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Electromagnetic Porosity Forecast in Depth

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ABSTRACT

Accuracy of the porosity forecasting below boreholes from the results of electromagnetic sounding in their vicinity and resistivity well logging are compared using the data collected in the northern Tien Shan area (Kyrgyzstan). It is shown that the prediction accuracy using only electromagnetic sounding data from the vicinity of the wells is approximately the same as in other geological regions (in average, 8-10%). Prediction by means of the Archie formula leads to worse results not only when using electromagnetic sounding data, but also in the case of using the resistivity logs. The best results are obtained in the case of joint application of both data types. In particular, in forecasting to a depth twice as large as the well depth the relative error is only 2%. This finding is a good basement for Forecasting-While-Drilling scheme aimed at assessing the porosity/fracturing trends at depths bigger than the drilling depths.

1. INTRODUCTION

Geothermal resources are traditionally estimated taking into account rock porosity, which, in turn, is estimated from borehole measurements. However, a more accurate reserves assessment requires estimation of porosity at depths greater than the depth of wells drilled. Currently, the assessment of reservoir properties is carried out on the basis of their interpolation / extrapolation outside the wells using seismic attributes determined as a result of correlation analysis (Pan and Ma, 1997; Dolberg et al., 2000). Meanwhile, this approach suffers from a number of shortcomings, which may result in loss of estimation accuracy and, as a consequence, may lead to erroneous reserves assessment. Firstly, the results of seismic tomography are averaged over the volume, and they are generally of low vertical resolution (Pan and Ma, 1997). Secondly, accuracy of estimates decreases sharply in the case of complicated subsurface geometry. Finally, involvement of seismic attributes maximally correlated with scarce porosity data from the wells may cause prediction errors in differing geological and geophysical conditions outside the wells (Kalkomey, 1997).

Alternative approach that doesn't require prior assumptions concerning the subsurface lithology and correlation of seismic attributes with porosity can be based on the involvement of such proxy parameter as electrical resistivity. Spichak and Zakharova (2015, 2016) carried out a feasibility study aimed at prediction of the porosity at depths below the bottomhole using resistivity logging data and the results of inversion of magnetotelluric (MT) data collected in an abandoned oil field in Alsace (France). It was shown that the proposed approach in principle allows predicting porosity from the electrical logging-based resistivity in the well and from the resistivity obtained using inversion of electromagnetic (EM) sounding data acquired in the well neighbourhood. In the case the predicted depths are not more than twice as big as the well depth, then the prediction based on the resistivity logging data is preferable; with a depth ratio of 5-10, the results of prediction based on inverted EM sounding data are noticeably better; in the intermediate range, the prediction errors are approximately the same.

The forecast accuracy is influenced by both the type of the data used and the forecast algorithm. The purpose of this study was to find the best way to predict the porosity at depth using electromagnetic data depending on the availability of well logging data and the results of electromagnetic sounding in the vicinity of the borehole. For this purpose, data from two wells drilled in the Chu depression (northern Tien Shan) (Makeev et al., 2004), as well as the results of magnetotelluric (MT) sounding carried out in this region previously (Rybin et al., 2008) were used (see Figure 1 for their locations).

2. LITHOLOGY AND POROSITY DATA

Deep-hole drilling in the East Chu depression was carried out in Serafimovsky (P1 well) and Belovodsky (P2 well). Below we discuss the porosity data obtained by measurements on core samples, and their relationship to lithology following to (Makeev et al., 2004).

Serafimovsky area is situated in the eastern part of the Cis-Kyrgyzsky trough. In accordance with lithologic composition and paleontological identification, geological section penetrated by P1 well is classified as follows: Quaternary deposits, Chu, Kyrgyz and Palaeozoic formations (Figure 2a). Quaternary deposits are represented by boulder and pebble formations with loam interlayers having open porosity factor (hereinafter - porosity) of about 30%. The Chu formation is represented by thin alternation of clay, sandstone, gritrock and pattum beds with average porosity ranging from 10 to 12%. Hydrocarbon gases registered in the well column are apparently not genetically associated with the rudaceous rocks; they are the result of migration from the underlying sediments. The Kyrgyz formation is about one and a half kilometre thick. It is represented by alternation of siltstone, clay, and sandstone with porosity ranging from 10% to 4-5%.

Belovodsky area is situated in the central part of the Cis-Kyrgyz trough. Well P2 penetrated the Quaternary boulder and pebble formations with loam interlayers having porosity ~20-22%; the Chu formations represented by thin alternation of clay, sandstone, gritrock, and pattum beds having average porosity about 10%; the Kyrgyz formation represented by alternation of sandstone, clay, siltstone having low porosity (about 3.5%); Kokturpak formation represented by clay, sandstone, pattum, and gritrock with a slightly higher average porosity (4%). Below the depth of 3106 m, the well entered the Carboniferous deposits and granite of the Alamin sequence with a porosity of about 2% (Figure 2b).

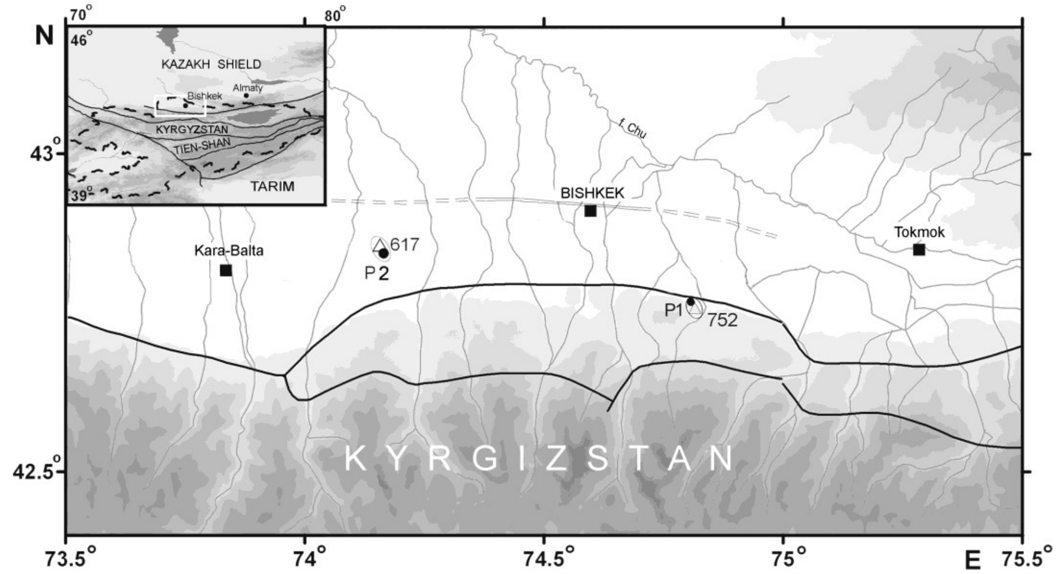

Figure 1: Map of the study area. Location of the boreholes P1 and P2 is marked by dots, while location of magnetotelluric sounding sites (752 and 617, accordingly) is marked by triangles. Black lines indicate deep faults.

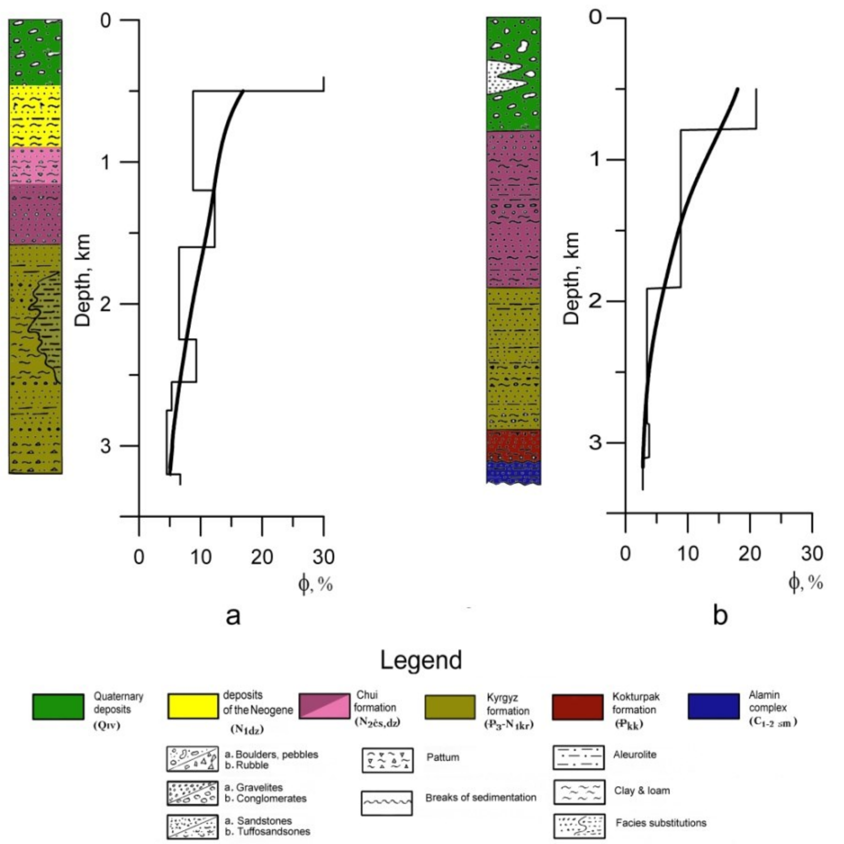

Figure 2. Porosity data synthesized from laboratory studies of the core samples in the boreholes P1 (a) and P2 (b). Lithology is shown in the left columns.

Synthetic data used for our studies were obtained by spline-approximation of the porosity profile in every well with a depth step 0.01 km (Figure 2a,b).

2. ELECTRICAL RESISTIVITY DATA

In order to predict porosity, the resistivity logging data (Makeev et al., 2004) were used together with the resistivity cross-sections obtained as a result of 1D inversion of MT sounding data in the vicinities of the wells (Rybin et al., 2008) (Figure 3).

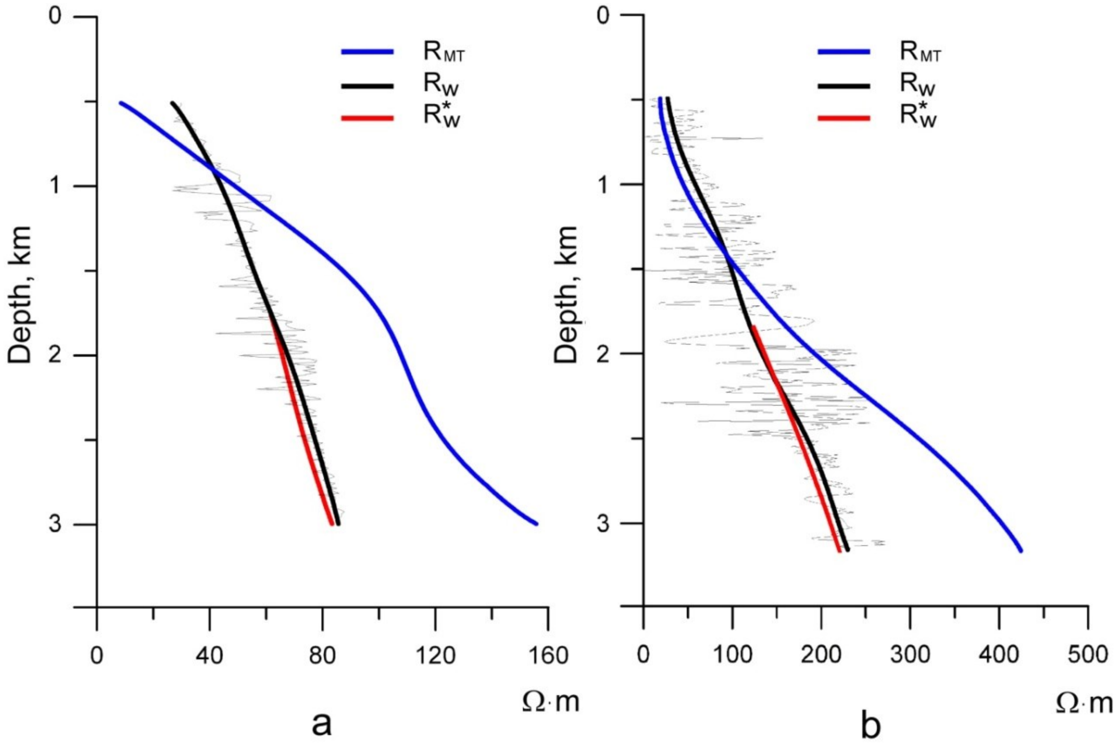

Figure 3. Electrical well logging data R_w, resistivity pseudo-logs R_w^* and results of 1D inversion of MT data (R_{MT}) in the boreholes P1 (a) and P2 (b).

2.1 Resistivity Logging

The lithology columns are represented by alternation of terrigenous rocks (Figure 2). Accordingly, initial resistivity well logs attracting the lithology manifest a strongly differentiated nature varying from 5-10 to 250-300 Ohm.m. Boulder and pebble formations have high resistivity (250-300 Ohm.m); resistivity of gritrock, sandstone, and clay beds is 40-80 Ohm.m, 30-40 Ohm.m, and 5-30 Ohm.m, respectively. Higher resistivity values are typical of the Palaeozoic formations. For instance, resistivity of Palaeozoic sandstone is 70-80 Ohm.m, while similar Neogene rocks have a resistivity of 30-40 Ohm.m. Resistivity of acid volcanic rocks reaches 300 Ohm.m.

2.2 Electromagnetic sounding data

Magnetotelluric data were collected in the sites 752 and 617 in the frequency range from $5 \cdot 10^{-4}$ to 300 Hz in the vicinity of the wells P1 and P2, respectively (see their location on the map in Figure 1). In order to build a resistivity cross-section at every site up to the depth of 3-4km 1D inversion of MT data was carried out (Rybin et al., 2008) (Figure 3). It was justified by the fact that the dimensionality indicator "skew" (Swift, 1967) for periods less than 1s corresponding to these depths did not exceed 0.1- 0.2 (Figure 4).

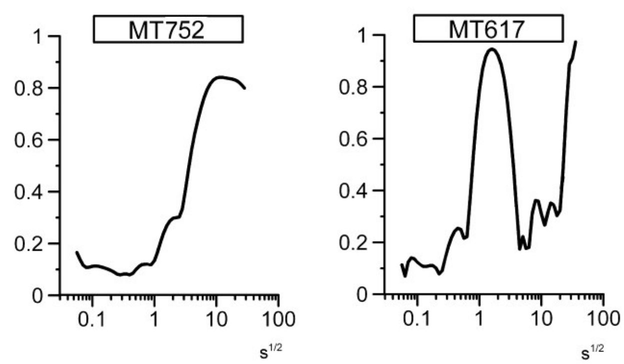

Figure 4. Graphs of the dimensionality indicator in the MT sites 752 and 617, adjacent to boreholes P1 and P2, respectively.

3. MODELING METHODOLOGY

Smoothed resistivity logging data (R_w) and the results of 1D inversion of MT sounding data (R_{MT}) in the vicinity of the considered wells (Figure 3) were used for porosity prediction at depth. All the input data were pre-interpolated in depth to the same grid with 0.01 km step.

Modeling of the porosity forecast in depth was carried out assuming presence of the porosity data in the drilled borehole and results of electromagnetic sounding in its vicinity. Comparison of 1D inversion graphs (R_{MT}) and resistivity logging (R_w) data in each well (Figure 3) shows that they are rather different. It was therefore important to compare accuracy of the porosity predictions based either on only EM resistivity data or on both of them. Additionally, forecasting porosity by means of application of the Archie formula (Archie, 1942) to electromagnetic or logging resistivity was considered.

All experiments were carried out similarly: synthetic porosity (φ) data from the upper halves of the boreholes and electrical resistivity (R_{MT}) values determined at the same depths were considered as input data; prediction was performed for the lower halves of the boreholes; forecasted porosity (φ^{for}) was compared with its true values (φ^{true}) from the lower halves and a mean relative error (ε) was determined according to the formula:

$$\varepsilon = \sqrt{\frac{\sum_n (\varphi_n^{for} - \varphi_n^{true})^2}{\sum_n \varphi_n^{true^2}}} x100\% \tag{1}$$

where n is a sequence number of porosity prediction point ($n = 1,\ldots,N$); N is a number of prediction points; φ_n^{true} and φ_n^{for} are the true and forecasted porosity values in the n-th point, respectively.

In all cases, except for estimates by means of the Archie formula, forecasting was carried out using a neural network approach (supervised neural networks) (Haykin, 1999), which is well-proven in solving various problems of geoelectrics (Spichak, 2011).

4. PREDICTION OPTIONS

Depending on the available well logging data, the following prediction options in the lower halves of the wells were considered.

1. Neural network prediction of porosity (φ) using the synthetic porosity values from the upper half of the borehole and 1D electrical resistivity profile R_{MT}:

- teaching of the artificial neural network (ANN) by the correspondence of φ and R_{MT} determined at the same depth;

- forecasting porosity in the lower part of the borehole using the R_{MT} values determined at these depths.

2. Prediction of porosity from R_{MT} using the Archie formula (A1) (see the Appendix A) assuming full saturation (S=1) and taking into account estimates of parameters m and R_f (A4).

3. Neural network prediction of porosity φ using the synthetic porosity and resistivity logs (R_w) and resistivity logging (R_w) from the upper half of the borehole, and 1D electrical resistivity profile (R_{MT}):

- teaching of the artificial neural network by the correspondence of synthetic porosity φ and resistivity logs (R_w) determined at the same depth in the upper half of the borehole;

- forecasting porosity in the lower part of the borehole using the values of so called "pseudo-log" (R_w^*) determined at these depths from R_{MT} and R_w according to a special algorithm proposed by Spichak and Zakharova (2018).

4. Prediction of porosity from pseudo-log (R_w^*) using the Archie formula (A1) assuming full saturation (S=1) and taking into account estimates of parameters m and R_f (A4).

5. RESULTS

Figure 5 and Table 1 demonstrate the results of modeling for both wells and four prediction options enumerated above. As can be seen from Table 1, prediction from resistivity R_{MT} taking into account the resistivity logging data R_w (options 3 and 4), gives better results than prediction using only R_{MT} data (options 1 and 2, respectively). Neural network prediction using the cited above algorithm (option 3) shows the mean error minimal among all the options (ε = 2.1%).

Table 1. Relative errors (ε) of the porosity forecast (in %) on the lower parts of the boreholes P1 and P2.

Borehole	Number of option			
	1	2	3	4
P1	7.8	43.6	1.4	8.1
P2	8.3	34.7	2.9	10.6
Average error	8.0	39.1	2.1	9.3

Comparison of neural net prediction with estimates obtained using the archie formula (compare options 1 and 2 and options 3 and 4) shows that application of the archie formula (options 2 and 4) gives the worst results, and this occurs not only with resistivity r_{mt} data (option 2), as might be expected, but also with resistivity logging data (option 4).

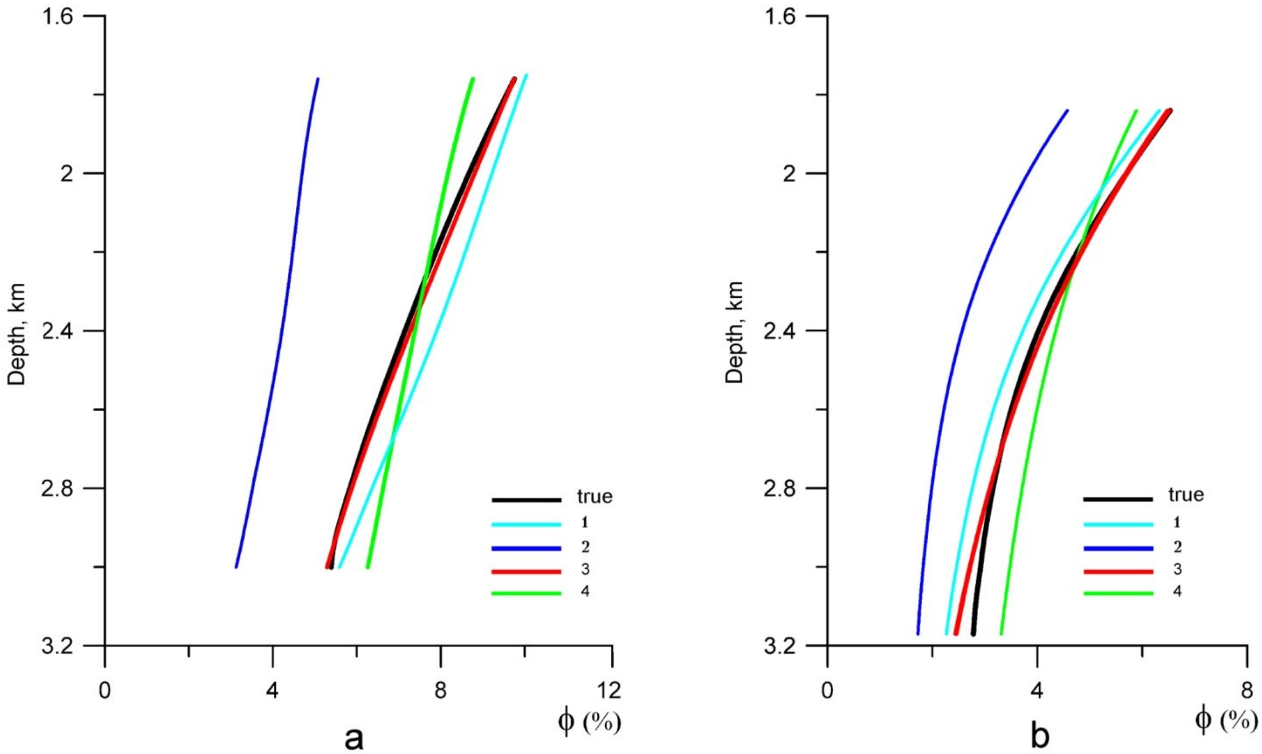

Figure 5. Porosity forecast at depths of lower halves of the boreholes P1 (a) and P2 (b) using: 1 - R_{MT}, 2 – R_{MT} and Archie formula, 3 - R_{MT} and resistivity pseudo-log R_w^*, 4 – resistivity pseudo-log R_w^* and Archie formula.

6. CONCLUSIONS

The obtained results of porosity prediction allow drawing the following conclusions. Accuracy of porosity prediction at depth using only EM sounding data from the vicinity of a well is approximately the same as in other geological regions (see, for instance, (Spichak, Zakharova, 2016)) (in average, 8-10%). Prediction using the Archie formula leads to worse results not only with EM sounding data, but also with resistivity logging data. At the same time, the prediction of porosity using both EM sounding data (note that magnetotelluric data is not the only possibility) in the vicinity of wells and resistivity logs opens the way for more accurate estimation of porosity at depths below the bottomhole (in particular, the mean relative error is around 2% when the target depth exceeds the drilling depth two times). Application of this approach can be especially relevant in on-line prediction of reservoir properties at depth in the course of exploration drilling using the Forecasting While Drilling scheme (Spichak, 2013, 2014).

APPENDIX A. ESTIMATION OF THE ARCHIE FORMULA'S PARAMETERS

Preliminary estimation of the Archie formula's parameters was conducted for each well to use them in prediction. According to (Archie, 1942), we write:

$$R_f = R\, \varphi^m S^n, \tag{A1}$$

where R is a resistivity of rock matrix; R_f is resistivity of a fluid; φ is porosity; S is fluid saturation.

From (A1) it follows that

$$-\log R = m \log\varphi - \log R_f + n \log S \tag{A2}$$

Considering for simplicity that S = 1 (100% fluid saturation) and assuming that $R_f \approx$ const can be accepted at the depths under consideration, we find m and $\log R_f$ as linear dependence coefficients:

$$Y = aX + b, \tag{A3}$$

where a = m, and b = - logR_f

To do this, we perform linear regression using all the available data (logR (z) and log φ (z)) both specified at the same depths. The following estimates of cementation factor m and fluid resistivity R_f were obtained:

Borehole P1: m ≈ 1.0, R_f ≈ 6.8 Ohm.m;

Borehole P2: m ≈ 1.0, R_f ≈ 7.3 Ohm.m (A4)

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