

## DEEP TEMPERATURE EXTRAPOLATION IN THE SOULTZ-SOUS-FORÊTS GEOHERMAL AREA USING MAGNETOTELLURIC DATA

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### **ABSTRACT**

An indirect electromagnetic geothermometer is used for the deep temperature estimations in the Soultz-sous-Forêts (France) geothermal area using magnetotelluric (MT) sounding data collected along West-East profile in 2007-2008. Validation of the temperature assessment using MT data is fulfilled by retro-modeling, i.e. by comparison of the forecasted temperature profile with real temperature logs from GPK2 geothermal borehole for two depth ranges 2000-3878m and 3878-5046m as if it was done before appropriate drilling. The relative forecast error for the extrapolation from the upper 2km to the depth range up to 3878m was 1.8 %, while in the latter case it was equal to only 0.4%.

Deep temperature forecast is provided for the well GPK2 up to the depth 8175m. The analysis of the profile beneath 5000m indicates that its behavior continues to be of the conductive type (as in the depth range 3500-5000m) up to the depth 6000m, while manifesting mixed conductive/convective type in the depth range 6000-8000m, which, in turn, may indicate the localization of the fluid circulation paths at these depths.

The temperature forecast up to the depth 2500m is carried out for defining the best location for the new geothermal well planned to be drilled in the Rittershoffen area. It is shown that application of the indirect electromagnetic geothermometer constrains the decision on the location of the new borehole. In particular, it indicates that deepening of the available borehole RT3 or drilling in the SE direction from RT3 could be the best alternative from the temperature point of view.

Finally, deep vertical temperature cross-section is constructed up to the depth 5000km for the profile starting from the borehole 4616 in the NW and

ending by the boreholes RT1 and RT3 in the SE. It manifests two local temperature maxima at the depths larger than 5km to the NW from the GPK2 and to the SE from RT3 boreholes the latter being bigger.

### **INTRODUCTION**

A number of the geological, geophysical and geochemical studies are provided in the Soultz-sous-Forêts geothermal zone (Genter et al., 2009) in the framework of the EGS project. The temperature distribution in this area is one of the most important parameters both at the exploration and exploitation stages. The knowledge about the temperature distribution comes from the temperature well logs, so, its values in the domains between the boreholes are usually assessed by means of the interpolation of the temperature logs or determined from the heat flow gradient data by routine mathematical tools, which often results in rather crude estimations (especially, in the geothermal reservoir, where the temperature is unstable during the exploitation process). The situation could be improved to some extent by using more sophisticated neural network based approach (Spichak, 2006), but it does not help too much in the case of extrapolation of the temperature logs, in particular, to large depths.

Meanwhile, the connection between the electrical properties of the earth rocks and the temperature enables to study the geothermal areas using electromagnetic (EM) sounding data (Spichak and Manzella, 2008). In particular, the use of an indirect electromagnetic geothermometer developed recently (Spichak, Zakharova, 2008; Spichak et al., 2007a,b, 2009) allows high accuracy temperature estimation in the Earth crust basing on the ground electromagnetic data and available temperature well logs used for the EM thermometer calibration. The goal of our studies was to provide deep temperature estimations in the Soultz-sous Forêts geothermal area using indirect EM geothermometry.

## GEOLOGICAL SETTING

The Soultz horst geothermal area is located within the Upper Rhine graben (Figure 1) which forms a part of the European Cenozoic rift system that extends in the foreland of the Alps from the Mediterranean to the North Sea coast. The Moho which is the boundary between the Earth's crust and the mantle shows a topography of its depth thickness with a doming structure below the Rhine graben.

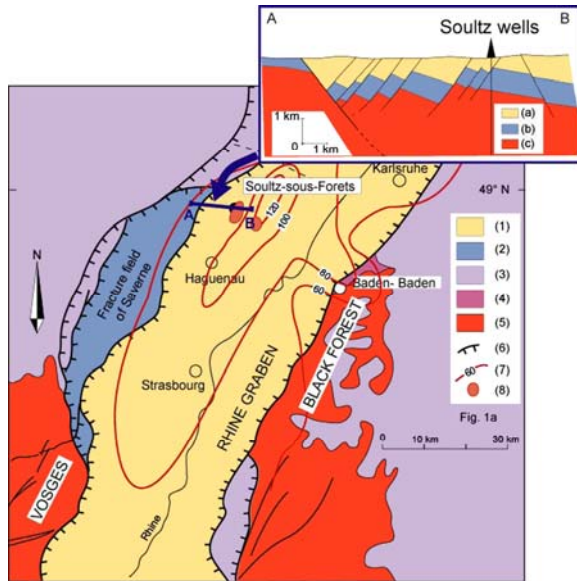


Figure 1: Location of the EGS Soultz site and geology of the Upper Rhine Graben: (1) Cenozoic sediments, (2) Jurassic, (3) Trias, (4) Permian, (5) Hercynian basement, (6) Border faults, (7) Temperature distribution in °C at 1500m depth (Haenel et al., 1979), (8) Local thermal anomalies (Haenel et al., 1979). Simplified cross-section through the Soultz site: (a) Cenozoic filling sediments (b) Mesozoic sediments, (c) granite basement (after Dezayes et al., 2005).

The sediments are made of Cenozoic and Mesozoic formations (Triassic to Middle Jurassic) lying on a Hercynian basement of porphyritic Soultz Granite (Figure 2). Both Mesozoic rocks and granite are affected by a series of subvertical North-South normal faults dipping westward or eastward. Two major tectonic phases have been recognized in the Rhine graben: an initial North-South compression (Eocene) is followed by an important East-West Oligocene extensional phase. The latter is responsible for most observed structures and the actual geometry of faults and layers. Actually, Soultz granite has undergone a complex tectonic history and many fault activations occurred (Dezayes et al., 2010).

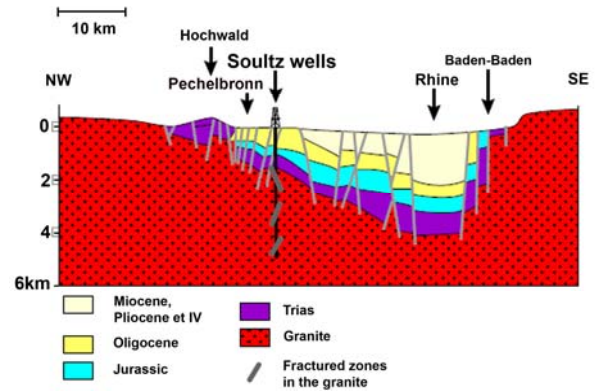


Figure 2: Schematic geological NW-SE cross-section of the Upper Rhine graben area (after Le Carlier et al., 1994).

The geological mapping, borehole data and interpretation of seismic profiles coming from previous oil field exploration provide a good basement for building a 3D geological model of the sedimentary cover (Renard and Courrioux, 1994), characterizing the major fault system which has a N20°E strike (Dezayes et al., 2010) (Figure 3).

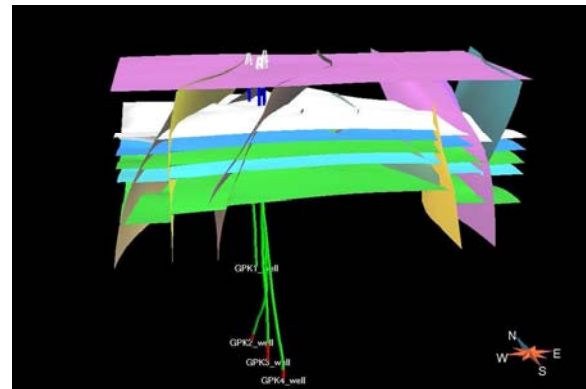


Figure 3: 3D model of the sedimentary cover (Renard and Courrioux, 1994) with the implantation of the Soultz wells (after Dezayes and Genter, 2008).

## PAST TEMPERATURE ASSESSMENTS

During oil exploration, numerous temperature measurements have been made in the Pechelbronn oil-bearing region (Haas and Hoffmann, 1929). Based on approximately 500 measurements, this old study shows that isotherms are influenced primarily by the tectonic structure of the Rhine graben (Figure 4).

At the hottest zone at 400 m depth is located along the western part of the Soultz horst and is characterized by NE-SW elongation (Haas and Hoffmann, 1929). It is remarkable that the configuration of the temperature contours at the depth 1500 m (Figure 1) is similar to those at the depth 400m with the extremum located in the Soultz area

and seem to be attributed to the fault saturated by hydrothermal fluids (Haenel et al., 1979).

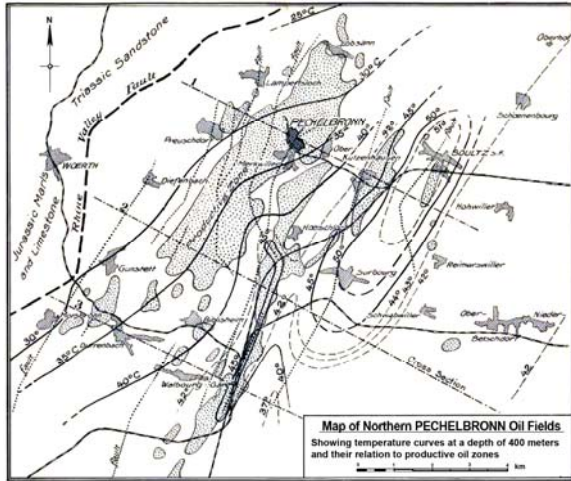


Figure 4: Temperature map done at 400 m depth based on data collected in oil wells between Merckwiller and Sultz (after Haas and Hoffmann, 1929).

It is worth mentioning in this connection that the temperature contour maps are constructed at different depths mainly by linear interpolation of the temperature records available at that depth from a number of boreholes (Haas and Hoffmann, 1929; Haenel et al., 1979; Pribnow and Schellschmidt, 2000). Under the conditions of irregular distribution of the wells in the studied area and different depth ranges, where the temperature records are available (often very few) it is practically impossible to draw reliable vertical temperature cross-sections especially for the depths exceeding the depths of the drilled boreholes.

The only example known from the literature concerns the vertical temperature cross-section for the profile crossing the Upper Rhine graben area from West to East reconstructed by Pribnow and co-authors (Pribnow and Schellschmidt, 2000; Pribnow and Hamza, 2000) by projecting to the vertical plane the 746 temperature values from 174 boreholes distributed in the 20km - vicinity from each side from the cross-section (Figure 5).

Despite this cross-section gives a general idea about the vertical temperature distribution in the Upper Rhine graben area up to the depths 1500-2000m, the accuracy of such temperature reconstruction for the Sultz area is doubtful, since it is implicitly based on the assumption on two-dimensionality of the temperature distribution in the W-E direction in the regional scale (at least, along 40 km), which is not justified by any facts. In contrary, the temperature map for the depth 800m provided in (Pribnow and Schellschmidt, 2000, Figure 1) clearly indicates that

the temperature contours do not manifest two-dimensionality 20 km apart the NW-SE profile crossing Sultz. Moreover, the maximal depth of the temperature contours is restricted by the lengths of the used boreholes (in the most cases bounded by 1500-2000m) (Figure 5). So, in order to get more reliable temperature estimations for the Sultz geothermal area, in particular, at large depths, we have to consider alternative ways.

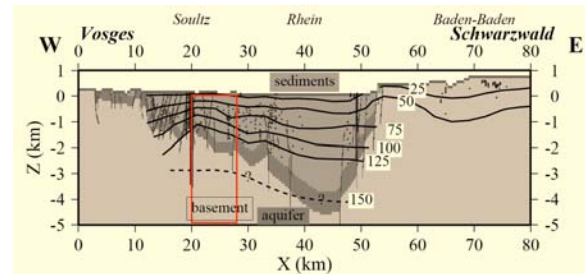


Figure 5: Temperature contours in the Upper Rhine Graben area revealed from borehole data. Subvertical structures are fault zones. The projected temperature data positions are marked with dots (746 values from 174 boreholes). Temperature contours are labeled in °C. The 150°C is dashed because these high temperatures have only been measured at Sultz (X=20 km) (after Pribnow and Hamza, 2000). The red rectangle bounds the studied area.

## INDIRECT GEOTHERMOMETRY

Temperature dependence of electrical conductivity of rocks enables its use for estimating the temperature profiles in the earth basing on the information about the conductance mechanisms and hypotheses on the rock thermal conductivity. However, complex inhomogeneous structure of geothermal areas and lacking information about their properties allow construction of only very coarse temperature models based on assumptions regarding the electrical conductance mechanisms. Meanwhile, if any wells with known temperature profiles are available, indirect estimation of temperature spatial distribution from the surface magnetotelluric measurements is possible (Spichak et al., 2007a). Its application enabled to get deep indirect temperature estimations in Bishkek seismically active zone of the northern Tien Shan (Spichak et al., 2007b) as well as in the Hengill geothermal area, Iceland (Spichak and Zakharova, 2009a,b).

Indirect electromagnetic geothermometer is based on the measurements of electromagnetic data at the Earth's surface, construction of vertical profiles of specific electrical resistivity, and further temperature estimation based on the artificial neural network (ANN) calibrated on the basis of the correspondence

between the calculated values of specific electrical resistivity and borehole temperature records (Spichak and Zakharova, 2008, 2009b).

### MAGNETOTELLURIC SOUNDING

In order to get the resistivity profiles required for ANN training we have used the results of MT sounding carried out in 2007-2008 along the 13km length W-E profile crossing the Soultz area (Schill and Geiermann, 2008) (Figure 6). The analysis of the MT data has shown that for the period range up to 40s (which in Soultz geological conditions corresponds to the depths up to 5-8 km) the data manifest 1-D/2-D dimensionality (Schill and Geiermann, 2008; Geiermann, 2009). Accordingly, in order to get information about the earth resistivity up to these depths these authors have fulfilled the 2-D inversion along the profile, which corresponds to the conditions of 2-D dimensionality (in the Figure 6 it is marked by white line rotated regarding the initial W-E profile).

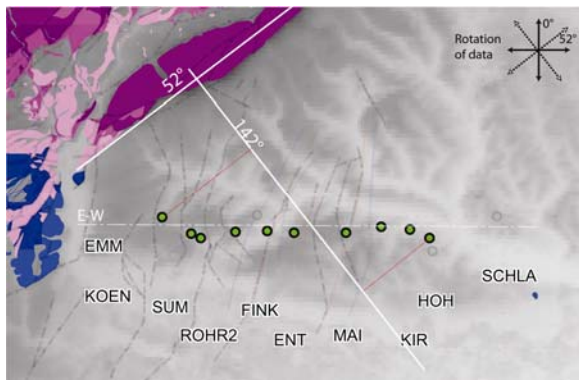


Figure 6: Map of the MT survey area (sites are marked by capital letters). White line labeled 52° approximates local graben strike, while line labeled 142° denotes the profile used for 2-D inversion. Red lines denote projection of MT sites locations on that profile. Dashed white line depicts E-W profile. The Cross in the upper right corner depicts rotation of the data. The faults are plotted less opaque (after Geiermann, 2009).

On the other hand, temperature maps constructed earlier for the depths 400 and 1500m manifest two-dimensionality of the temperature contours (at least, in the local scale) in approximately the same direction. These two factors justify indirect temperature estimations in the vicinity of the rotated survey line using vertical resistivity profiles from the model determined in the nodes of 2-D grid by means of 2-D inversion of MT data. Figure 7 indicates locations of appropriate grid nodes at the surface (circles). Numbers correspond to the resistivity

profiles actually used for the temperature estimation while the black triangles denote the related boreholes used for the calibration.

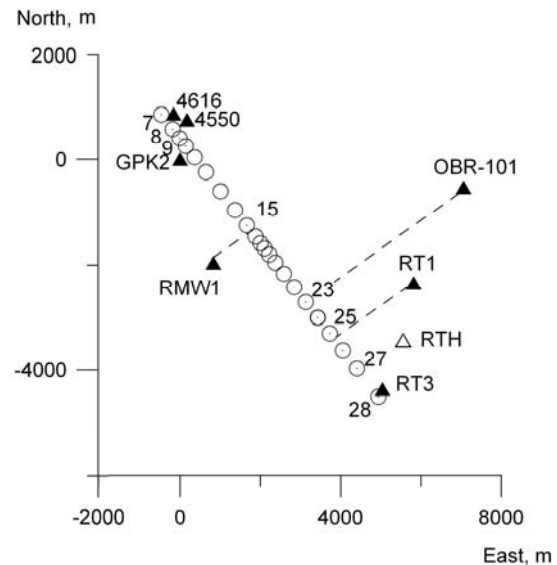


Figure 7: Map of the grid nodes (circles) and adjacent boreholes (black triangles) used for the EM geothermometer calibration.

### VALIDATION OF THE INDIRECT EM GEOTHERMOMETER

Validation of the temperature assessment using MT data is fulfilled by retro-modeling, i.e. by comparison of the forecasted temperature profile with real temperature log from GPK2 borehole for two depth ranges 2000-3878m and 3878m-5046m as if it was done before appropriate drilling.

To this end we have used the 9-th vertical resistivity profile (see Figure 7) from the 2-D resistivity model nearest to the borehole GPK2 and calibrated the EM geothermometer by the correspondence between the appropriate resistivity and temperature values.

After calibration the geothermometer was applied for successive temperature extrapolation downward. The Figure 8 shows the results of the indirect temperature extrapolation (red line) in comparison with the temperature well log (black line). The relative forecast error for the extrapolation from the upper 2km to the depth range up to 3878m was only 1.8 % (Figure 8), while in the latter case it was equal to 0.4%.

In order to estimate the effect of lacking the information about the temperature at depth we have carried out the temperature estimation for the depth range 3878-5046m as if we had the temperature profile only for the depth range 0-2000m. The

resulting profile is indicated in the Figure 8 by dashed red line. The absence of the information about the temperature profile for the intermediate depth range (2000-3878 m) would negatively affect the accuracy of the temperature prognosis for the depth range 3878-5046 m. The relative error of such a forecast was 18.5 % (maximal underestimation of the real temperatures is equal to around 50°C). This result corresponds to the errors of the temperature extrapolation to the depths three times as big as the borehole length (Spichak and Zakharova, 2009).

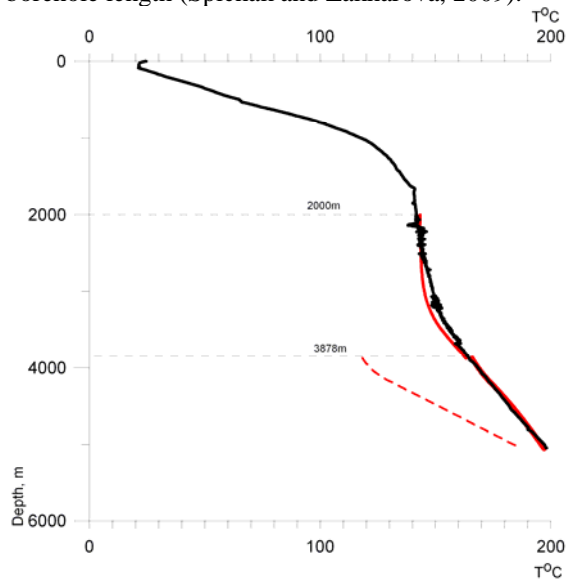


Figure 8: Comparison between the temperature log in the well GPK2 (black line) with estimated temperature profiles (red line) for the depth ranges 2000-3878 m and 3878 - 5046 m. Comparison with the temperature forecast from the depth range 0-2000m directly to the depth range 3878-5046 m is shown with dashed red line.

### TEMPERATURE EXTRAPOLATION IN THE WELL GPK2

The temperature extrapolation in the well GPK2 was carried out using the vertical resistivity profile 9 from the nearest location on the rotated NW-SE profile (see Figure 7). The indirect EM geothermometer was calibrated using the resistivity and temperature data from this borehole for the depth range 0-5046m and used then for the temperature extrapolation to the depth range 5046-8175m. It is worth mentioning in this connection that the maximal depth for the temperature extrapolation is bounded by the resolution depth of 2-D MT data inversion (Schill and Geiermann, 2008).

Figure 9 indicates the result of the temperature extrapolation. The analysis of the profile between the depths 5000m and 6000m indicates that the temperature gradient continues to be as high as in the

depth range 3500-5000m, which agrees with the temperature forecast for this depth range made by Pribnow et al. (1997) using the heat flow gradient data and estimation of the thermal conductivity from the drill cores and cuttings (Figure 10). According to this paper the temperature at the depth 6000m could reach 217.3°C, while indirect EM geothermometry results in 220.6°C.

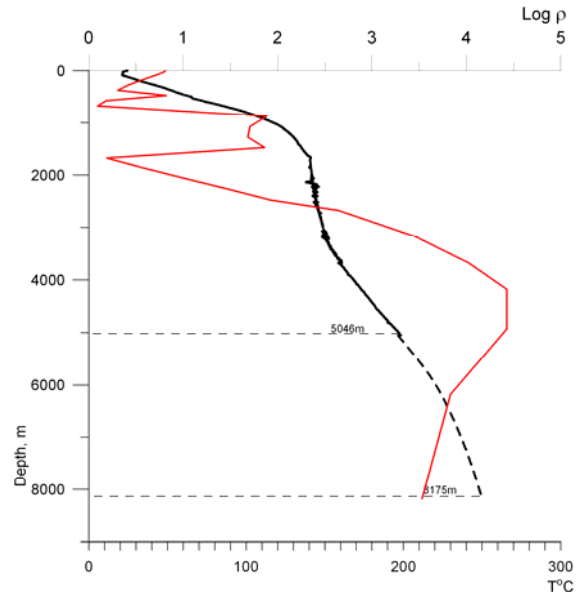


Figure 9: Temperature forecast for the depth range 5056-8175 m in the borehole GPK2. Black line indicates the well log, dashed black line – extrapolated temperature, red line – resistivity profile used for indirect temperature estimation. Upper axis is scaled in the resistivity logarithm.

As it is seen from the Figure 9, the temperature gradient becomes slowly decreasing down from the depth 6500m that may indicate that the thermal regime switches from the conductive (at the depth range 3500-6500m) to convective one, which may be caused by fluid circulation at large depths. This behavior is implicitly supported by three indirect temperature estimations made by Pauwels et al. (1993) using different geothermometers, who have forecasted location at large depths of thermal fluids with temperatures in the range 220-260°C. More recently, Sanjuan et al. (2010) have suggested a sedimentary origin and equilibrium temperatures close to 230°C for the Soultz geothermal fluids.

On the other hand, Pribnow et al. (2001) have reported about similar temperature range (220-270 °C) at the depth 8000m postulating the conductive temperature distribution and assuming an overall thermal conductivity of  $2.5 \text{ Wm}^{-1}\text{K}^{-1}$ .

## DEEP VERTICAL TEMPERATURE CROSS-SECTION ALONG THE NW-SE PROFILE

Construction of the vertical cross-sections along the NW-SE profile up to the depth 5000m not reachable by the wells (except GPK2-GPK4) was made in two stages. First, we have extrapolated temperature logs in the boreholes located in the vicinity 2-4 km from the rotated profile (RMW1, OBR101, RT1 and RT3) (see Figure 7 for their locations).

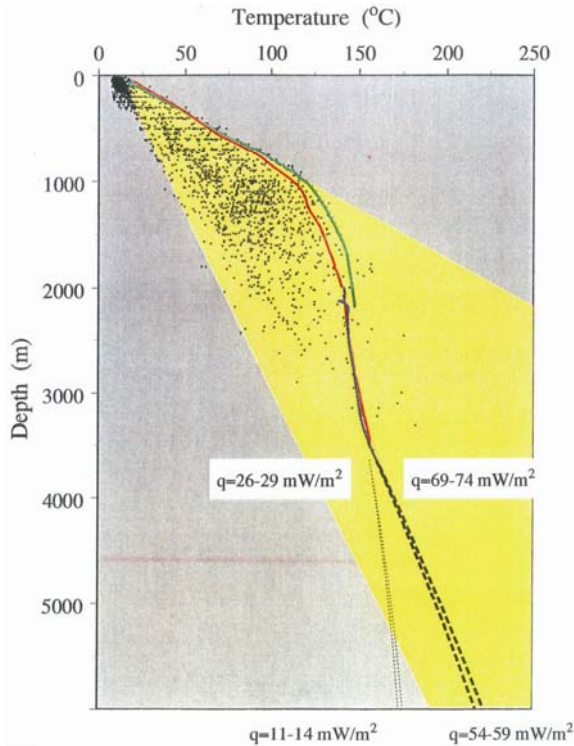


Figure 10: Temperature from boreholes GPK1 (red), GPK2 (blue) and EPS1 (green) together with temperature extrapolations according to Scenario 1 (dotted black lines) and Scenario 2 (dashed black lines) for the range of observed temperature gradients;  $q$  is the corresponding vertical component of heat flow density at 3.6 km and 6 km. Dots represent temperature measurements from the Rhine graben as compiled by Schellschmidt and Clauser (1996) framed by gradients of 30 K/km and 110 K/km (yellow area) (after Pribnow et al., 1997).

To this end we have used the nearest vertical resistivity profiles from 2-D model. Figure 11 shows the temperature profiles consisting from real logs (solid lines) and extrapolated parts (dotted lines) as well as the resistivity profiles (dashed lines) MT15, MT23, MT25 and MT28, accordingly, used for indirect temperature estimation.

At the second stage we used the temperature profiles constructed for the above mentioned sites as well as for the site GPK2 for artificial neural network based reconstruction of the vertical temperature cross-section in the studied area up to the depth 5000m (Figure 12).

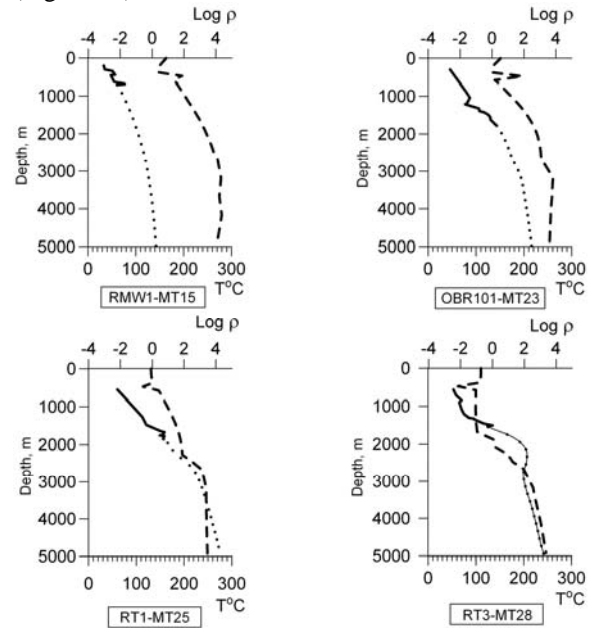


Figure 11: Resistivity profiles from the 2-D model (dashed lines) and the temperature profiles in the adjacent boreholes (solid line – well log, dotted line – extrapolated temperature profile).

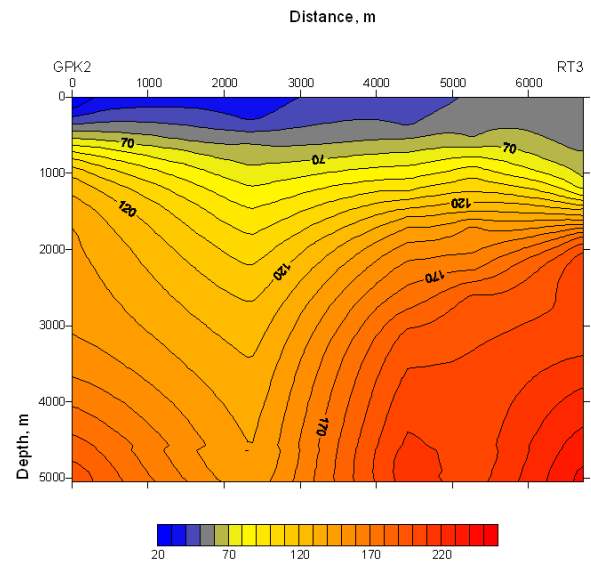


Figure 12: The vertical temperature contour map (in °C) along the profile between the boreholes GPK2 and RT3.

The resulting temperature cross-section differs from that reconstructed in (Pribnow and Schellschmidt, 2000), and (Pribnow and Hamza, 2000) using all available boreholes at the distance 20km from each side of the NW-SE profile (see Figure 5). In contrary to the latter one, it clearly indicates two temperature anomalies located at the depths deeper than 5km to the NW from GPK2 and to the SE from RT3 boreholes the latter having larger maximum. The appropriate temperature gradients are directed to the heat sources that are located somewhere deeper than 5km. In order to get more reliable and comprehensive information about the temperature distribution in the studied area 3-D MT survey is evidently required.

### **TEMPERATURE FORECAST IN THE NEW SITE**

We have estimated the temperature profile for the site at Rittershoffen (RTH), where a new well is planned to be drilled (see its location in the Figure 7). This site is located just between boreholes RT1 and RT3, so, we had three options for indirect temperature estimation using the nearest resistivity profiles revealed from MT data.

The actual profile in RTH could be close to one of the extrapolated temperature profiles in the nearest sites RT1 and RT3 (marked in the Figure 13 by red and blue lines, accordingly).

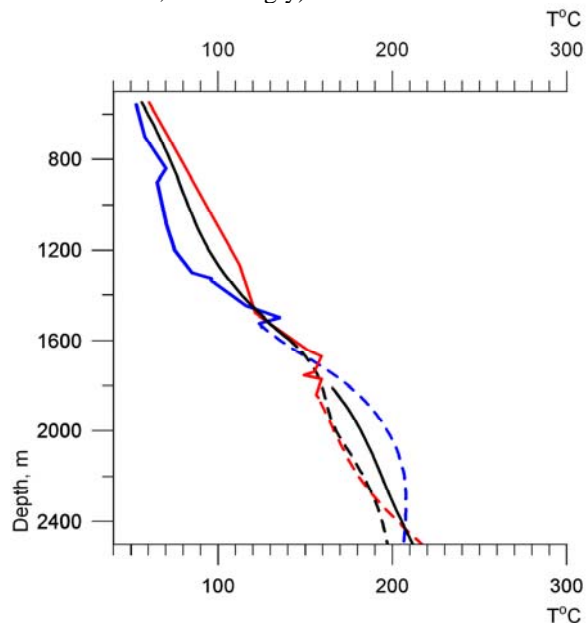


Figure 13: The indirect temperature forecast for the new site located in the Rittershoffen (RTH). The temperature in the borehole RT1 is marked by red line, in RT3 – by blue line, in RTH – by black line. Dashed lines indicate extrapolated temperatures in the wells RT1 and RT3 and in the RTH (using the nearest resistivity profile).

Alternatively, we can consider that the temperature profile in a new Rittershoffen site is a mixture of two available profiles in the boreholes RT1 and RT3. Under this assumption we have averaged the temperature values at the same depth locations in the depth range 545-1850m (solid black line) and then extrapolated this profile down to the depth 2500m (dashed black line) using the nearest resistivity profile. The temperature profile created by simple averaging of the profiles for the boreholes RT1 and RT3 for the whole depth up to 2500m is marked by solid black line.

As it is seen from the Figure 13, the resulting profiles at the sites RT1 and RT3 differ from each other both in the shallow and deeper (extrapolated) parts the main difference being the negative temperature gradient revealed in the site RT3 at the depth range 1800-2500m (though it switches again to the positive one at the depths deeper than 2800m (compare with Figure 11)).

The temperature profile at RTH based on the EM temperature extrapolation using the nearest resistivity profile (marked by 27 on the Fig. 7) manifest the minimal temperatures in the depth range 1800-2500m from all profiles, while the extrapolated profile at RT3 gives the maximal temperatures at the depth range of 1500-2400m. So, we conclude that deepening of the borehole RT3 or drilling in the SE direction from RT3 (instead of RTH) could be the best alternative.

### **CONCLUSIONS**

Basing on the results of our studies we could draw the following conclusions.

1. High accuracy temperature extrapolation to the depth 8175 m provides indirect estimation of the dominating heat transfer mechanisms at large depths and possible localization of the deep fluid circulation beneath the depth 6 km.
2. The deep vertical temperature cross-section reconstructed based on 2-D MT data profile differs from those constructed for this area earlier and clearly indicates locations of two temperature maxima at depths larger than 5km to the NW from GPK2 and to the SE from RT3 boreholes.
3. Application of the EM geothermometer to forecasting the temperature profiles in the Rittershoffen constrains the decision on the location of the new borehole. In particular, it indicates that deepening of the borehole RT3 or drilling in the SE direction from RT3 (instead of RTH) could be the best alternative from the temperature point of view.

4. It is shown that the indirect EM temperature estimation in the geothermal area with highly conductive sediments could be carried out using the resistivity cross-section resulting from 2-D MT data inversion. The methodology of the indirect temperature estimation used to this end could be extended to other geothermal areas of interest.

5. In order to get more information about possible heat transfer mechanisms at depths exceeding 8km as well as to forecast the temperature in the new locations a 3-D MT survey of the Upper Rhine graben area is required.

### **ACKNOWLEDGEMENTS**

One of the authors (V. Spichak) acknowledges the BRGM, GEIE EMC and French Ministry of Foreign Affairs for support of this study.

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