PROCEEDINGS, Thirty-Fourth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 9-11, 2009
SGP-TR-187

ELECTROMAGNETIC TEMPERATURE EXTRAPOLATION IN DEPTH IN THE HENGILL GEOTHERMAL AREA, ICELAND

Viacheslav V. Spichak and Olga K. Zakharova

Geoelectromagnetic Research Centre IPE RAS
Troitsk, Moscow Region, 142190, Russia
e-mail: v.spichak@ru.net

ABSTRACT

Indirect electromagnetic (EM) geothermometer developed recently in (Spichak et al., $2007_{a,b}$) is applied to the temperature extrapolation in depth in the Hengill geothermal zone (Iceland). The approach used is based on the artificial neural network (ANN) analysis of the implicit conductivity-temperature relations rather than on the prior assumptions of the electrical conductivity mechanisms.

The samples for indirect EM geothermometer calibration consisted from the well temperature records and electrical conductivity values determined for the same depths from the magnetotelluric data measured in the vicinities of 8 boreholes. The testing of the estimates was carried out using the temperature records not involved in the calibration. The results indicate that the temperature extrapolation accuracy essentially depends on the ratio between the well length and the extrapolation depth. In particular, in extrapolation to a depth twice as large as the well depth the relative error is 5-6%, and in case of its threefold excess the error is around 20%.

This result makes it possible to increase significantly the deepness of indirect temperature estimations in the geothermal areas without additional drilling. The method developed could be especially useful when exploring supercritical geothermal resources located at depths 4-5 km or deeper, where the temperature estimates could be made using the EM geothermometer calibrated by the shallow parts of the available temperature logs.

INTRODUCTION

Temperature estimation in the Earth's crust is usually based on the temperature logs or the heat flow gradient data. Actual data about the measured temperatures are limited to the borehole depths amounting in most cases to 1 - 3 km. Studies of hydrothermal processes showed that specific properties of the underground fluid composition are closely related with the geothermal conditions of their formation. Therefore, studying of these properties provides information about the thermal state of the interior that complements the results of direct thermometry and serves as a basis for forecasting the deep geothermal conditions in scantily explored regions.

Established experimentally is a temperature dependency of the composition of some characteristic hydrothermal components (the so called indirect geothermometers). Using empirical or semi-empirical formulas, one can roughly estimate the "base depth" temperature from the known amount or proportion of these components in areas of surface manifestations of thermal activity. Researchers frequently use indirect estimates based on geological, geochemical or geophysical data (Harvey and Browne 1991; Kharaka and Mariner, 1989; Arnorsson and Gunnlaugsson, 1985; Bjornsson, 2008; etc.) to guess the temperature at characteristic depths.

Despite the indirect geothermometers mentioned above could serve as useful tools for estimating the temperatures at some depths and, thus, for constraining the sub-surface temperature, they cannot be used neither for constructing the temperature distribution in the studied area not for its interpolation / extrapolation given the temperature well logs.

The use of information about the electrical conductivity of rocks seems to be the most natural approach to the temperature estimation because this property is a function of temperature (more information about the dependence of the electrical conductivity on other physical parameters of rocks one can find in the Section 3 of the review paper by Spichak and Manzella (2008)). So, estimating the electrical conductivity in the Earth from ground electromagnetic measurements it should be, in principle, possible to provide a quantitative assessment of the temperature values in the same locations.

A principally new approach to the underground temperature estimation using its implicit relation with specific electrical conductivity (so called indirect electromagnetic geothermometer) was developed recently in (Spichak et al., $2007_{a,b}$; Spichak and Zakharova, 2008_b). It was shown that being properly calibrated it provides more accurate temperature estimations than those obtained using any horizontal interpolation or extrapolation of the temperature well logs and is more robust against geological noise.

On the other hand, it is often necessary to estimate temperature distribution in geothermal or other reservoirs lying at depths that exceed lengths of the drilled wells. The objective of the present paper is to study feasibility of application of indirect EM geothermometer to electromagnetic temperature extrapolation in depth using data collected in the Hengill geothermal zone (Iceland).

GEOLOGICAL SETTING

Iceland is very active tectonically as it is crossed by the Mid-Atlantic Ridge and its associated rift zones and transform faults. The Icelandic crust is mostly of volcanic origin, with both intrusive and extrusive rocks (mainly oceanic-type flood basalts, tuffs, hyaloclastites and some acidic rocks) that were erupted under rift conditions. The abundant geothermal systems in Iceland are the results of volcanic activities and high heat flows. The Hengill volcanic complex located at south-west of the island is a high-temperature geothermal system.

DATA AND THERMOMETER CALIBRATION

For the temperature extrapolation in depth, we used magnetotelluric data measured at 8 sites (MT38, MT44, MT46, MT49, MT52, MT53, MT81, MT192) close to the wells T4, T3, T11, T6, T5, T8, T10 and T15, respectively (Figure 1). Profiles of apparent conductivity reconstructed from the measured MT data are shown in Figure 2 together with the well temperature logs. As it is seen from Figure 2, in the majority of sites the temperature monotonically increases with depth reaching values as high as 250°-300° at depths of about 0.8-1.0 km.

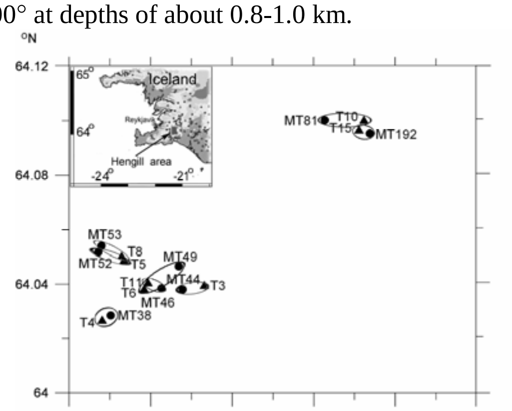

Figure 1: Location scheme of MT sites (circles) and wells (triangles) for which temperature data are available.

At the same time, the apparent conductivity in most MT sites is first increasing with depth and, after its maximum is reached at a depth of 0.5-0.6 km, is then decreasing. According to (Oskooi et al., 2005) the presence of an outcropping resistive layer in this area is identified as the typical unaltered porous basalt of the upper crust. This layer is underlain by a highly conductive cap resolved as the smectite-zeolite zone. Below this cap a less conductive zone is identified as the epidote-chlorite zone.

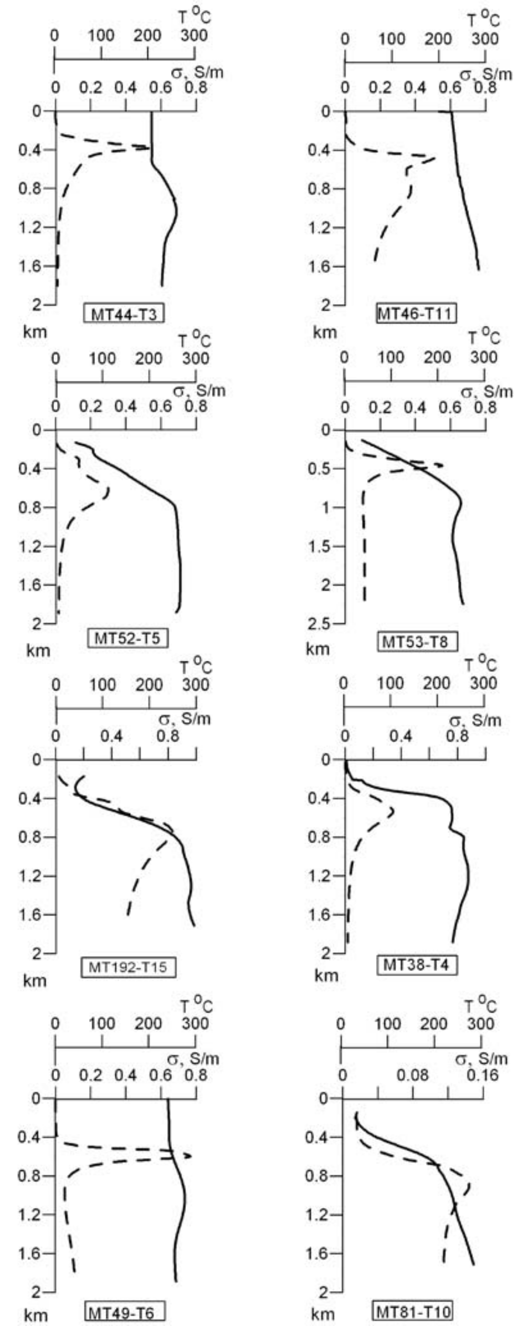

Figure 2: Temperature well logs (solid lines) and electrical conductivity profiles beneath adjacent MT sites (dashed lines).

The indirect EM temperature estimation is based on the neural network formalism discussed in (Spichak, 2006, and Spichak et al. 2008_a). Similarly to the latter paper for the geothermometer calibration we trained the neuronets by the correspondence between the values of apparent electrical conductivity and temperature within the upper halves of the profiles for each well.

EM TEMPERATURE ESTIMATION

In Figure 3 actual temperature values for 8 wells and temperature predictions for the lower half-depths of the profiles are shown. As it is seen from the Figure 3, the most noticeable discrepancy (particularly at great depths) between the prognostic and actual values is observed for wells T3, T6, T8 and T10. In the case of wells T3 and T6 this could be associated with an anomalous character of temperature changes with depth; however, also a general reason exists that can explain the divergences in all the four cases. In Table 1 the extrapolation errors are shown for all wells, and the distances are indicated between the wells and sites providing MT data for the analysis.

Table 1. Temperature prognosis errors (in per cent) for Hengill area depending on the extrapolation technique used: ε corresponds to indirect EM geothermometer, while ε relates to ANN temperature extrapolation using only the temperature records.*

Well	MT site	T-MT spacing (km)	ε (%)	**ε*** (%)
T3	MT44	0.55	8.9	5.0
T4	MT38	0.27	2.9	8.1
T5	MT52	0.21	2.8	3.5
T6	MT49	0.91	6.0	3.3
T8	MT53	0.42	6.1	25.4
T10	MT81	0.93	7.7	18.8
T11	MT46	0.42	2.7	9.0
T15	MT192	0.30	2.0	4.9
Average			4.9 ± 0.9	9.8±2.7

It is noteworthy in this connection that the errors of lateral electromagnetic temperature extrapolation depend rather on the geological heterogeneities of the medium (e.g., faults) than on the distances between the MT sites and wells from which the temperature logs are taken for calibration of indirect electromagnetic thermometer (and could be further diminished if the geology is taken into account during MT survey (Spichak et al., 2007_b)).

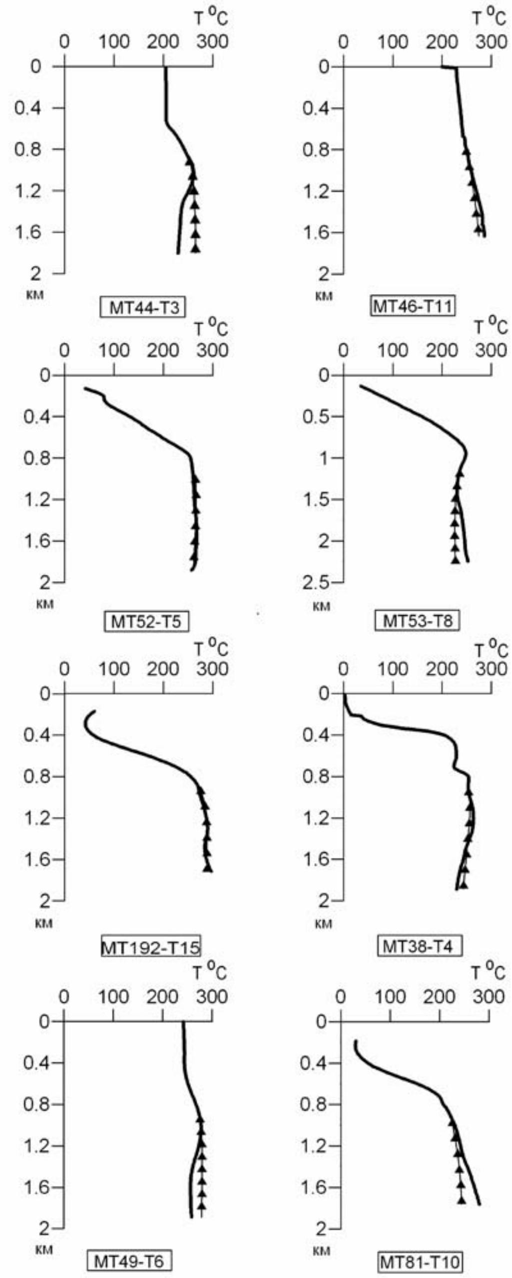

Figure 3: Well logs (solid lines) and estimated temperature profiles (lines with triangles) obtained using extrapolation on the lower half of the profile by the net trained on the correspondence between the electrical conductivity and temperature at the points belonging to the upper half of the profile.

As it is seen from the Table 1, these distances are maximal exactly in the cases mentioned above. On the other hand, in areas where they are minimal, in most cases the minimal discrepancies are observed. The correlation coefficient between the extrapolation errors and the spacing between the MT sites and boreholes was found equal to 0.95. This argues for the conclusion that in order to minimize the errors in temperature prognosis at depths exceeding the well lengths, it is necessary to measure electromagnetic data in the closest proximity of the wells.

It is noteworthy in this connection that the errors of lateral electromagnetic extrapolation of temperature depend rather on the geological heterogeneities of the medium (e.g., faults) than on the distances between the MT sites and wells from which the temperature logs are taken for calibration of indirect electromagnetic thermometer (and could be further diminished if the geology is taken into account during MT survey (Spichak et al., 2007_b)).

Comparison with the case if the temperature in the bottom halves of the boreholes is estimated by ANN extrapolation using only the temperature records in the upper halves shows that the average error is twice less (4.9%) than in the latter one (9.8%) with errors being less in 6 boreholes from 8.

Thus, application of the indirect EM geothermometer to the temperature extrapolation indicates that the average errors could be significantly reduced in comparison with ANN temperature extrapolation based on well temperature records only.

ROBUSTNESS ESTIMATION

In order to study how the prediction errors depend on the behaviour of the conducivity-temperature profiles used for the EM geothermometer calibration and the conductivity profiles used for the temperature extrapolation the following experiments were provided (Spichak and Zakharova, 2008_b). The whole set of conductivity and temperature profiles were divided into 200 m thick sections starting from the depth of 150 m. Then the neuronets were trained on the data corresponding to these intervals. The taught neuronets were then tested on 200 m thick intervals proximate in depth to the given ones.

Table 2 shows the extrapolation errors made in such a way. The analysis of the obtained results indicates that the average errors of interval prognosis for each well are rather big for subsurface sections (reaching as high values as 87% at T4 well), but farther with depth the errors gradually decrease. In principle, this could be related to MT data distortion by subsurface geological noise (so called static shift effect). But the correction of MT curves employing the TEM data inversion results, however, caused no reduction of the extrapolation errors. Common reason for such a behavior of errors is presumably a decrease in the vertical inhomogeneity of the medium with depth.

Average relative extrapolation errors for all wells are shown in Figure 4. The curves reach their asymptotic values already starting from the depth of about 1 km (N=4 in Figure 4) that characterizes the transition to the homogeneous distribution in both the conductivity and temperature for most wells in this geothermal zone (see Figure 2).

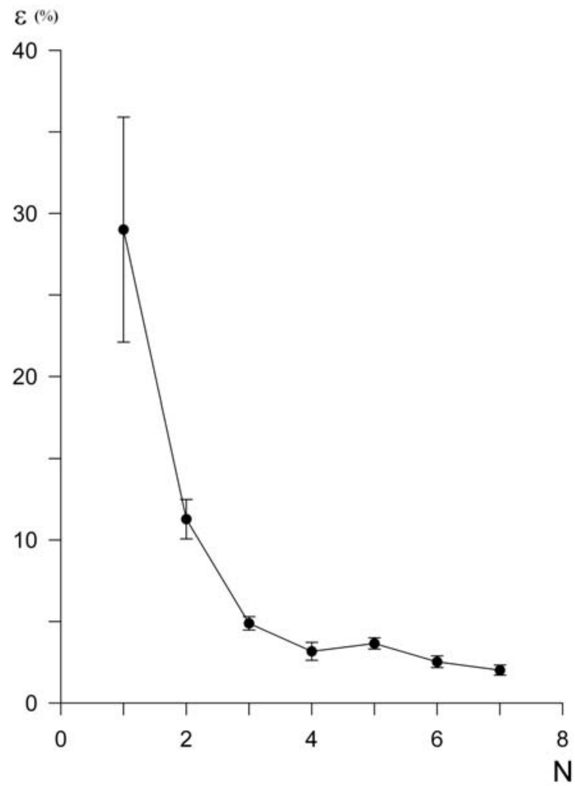

Figure 4: Temperature estimation errors (in per cent) depending on the number of the depth interval used for indirect EM geothermometer calibration and testing.

On the basis of the obtained results, an important practical recommendation can be proposed: when calibrating an indirect EM geothermometer it is advisable to avoid using the subsurface sections of temperature and conductivity profiles that are characterized by the strongest vertical inhomogeneity.

CONCLUSIONS

Thus, the use of the indirect electromagnetic geothermometer allows high accuracy temperature estimation at depths exceeding the depths of drilled wells for which temperature data are available. Here, for example, in extrapolation to a depth twice as large as the well depth the relative error is 5-6%, and in case of its threefold excess the error is about 20%. This result makes it possible to increase significantly the deepness of the indirect temperature estimation in the geothermal areas based on the available temperature logs in wells (often insufficiently deep).

Table 2. Temperature estimation errors (in per cent) for Hengill area depending on the depth range used for indirect EM geothermometer calibration and testing.

Depth range (km)		T3-MT44	T4-MT38	T5-MT52	T6-MT49	T8-MT53	T11-MT46	T10-MT81	T15-MT192
Calibration	Testing								
0.15-0.35	0.35-0.55	2.4	87.0	26.9	0.5	21.9	1.9	33.9	57.7
0.35-0.55	0.55-0.75	11.0	14.8	13.8	4.1	6.0	2.8	18.1	19.8
0.55-0.75	0.75-0.95	3.4	6.0	9.3	6.2	4.5	3.6	2.8	3.4
0.75-0.95	0.95-1.15	2.1	9.9	1.6	2.6	2.9	3.9	1.9	0.4
0.95-1.15	1.15-1.35	1.9	3.1	1.0	2.7	6.0	4.2	4.6	5.9
1.15-1.35	1.35-1.55	2.6	1.3	1.2	4.6	0.7	2.7	6.0	1.1
1.35-1.55	1.55-1.75	1.2	5.7	0.4	1.3	2.5	1.2	2.5	1.3

The method developed could be especially useful when exploring supercritical geothermal resources located at depths 4-5 km or deeper, where the temperature estimates could be made using the EM geothermometer calibrated by the shallow parts of the temperature logs.

Finally, it is worth mentioning that since the profiles of electrical conductivity are required for electromagnetic depth extrapolation, it is, generally, not obligatory to use the MT soundings to obtain such profiles as it has been done in the present work. It is important, however, that the EM soundings were carried out close to the wells from which the temperature data are taken for calibration of the geothermometer.

ACKNOWLEDGMENTS

The authors acknowledge Dr. H. Eysteinsson and Reykjavik Energy Inc. who kindly offered temperature well logs collected in the Hengill area. This work was supported by the INTAS (project no. 03-51-3327) and the Russian Foundation for Basic Research (project no. 07-05-00017).

REFERENCES

Arnorsson, S. and Gunnlaugsson, E. (1985), “New gas geothermometers for geothermal exploration-calibration and application”, *Geochimica et Cosmochimica Acta*, **49**, 6, 1307-1325.

Bjornsson, A. (2008), “Temperature of the Icelandic crust: inferred from electrical conductivity, temperature surface gradient, and maximum depth of earthquakes”, *Tectonophysics*, **447**, 136-141.

Harvey, C.C. and Browne, P.R.L. (1991), “Mixed-layer clay geothermometry in the Wairakei geothermal field, New Zealand”, *Clay and Clay Minerals*, **39**, 614-621.

Kharaka, Y.K and Mariner, R.H. (1989), “Chemical geothermometers and their application to formation waters from sedimentary basins”. In: *Thermal History of Sedimentary Basins* (Ed. N.D. Naeser and T. McCulloch), S.C.P.M. special issue, Springer Verlag, 99-117.

Oskooi, B., Pedersen, L. B., Smirnov, M., Árnason, K., Eysteinsson, H. and Manzella, A. (2005), “The deep geothermal structure of the Mid-Atlantic Ridge deduced from MT data in SW Iceland”. *Phys.Earth Planet. Int.*, **150**, 183–195.

Spichak, V.V. (2006), “Estimating temperature distributions in geothermal areas using a neuronet approach”. *Geothermics*, **35**, 181-197.

Spichak, V.V. and Manzella, A. (2008), “Electromagnetic sounding of the geothermal zones”. *J. Appl. Geoph.*, doi:10.1016/j.jappgeo.2008.05.007.

Spichak, V.V. and Zakharova, O.K. (2008_a), “Application of indirect electromagnetic geothermometer to the temperature extrapolation in depth". *Geophysical Prospecting* (submitted).

Spichak, V.V. and Zakharova, O.K. (2008_b), "A technique for the temperature estimation in the Earth's interior". *Patent of Russian Federation* № 2326413 of 10. 06. 2008.

Spichak, V.V., Zakharova, O.K. and Rybin, A.K. (2007_a), "Estimation of the sub - surface temperature by means of magnetotelluric sounding". *Expanded Abstr. XXXII Workshop on Geothermal Reservoir Engineering*, Stanford, USA.

Spichak, V.V., Zakharova, O.K. and Rybin, A.K. (2007_b), "On the possibility of realization of contact-free electromagnetic geothermometer". *Dokl. Russian Academy of Sci*. **417A**, 9, 1370-1374.