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Indirect Electromagnetic Geothermometer— A Novel Approach to the Temperature Estimation in Geothermal Areas

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Geothermal, indirect electromagnetic geothermometer, temperature extrapolation, interwell space, Soultz-sous-Forêts, Hengill

ABSTRACT

The paper presents a review of the advances in the temperature estimation in the geothermal areas based on the recently developed indirect electromagnetic (EM) geothermometer. Unlike other indirect geothermometers, it enables the temperature estimation in the given locations in the earth, which makes it an indispensable tool in geothermal exploration and exploitation.

Application of indirect EM geothermometers to the temperature interpolation in the interwell space is discussed. It is shown that the indirect EM geothermometer provides more accurate temperature interpolation in the interwell space than routine mathematical procedures (the relative errors being typically equal to 12% and 30%, accordingly).

Special attention is paid to the temperature extrapolation in depth. The results obtained in the northern Tien Shan area indicate that the temperature extrapolation accuracy essentially depends on the distance between the location of the EM sensor at the surface and the borehole where the temperature is to be extrapolated as well as on the ratio between the well length and the extrapolation depth. It is shown that it is possible to increase significantly the deepness of indirect temperature estimation in the earth's interior based on the available temperature logs.

Application of the indirect EM geothermometer in two geothermal areas (Soultz-sous-Forêts, France, and Hengill, Iceland) is presented. The analysis of the appropriate temperature models built using indirect EM geothermometers is used for drawing important conclusions regarding structure of the areas under study; heat sources' location; the dominating heat transfer mechanisms; fluid circulation paths; and optimal location for drilling geothermal wells.

1. Introduction

Using the data on electrical conductivity of rocks seems to be the most natural approach to the temperature estimation because this property is commonly a function of temperature. Temperature dependence of the electrical conductivity of rocks permits its use for the direct temperature estimation using well known Archie formula (Archie, 1942). Similar methods can be applied accordingly on a regional or even global scale based on empirically matched data (Shankland and Ander, 1983) or data determined from the global magnetovariational sounding (Dmitriev et al., 1988). At the same time, the complex, non-homogeneous structure of the Earth and the lack of information about its properties allow construction of only very crude temperature models based on assumptions regarding the electrical conductance mechanisms.

On the other hand, the electromagnetic sounding of geothermal areas (Spichak and Manzella, 2009) may provide indirect temperature estimation in the Earth's interior based on electromagnetic measurements at the surface. Spichak et al. (2007a) have recently developed an indirect EM geothermometer, which does not require

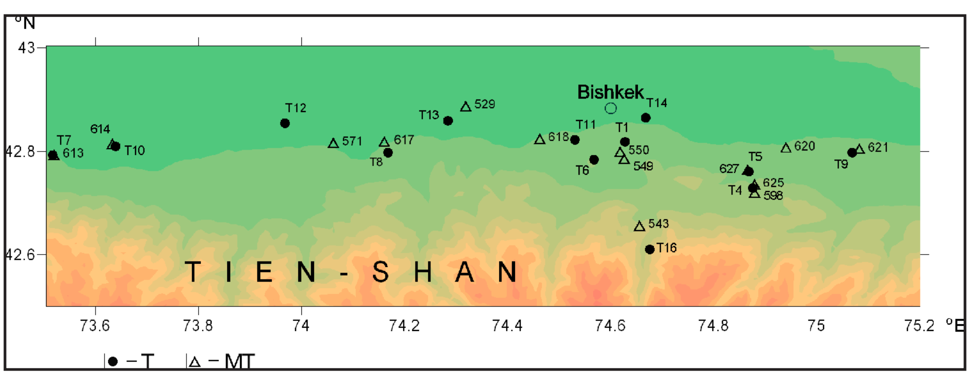

Figure 1. Location of MT sites and wells for which temperature data are available (after Spichak et al., 2011a.)

prior knowledge or guessing regarding the electrical conductance mechanisms in the Earth's crust. This paper presents a review of the basic methodological issues of its application as well as two recent case histories (Soultz-sous-Forêts, France, and Hengill, Iceland, geothermal areas).

2. EM Temperature Estimation in the Interwell Space

The indirect EM temperature estimation is carried out by means of the artificial neural network calibrated by the correspondence between electrical conductivity profiles revealed from EM (in particular, magnetotelluric (MT)) data collected on the surface in the vicinity of available wells and appropriate temperature logs (Spichak et al., 2007a,b; Spichak and Zakharova, 2008).

Spichak et al. (2007b, 2011a) have developed the methodology aimed at the temperature estimation in the interwell space. To this end they studied the effect of the number of temperature logs used for the geothermometer calibration as well as different calibration strategies. Below we will discuss briefly these methodological issues following the papers mentioned above.

The feasibility studies were provided in the Chu Basin (northern Tien Shan), where magnetotelluric and temperature measurements were carried out (Figure 1).

2.1. Data Volume Effect

In order to estimate the effect of the data volume used for the thermometer calibration Spichak et al. (2011a) trained neuronets successively with 2, 4, 6, 8, 10 and 12 pairs of temperature and electrical conductivity profiles (here and after "T-MT") that were randomly selected from the total data set. For comparison, the neuronets were alternatively trained using temperature logs alone. The trained ANNs were tested then on data from MT sites closest to boreholes for which temperature logs were available. The relative *rms* errors of temperature predictions in boreholes are plotted in Figure 2 for the cases of temperature data alone (red line) and electromagnetic data paired with temperature logs (blue line).

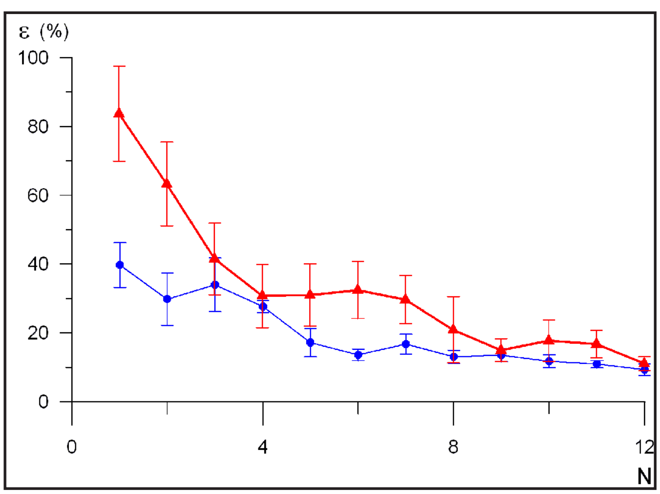

Figure 2. Average relative error ε (%) of temperature estimations based on electricalal conductivity data paired with temperature logs (blue line) and temperature logs alone (red line) as a function of the number (N) of profiles involved in neuronet training (after Spichak et al., 2007a, 2011a).

Comparison of the graphs shows that, if both temperature and electromagnetic data are used for temperature prediction, an increase in the training sample size decreases the relative error more rapidly than if temperature logs are used alone. Moreover, the prediction error reaches a minimum value for a sample consisting only of six T-MT pairs, whereas the estimation from temperature logs attains the same level with the use of data of eight to ten boreholes. The important implication of this is that if borehole measurements of temperature are limited, the temperature prediction error can be substantially reduced (by nearly two times) by using both temperature and MT data.

2.2. Effects of the Calibration Strategy

To examine the effect of the calibration strategy on the error of the temperature prediction in the interwell space from electromagnetic data, Spichak et al. (2011a) compared two strategies. In the first case, neuronets were trained with five samples of 12 randomly selected T-MT pairs, and the temperatures in three boreholes whose data were not used for training were then predicted from the electrical conductivity data of the nearest MT points. The temperatures in boreholes T5 and T6 were predicted separately for the conductivity profiles from sites 627 and 618 (T5) and from sites 620 and 549 (T6). In contrast, the electromagnetic data at

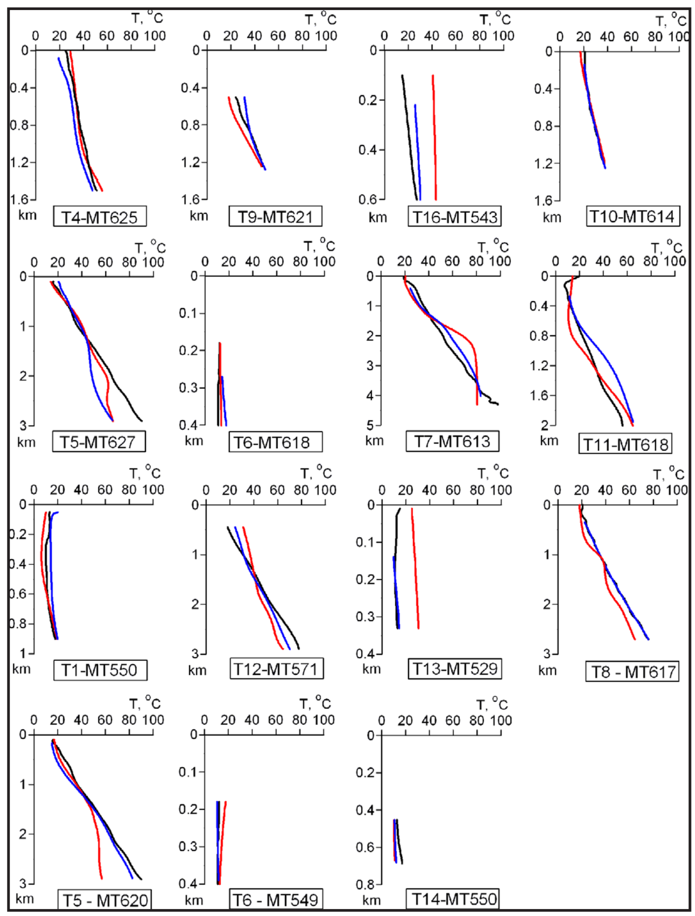

Figure 3. Measured and modeled distributions of temperatures in wells. Black line – measured temperature, red line – temperature profile based on the interwell interpolation of the temperature data only, blue line – temperature profile based on MT and temperature data (after Spichak et al., 2007a, 2011a).

MT sites 618 and 550 were analyzed together with temperature profiles measured not only in boreholes T6 and T1, but also in the wells T11 and T14, respectively.

In the framework of the second strategy, the neuronet was trained with all available MT data, after which this neuronet was used for predicting the conductivity at the depths of borehole temperature records. Finally, the neuronet trained on the basis of the correspondence between conductivity and temperature in 14 T-MT pairs was used to predict the temperature in a borehole whose data were not used for training. In order to compare the results of temperature prediction based on electromagnetic and geothermal data with results obtained by means of neuronets trained with temperature data alone, neuronets were trained only with the same temperature logs, and the temperatures in the same boreholes were predicted.

The predicted results are presented in Figure 3. The average relative error of the temperature prediction evaluated by the first technique was 11.9%, which is an unexpectedly good result for this region, which is characterized by a complex geological structure and a large scattering of temperature distributions (Zakharova et al., 2007). The average relative errors of prediction by the second and third methods were 29.9% and 29.5%, respectively. Although the prediction errors of the second and third techniques were in three cases smaller than those of the first one, the results predicted by the first technique were better in 80% of the cases.

In other words, a reasonable choice of MT sites as close as possible to the points at which the temperature is to be predicted yields the best results. However, the distance between the temperature prediction point, on the one hand, and MT sites and the corresponding boreholes whose data were used for training the neuronet is not a decisive factor.

3. EM Temperature Extrapolation in Depth

It is often necessary to estimate the temperature distribution in geothermal reservoirs lying at depths that exceed the depths of the drilled wells. Spichak and Zakharova (2009a,b) studied

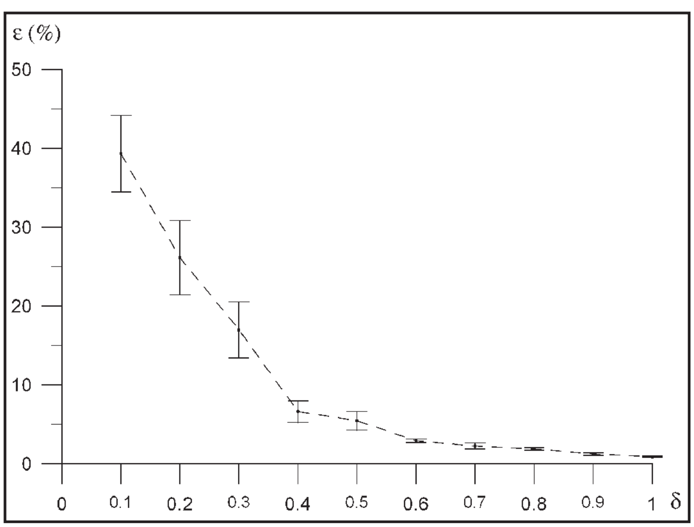

Figure 4. Dependence of the average relative error ε of the EM temperature extrapolation on the portion δ of the temperature well logs used for the neuronet training (after Spichak and Zakharova, 2009a).

the feasibility of the indirect EM geothermometer application to the temperature extrapolation with depth using EM data and temperature well logs (collected in the northern Tien Shan area).

At the stage of the thermometer calibration, the artificial neuronets were trained by correspondence between the values of measured temperature and electrical conductivity estimated from MT data at a neighboring site (see Figure 1). The depth of each well was divided into 10 intervals, and the training was carried out successively at the shallower intervals. After the training,

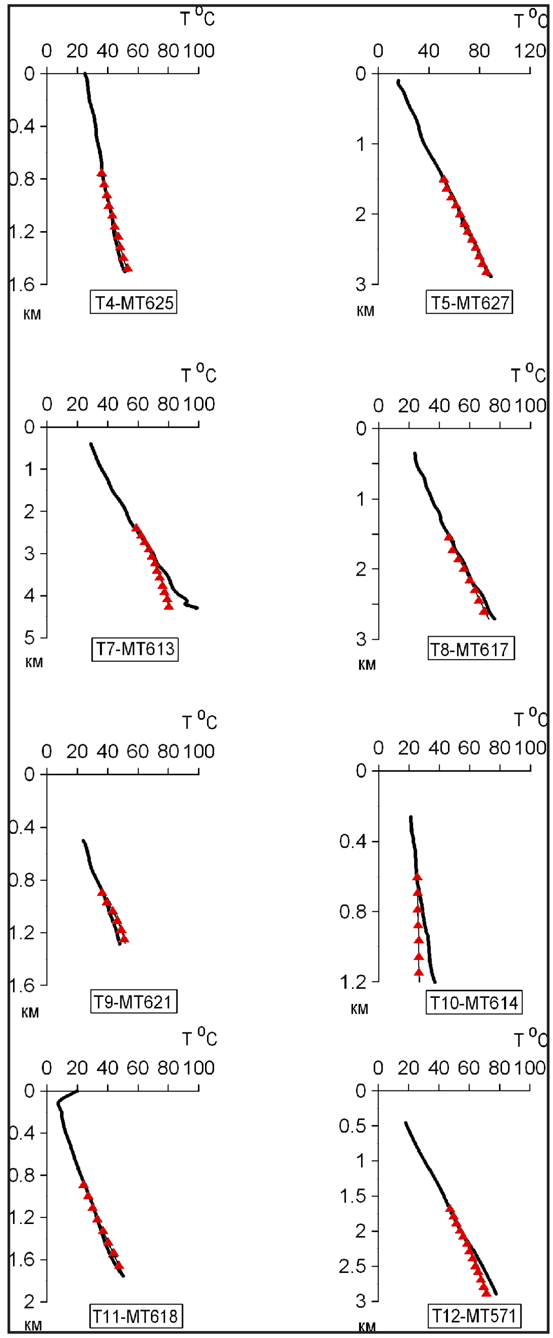

Figure 5. Well logs (black lines) and estimated temperature profiles (red lines with triangles) obtained by extrapolation on the lower half of the profile using the ANN trained on the correspondence between the electrical conductivity and temperature values at the depths belonging to the upper half of the profile (after Spichak and Zakharova, 2009a,b).

the neuronets were tested at the remaining (deeper) parts of temperature profiles, the data from which were not used for training.

In Figure 4, a graph is shown illustrating the dependence of the mean relative error ε of the neuronet temperature extrapolation with depth (based on electromagnetic data measured at the MT site closest to the well) on the portion of the electrical conductivity and temperature profiles used for the neuronet training. From this graph, one can conclude that to reach, say, a 5-6% error, it is quite sufficient to use for ANN training only the temperature and electrical conductivity data for the upper half of the profile. (It is worth mentioning in this connection that the average relative error of the ANN temperature extrapolation using only temperature data equals 27.4% (Spichak, 2006; Spichak and Zakharova, 2009a.) In other words, the application of indirect electromagnetic geothermometer could enable obtaining high-accuracy temperature estimates at depths twice as large as the depths of the drilled wells for which the temperature data are available.

Predicted and actual temperature values in 8 wells are plotted in Figure 5. Based on the above results, the extrapolation was confined to the lower half of depths for all temperature profiles. As can be seen in Figure 5, the predicted curves insignificantly depart from the actual ones only in 3 of 8 cases. Moreover, the departure was observed at depths from 2.5 to 4.5 km in only two cases (T7-MT613 and T12-MT571).

4. Estimating Deep Temperatures in the Soultz-sous-Forêts Geothermal Area (France)

Indirect temperature estimation by the EM geothermometer enables building of more accurate deep temperature cross-section of the geothermal area than that determined by linear extrapolation of the temperature well logs to the large depth or averaging of the temperature records from all available boreholes at some distance (often tens of km) from each side of the profile (see, for instance, Bjornsson (2008) and Pribnow and Hamza (2000), accordingly). Spichak et al. (2010) have used indirect EM geothemometer for estimating deep temperature cross-section in the Soultz-sous-Forêts (France) geothermal area from the ground magnetotelluric data and available temperature well logs. This, in turn, has enabled to estimate the dominant heat transfer mechanism and determine fluid circulation paths at large depth as well as to constrain the location for drilling new borehole.

In order to determine the resistivity profiles required for ANN training Spichak et al. (2010) have used the results of the MT survey carried out along a 13 km long W-E profile crossing the Soultz area (Schill et al., 2010). Indirect temperature estimations were made in the vicinity of the rotated survey line using vertical resistivity profiles from the model determined in the nodes of 2-D grid as a result of MT data inversion. Figure 6 shows 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.

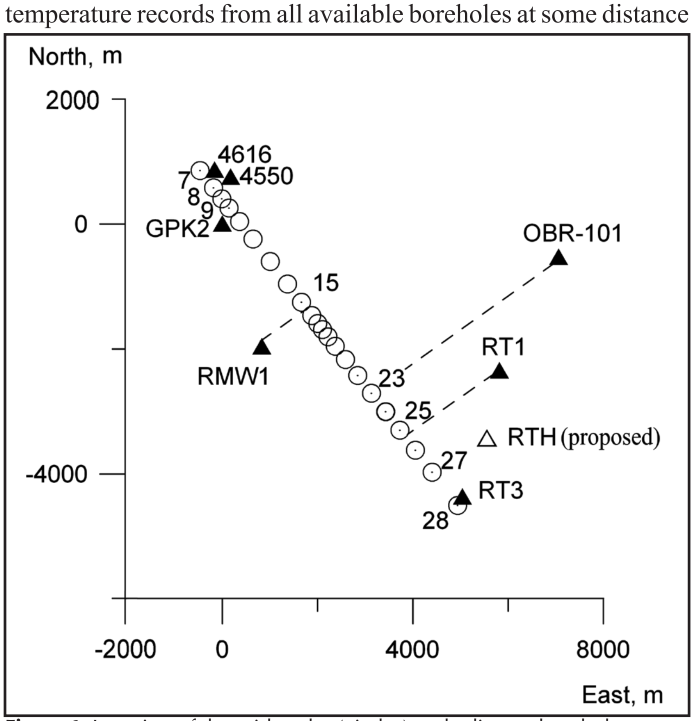

Figure 6. Location of the grid nodes (circles) and adjacent boreholes (black triangles) used for the EM geothermometer calibration (after Spichak et al., 2010).

4.1. Deep Vertical Temperature Cross-Section Revealed from MT Data

Construction of the vertical cross-sections along the NW-SE profile up to the depth 5000m not reachable by the wells was made in two stages. First, temperature logs in the boreholes located in the vicinity 2-4 km from the profile (RMW1, OBR101, RT1 and RT3) (see Figure 6 for their locations) were extrapolated up to the depth 5 km using the nearest vertical resistivity profiles from 2-D model. At the second stage the temperature profiles constructed for the above mentioned sites as well as for the site GPK2 were used for the artificial neural network reconstruction of the vertical temperature cross-section in the studied area up to the depth 5000m (Figure 7).

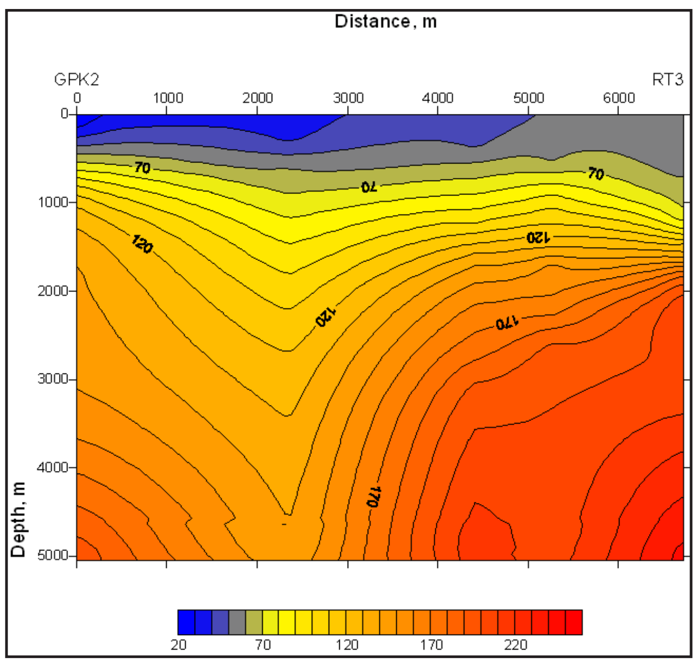

Figure 7. Estimated temperature cross-section (in °C) along the profile between the boreholes GPK2 and RT3 (after Spichak et al., 2010).

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 20 km from each side of this profile. 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.

4.2. Guiding the Location for Drilling Borehole

Spichak et al. (2010) have estimated the temperature profile for the site at Rittershoffen (RTH), where a new well is planned to be drilled up to the depth 2500 m (see its proposed location in the Figure 6). Since the site RTH is situated just between the boreholes RT1 and RT3, its temperature profile could be close to either of their profiles (marked in the Figure 8 by red and blue lines, accordingly) estimated earlier using indirect EM thermometry.

Under the assumption that the temperature varies linearly in the space between these profiles, the vertical temperature distribution in a Rittershoffen site could be determined by averaging of two abovementioned profiles in the boreholes RT1 and RT3. Alternatively, the lower part of the temperature profile in RTH was forecasted by extrapolating the averaged upper parts of profiles in RT1 and RT3 (solid black line) using the nearest resistivity profile at MT27.

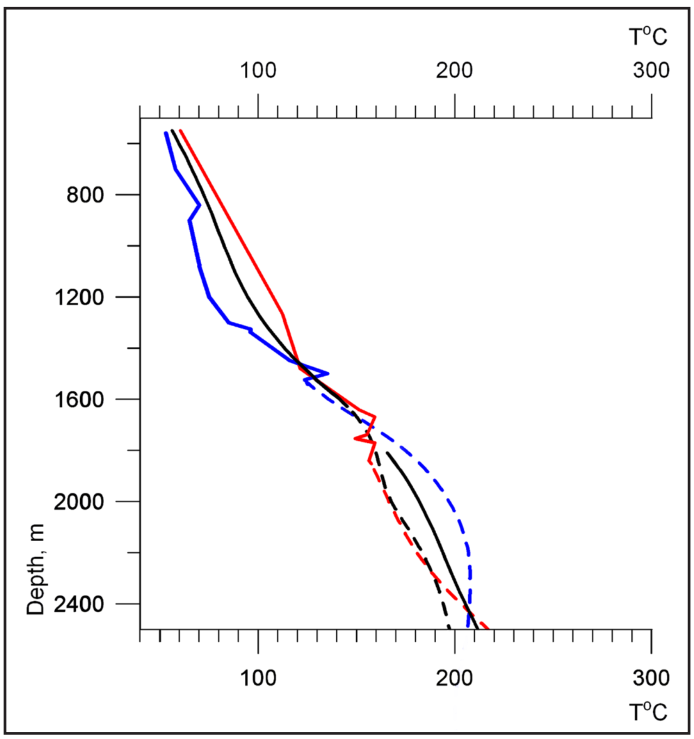

Figure 8. The indirect temperature forecast for the new site planned to be located in the Rittershoffen (RTH). The temperature profile in the borehole RT1 is marked by the solid red line, in RT3 – by solid blue line; extrapolated temperature profiles in the boreholes RT1 and RT3 – by dashed red and blue lines, accordingly; averaged temperature profile – by solid black line; temperature profile extrapolated using the nearest resistivity profile (MT27) – by dashed black line. (After Spichak et al., 2010.)

As it is seen from Figure 8, 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 depth range 1800m - 2500m (though it switches again to the positive one at depths deeper than 2800m).

The temperature profile at RTH based on the EM temperature extrapolation using the nearest resistivity profile manifest the minimal temperatures in the depth range 1800m - 2500m from all profiles, while the extrapolated one at RT3 has the maximal temperatures at the depth range of 1500m-2400m. So, based on the temperature constraints, it was concluded that deepening of borehole RT3 or drilling in its close vicinity (instead of RTH) could be the best recommendation for the decision-makers.

5. 3D Temperature Model of the Hengill Geothermal Area (Iceland)

The inferences on the temperature distribution in the geothermal areas are usually drawn based on the temperature measurements in the boreholes and heat flow data. The role of geophysical and geochemical methods is commonly reduced to the constrains placed upon the temperature values at characteristic depths. Meanwhile, the application of the indirect EM geothermometer technology enables building a 3D temperature model of the area, which could offer a comprehensive database for further analysis in geothermal terms. Spichak et al. (2011b) have constructed the first 3D temperature model of the Hengill geothermal area, Iceland from the magnetotelluric and transient domain EM (TDEM).

The reconstruction of 3D temperature model of the studied area was fulfilled in two steps. First, the resistivity model was determined by means of the joint inversion of the MT and TDEM data. The temperature values were than estimated from the depth 0.5 km up to the depth 20 km in the same nodes of the spatial grid, in which the resistivity values were determined. It is worth mentioning in this connection that according to the testing carried out in (Spichak et al., 2011b) the relative errors of the temperature reconstruction ranged from 15.4% to 36.6%. Figure 9 shows horizontal temperature slices at different depths.

The preliminary analysis of this model enabled to draw the following main conclusions about the structure of this geothermal area and location of heat sources:

- the temperature up to the depth of 20 km is mainly subsolidus which supports the hypothesis on the “cool and thick” Icelandic crust (Bjarnason et al., 1993; Menke and Sparks, 1995, etc.);
- the high temperatures in the studied area originate from the molten liquid magma (with temperature higher than liquidus) upwelling from the mantle and accumulating in the shallow reservoirs. It supposedly further leakages in the reologically weak layer in the depth range 5-15 km.

Conclusions

In contrast with known indirect geothermometers, which attribute the temperature dependency of the composition of

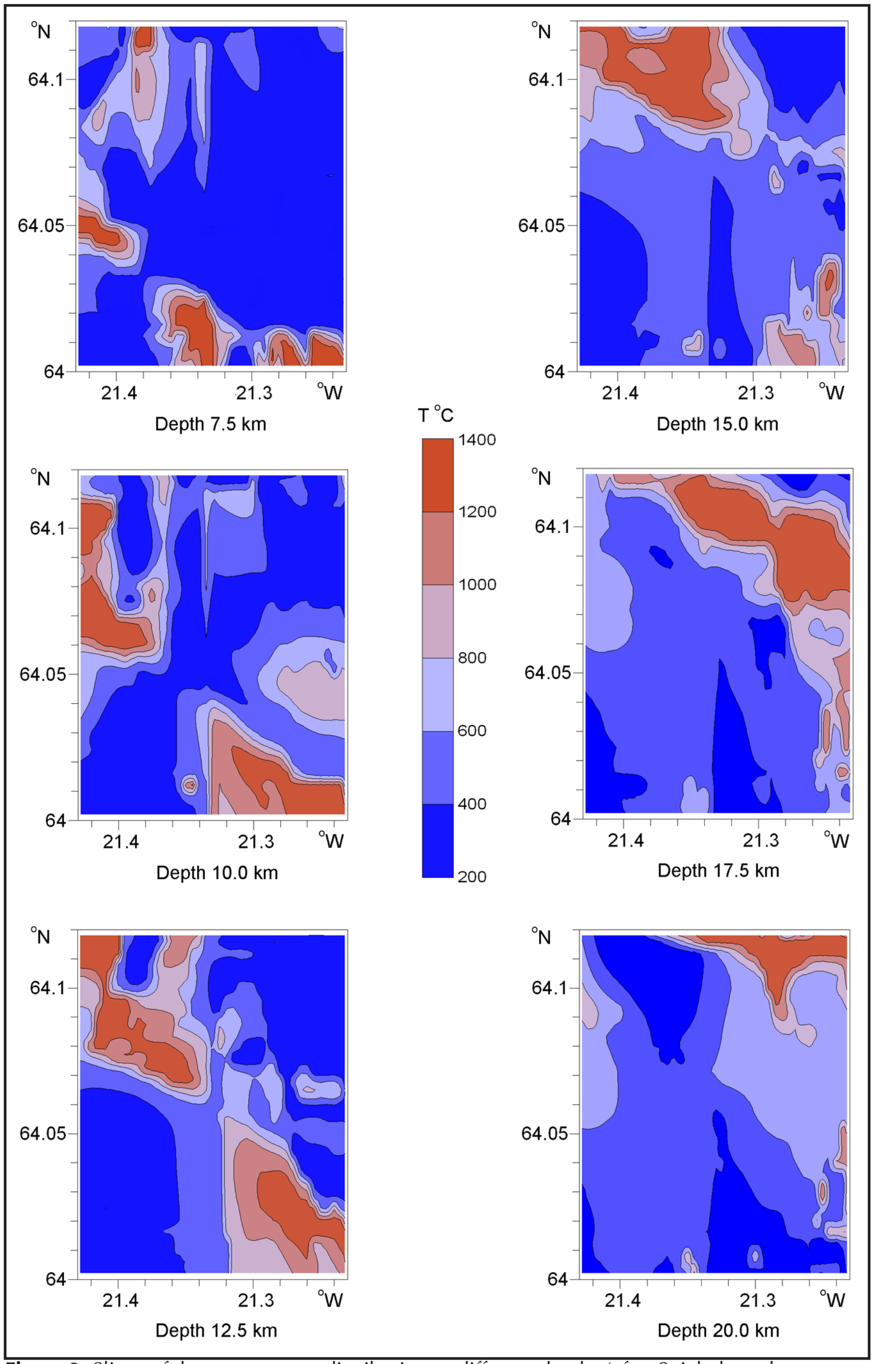

Figure 9. Slices of the temperature distribution at different depths (after Spichak et al., 2011b).

some characteristic hydrothermal components observed at the surface to the supposed depth of their origin, the electromagnetic geothermometer provides the temperature model of the studied area in the absence of manifestations of geothermal activity on the surface. The analysis of this model could be used for building important conclusions regarding structure of the area; heat sources' location; the dominant heat transfer mechanisms; geothermal fluid circulation; finally, optimal location for drilling geothermal wells.

The indirect EM geothermometer provides more accurate temperature interpolation in the interwell space than routine mathematical procedures (the relative errors being typically equal to 12% and 30%, accordingly). Its application allows high accuracy temperature estimation at depths exceeding the lengths of drilled wells for which the temperature data are available. In particular, when extrapolating to a depth twice as large as the well depth the relative error is 5-6%, and if the extrapolation depth is three times as large, the error is about 20%. This result makes it possible to increase significantly the deepness of the indirect temperature estimation in geothermal areas without extra drilling. This, in turn, allows remote temperature estimations in the boreholes with extreme conditions unsuitable for traditional thermometers as well as in productive wells without disturbing the production process. It is also useful for the remote temperature monitoring in the geothermal reservoirs under exploitation.

Finally, the temperature estimates obtained with indirect EM geothermometers are based on its advance calibration using electrical conductivity - temperature relationships in a few wells (6-8 pairs are usually sufficient for the relative accuracy less than 10%). Due to this, the temperature estimates do not depend explicitly on alteration mineralogy or other factors influencing the temperature reconstruction in different geological environments.

Acknowledgments

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