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MULTI-DISCIPLINARY PROSPECTION APPROACH FOR EGS RESERVOIRS IN THE GERMAN VARISCIAN BASEMENT

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ABSTRACT

The central and south German Variscian crystalline basement is considered to be the largest geothermal resource of Germany. The southern Black Forest is a representative example of this basement and has thus been selected for the investigation of exploration tools.

It is an issue, in particular for the geophysical exploration to image fractured zones and potential reservoirs in a basement environment at greater depth since seismic methods require complex and costly processing. Often they are anyhow limited to the topmost part of the basement. In the presented GKW project geological, geophysical and numerical methods have been combined in order to assess geothermally interesting structures in the Southern Black Forest.

A 3D geological model has been the base for spatial temperature prediction. Sophisticated structural methods such photogrammetric have completed the surface studies and used for assessing the different type on fault zones. Magnetotelluric studies were applied to investigate the deep structures and their distribution of electric conductivity, which has been shown to be a good indicator of thermal anomalies. The investigation of Bouguer anomalies may provide a link between the surface structures and the electric conductivity anomalies at depth.

Re-coupling between the different anomalies and the temperature model allows for identification of the optimal geothermal site in the investigated area from the point of view of the underground. In the same project a heat sink analysis has revealed also potential users with different temperature levels.

INTRODUCTION

The central and south German Variscian crystalline basement is considered to be the largest geothermal resource of Germany with an estimated utilizable energy of about 180'000 EJ in a depth of 3-7 km (Paschen et al., 2003). The Black Forest in southern Germany is a typical low mountains range of this Variscian basement. It extends from Karlsruhe in the North to the Swiss border in the South and forms the eastern shoulder of the Upper Rhine Graben system. The geothermal potential of the Southern Black forest is well documented in the surface heat flow, which reveals an anomaly of up to 140 mW m^{-2} in the area of Waldshut-Tiengen (Medici and Rybach, 1995). Utilization of the geothermal resources in the area for balneology purpose such as Bad Zurzach (Switzerland), with production rates of 10 to 23 l s^{-1} originating from an artesian spring (Sonney and Vuataz, 2008), are known since Romain times. It is supposed that this and other zones of artesian flow observed in different wells are related to fault zones, which provide pathways for deep circulation and are alimented in the southern Black Forest. A set of parallel WNW-ESE striking fault zones (Eggberg, Vorwald and Zurzach) can be traced from the surface in the Black Forest to the different wells in the northern part of Switzerland.

The probability of finding a productive reservoir in this tectonic context is related to geophysical methods, which are able to visualize the approximately vertical fault zones in the basement which are linked to open fracture zones. The geophysical exploration in the basement is a challenge, since the usually applied reflection seismics is often limited to the sedimentary cover and the top crystalline. The investigation of the inner structure of the crystalline basement requires at least special processing procedures and typically 3D seismic (e.g. Nyguen et al., 2009). Other geophysical methods such as gravity and magnetotellurics have been tested in the Soultz-sous-Forêts geothermal site. While magnetotelluric measurements have been able to image changes in electric resistivity due to the thermal anomaly only in the top part of the crystalline (Geiermann and Schill, 2010), a negative density anomaly in the deeper part of the granite has been obtained by inversion of gravity data (Schill et al. 2010).

It is the concept of the GKW project to combine geophysical and structural observations from the surfaces of shallow subsurface with the latter tow methods in order to investigate the fault systems in the Southern Black Forest. The aim of the GKW project is to develop an integrative prospection methodology for the Variscian basement in general. Thus, different geological and geophysical methods are validated for geothermal applications and combined with investigation of surface parameter such as heat consumer. In the following, we will focus on the presentation of the geophysical and geological prospection methods.

GEOLOGICAL SETTINGS

The area of investigation is separated by important faults into different structural units (Figure 1). In the western part, the outcropping granite of the Black Forest in the N is separated to the S by the Kandern fault. South of it we find the Dinkelberg unit, which is part of the Jurassic sediment unit (Geyer et al., 2003). To the E of the Dinkelberg unit is separated from the crystalline basement by the normal fault zone of Wehr. In this part the basement is subdivided into different units, SW from the NW-SE striking Vorwald fault we find the Vorwald unit and to the NE the Hotzenwald unit. In the eastern part of the area we find an increasing thickness of the overlying Mesozoic to Tertiary sediments.

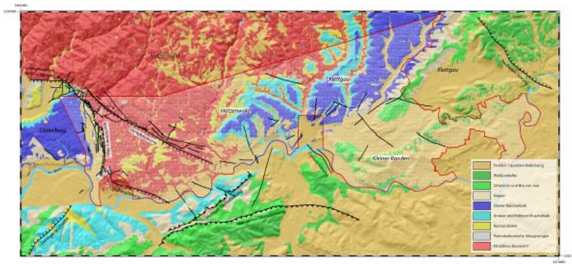

Figure 1: Geological map of the area of investigation (red surrounded) in the German southern Black Forest with the principal faults (after Gautschi et al., 2008).

The crystalline basement includes a Pre-variscian to Variscian poly-metamorphic gneiss complex (Geyer et al., 2003). It is part of the Moldanubic zone.

The main fault systems and their activity periods are shown in Figure 2. The fault systems in the area reveal mainly Hercynian and Rhenian strike directions with the ESE-WNW striking Vorwald and Eggberg faults and the N-S striking normal fault system of Wehr, respectively. The 20km long Vorwald fault is separated at its southern end into different en-echelon structures near Albbruck (Huber, 1984). The age of the fault is assumed to be Pre-Variscian (Wirth, 1984). Indication for a SSW directed normal faulting are assumed to be of Eocene and up to Oligocene age (Metz, 1980). A displacement of the Quaternary sediments is not observed, thus it is seems to be currently inactive (Diebold, 1991). Recent displacements are observed, however, at the Kandern fault which is a prolongation of the Vorwald fault (5.5.2009 M 4.5 Schopfheim earthquake). The thickness of the fault can be estimated in the northern part by 100m.

During the Variscian orogeny and Permian time the main fault systems were active, such as the Vorwald, Wehr, Zeininger and Eggberg faults. After a period of inactivity in the Mesozoic, the faults restarted their activity. During this time the major thrust faults appear such as the Mettauer and Mandacher thrust faults.

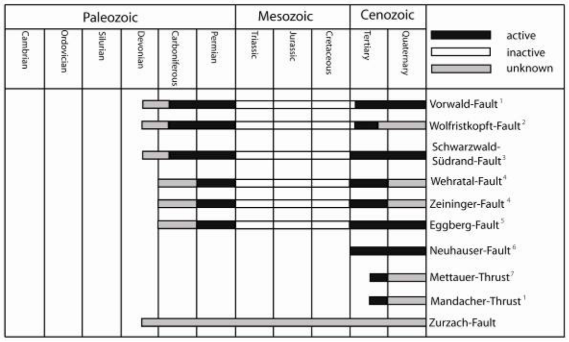

Figure 2: Age and main activity phases of the major fault systems in the area of investigation. 1. (Diebold, 1991), 2. Parallel to the Vorwald fault with similar activity, 3. (Zimmerle, 1958), 4. (Laubscher, 1982), 5. (Huber, 1984), 6. (Müller, 2002), 7. (Thury, 1994).

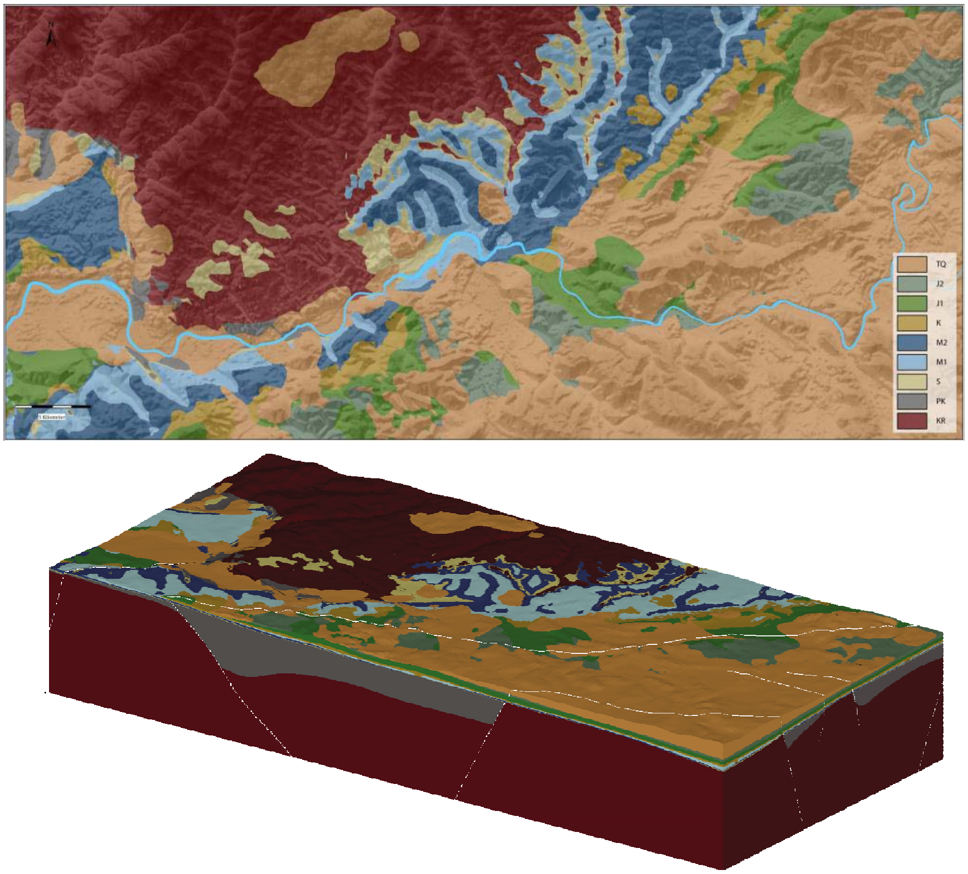

Figure 3: a) Top view of the 3D geological model of the area of investigation. TQ: Tertiary/Quaternary sediments, J2: Upper Malm, J1: Jurassic sediments, K: Keuper sediments, M1: Upper Muschelkalk, M2: Muschelkalk, S: Buntsandstein, PK: Permo-Carboniferous sediments, KR: crystalline basement. b) 3D view from SE.

Offsets in the terraces of the Rhine River indicate a Quaternary extension tectonic along the Rhenian striking faults in the Dinkelberg unit (Haldimann, 1984). In the southernmost Black Forest there is indication for displacements along the faults with Hercynian direction, revealed by the earthquake of Schopfheim. It should be mentioned that the morphology in the Hotzenwald follows the active fault zones.

3D GEOLOGICAL MODEL

In a first step, a 3-D geological model has been established on the basis of seismic section and borehole information using 3 D Geomodeller (Intrepid) considering the location of the geological interfaces and orientation data from structural field. In this implicit approach, both types of data are co-kriged to interpolate a continuous 3-D potential-field scalar function describing the geometry of the geology (Lajaunie, 1997).

The database used for the geological model contains 44 wells between 125m and 2482m depth (8 of those are >1000 m deep) and 27 seismic sections (references are given in the final report Schill et al., 2011).

The final 3D geological model is shown in Figure 3. It is in good agreement with the geological surface map (Figure 1).

3D TEMPERATURE DISTRIBUTION

A finite element (FE) discretization of the 3D geological model was carried out using the mesh generator WinFra Version 086v4 (Kohl et al, 1993). This discretization is based on a CAD processing and automated pre-processing. In this semiautomatic procedure, a first 2D discretization of the geological layers is executed, which is in the following vertically extended to a 3D space. The 3D geological model is finally described in a FE mesh consists of roughly a half million elements and nodes.

The theoretical base of the numerical code Hex-S (Kohl and Mégel, 2005), which has been used to predict the temperature distribution in the deep underground of the area of investigation, is shortly described in the following:

In a first step it is assumed that only diffusive heat transport processes such as heat conduction and production contribute to the distribution of temperature at depth. The influence of 3D topography and transient terms such as the ice-age effect is included. The surface temperature and basal heat flow are treated as Dirichlet and Neumann boundary conditions, respectively. It should be mentioned that the basal heat flow is not assumed to be uniform, but has been inferred from the petrophysical and temperature data of the wells.

The following temperature information from deep wells was used to calibrate the temperature model (Figure 4).

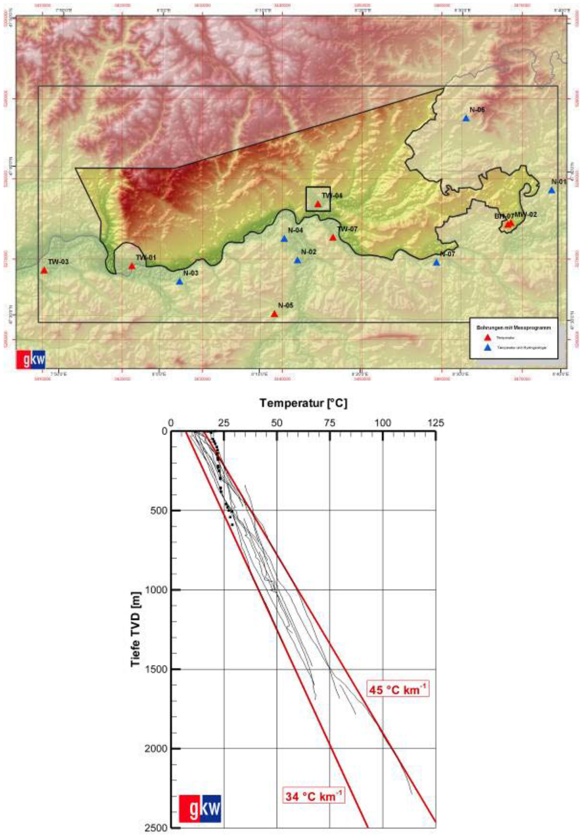

Figure 4: top: Topographic map with the geographic distribution of the deep wells in the area of investigation. Bottom: Summary of the temperature information revealing an enhanced geothermal gradient.

The temperature model has been calibrated using the temperature from the wells shown in Figure 4. In general a good agreement between those and the model has been observed.

The simulated temperature distribution in 5 km depth (Figure 5) reveals a variation between 165°C and 205°C. The trend from lower temperatures underneath the Black Forest in the NW and higher temperatures underneath the Molasse basin can be explained by the influence of topography and the sedimentary cover, which has a lower thermal conductivity compared to the crystalline, as well as the changes in basal heat flow over the area.

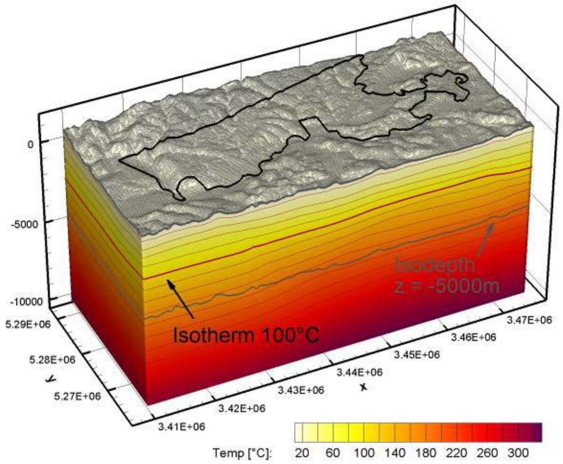

Figure 5: Simulated 3D temperature distribution with 5000 m depth plane (4-times vertically exaggerated).

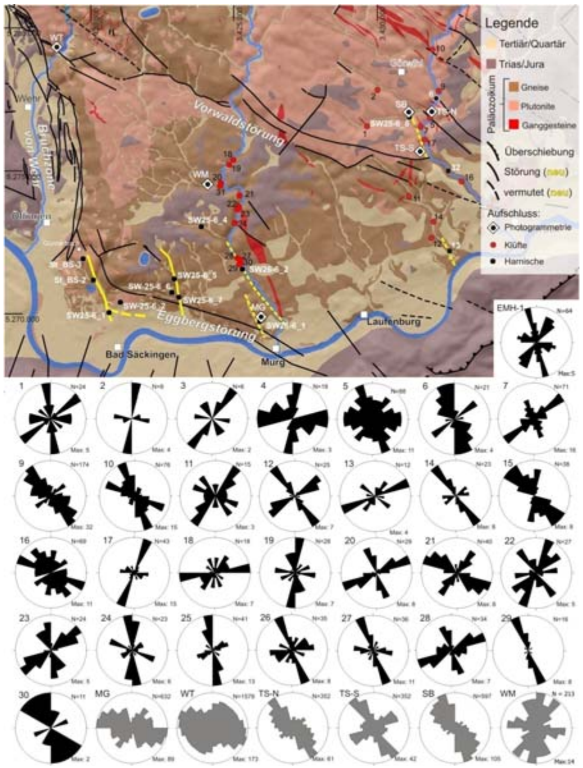

Figure 6: Fracture orientations measured in the Vorwald and Hotzenwald units (grey plots are results from photogrammetric investigation.

DETAILED STRUCTURAL INVESTIGATION

Different structural investigations have been carried out along the major fault systems in the area of investigation. They are summarized in Figure 6 with their respective observed fracture orientations.

In the following we will discuss an example for the investigation of the internal structure of the Vorwald fault system, since this is the fault, which is the most prominent in the later geophysical imagine.

Apart from the description of the orientation or distances between the fractures in a fault system, photogrammetric studies may be used for quantification of the fracture density. A number of 1’600 planes were identified and analyzed for their orientation (Figure 7).

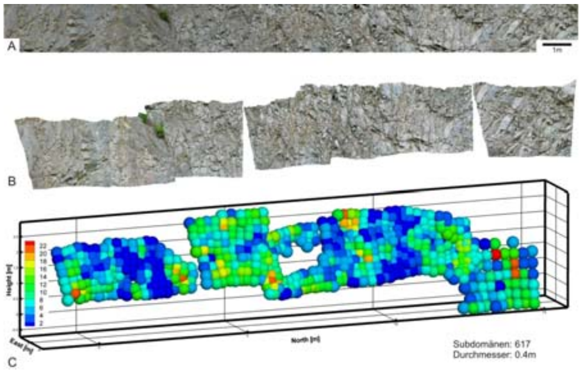

Figure 7: Strongly deformed rock at the northwestern edge of the Vorwald fault. a) orthographic projection, b) geo-referenced digital model, c) color-coded fracture density.

In order to assess possible heterogeneities in the fracture distribution the fracture planes were counted in single sub-domains (Drews & Deckert, 2008). In contrast to the fracture densities in other fault zones of the investigated area, in this case a strong density is observed. That may be related to the position of the outcrop, which belongs to the Vorwald fracture system and is close to the Wehratal fault zone.

THE DEEP UNDERGROUND INVESTIGATED BY MAGNETOTELLURICS

Magnetotelluric measurements aim to assess among others the distribution of the electric resistivity in the subsurface. The electric resistivity has also been assessed in different wells in the investigated area. For example, in the well Kaisten a decrease in electric resistivity from 20’000 Ωm to less than 50 Ωm was could be related to a zone with high fracture density. In the case of large fractured zones with more than 100 m thickness the resistivity of the surrounding volume can be reduced significantly.

In earlier magnetotelluric studies, the focus of depth of investigation was at about >10s (Teufel, 1986, Tezkan, 1994, Cerv et al., 1992). Increasing noise towards the N into the more granitic part of the Black Forest has been observed (Teufel, 1986). Large-scale correlation of noise and between the electric and magnetic components are observed, which limits the interpretation of AMT data with periods between 0.001 s to 1 s. Electric current channeling in the sediments of the nearby Upper Rhine valley may have a particular influence on the data acquired in the investigation area (Albouy 1981). Furthermore, a crustal high conductive layer has been identified in a depth of 12 km (Tezkan 1994). In high resistive environment such as the Black Forest noise can be distribute very far.

The signal to noise ratio could be reduced using remote referencing, since the undisturbed natural part of the induced magnetic field at intermediate latitude is homogenous, local artificial noise can be extracted from the measurements. The remote stations were located at a distance of about 200 km near Kempten and at a distance of about 1000 km at the island of Rügen. A delay line filter was applied to filter out the 16 2/3 Hz and its harmonics. For longer periods unfiltered data were used. These datasets were filtered again with a band pass filter and referenced with the two remote sites. Good quality transfer functions were selected for robust stacking which resulted in a smoothing of the functions (Figure 8).

A 2D Inversion was carried using the sites along an SW-NE striking profile across the Vorwald fault (Figure 1). Thus, a regional coordinate system was chosen, which corresponds to the major strike direction. This defines the TE and TM modes. In a first approximation the strike direction is set to N118°E and the rotation angle is N28°E. Thus the XY polarization corresponds to TM and YX to TE.
After the rotation to N28°E, strong static shift is observed in several sites. Both, manual correction and non-corrected transfer functions were inverted separately. In the latter case during inversion best fit for the phase was searched. In Figure 9 an inversion result for a weak regularization leading to a RMS of 1.2, which is considered to be well fitted.

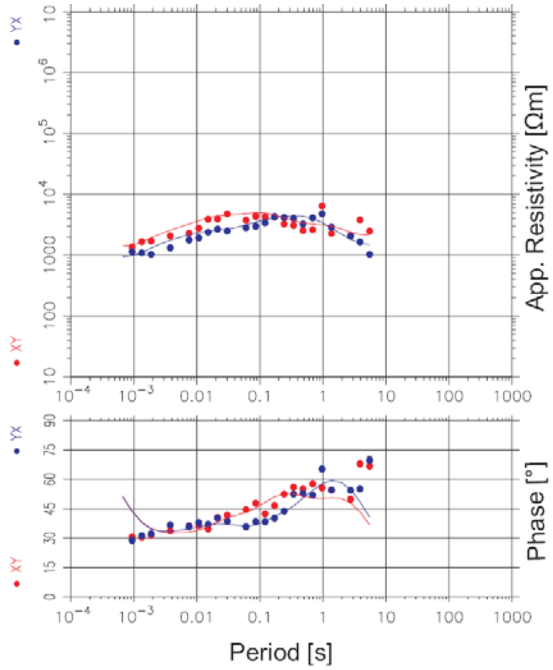

Figure 8: Transfer functions of site 103 after all processing steps described in the text.

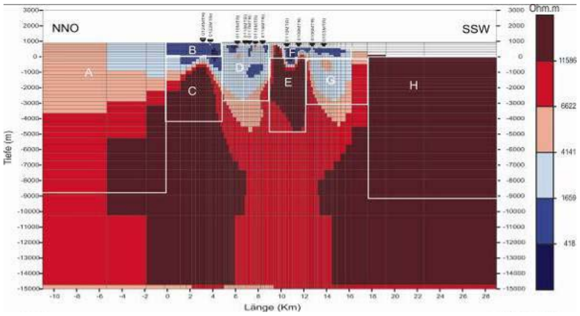

Figure 9: Inversion result of the electric resistivity using best quality stations (no static shift correction). Weak regulation ($\tau = 1.5$, $\alpha = 1$, $\beta = 3$) leads to a less smooth result and a good data fit (RMS = 1.2).

The inversion results are similar for the two procedures and reveal small inhomogeneities at the near-surface (B, F) of several 100Ωm as well as an area of a few 1000Ωm (D), which reaches a depth of about 3.5km. The area D is limited to the NE and SW by two units with resistivities of more than 10’000 Ωm (C, E). South of zone C, a zone of few 1000 Ωm (G) is located. These resistivities (C, E, G) in contrast to the others, however, are strongly dependent on the selection of the boundary condition. In conclusion, a clear interpretation of the deep subsurface is not evident at this stage. The areas B and F can be probably related to thin sedimentary layers on top of the crystalline. The area D corresponds to an area, where the crystalline basement outcrops at the surface. The Vorwald fault, however, passes the boundary between the sections D and E, which reveals large electric resistivity contrast.

EVALUATION OF GRAVITY DATA

For the evaluation of the gravity data, the dataset of swisstopo was used. It is published in the Swiss gravity atlas (Olivier et al, 2010). For the topographic correction of the gravity data the following procedure was applied. Above the reference ellipsoid prisms of z x 23 m x 23 m have been used, where z is the elevation above the ellipsoid. For each measuring point the gravity effect of all prisms was calculated. This was carried out for a density of 2’670 kg/m^3. The following anomaly was obtained for the area of investigation (Figure 10).

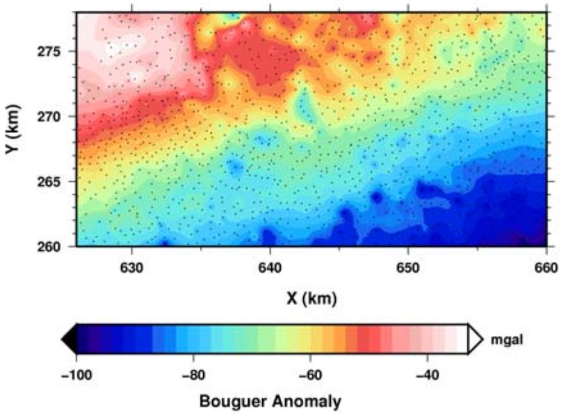

Figure 10: Bouguer anomaly of the SW part of the area of investigation.

To compare the measured Bouguer anomaly with the results from the geological model, a forward modeling was carried out using the software 3D Geomodeller.

In a large part of the modeled area the anomalies correspond to the observed gravity data (Figure 11). The dynamic of the anomalies, however is different in the to results. A difference can be observed for the Dinkelbergscholle, which reveals a more moderate anomaly in the forward modeling compared to the relatively positive anomaly in the measured data.

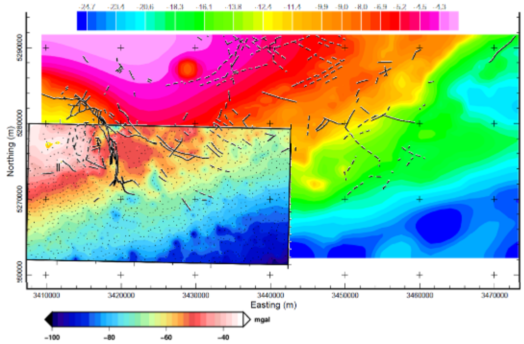

Figure 11: Bouguer anomaly of the SW part of the area of investigation.

The comparison between the fault structures and the measured gravity anomaly shows that along the fault zones the Bouguer anomaly is rather variable. It is minimal (about -75 mgal) close to the area where the Wehratal and the Vorwald fault zone cross each other.

DICUSSION AND CONCLUSION

The investigation of the deep underground using magnetotelluric methods was carried out across the Vorwald fault. It reveals a strong change in electric resistivity at the Vorwald fault. A very low resistivity in the order of a few Ωm, which is typical for geothermal reservoirs, e.g. at Soultz-sous-Forêts (Geiermann and Schill, 2010) is not observed along the profile.

The distribution of Bouguer anomalies reveals strongest negative values in the NW edge of the Vorwald fault system. It is well-known that enhanced porosity reduces the density and thus affects the Bouguer anomaly. This corresponds to the observations in the structural studies along the different fault systems, where this area reveals highest fracture density. The second largest density minimum in the central part of the Vorwald fault close to the magnetotelluric profile has not been investigated structurally due to the absence of outcrops. A magnetotelluric investigation of the area of largest density anomaly has not been carried out.
It can be concluded that at the current stage of the project the NW edge of the Vorwald fault seems to be the most appropriate location for a geothermal site from the geological and geophysical point of view.
The temperature distribution in the investigated area however would favor either the Wehratal valley or the opposite side of the mountain range towards the Swiss border. In both areas temperatures at 5km depth in the order of about 180°C are predicted by the numerical simulation.

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