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Integrated electromagnetic and geochemical surveys for petroleum exploration in West Siberia

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Abstract

Electromagnetic soundings with controlled and natural sources (TEM and MT, respectively) integrated with IP and geochemical surveys have been tested for petroleum exploration in West Siberia. The TEM method, with loop sizes smaller than the depth to the target, provide high resolution, sufficient penetration depth, and data locality. The MT method sounds deeper earth and can place constraints on the Paleozoic basement structure and its electrical properties. The petroleum implications of IP and geochemical data are associated with secondary alteration (mineralization) of rocks over oil traps.

Keywords: transient electromagnetic (TEM) sounding; magnetotelluric (MT) sounding; induced polarization (IP); geochemical survey; joint data processing and interpretation

Introduction

The subsoil of West Siberia is exceptionally rich in fuel resources. It may store 40% to 50% of Russia's recoverable original oil-in-place (OOIP) yet to discover, which can maintain long-term stable production (Karogodin, 2003; Kontorovich, 2008).

The West Siberian plate has a rather homogeneous sedimentary cover consisting of sand-silt and shale. The lithologically uniform sediments are hard to divide according to electrical properties, and special approaches are required to obtain reliable reservoir models based on resistivity surveys. In this respect it is reasonable to integrate the transient electromagnetic (TEM) and magnetotelluric (MT) soundings with controlled and natural sources that can sound shallow and deep earth, respectively. Joint use of the two electromagnetic (EM) methods has been practiced broadly in Russia and worldwide, but we suggest a new modification to the approach by integrating geophysical and geochemical data; the latter are used to trace secondary alteration of rocks by hydrocarbons percolated from below. The new approach has been tested successfully at two prospects in West Siberia (Trigubovich and Epov, 2008).

The TEM and MT datasets complement one another, each method having its advantages: a higher resolution to 3–4 km depths in the former (depending on the earth electrical properties and survey configuration) and a greater depth of exploration (to 10–15 km) in the latter.

The petroleum implications of geochemical data stem from the fact that flow of hydrocarbons causes marked physical changes and chemical reactions in a bulk of rocks over an oil trap. Sulfide (pyrite or other) mineralization and calcite cement in sands above oil accumulations were first noted in the US and Iraq and were also found later elsewhere in petroleum provinces. These effects received quite little research at that time, but the interest has been rekindled recently with the advent of advanced instruments. Secondary alteration of rocks is commonly well pronounced and restricted to shallow depths, where it is detectable by the cheap and fast techniques of geochemical surveys.

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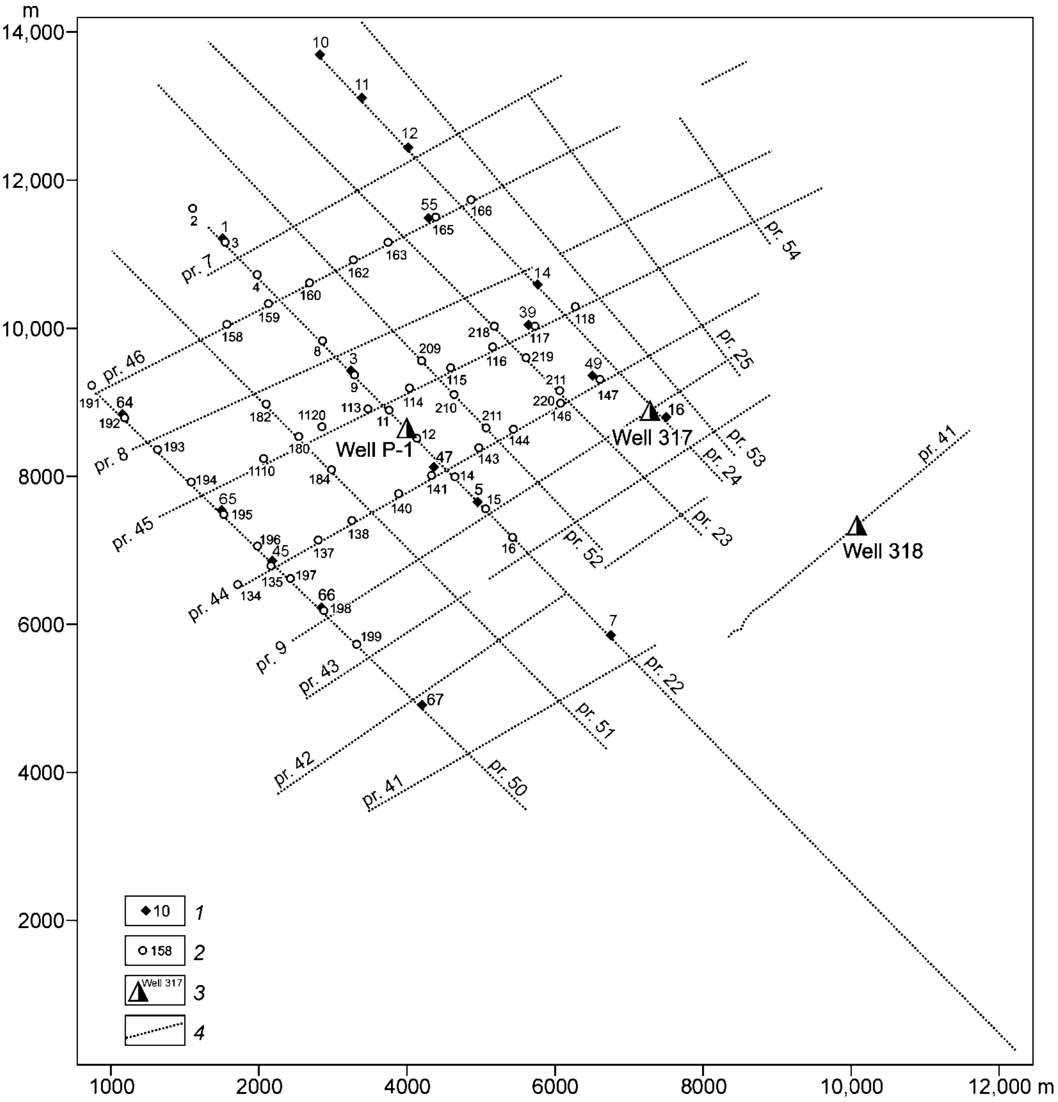


Fig. 1. Integrated geophysical and geochemical surveys in Tomsk region. *1*, MTS stations; *2*, TEM stations; *3*, wells and their numbers; *4*, sampling sites for chromatography and ionometry.

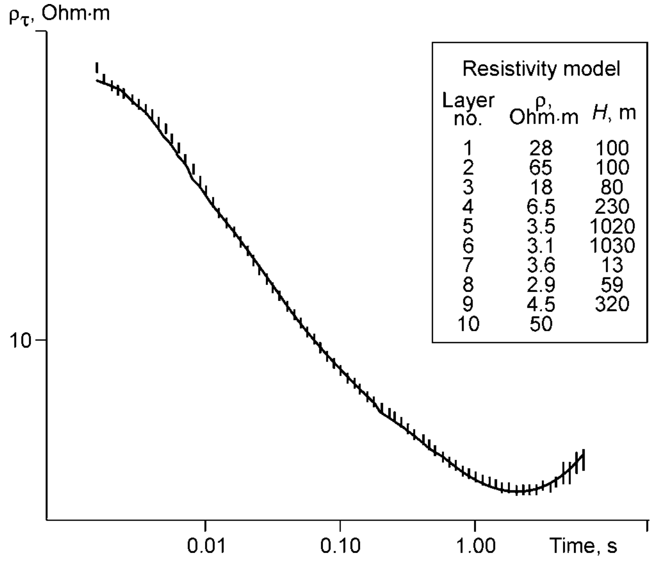
Resistivity and geochemical surveys of a prospect in the northern Tomsk region

Integrated surveys with the TEM, MTS, and IP methods have been run in a prospect located in the northern Tomsk area along a system of seismic profiles collected in previous years (Fig. 1).

TEM data were acquired with in-loop and off-loop systems at 52 points. The square ungrounded transmitter and receiver loops had the sizes 500 × 500 and 75 × 75 m, respectively. The primary EM field was generated by a 400 V and 100 kW AC source; the maximum transmitter current was 150 A.

The quality of field data being critical for the lithologically uniform rocks in West Siberia, interpretation began with analysis of all available TEM results. The viewed curves were examined in terms of instrument errors, distortions (Epov et al., 2006), variation patterns, and correlations, in order to select points where the acquired responses were complete, free from distortions, and having prominent minimums and right-hand ascending branches. Thus selected curves fitted the layered-earth assumption and could provide reliable estimates of depths to the reference geoelectric layer (basement) and its resistivity. The selected high-quality curves, along with well-log data (well 317, 318, P-1), were used to create a starting resistivity model which was further updated in the course of inversion. At the first step of data processing, differentiation curves were obtained that represented the layered section with thick low-resistivity layers. Most of the curves had an ascending right-hand branch indicative of the depth and resistivity of the basement being times more resistive than the overlying sediments.

Figure 2 shows a typical measured transient response and the respective computed curve on the left and the resistivity model derived therefrom on the right, for station 15 in the eastern part of the prospect. The two curves match well over the entire time range, except for minor misfit at early times possibly due to near-surface heterogeneity. The model predicts relatively high resistivities in three upper layers, ~300 m thick



Layer no.	ρ, Ohm·m	H, m
1	28	100
2	65	100
3	18	80
4	6.5	230
5	3.5	1020
6	3.1	1030
7	3.6	13
8	2.9	59
9	4.5	320
10	50	

Fig. 2. Typical measured and computed transient responses and the respective resistivity model for station 15 in the eastern part of survey area. Field data are shown as vertical bars, with their length proportional to error (within 5%) and the computed curve is shown as solid line. In-loop configuration, transmitter and receiver loop sizes 500 × 500 m and 67 × 67 m, respectively.

in total, and in the reference basement layer (about 50 Ohm·m throughout the survey area), while the other six geoelectric layers are times more conductive (Fig. 2).

The collected responses have been processed with the *Era* and *EMS* software packages (Epov et al., 1990; Khabinov, 2009). Consider, for example, *EMS* processed data from profile 22 running from northwest to southeast (Fig. 3). The resistivity variations within each geoelectric layer are shown by a color scale. The basement is the most resistive: from 40–50 Ohm·m in the southeast (TEM points 14, 15, 16) to 100 Ohm·m in the northwest (TEM points 3–12). Resistivity is the most variable in the uppermost layer, while all sediments below 200–250 m are conductive and more uniform. Nevertheless, the field data resolve several layers with their resistivities and thicknesses (estimated for each sounding) suitable to create maps and sections (Nevedrova and Sanchaa, 2013).

Of special interest is a map of depths to the Bazhenovka Formation surface (Fig. 4) imaging an asymmetrical low anticlinal uplift elongate in the SE–NW direction. Geological reservoir modeling using the mapped thickness and resistivity patterns of Jurassic reservoirs (Bazhenovka, Vasyugan, Tyumen), with reference to well-log, seismic, and geochemical data, predicts that the uplift may be a promising target.

The maps of geoelectric parameters may furnish additional knowledge of prospect areas. See, for instance, a resistivity map of sediments overlying the Bazhenovka reservoir (Fig. 5). Comparison with the map of Fig. 4 shows that sediments are more resistive over the Bazhenovka surface uplift.

Qualitative and quantitative interpretation of *MT data* consisted, respectively, in the choice of a starting resistivity model and estimating its parameters. The model choice is especially difficult and the interpretation modeling of MT data is of great importance because the true MT pattern depends

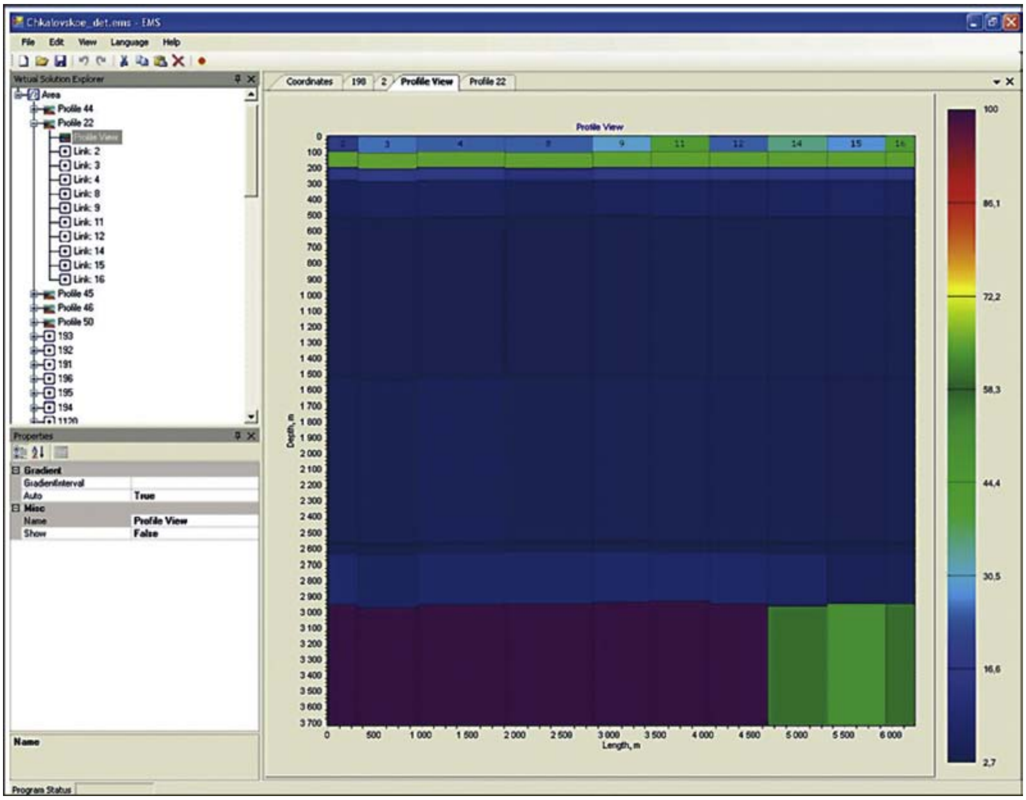


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Fig. 3. *EMS*-processed TEM data from profile 22 (Trassovy prospect, Tomsk region).

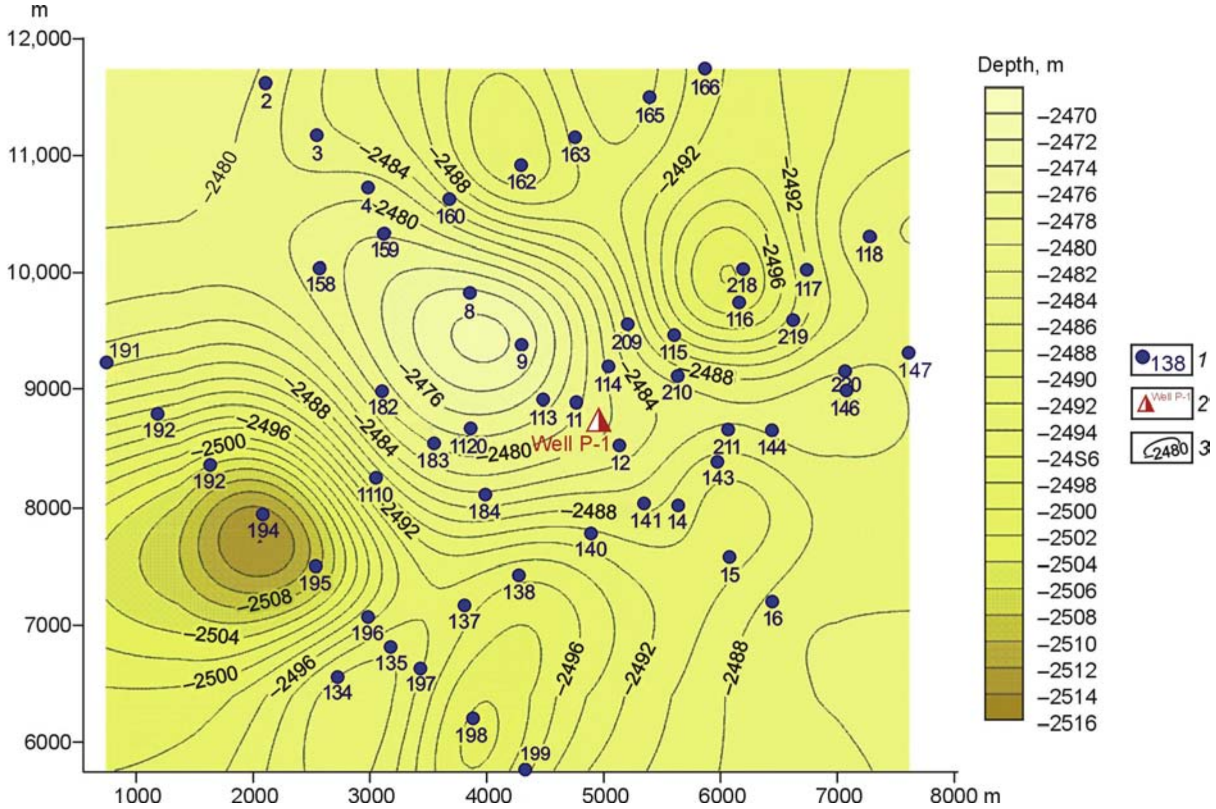

Fig. 4. Map of depths to the top of Bazhenovka Formation, from TEM data for Trassovy prospect, Tomsk region. *1*, TEM stations; *2*, wells; *3*, basement surface contour lines.

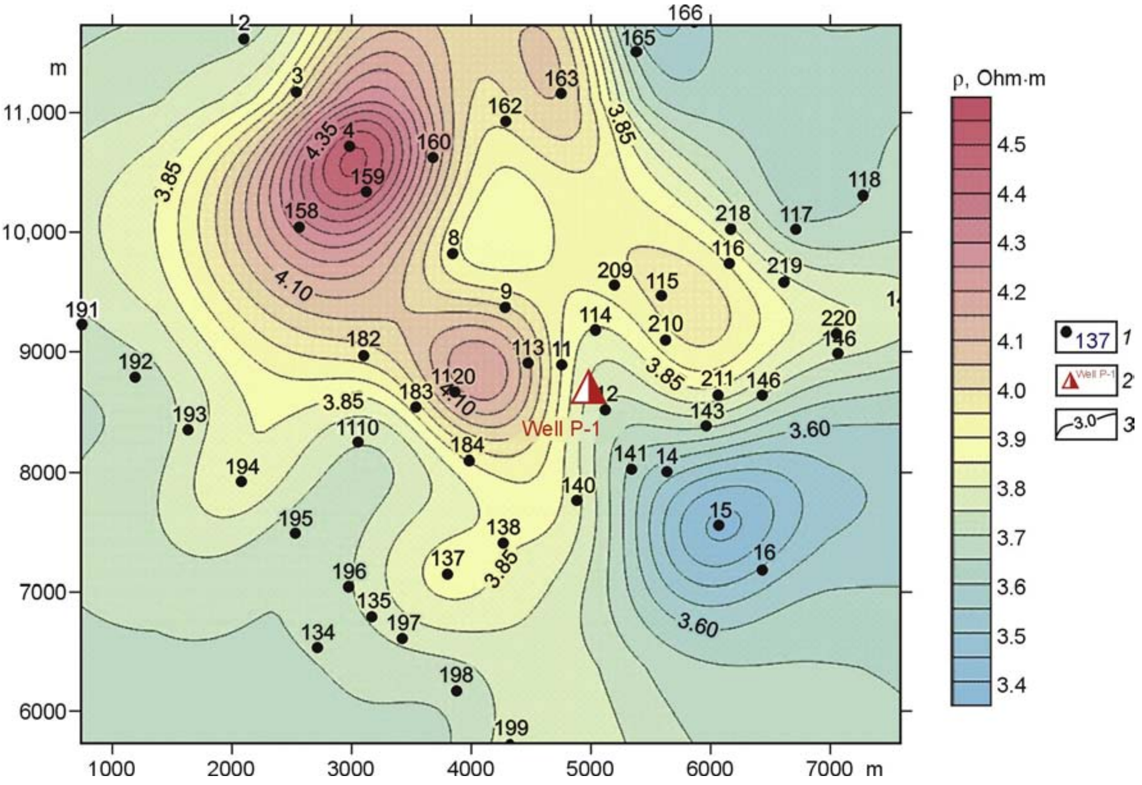

Fig. 5. Resistivity map of the layer above the Bazhenovka reservoir. Trassovy prospect, Tomsk region. *1*, TEM stations; *2*, wells; *3*, electrical resistivity isolines.

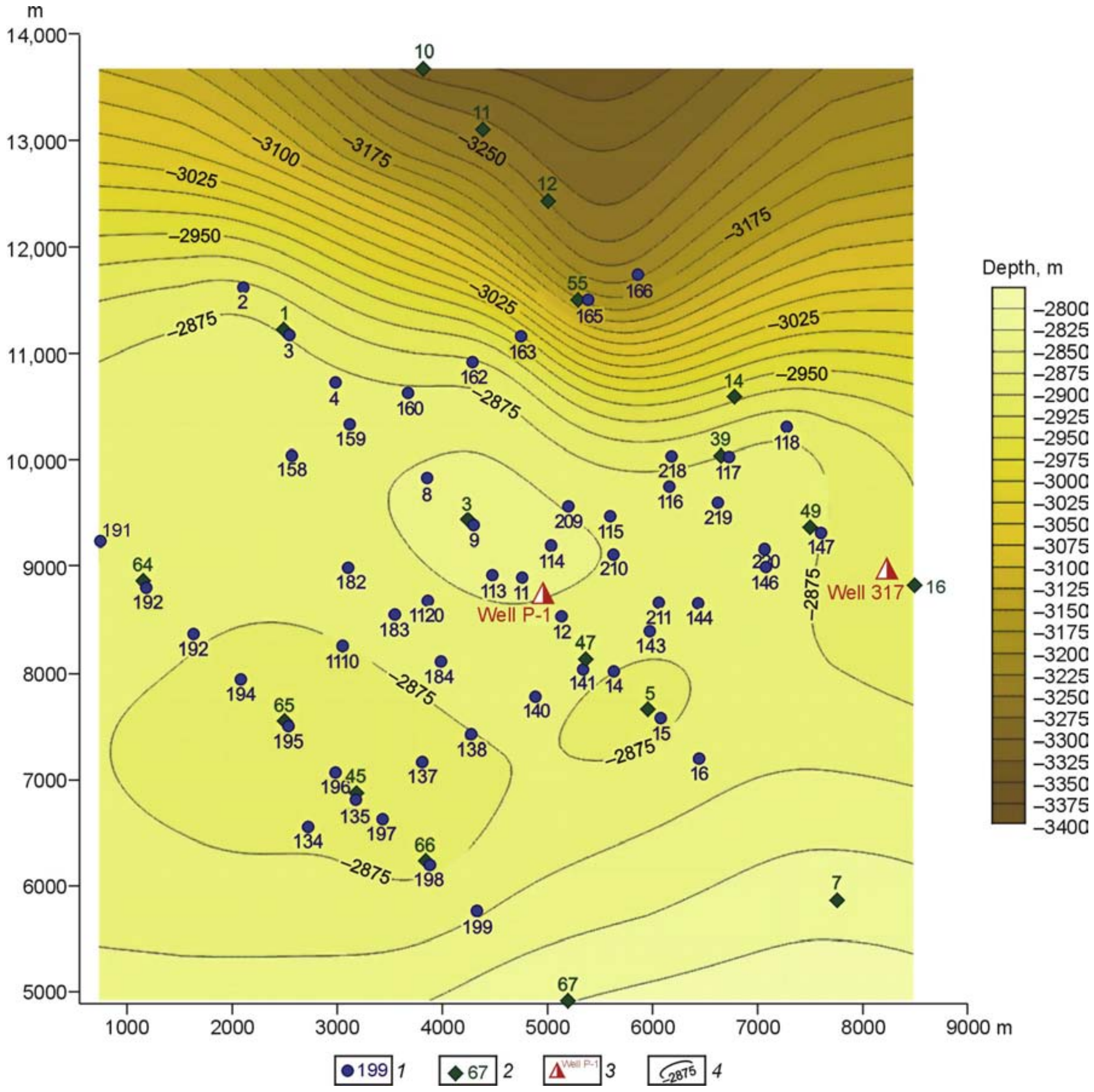

Fig. 6. Map of sediment thickness (depths to Paleozoic basement), from TEM and MTS data. *1*, TEM stations; *2*, MTS stations; *3*, wells; *4*, basement surface contour lines.

on the distribution of rock properties in both vertical and lateral dimensions (Berdichevsky et al., 1997). The measured resistivities vary in three dimensions, but the dimensionality can be reduced to 2D or 1D approximations (more or less accurate), for the sake of simplicity.

In order to estimate the data quality, the left-hand branches of MT curves were normalized to the TEM curves that were free from effects distorting the MT field. The right-hand branches can be likewise normalized, either against “normal” model curves that represent the local thermodynamic conditions or against Vanyan’s curve (Berdichevsky and Logunovich, 2005). The data were processed with the *SEMAPMTZ* software (designed by N.O. Sviridova and Yu.V. Utyupin) based on the algorithm of equivalent points which enables semiautomated processing. The resistivity–depth profiles were obtained at the final phase of quantitative processing with the *LineInterMT* software (by A.V. Pospeev). Then the resistivity models derived from the two (TEM and MTS) datasets were correlated.

The map of sediment thickness (depths to the surface of the Paleozoic basement) created on the basis of jointly processed TEM and MT data (Fig. 6) likewise images a positive structure traceable throughout the sedimentary section. The basement subsidence in the northern and northeastern directions (Fig. 6) is consistent with seismic data.

The geological interpretation of the resistivity surveys (Karogodin, 2006; Orlov, 2000; Shemin, 2007) confirmed good petroleum prospects of the uplift at the Bazhenovka level, and pay zones were also inferred in the uplift of the Paleozoic basement (Shemin, 2007). The inferences were proved valid by an economic oil flow obtained during later drilling in the southwestern part of the structure.

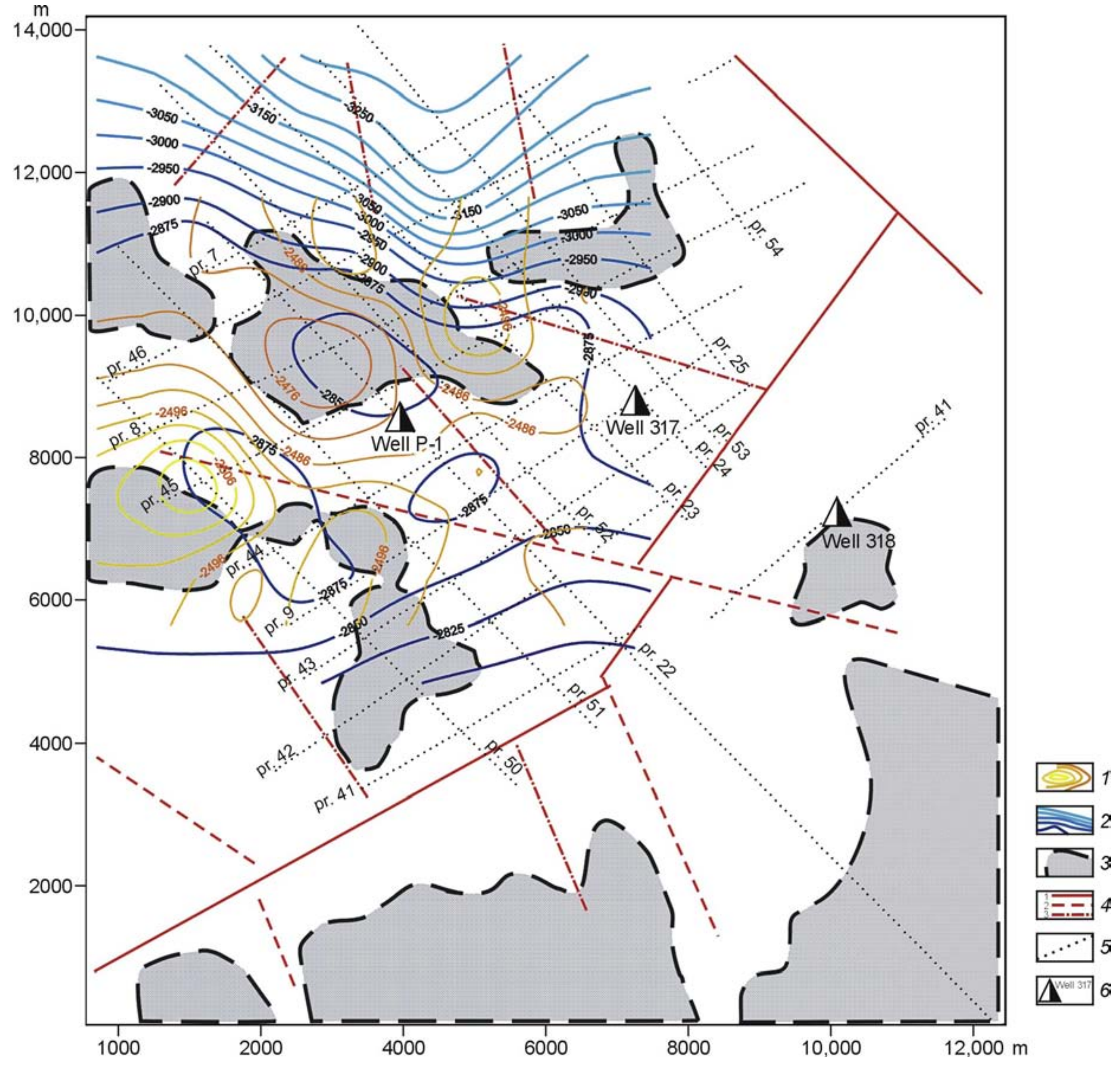

Fig. 7. Results of joint processing of geomorphology and resistivity data. *1*, contour lines of depths to Bazhenovka Formation base from TEM data; *2*, contour lines of depths to Paleozoic basement from TEM and MT data; *3*, contours of residual elevation highs; *4*, first-order (1), second-order (2), and third-order (3) faults from geomorphic analysis; *5*, sampling sites; *6*, wells.

Thus, the joint processing of TEM and MTS data has arrived at its main goal of resistivity-based reservoir characterization and detection of an oil-bearing structure.

The petroleum exploration implications of *chemical data* are due to mineralization haloes produced by upward percolation of oil when its flow encounters the first effective regional seal. Changes in the stability fields of some minerals and in mobility of some elements within the affected zone change the rock compositions. These processes show up as anomalies in acoustic, electric, magnetic, radiation, and geothermal fields over the oil traps, which may be detected by shallow geophysical and geochemical surveys.

Even small oil traps can manifest themselves in the near-surface sediments in different ways depending on the conditions of oil generation, migration, and accumulation, as well as on subsequent processes increasing the seal permeability (especially erosion). There have been a number of models, mostly similar or complementary in some details, which use different case studies to explain the origin of anomalies over oil accumulations. For instance, the model of Pirson (1981) with currents in an "oil–surface" system and related electric and magnetic anomalies appearing both in drill holes and on the surface.

Microseepage ("breathing") of oil increases the concentrations of hydrocarbons and nonhydrocarbon gases (He, Rn, I, etc.) in rocks, soils, and air over the trap, and causes changes to pH and Eh favorable for mineralization (secondary calcite, pyrite, magnetite, U salts), as well as changes in clay mineralogy and trace element abundances (Saunders et al., 1999; Schumacher, 1996). Pyrite and other sulfide mineralization of rocks lying over an oil accumulation was first reported in the early 1900s from Louisiana (Schumacher,

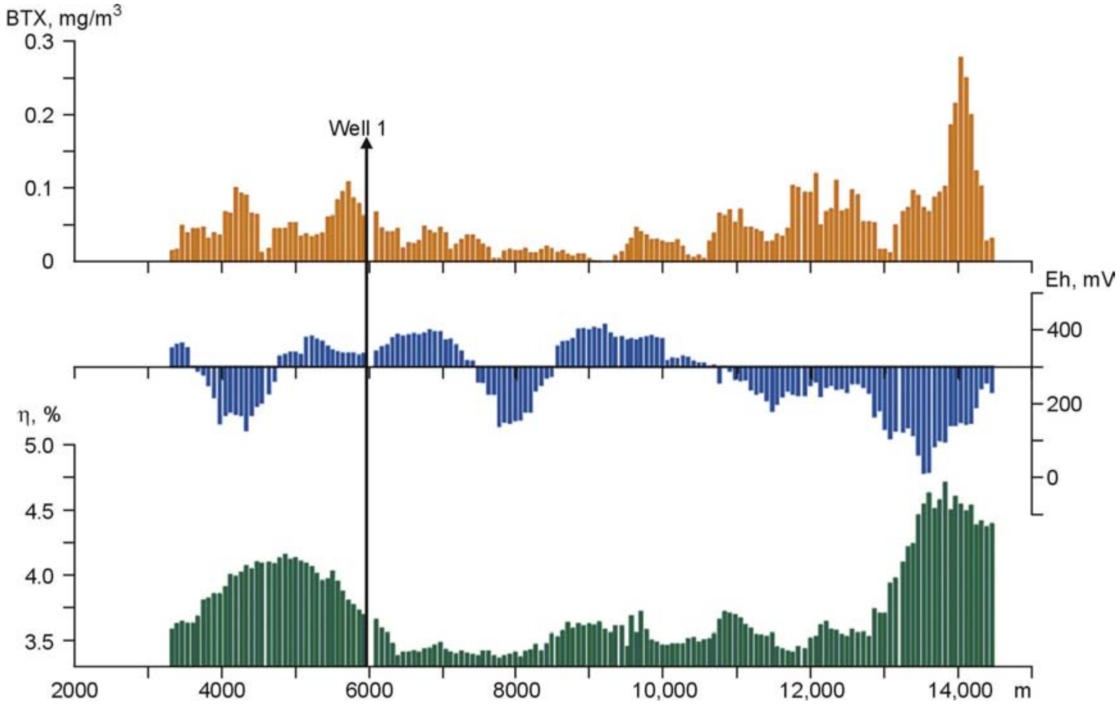

Fig. 8. BTX, Eh, and chargeability values for Quaternary clay samples.

1996). After that first discovery, the respective exploration methods developed rapidly in the USSR, USA, and Germany. Gas and microbiological surface surveys in the USSR led to some minor discoveries, but the research stopped then to be resumed only in two or three recent decades.

However, mineralization and related physical and chemical anomalies associated with oil and gas accumulations have been largely encountered in the exploration practice. Chemical reactions over oil traps give rise to telluric currents as a result of electrochemical processes. The altered rocks stand out against the background in their electrical and chemical properties and thus make hydrocarbons detectable by on-site methods.

Rocks at the prospect in the Tomsk region were sampled by auger drilling from the depths of 3.5–4.0 m for laboratory analyses. The core samples were mostly Quaternary clay and heavy-textured clay silt (loam), and few samples were light-textured loam and peat–clay mixture. The analytical procedures included chromatography, pH, Eh, magnetic susceptibility, and gamma spectrometry, as well as measurements of chargeability by the fast-decaying IP method performed for the first time in area. The concentrations of aromatic hydrocarbons (benzene, toluene, xylene) were measured by liquid-gas chromatography (LGC-1); electrochemical analyses were performed with a *Multitest IPL-103* ionometer; fast-decaying IP was measured using a software–hardware system designed at SPE GE *LOOCH*.

The geochemical data were interpreted with reference to the results of geomorphological and resistivity (TEM and MTS) modeling. The electromagnetic methods revealed a potentially oil-bearing low uplift of the Paleozoic basement surface. The Paleozoic rocks being markedly more resistive than the Mesozoic sediments, their top was clearly pronounced in TEM and MT data, as well as the Bazhenovka surface. The existence of highs in the basement and Bazhenovka surfaces was further confirmed by residual elevation highs: comparison of the geomorphology-based residual elevation map with the sediment thickness contour lines derived from resistivity data showed a satisfactory agreement, both imaging an uplift north of well 1 (Fig. 7).

Then interpretation criteria were selected for the chemical methods on the basis of depth-dependent values of measured parameters and their diagnostic importance. The zones of high concentrations of benzene, toluene, xylene (BTX) were found out to spatially coincide with Eh lows and chargeability highs (Fig. 8). Therefore, the combination of related BTX, Eh, and chargeability parameters was selected as a criterion diagnostic of petroleum potential.

The obtained spatial patterns of chemical parameters were then correlated with the structural maps based on geophysics (see them compared in Fig. 9). The IP-based chargeability anomalies have quasi-annular shapes and fall within the slopes of structural highs (surface projections of the anticline limbs).

The BTX anomalies, with 0.04 mg/m^3 contours (20 times the background), match the slopes of residual elevation highs. Note that the BTX anomalies contour the whole uplifted structure in the northwest, which may be part of an open ring structure. There is another BTX anomaly in the southeastern part of the survey area, but it cannot be reliably constrained for data shortage.

The map of jointly processed geochemical and geomorphic data (Fig. 9) also images anomalies of the redox potential

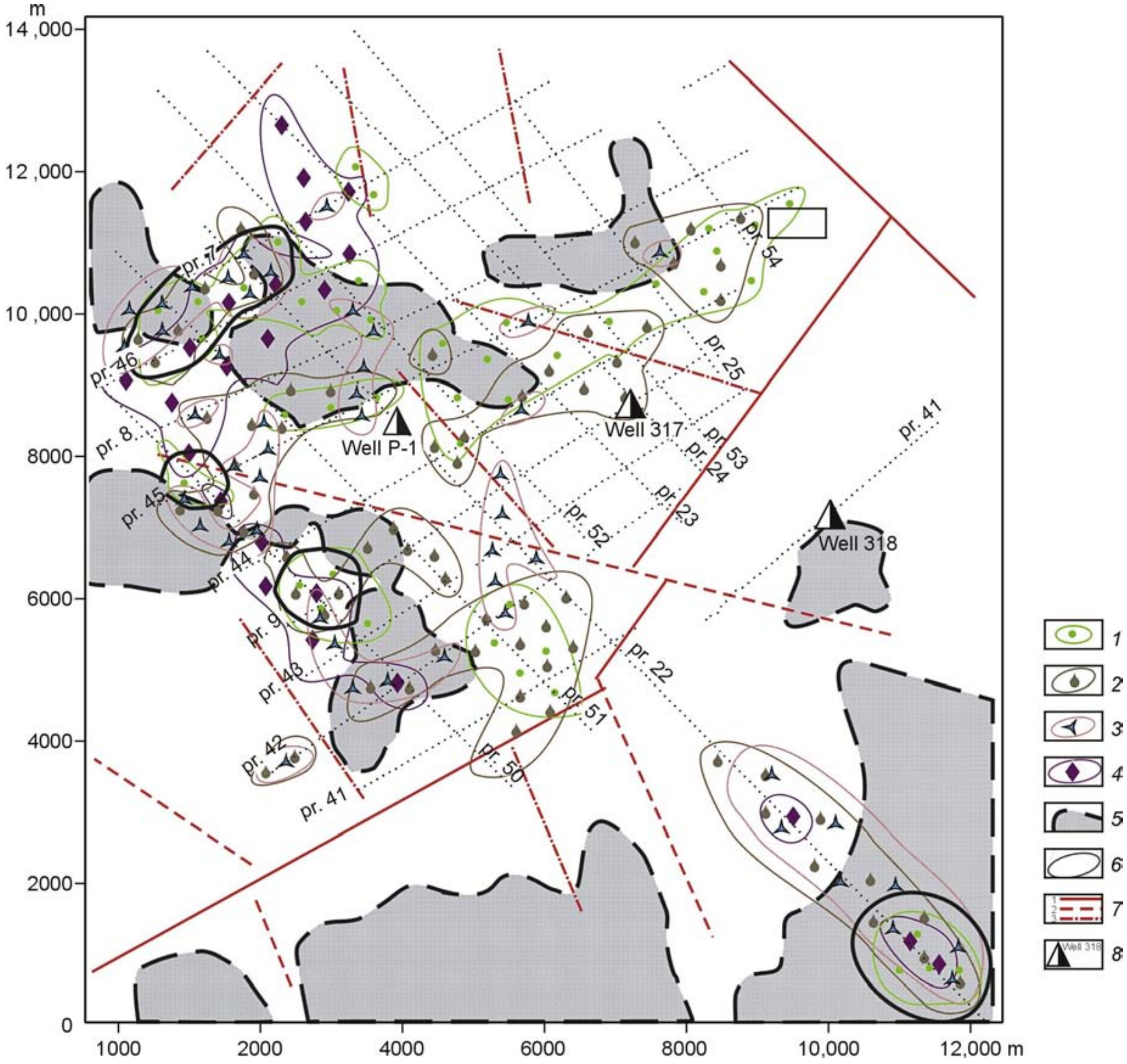

Fig. 9. Results of joint processing of geomorphology and geochemistry data. *1*, chargeability anomalies ($m > 0.04$); *2*, benzene and toluene anomalies (BTX > 0.04 mg/m^3; *3*, redox anomalies (Eh < 350 mV); *4*, magnetic susceptibility anomalies ($\kappa < 240 \times 10^{-5}$ SI units); *5*, residual elevation highs; *6*, composite anomalies; *7*, first-order (1), second-order (2), and third-order (3) faults from geomorphic analysis; *8*, wells.

value (Eh < 350 mV) and magnetic susceptibility ($\kappa < 2.4 \times 10^{-3}$ SI units). According to the selected interpretation criteria, four potentially petroliferous zones have been distinguished in the survey area (Fig. 9), which can be recommended for checking by 3D seismic.

Anticlinal uplifts of the Paleozoic basement in the Trassovy area show up in TEM and MTS data and correlate with residual elevation highs. The BTX anomalies spatially match the slopes of geomorphic highs and are associated with Eh lows, high chargeability, and low magnetic susceptibility.

Thus, integrated resistivity (TEM and MTS) and geochemical data have revealed zones of good prospects and have implications for well placement and location of high-resolution 3D seismic.

To sum up, the geomorphological, geophysical, and geochemical studies in the Trassovy license area allow the following inferences.

1. The Trassovy prospect has been studied, for the first time, by integrated geomorphological, geophysical and geochemical surveys with subsequent joint data processing.

2. The geophysical data included transient electromagnetic (TEM) and magnetotelluric (MT) resistivity surveys of Mesozoic sediments and the Paleozoic basement, which allowed obtaining depth sections and maps based on the resistivities (ρ, Ohm·m) and thicknesses (H, m) of geoelectric layers.

3. Geological interpretation of the TEM and MTS results, with reference to well-log data (well P-1), has revealed potentially petroliferous anticlinal folds on the Paleozoic basement surface.

4. The basement uplifts detected by MT and TEM soundings show good correlation with residual elevation highs (the Northwestern, Western, and Southeastern first order structures) inferred from geomorphology.

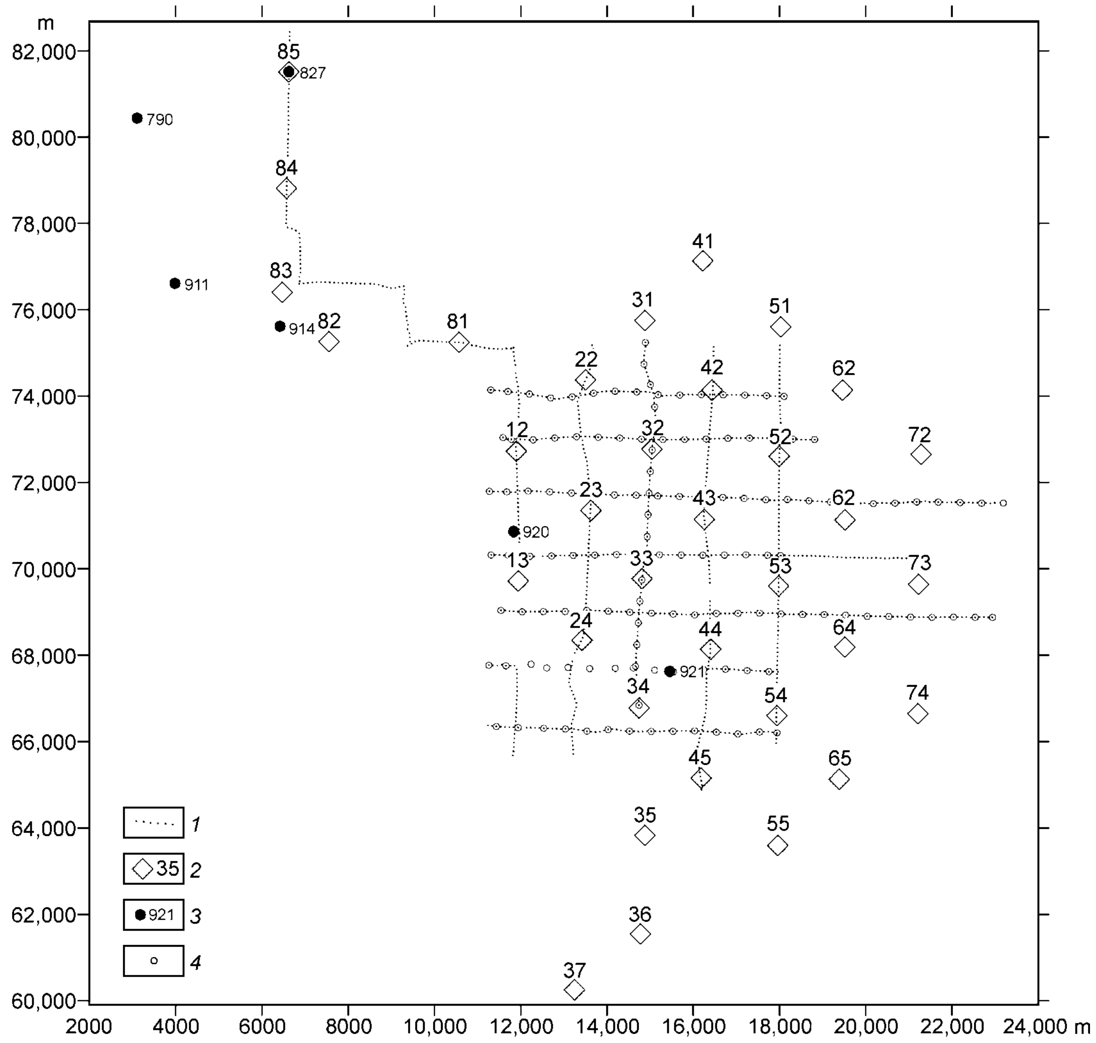

Fig. 10. Integrated geophysical and geochemical surveys in Rogozhnikov oil field. *1*, sampling sites for chemical analyses; *2*, MTS and TEM stations (in-loop configuration); *3*, wells and their numbers, *4*, gravimetry stations.

5. Chargeability (fast-decaying IP) highs spatially correlate with high BTX contens and low values of Eh and magnetic susceptibility. These anomalies fall within the slopes of residual elevation highs and form quasi-annular structures. Taken together, these factors have petroleum implications.

6. The field survey results interpreted jointly with laboratory data have made basis for reservoir potential zoning of the territory. Several zones within the prospect may be of interest for further exploration by 3D seismic or drilling. The geophysical and geochemical results agree quite well with seismic evidence and allow further constraints on the structure of the J_1 reservoir.

Thus, the southwestern part of the area is worth being further studied within the outlined zones.

Resistivity and geochemical surveys of a prospect in the Rogozhnikov oil field

TEM and MT soundings along the previously collected seismic profiles have been performed also in a prospect within the Rogozhnikov oil field. In addition to the geophysical surveys, rock samples from the area were likewise analyzed in laboratory (chromatography, pH, Eh, magnetic susceptibility, gamma spectrometry) and measured for chargeability by the fast-decaying IP method (Fig. 10).

The prospect lies at the boundary of the Krasnoleninsk Arch and the Frolov basin within a damage zone of a large fault. Faults bound multiple basement blocks and complicate the sedimentary structure. The area underwent tectonism and volcanism, especially active in the Triassic (Gilyazova, 2009).

Reservoir rocks in the oil field lie at different stratigraphic levels, including the pre-Jurassic basement with volcanics. Triassic basaltic lavas were deposited in a shallow basin and then faulted, whereby fractured reservoirs arose in most heavily faulted zones. Then the volcanic strata became subsided and buried under sediments. Oil reservoirs exist in the Vikulovo, Tyumen, and Bazhenovka sedimentary formations and in the pre-Jurassic basement (Gurari, 2000; Kontorovich, 2009).

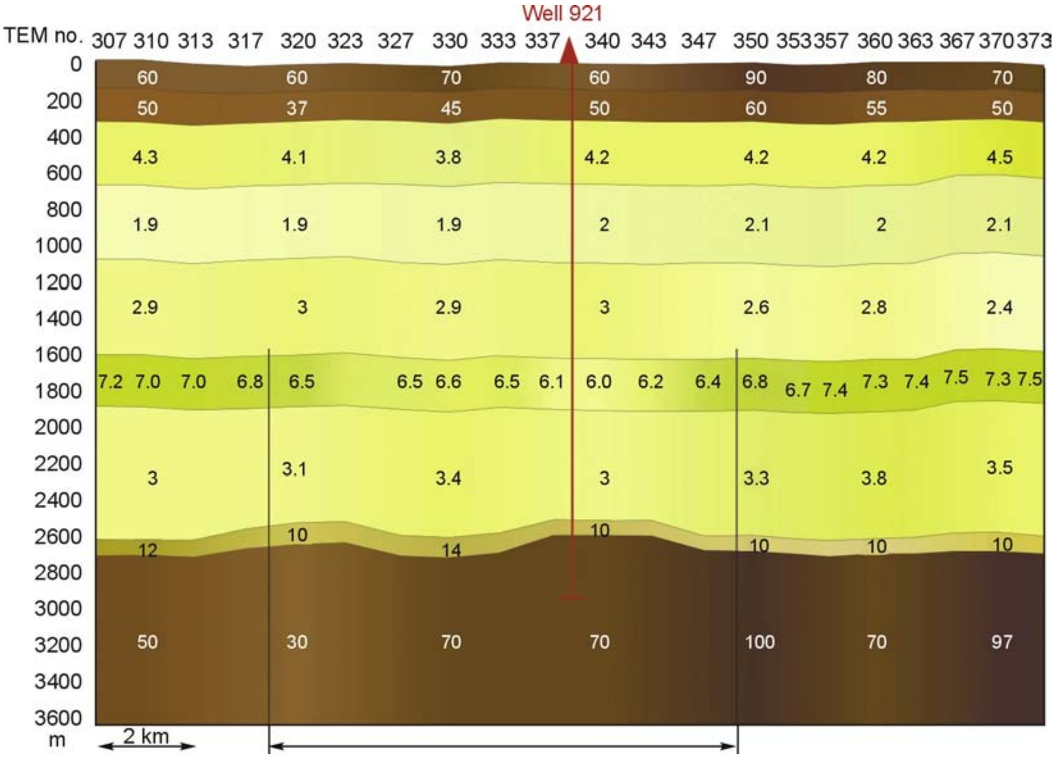

Fig. 11. Resistivity section along profile TEM 307–TEM 373 across a conductive zone in Vikulovo Formation, from inversion of in-loop and off-loop transient responses.

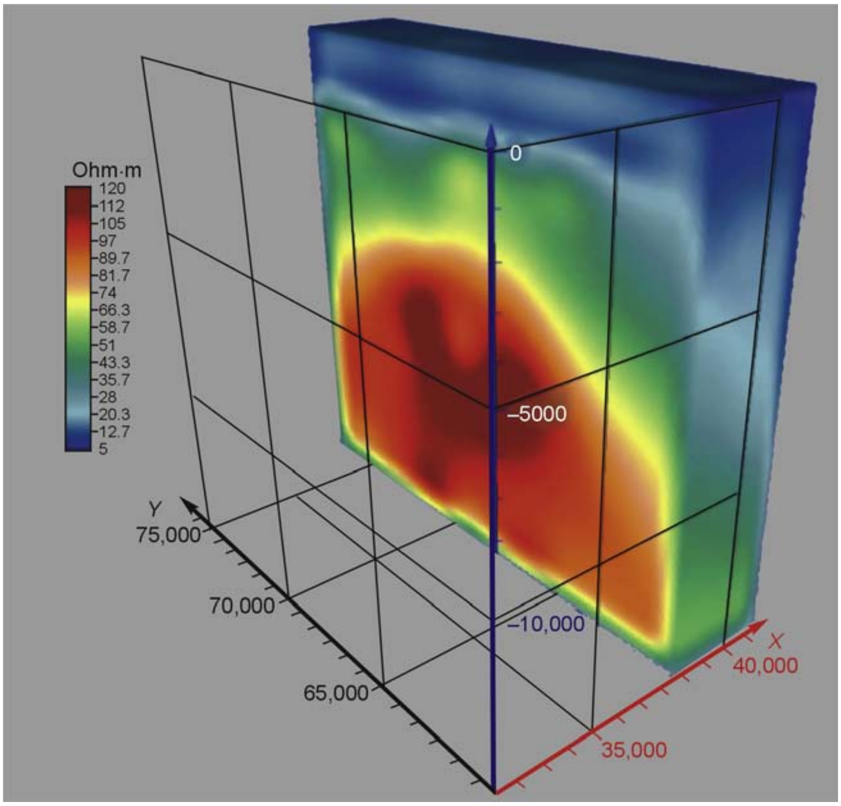

Fig. 12. Resistivity model obtained by joint processing of TEM and MTS data from Rogozhnikov oil field.

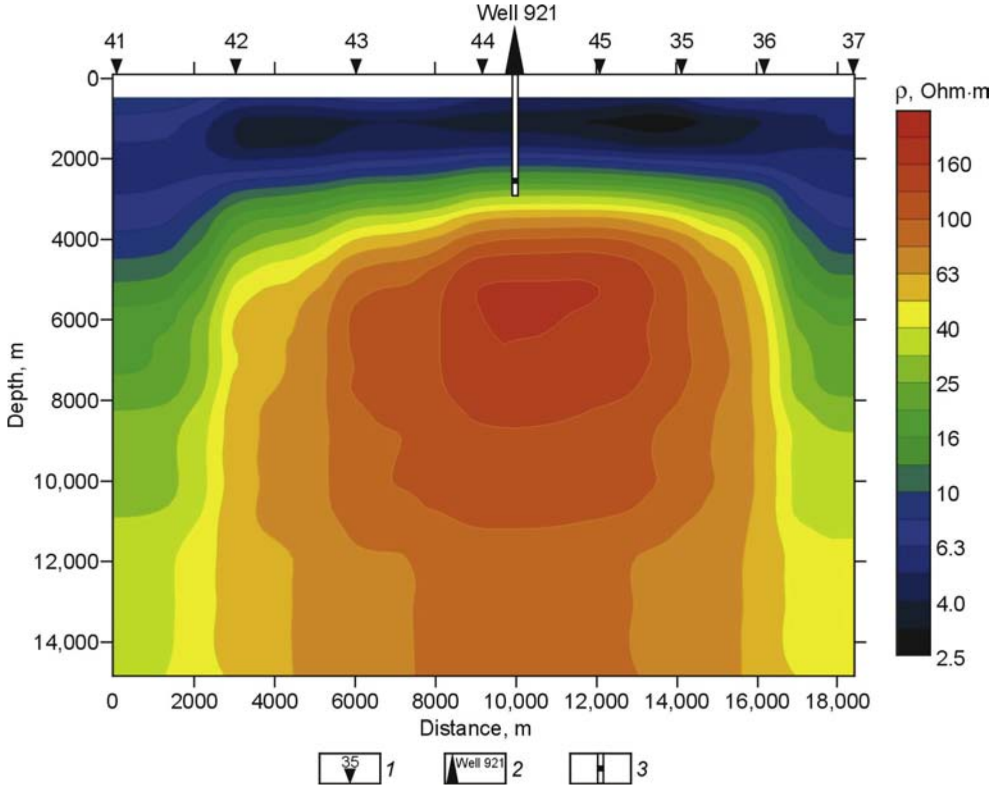

Fig. 13. 2D section from MTS data. *1*, MT stations; *2*, well; *3*, pay zone in Paleozoic reservoir.

The methods of resistivity data acquisition and processing were the same as for the Trassovy prospect in the Tomsk region. The TEM interpretation model was obtained with reference to all available a priori data. The resistivity ranges for the layers were additionally estimated from gamma, SP, and normal well logs. The in-loop and off-loop transient responses processed (*EMS*, *Era*) with regard to typical distortions showed the section to generally fit the layered-earth approximation. The obtained resistivity models provided qualitative characteristics of Cretaceous, Jurassic, and upper Paleozoic strata. The models resolved the layer boundaries corresponding to the geologically tied top surfaces of large reservoir formations (Vikulovo, Bazhenovka, and upper pre-Jurassic basement). The processed TEM data have been presented as resistivity sections (along N–S profiles) and maps of sediments and upper basement. See Figure 11 for a resistivity section along profile TEM 307–373 in the western part of the area with low-resistive reservoir rocks of the Vikulovo Formation.

The 3D resistivity model obtained by joint processing of TEM and MT data to the 15 km depths (Fig. 12) images uplifts in upper Paleozoic strata, with high resistivity gradients within them.

The resistivity patterns of pre-Jurassic rocks reveal three large blocks (northwestern, western, and eastern ones) and linear low-resistivity zones corresponding to faulted rocks with graphite-filled cracks. Judging by their generally low resistivity, the pre-Jurassic rocks must be strongly disintegrated.

The relationship between linear resistivity anomalies and faults was inferred from correlation of resistivity and structural models, which allowed detecting and mapping active faults. Two geochemical zones were distinguished in the area, separated by a fault which may break hydraulic connectivity between oil accumulations of the same stratigraphic level. The latter inference was used as an assumption in further modeling.

Geochemical anomalies structurally associated with uplifts have been revealed at different stratigraphic levels. The accumulation in the Vikulovo Formation contributes the most to the geochemical signal, with anomalies on the periphery matching the structures at the Bazhenovka level. Other peaks and troughs can be tentatively assigned to the Paleozoic basement and correlated with resistivity heterogeneities detected by the EM surveys.

Note that an anomaly possibly related to an oil trap was also revealed in the regional geochemical profile outside the prospect, in the middle of the basin side. It may record a depositional trap and can be recommended for further exploration.

The geophysical and geochemical studies in the Rogozhnikov oil field allow the following *inferences*.

1. The quantitative resistivity model based on TEM data provides constraints on resistivities and thicknesses of Cretaceous, Jurassic, and upper Paleozoic strata. The resistivity models reveal the boundaries corresponding to the geologically tied top surfaces of large reservoir formations (Vikulovo, Bazhenovka, and upper pre-Jurassic basement). Anticlinal

uplifts have been detected in the upper Paleozoic section at wells 920, 921, with the highest resistivity gradients within their limits and resistivity lows at the level of the Vikulovo Formation. According to correlation with geochemical and seismic data, the boundaries of resistivity lows may delineate a potentially petroliferous zone.

2. MTS data reveal an isometric resistivity high lying at the depth about 3500 m. The anomaly may be associated with intrusive magmatism, as one may infer from the knowledge of local geology. As shown by 2D inversion of MT data, pay zones stripped by drilling are associated with structural highs in the basement and differ in a high resistivity (Fig. 13).

3. The outlined near-surface chemical and physical anomalies are caused by underlying oil traps, according to a number of indicators.

Conclusions

Integrated geochemical and geophysical (TEM and MTS) studies in two prospects of West Siberia have furnished additional evidence of the vertical and lateral patterns of electrical and chemical properties of rocks and their correlation with geomorphic and structural patterns.

Joint use of TEM and MT surveys is a promising approach as it combines the advantages of the two methods: TEM provides reliable high resolution images of the subsurface to depths within 3 km on average while MTS can sound deeper earth (~15 km) and place constraints on the Paleozoic basement structure and its electrical properties. The petroleum implications of IP and geochemical data are associated with secondary alteration (mineralization) of rocks over oil traps.

As demonstrated by the field tests, the approach of integrated geochemical and geophysical surveys is applicable to petroleum exploration in the conditions of West Siberia, with weak resistivity contrasts between different layers. The results have been further validated by deep drilling.

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