4}$ m s^{-1}, respectively, are by two orders of magnitude higher. It is evident at Riehen, that the Rheintal boundary fault has a large influence on the hydraulic conductivity of the reservoir, although geochemical investigation suggests a contribution of influx of thermal water from the Permo-Carboniferous sediments. A recent tracer test indicates no direct hydraulic connection between the production and injection well. Thus, two possible reservoir situations can be discussed. One possibility is that both well are drilled into the same aquifer, which reveals a hydraulic flux from the production to the injection well, which is stronger than the flux from the injection to the production well. This hypothesis however would imply a hydraulic gradient and a direct pressure connection. The difference in hydraulic head between the two wells is about 1m could be interpreted as hydraulic gradient. The long-term pumping experiment also reveals draw down in the injection well. A second hypothesis is that the pressure is transmitted over a long distance, in this case over two parts of an aquifer, which are connected only through a far field. This hypothesis is supported by the observation that the fault of Weil am Rhein separate structurally the two wells, such as both each well belongs to a separate tectonic unit.

CONCLUSION

Heat flux anomalies in Switzerland have been related to the occurrence of Permo-Carboniferous graben structures within the crystalline basement.

Thus, a major task in this study was to locate the Permo-Carboniferous structures using gravity data. We have shown that gravity confirms the existence of such trough structures in particular on the Western side of the Rheintal boundary fault. Our data, however, suggest that this structure occurs further to the South than interpreted from the interpolation of borehole data.

Furthermore, gravity data have provided a first estimate of porosity changes within the Zeininger fault area. This reveals the probable hydraulic significance of such fault systems which are oriented parallel to the Rheintal boundary fault.

The relocation of the Permo-Carboniferous trough in the Basel-Riehen area has as consequence that both geothermal sites seem to be related to the boundary fault area of this trough system.

Compilation the thermal data reveal similarities to the Permo-Carboniferous trough in the area of Bad Zurzach. The hydraulic properties, however, seem to be governed by the more recent tectonic deformation in relation with the formation of the Upper Rhine graben (e.g. Zeininger fault area), as well as the re-activated Herzynian structures (e.g. Weil am Rhein fault zone), which are equivalent to the Vorwald fault.

In conclusion, we have refined the geology of the Basel-Riehen area and analyzed the structures, which may contribute to the hydrothermal flow in the Basel-Riehen area. We have also linked our findings to the regional distribution of heat flux in Switzerland and illustrated the similarity of tectonic structures. In the future we will mesh our geological model and carry out a more refined thermo-hydraulic modeling.

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