ROLE OF GEOELECTRIC METHODS IN HYDROCARBON
AND DEEP STRUCTURAL INVESTIGATIONS IN RUSSIA

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Editorial Note
The Editorial Board is aware of the unusual content of this paper; it differs from those generally published in Geophysical Transactions. The paper was accepted in spite of the fact that the theoretical considerations tend to be qualitative descriptions, and the case histories do not go into detail; identification of the geographic locations is by no means an easy task.

In our opinion, however, this review by Professor BERDICHEVSKY provides an insight — probably the first — into an area in which only a limited amount of information is available.

The history of geoelectric methods in Russia started with the resistivity method in the USSR before World War II. After the initial successes, however, frequency and transient soundings, and the magnetotelluric (MT) and telluric methods became dominant. Geoelectric methods are of great practical importance because they are used to investigate non-structural hydrocarbon deposits as well.

Theoretical aspects of the MT method, data processing, effects of lateral inhomogeneities, solutions to 2D and 3D in inverse problems are discussed. MT case histories from the Moscow synclise, Western Siberia, Eastern Siberia (Siberian Platform), and Sakhalin are presented. Examples from investigating non-structural deposits are shown from Western Siberia, the Caspian Basin and Turkmenistan.

Techniques of S-transform, multiple overlap and normalized second differences used in transient soundings are illustrated by case histories from the Caspian Depression, Eastern Siberia and the Black Sea.

Frequency domain induced polarization profiling has successfully been applied to hydrocarbon detection in the North Caspian Depression.

Finally physical background and some results (Eastern Europe and Russia and, in detail, Kamchatka) of deep geomagnetic and magnetotelluric soundings are discussed.

Keywords: geoelectric methods, hydrocarbons, Russia

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1. Introduction

The paper reviews the geoelectrical investigations carried out in Russia and the former Soviet Union. Interesting conclusions can be drawn from the history of these investigations; in addition, their efficiency, scale of application, and their perspectives are also discussed. Development and results achieved in electric, time and frequency domain electromagnetic methods and deep magnetic sounding are summarized.

2. Electric and electromagnetic prospecting

2.1. A piece of history

The application of electrical and electromagnetic methods to oil and gas prospecting is discussed.

Nowadays only few people know that geoelectrical prospecting, primarily the direct current resistivity method, played the dominant role in geophysics applied to oil and gas prospecting before World War II. In fact, between 1932 and 1935 the Oil Ministry of the Soviet Union had about 50 field groups that used the resistivity method, but only 5 to 10 seismic groups. After the rapid progress experienced in the 1930s, however, the activity in resistivity prospecting decreased due to the limitations of direct current (cumbersome equipment, screening caused by high resistivity layers). Thus, electrical prospecting lost its importance and gave way to seismics with its higher resolution and processing potential. In the early 1950s the number of electric exploration groups working in regions of hydrocarbon potential in the Soviet Union was close to zero. Renewal of electrical prospecting needed innovative ideas. Three novel methods based on the use of electromagnetic fields varying with time were suggested:

1) Frequency sounding — FS [KRAJEV 1941, TIKHONOV 1950]. The frequency response of the earth determined by means of an artificial multifrequency electromagnetic field is inverted into a geoelectrical section.

2) Transient sounding — TS [TIKHONOV 1946, SHEINMANN 1947]. The time response of the earth determined by means of a series of artificial electromagnetic impulses is inverted into a geoelectrical section.

3) Magnetotelluric sounding — MTS [TIKHONOV 1950, CAGNIARD 1953]. The earth’s impedance determined by means of the natural electromagnetic field is inverted into a geoelectrical section.

In addition, the old idea of the telluric current method — TM [SCHLUMBERGER 1920, 1939] was also renewed. In tellurics the electric component of
the earth’s response to the natural electromagnetic field is studied and a qualitative or even quantitative representation of basement topography can be obtained if there is a resistivity contrast between the basement and the overlying formations.

All these ideas were realized in the Soviet Union in the 1950s and 1960s [VANYAN, DMITRIEV, SIDOROV, KULIKOV, BERDICHEVSKY]. The rapid introduction and the scale of routine application of these new geoelectric methods were impressive. About 150 TM, TS and MTS groups worked in 1965 and the area covered by geoelectric surveys reached $3 \times 10^6$ km$^2$. Such activity could be observed until the early 1980s. During this period electric prospecting methods contributed to the construction of tectonic maps of regions having hydrocarbon potential, and were responsible for detecting numerous local elevations. The most important results were obtained in Siberia, mainly by magnetotellurics. A highly spectacular outcome of electric prospecting was the discovery of the famous Urengoy gas field (Western Siberia) which is connected to an uplift of Paleozoic rocks revealed by MTS.

Recently electric prospecting has had to cope with new problems. The challenge for geophysicists is to search for oil and gas reservoirs of non-structural type. It seems that existing capabilities of electric and electromagnetic methods which proved to be useful in regional structural studies, are not sufficient to solve these new tasks. Therefore, this kind of activity has decreased in many countries in the world. At the same time, intensive development of new approaches opening new horizons in electric prospecting, has continued in the Soviet Union. Transient and frequency soundings (including induced polarization measurements) have come to the forefront due to their higher resolution. It can be said that electric prospecting has overcome the crisis in its utilization in the Soviet Union. In 1992 we had 25 to 30 MTS and 50 TS and FS teams.


2.2.1. Characteristic features of MT processing in the Soviet Union

Mathematical filters are applied to the spectral analysis of magnetotelluric variations. The impedance tensor is determined from narrow-band telluric and magnetic oscillations using the method of least squares. Both the stability and plausibility of results obtained can be checked by evaluating the misfits $|E_x - Z_{xx} H_x|$, $|E_y - Z_{yy} H_y|$, $|E_x - Z_{xy} H_y|$, $|E_y - Z_{yx} H_x|$ and comparing the impedance matrix with inversion of the admittance matrix. Robust statistics and Gamble’s remote reference magnetotellurics [GAMBLE 1978] are used to suppress instrument and industrial noise. If observations are carried out simultaneously at moving
and fixed stations, the favourable time intervals of low model noise can be chosen. In this way an accuracy of 2 to 5% in the modulus of the impedance components can be achieved. Finally, the principal values $Z^+_P, Z^-_P$ of impedance tensor determined by Eggers’ eigenstate technique are transformed into principal apparent resistivity curves $\rho^+_P, \rho^-_P$ [EGGERS 1982].

Great importance is devoted to the analysis of MTS distortions caused by lateral inhomogeneities. MTS interpretation starts with diagnostics of lateral effects. Some simple transformations are used which allow one to eliminate these effects. Geological noise caused by small subsurface inhomogeneities is smoothed by spatial filtering.

NOVIKOV, BERDICHEVSKY et al. [1992] elaborated the MTM(at) system for space and frequency analysis and transformation of MT data that includes the experience gained in magnetotellurics all over the world. In this context analysis means determination of space and frequency characteristics that enable us to estimate the degree of horizontal inhomogeneity of the medium, to locate geoelectric structures, to outline their form, and to determine the strike. The transformation consists of apparent resistivity calculations and construction of geoelectric pseudo-profiles, sections and maps that provide a qualitative image of the electric conductivity distribution within the earth. The system includes both traditional techniques (e.g. the Niblett transform or amplitude polar diagrams) and the latest display tricks (e.g. phase polar diagrams that can be used to distinguish galvanic and inductive effects and show the effects of deep structures without near surface distortions, the Vozoff, Berdichevsky tippers that provide a more visual and distinct image of geoelectric structure than the traditional induction arrows, and the BAHR [1988] decomposition that separates near surface and deep effects).

The capabilities of the MTM(at) system are illustrated by Figs. 1. and 2.

Fig. 1 shows the model with a near surface 3-D inhomogeneity of lower conductivity and a deep 2-D inhomogeneity of higher conductivity. The near surface and deep inhomogeneities have different strikes. The amplitude polar diagrams are affected by the near surface inhomogeneity (even at very low frequencies) while phase diagrams reflect the orientation of the deep inhomogeneity. It is stressed that polar diagrams offer the simplest way of separating near surface and deep effects.

Fig. 2 shows the model with a near surface 3-D inhomogeneity of higher conductivity. The model provides an opportunity to compare the Vozoff-Berdichevsky tippers with induction arrows. The tipper is based on maximizing $|H_z| / \sqrt{|H_x|^2 + |H_y|^2}$. Its magnitude is equal to the norm $||\hat{W}||$ of the Wiese-Parkin­son matrix $\hat{W} = [W_{zx} W_{zy}]$ while its orientation coincides with the magnetic eigenfield of the matrix. In addition, the phase of matrix invariant $\Psi = \arcsin \sqrt{W_{zx}^2 + W_{zy}^2}$ is also determined. It seems that tippers are more sensitive than induction arrows. The informative pattern is given by phases: they reflect the relationship between active and reactive excessive currents (if $\Psi$ is close to $\pi/2$, the reactive currents are dominant).
The MTM(at) system has a clear algorithmic base and helps
a) to construct a normal conductivity distribution,
b) to evaluate the degree of lateral inhomogeneity,
c) to locate the geoelectrical structures,
d) to classify them according to their dimensions,
e) to outline zones of low and high conductivity,
f) to construct the interpretation model,
g) to choose the inversion strategy.

The inverse magnetotelluric problem is unstable and, therefore, it is ill-posed. It means that any arbitrarily small error in the initial MT data may cause an arbitrarily large error in their inversion, i.e. in the electric conductivity distribution. The inversion is feasible provided that a priori information about the geoelectric structure of a region provides limits: 'you have to know generally what is to be sought and where it is to be sought'. It is evident that the effectiveness of MT interpretation strongly depends on the available amount
of a priori geological-geophysical information. If there is no a priori information we can obtain only either one of the equivalent models which might be very different from the real structure, or a model with a significantly smoothed conductivity distribution neglecting essential details.

The corner-stone of MT interpretation is the theory of ill-posed problems elaborated by TIKHONOV, ARSENIN [1976], GONCHARSKY [1987], LAVEREJTEV et al [1980], DMITRIEV [1987].

Within the Tikhonov theory there are two methods of solving the inverse magnetotelluric problem.

The first method is to select a set of models (compactum) and to find within this set a model which best agrees with the a priori information and provides the misfit not exceeding the errors of initial MT data. An example of this approach is regularized fitting.

The second method includes the construction of an approximate inverse operator which acts as a spatial filter and provides a smoothed geoelectric pattern. An example of this approach is the Backus-Gilbert method [BACKUS, GILBERT 1968].
Algorithmically the two methods are based on making an approximate solution more and more accurate by reducing the errors in data. Correctness of the solution results from its fitting to the a priori information. The choice of a specific computational scheme is a question of technology (computer type, CPU time, convenience of entering a priori information, etc.). Whereas some of us prefer the deterministic scheme, others prefer the probabilistic one. It is hardly worth arguing which of the schemes is better: algorithmically they are equivalent.

If lateral resistivity variations are rather slow and the difference between the principal apparent resistivities is sufficiently small, the MT curves can be interpreted using 1-D models at every station. Here the S-method developed by DMITRIEV [1987] is popular. The method divides the inversion (non-linear ill-posed problem) into two parts: the S-transformation that provides stable integral characteristics \( S(z) = \int_0^z \sigma(z) \, dz \) (non-linear well-posed problem) and \( \sigma \)-inversion that reduces to differentiating \( S \) (linear ill-posed problem). An attractive feature of the S-method is that S-transformation characterizes the whole set of equivalent models facilitating the input of a priori information and estimation of the limits of equivalence. The results obtained by 1-D inversion should be checked by 2-D and 3-D modelling specifying the influence of lateral inhomogeneities. If this checking does not provide acceptable results we have to reject the 1-D interpretation and change to 2-D or 3-D inversion.

The 2-D inversion is carried out by automatic or interactive (intuitive) fitting. Both E- and H-polarization modes are used. E-polarization data reflect the effects of deep structures covered by resistive screening layers. H-polarization data provide information about the shallow layers and allow one to determine the resistivity of the screening layers as well. Thus, bimodal inversion is the most effective. In 3-D inversion we use the thin-sheet approximation [ZINGER, FAINBERG 1985] and a quasi-1-D technique that reduces the 3-D inversion to an iterative sequence of 1-D inversions corrected by 3-D misfit [Dmitriev 1987, Barashkov et al. 1988, Oldenburg 1988].

2. 2. 2 MT practice: Case histories

Fig. 3 gives the tectonic map of the Moscow syncline* constructed from MTS data. The map shows the relief of the crystalline basement and numerous small uplifts detected by the telluric current method. Several uplifts were

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* Syncline: A negative or depressed structure of the continental platform; it is of broad, regional extent (tens to hundreds of thousands of square kilometres) and is produced by slow crustal downwarp during the course of several geologic periods. The term is used mainly in the Russian literature, e.g. the Caspian syncline [BATES R. L., JACKSON J. A. (editors): Glossary of geology, American Geological Institute, 1980, p. 633.]
confirmed by seismics and drilling too. The accuracy of MTS interpretation is rather high. It can be seen in Table I that the difference between the MTS and drilling data does not exceed 5 to 10 %. Thus, the electrical prospecting was very helpful in studying this huge area.

The efficiency of magnetotellurics was observed in Western Siberia as well. The bulk of the oil reserves in Russia has been found in this region, especially in its northern part. Between 1960 and 1975, telluric and magnetotelluric groups investigated an area of $10^6$ km$^2$ and became pioneers in discovering some oil and gas fields (e.g., the Shain oil field or the Urengoy gas field). A significant amount of information about the topography of the Paleozoic basement and resistivity of the Mesozoic sediments has been collected.
<table>
<thead>
<tr>
<th>Well identification</th>
<th>Depth to basement (in km)</th>
<th>Difference (per cent)</th>
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<td>from drilling</td>
<td>from magnetotellurics</td>
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<td>Dyakonov-1</td>
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<td>Neya-1</td>
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<td>Orekhov</td>
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*Table 1. Differences in depth to the basement from drilling and magnetotellurics*

Fig. 4 shows a geoelectric cross-section typical of the Urengoy region. Magnetotellurics and seismics give almost the same basement relief at depths of about 6 to 8 km. The geoelectric boundaries in sediments correlate well with the seismic ones. The lateral changes in sediment resistivity reflecting lithologic variations are clearly seen. Fig. 5 illustrates the scale of magnetotelluric surveys applied in the oil industry in Western Siberia. It shows the conductance of the unconsolidated sediments in the northwestern regions (500 000 km²). The contour line of 850 S outlines the zone where the pre-Jurassic sediments wedge out and this information is of great importance because oil fields occur mainly in this zone.

Interesting results were obtained by telluric and magnetotelluric methods east of this region, on the Siberian platform (Tungus and Vilyuis synclises, Aldan antecline*) as well. Here the occurrence of oil and gas fields is connected with the Mesozoic and Paleozoic sediments. Fig. 6 is the schematic map of the

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*Antecline: A positive or uplifted structure of the continental platform, it is of broad, regional extent (tens to hundreds of thousands of square kilometres) and is produced by slow crustal upwarp during the course of several geologic periods. The term is used mainly in the Russian literature; e.g. the Belorussian anteclices of the Volga-Urals. Also spelt: anticlise [BATES R. L., JACKSON J. A. (editors): Glossary of geology, American Geological Institute, 1980, p.26.]
Fig. 4. Geoelectric section along a profile in Nadim-Urengoy region [according to Sisoev].
1—relief of the basement from MTS data; 2—relief of the basement from seismics; 3—tectonic
disruption from seismics; 4—tectonic disruption from magnetotellurics; 5—geoelectric
boundary; 6—seismic reflection horizon; 7—zones of sudden changes in conductivity; 8—MT
sounding; 9—resistivity (ohmm)

4. ábra. A Nadim-Urengoy terület egy szelvényének geoelektromos metszete [Sisoev nyomán].
1—az aljzat domborzata MTS adatok alapján; 2—az aljzat domborzata szeizmikus adatok
alapján; 3—tektonikai vonal szeizmikus alapján; 4—tektonikai vonal magnetotellurika alapján;
5—geoelektromos réteghatár; 6—szeizmikus reflexiós szint; 7—hirtelen vezetőképesség változás
zónái; 8—MT szondázás; 9—fajlagos ellenállás (ohmm)

Fig. 5. Map of the sediment conductance in the northwestern part of the West Siberian plate
[according to Kopelev, Sisoev].
1—isoline of conductance (siemens); 2—boundary of pre-Jurassic sediments; 3—MTS
profile; 4—oil field; 5—gas field

5. ábra. Az üledék összegzett hosszirányú vezetőképességének térképe a Nyugat-Sziberiai-lemez
északnyugati részén [Kopeclev, Sisoev nyomán]. 1—an összegzett hosszirányú vezetőképesség
izovonala (siemens); 2—a júra idősebb üledékek elterjedésének határa; 3—MTS szelvény;
4—olajmező; 5—gázmező
Fig. 6. Schematic map of the geoelectric surveys in Eastern Siberia [according to JAKOVLEV]. Magnetotelluric surveys: 1—traverse; 2—area. Transient soundings: 3—traverse; 4—area

6. ábra. A Kelet-Szibériában végzett geoelektromos kutatások vázlatos térképe [JAKOVLEV nyomán]. Magnetotellurikus kutatások: 1—szelvénymenti; 2—területi; Tranziens szondázások: 3—szelvénymenti; 4—területi
geoelectric investigations carried out in *Eastern Siberia*. Magnetotelluric surveys have covered an area of about $10^6$ km$^2$. Almost the whole area is permafrost.

It is noteworthy that the geological structures revealed by MTS data are close to the seismic ones in many regions of Eastern Siberia. This is demonstrated by three examples. Fig. 7 shows the seismic and geoelectric boundaries along a profile crossing the *Linden depression* (Vilyuisk synclise). It can be seen that these boundaries practically coincide in the Upper Paleozoic sequence. The same can be said about the basement topography. The next example is given in Fig. 8. The profile crosses the *Igiattan* and *Linden depressions*. Similarly to the previous case, the geoelectric and seismic boundaries coincide quite well in the Upper Paleozoic sequence. The geoelectric boundary identified as the basement surface follows the seismic horizon but exaggerates the local structures in the Linden depression. Fig. 9 shows the last example. This is part of a telluric field intensity map. Minima of telluric intensity correspond to the uplifts of the conductive Cambrian layer appearing in the seismic horizon as well.

Results of all magnetotelluric surveys were summarized in the tectonic map of the eastern part of the *Siberian platform* (Fig. 10). The map shows the main structures of this region and numerous local uplifts. The most significant
Fig. 8. Geophysical section along the profile Oczuguy–Botuobia Linden [according to JAKOVLEV]. I—Mirmin dome; II—Igiattan depression; III—Linden depression; 1—basement relief from seismics; 2—seismic horizon in Permian; 3—in Cambrian; 4—basement relief from MTS data; 5—top of conductive Paleozoic sediments from MTS data; 6—fault from seismic data.

8. ábra. Geofizikai metszet az Oczuguy–Botuobia–Linden szelvény mentén [JAKOVLEV nyomán]. I—Mirmin boltozat; II—Igiattan süllyédék; III—Linden süllyédék; 1—az aljzat domborzata szeizmika alapján; 2—szeizmikus szint a permi képződményekben; 3—szeizmikus szint a kambrium képződményekben; 4—az aljzat domborzata MTS adatok alapján; 5—a jól vezető paleozoós üledékek felszíne MTS adatok alapján; 6—vető szeizmikus adatok alapján.

Fig. 9. Map of telluric field intensity in Yakutia [according to JAKOVLEV]. 1—contour of telluric intensity (conventional units); 2—contour of a seismic horizon in Permian formations (km); 3—location of reference MT soundings.

9. ábra. A tellurikus intenzitás térképe Jakutianban [JAKOVLEV nyomán]. 1—a tellurikus intenzitás izovonala (konvencionalis egység); 2—egy permi formáció belüli szeizmikus szint szintvonal (km); 3—MT szondázási alappontok helye.
result of these surveys is that highly fractured Paleozoic limestones have been detected in the Vilyuis synclise resulting in a new oil and gas perspective.

Sakhalin is the scene of the next case history. For many years MT sounding has been the main geophysical method used for regional investigations in the island. Fig. 11 presents one of the results obtained, viz. the map of the thickness of the unconsolidated sediments. The largest thicknesses can be found in the depressions XV, XVI and XVII. These zones are the most promising ones. Fig. 12 shows a part of the MT interpretation, this being the geoelectric cross-section along the eastern part of the island. The major tectonic elements and even the lithologic boundaries can be seen here. All these results serve to evaluate the potential of oil and gas occurrence.

Magnetotellurics has been most efficient in searching for oil and gas fields that are governed by tectonics. Recently oil and gas prospecting has been directed toward the fields of non-structural type in many regions of our country, and the geologists have to cope with more subtle lithologic problems. In Western Siberia, for instance, the lithologic changes in thin Jurassic layers (100 to 250 m) at a depth of about 3 km are to be studied and the problem is beyond the resolution of magnetotellurics. Therefore, the magnetotelluric surveys have
Fig. 11. Map of sediment thickness in North Sakhalin [according to ALPEROVICH].
1—isopach of the sediments (metres);
2—pre-Neogene outcrops; 3—wells penetrating the pre-Neogene

11. ábra. Az üledékvastagság térképe Észak-Szachalinon [ALPEROVICH nyomán].
1—az üledékek izopach vonala (m);
2—neogénnél idősebb kőzetek kibúvasai;
3—a neogénnél idősebb képződményt elérő fúrások

Fig. 12. Geoelectric section along the eastern part of Sakhalin [according to ALPEROVICH].
1—argillaceous sediments, ρ <10 ohmm; 2—sandy-argillaceous sediments, ρ ~ 20-30 ohmm;
3—sandstone, ρ > 30 ohmm; 4—stratigraphic boundaries; 5—lithologic boundaries;
6—basement; 7—drilling

12. ábra. Geoelektromos szelvény Szachalin keleti részén keresztül [ALPEROVICH nyomán].
1—agyagos üledékek, ρ>10 ohmm; 2—homokos-agyagos üledékek, ρ ~ 20-30 ohmm;
3—homokkő, ρ > 30 ohmm; 4—sztratigráfiai határok; 5—litológiai határok; 6—aljzat; 7—fúrás
been stopped in this region. It might be of interest, however, to discuss some recent results obtained in areas where magnetotellurics has proved to be successful.

Rich oil and gas fields have been discovered in the North Caspian Basin. The region is characterized by diapiric structures and the reservoirs that are to be searched for lie beneath a salt cover of varying thickness. Two typical examples from the results obtained here by MT soundings are presented. Fig. 13 shows a smoothed geoelectric cross-section from the central part of the Astrakhan anteclise. The low resistivity zone (hatched) outlined at a depth of more than 4 km (i.e. beneath the salt cover) is of great interest because it is the zone of highest porosity. The next example (Fig. 14) shows the geoelectric structure of the slope of the Astrakhan anteclise as a set of vertical conductivity profiles. These outline zones of higher and lower conductivity. In the centre of this cross-section a downthrown part of the conductive sediments underlying the salt and bordered by faults can be seen. It is significant that this promising zone (of higher porosity?) is not reflected in seismic data. It is evident that magnetotellurics is a useful supplement to seismics in this region.

One more example is shown in Fig. 15. This is a geoelectric cross-section constructed from MT data in Southwestern Turkmenistan. Gas-condensate deposits are known in this region. Magnetotellurics has detected highly conductive zones in the hydrocarbon-bearing stratum that can be interpreted as the zones of increased water saturation favourable for gas deposits.

2.3. Transient sounding [SIDOROV 1985, TIKSHAEV 1984, NEBRAT 1990]

In contrast to the situation concerning magnetotelluric activities — which are on the decrease — the method of transient sounding has come to the foreground. The traditional approach using the principle of apparent resistivity is widely used. At the same time some non-traditional approaches have also appeared. It seems, however, that these are poorly known in the West. In view of this, it would be reasonable to discuss these approaches in more detail.

2.3.1 The S-transform

SIDOROV proposed that the transient electric or magnetic field, $E(t)$ or $B(t)$ be transformed into $S(z)$ where $S$ is the conductance of layers affecting the field at the moment $t$; and $z$ is their total thickness. The transformation is carried out by means of the equivalent model which replaces the layered medium with a thin sheet located in the non-conducting space. Fig. 16 shows two $S$-profiles obtained near drillholes. They correlate well with the well-logging data, the inclined sections correspond to the layers of higher conductivity. In Fig. 17 the geoelectric cross-section along a profile in the northwestern part of the North
Caspian depression can be seen. Changes in the conductance of the layers overlying the salt reflect the salt topography. Changes in the conductance of the layers underlying the salt are more interesting because they reflect the relations between the terrigenous and carbonate components in the rocks having hydrocarbon potential. It is worth mentioning one episode from the history of this method. Four soundings revealed the topography of salt in the Altatin area (in the North Caspian depression) but seismics provided different data. Moreover, these soundings outlined terrigenous layers within the salt body. Geologists did not accept this assumption but some years later drilling confirmed the interpretation of the geoelectric data.

2.3.2. The method of multiple overlapping

TIKSHAEV [1984] suggested a special technique of $S$-transformation based on a series of measurements with overlapping receivers (loops or grounded dipoles). Spatial averaging smooths out the field distortions caused by local lateral inhomogeneities and provides high measurement stability. This makes
Fig. 14. Geoelectric section on the slope of the Astrakhan anteclise [according to PLAKHOV]. 1—conductivity profile; 2—tectonic disruption; 3—contour of conductivity ($10^{-3}$ S/m); 4—zone of increased conductivity $\sigma > 0.1$ S/m; 5—zone of decreased conductivity $\sigma < 0.1$ S/m; 6—seismic horizon $P_1$.

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Fig. 15. Geoelectric section in Southwestern Turkmenistan [according to Chernjavsky].
1—resistivity (ohmm); 2—geoelectric boundary; 3—tectonic disruption; 4—zone of increased water saturation; 5—drilling

15. ábra. Geoelektromos metszet Délnyugat-Türkmenisztánban [Chernjavsky nyomán].
1—fajlagos ellenállás (ohmm); 2—geoelektromos határ; 3—tektonikai vonal; 4—megnövekedett víztelítettségű zóna; 5—fúrás

Fig. 16. Vertical profiles of conductance [according to Sidorov]. 1—well-logging data; 2—data from transient sounding; 3—horizons of higher conductivity

16. ábra. Az összegzett hosszirányú vezetőképesség függőleges szelvényei [Sidoróv nyomán].
1—mélyfurásgeofizikai adatok; 2—tranzíusi szondázásokból kapott adatok; 3—nagyobb vezetőképességű szintek
Fig. 17. Geoelectric section in the northwestern part of the North Caspian depression [according to SIDOROV]. 1 — sediments overlying the salt; 2 — salt; 3 — sediments underlying the salt; 4 — crystalline basement; 5 — seismic horizon; 6 — unreliable seismic horizon; 7 — drilling; 8 — transient sounding; 9 — scattering of S-values; $S_1$ — conductance of the layers overlying the salt; $S_2$ — conductance of the layers underlying the salt.

17. ábra. Geoelektromos metszet az Észak-Kaspi-süllyedék északnyugati részén [SIDOROV nyomán]. 1 — a sóréteg felett települő üledékek; 2 — sóréteg; 3 — a sóréteg alatt települő üledékek; 4 — kristályos aljzat; 5 — szeizmikus szint; 6 — bizonytalan szeizmikus szint; 7 — fúrás; 8 — tranziens szondázás; 9 — az S értékek szórása. $S_1$ — a sóréteg feletti rétegek összegzett hosszirányú vezetőképessége, $S_2$ — a sóréteg alatt települő rétegek összegzett hosszirányú vezetőképessége.
it possible to determine a ‘differential’ conductivity such as \( \sigma(z) = dS(z)/dz \). In
order to reduce the range of conductivity variations the function \( \tanh \sigma(z) \) is
used for graphic representation.

Fig. 18 shows an example where the geoelectric section is plotted in such
a manner. The similarity between the geoelectric and seismic sections is
striking. It is reasonable to combine seismic and geoelectric sections and to
correlate the seismic horizons with conductivity changes. This idea gives rise
to ‘seismoelectrostratigraphy’, a method that is very efficient in outlining the
highly porous zones. Even a joint parameter has been introduced that reflects
variations both in velocity and resistivity, therefore it is sensitive to non-structural
oil reservoirs. The method of multiple overlapping was successfully
applied in the North Caspian region and in Eastern Siberia. Drilling confirmed
the predicted reservoir characteristics of the carbonate rocks. Reef bodies were
discovered and classified according to their hydrocarbon potential. Exploitable
deposits have recently been discovered in two reefs.

Fig. 18. Comparison of geoelectric and seismic sections [according to Tikshaev]. a—geoelectric
section; b—seismic time section

18. ábra. Geoelektromos és szeizmikus szelvény összehasonlítása [Tikshaev nyomán].
a—geoelektromos metszet; b—szeizmikus időszelvény

2. 3. 3 The method of normalized second differences

NEBRAT proposed another approach providing a qualitative image of
geoelectric structures. Data processing consists of three phases:
1) detection of fast field variations as a difference $\Delta F = F_s - F_l$ between two spline approximations, one with small steps ($F_s$), the other with large steps ($F_l$),
2) spatial averaging of $\Delta F$ and determination of the second differences $\Delta \Delta F = \Delta F - \Delta \bar{F}$ where $\Delta \bar{F}$ is the mean (median) value for all stations,
3) spatial averaging of $\Delta \Delta F$ and its normalization, $L = \Delta \Delta F / \Delta \bar{F}$ where $\Delta \bar{F}$ is the mean (median) value for all stations.

The method is widely used in marine prospecting. It is highly cost-effective because the electromagnetic observations are carried out simultaneously with seismic data acquisition (on the same ship). Fig. 19 shows an electric time section of normalized second differences, together with the seismogeological section (Black Sea). The time section reflects rather well the main tectonic features of the region. Fig. 20 shows another example from the same region. Here the zones of positive $L$ that are outlined in the time interval 1.5–4.5 s correspond to the reef structures at a depth of about 2 to 3 km.

2.4. Frequency domain induced polarization

[KULIKOV, SHEMJAKIN 1978]

Frequency soundings were applied only on a small scale in the Soviet Union. There is now a tendency to increase the number of FS-teams due to the integration of frequency soundings with induced polarization (IP) profiling. This combination has proved to be very successful because frequency sound-
ings help to distinguish induction and polarization effects. Fig. 21 shows the results of IP-profiling performed in the North Caspian depression. In order to reduce the induction effects the perpendicular layout was used and a sufficiently low frequency was chosen. It can be seen that oil fields manifest themselves as phase and polarizability maxima.

3. Global geomagnetic and deep magnetotelluric soundings


In geoelectric investigation of the middle and lower mantle the global geomagnetic sounding is the leading method. Fundamental results have been obtained by FAINBERG, ROTANOVA, SEMENOV using this method. Fig. 22 shows the global apparent resistivity curve plotted by ROTANOVA. It represents the conductivity distribution in the mantle between 400 and 1500 km. DMITRIEV et al. [1986] performed the inversion of this curve using a set of models
which are consistent with modern geothermal concepts and physical laws determining the electric conductivity in this depth range. The solution obtained is shown in Fig. 23. As can be seen, the middle mantle has a clearly identifiable interval of steeply rising conductivity (between 400 and 700 km). This interval
encompasses the zone of presumable transitions ‘olivin-spinel’ and ‘spinel-stishovite’. The conductivity of the lower mantle varies much more slowly and this suggests phase stability in this zone. The conductivity follows the Jeffreys-Gutenberg distribution of seismic velocity qualitatively.

Fig. 23. Distribution of electric conductivity [according to Dmitriev, Rotanova] and P-wave velocity \( V_p \) [according to Jeffreys, Gutenberg]

3. 2. Deep magnetotelluric sounding and magnetovariation profiling


In geoelectric investigation of the crust and upper mantle, deep magnetotelluric sounding and magnetovariational profiling play the dominant role. For many years geophysicists believed that the Earth’s crust had a high resistivity, as it should be for the dry crystalline rocks of the granite and basalt series. It seems that Pospeev was the first who revealed highly conductive formations within the crystalline crust. Deep geoelectric investigations provided more and more data, and it was concluded that some parts of the Earth’s crust are more or less conductive. The high conductivity of the crystalline rocks can be explained by the presence of conductive fluid or graphite. This new model of the lithosphere is gaining ground and opens new possibilities for metallogenic and hydrocarbon prognosis.

Deep geoelectric investigations were carried out in many regions of the former Soviet Union in the last two decades. A large amount of information on the conductivity of the Earth’s crust has been collected. Therefore it has become possible to construct a map of crustal conductivity covering huge areas of Eastern Europe and Northern Asia. Fig. 24 is a preliminary sketch
of such a map constructed by ZHAMALETDINOV. It shows numerous linear zones and larger areas of high conductivity within the upper and lower part of the Earth’s crust. The well-known arc-shaped Carpathian anomaly borders the Pannonian Basin. Its nature has long been a subject of discussion (fluid? partial melting? subduction?). Remarkable is the linear Kirovograd anomaly which can be traced for 600 km, from the Crimea to the Moscow synclinose. It is interpreted as a belt of deserpentinization caused by recent tectonic activity. One of the most intensive anomalies is the Tien-Shan anomaly caused by graphite-containing formations. High crustal conductivity can be observed within the Baikal rift zone, the Tungus synclinose and the Vilyuisk synclinise. The anomaly is assigned to crustal fluids forming a deep hydrosphere. These items of information are still awaiting geological analysis and generalization.
To get a better insight into deep geoelectrics, let us consider the Kamchatka region of the crustal conductivity map. Fig. 25 shows the development of a highly conductive layer. This layer is uplifted in the central part of the peninsula and sinks at its flanks, with conductance decreasing from 6000-
8000 S to 1000–2000 S. The zone of highest conductance coincides with the area of heat flow maximum. It is emphasized that almost all ore occurrences and hydrothermal phenomena are confined to this zone. The deep geoelectric cross-section of the Kamchatka peninsula is shown in Fig. 26. Two areas of lower resistivity are outlined within the Earth’s crust. They are located in the zones of recent and ancient vulcanism. One of them coincides with a seismic velocity minimum. It seems that both areas can be interpreted as magma chambers. An elevation of the highly conductive asthenosphere is detected in the zone of recent vulcanism. The geoelectric pattern correlates well with the geothermal results. It is obvious that geoelectrics provides unique information about the deep structure of this region.

Fig. 26. Deep geoelectric section of the Kamchatka peninsula [according to MOROZ]. 1—contour of resistivity (ohmm); 2—zone of decreased seismic velocity; 3—regional heat flow profile; 4—contour of temperature (°C); 5—zone contemporary vulcanism; 6—zone of volcanic origin

26. ábra. A Kamcsatka-félsziget mély geoelektromos szelvénye [MOROZ nyomán]. 1—a fajlagos ellenállás izovonala (ohmm); 2—csökkent szeizmikus sebesség zónaja; 3—regionális hőáram szelvény; 4—hőmérséklet izovonala (°C); 5—jelenlegi vulkanizmus zónaja; 6—vulkáni eredetű zóna
4. Conclusions

Experience gained in the former Soviet Union and latterly in Russia suggests that new geoelectric prospecting techniques might provide spectacular results which contribute to the characterization of oil and gas reservoirs. Geologists acknowledge the potential of modern geoelectric prospecting methods that are capable of improving the discovery ratio. Nowadays we have about 80 teams in the petroleum industry applying transient, frequency, IP and magnetotelluric soundings. The use of geoelectric data in selecting drilling sites has become the practice in a number of geophysical enterprises. Great importance is attributed to deep geoelectric investigations aimed at metallogenic and hydrocarbon prognosis, and at dealing with general problems of regional structural geology.

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A GEOELEKTROMOS MÓDSZEREK SZEREPE A SZÉNHIDROGÉNEK ÉS MÉLYSZEKERKEZETEK KUTATÁSÁBAN OROSZORSZÁGBAN — ÁTTEKINTÉS

Mark N. BERDICHEVSKY

A geoelektromos módszereket története Oroszországban az ellenállás módszerrel kezdődött a II. világháború előtti Szovjetunióban. A kezdeti sikerek után azonban a frekvencia tartománybeli és tranziens szondázás, a magnetotellurikus (MT) és tellurikus módszer vált uralkodóvá. A geoelektromos módszereket nem szerkezethez kötött szénhidrogén telepek kutatására is alkalmazták.

Az MT módszer elméleti kérdéseit, az adatfeldolgozást, a vízszintes inhomogenitások hatásait, valamint a 2-D és 3-D inverz probléma megoldásának kérdéseit is tárgyalja. MT kutatási példákat mutat be a Moszkvai-színesklízis területéről, Nyugat-Szibériából, Kelet-Szibériából (Szibériai Tabla) és Szachalinból. A nem szerkezethez kötött telepek kutatására hoz példákat Nyugat-Szibériából, a Kaspi-medencéből és Türkmenisztánból.

A tranziens szondázásokban használt S-transzformációs, többszörös átfedéses és normált második különbséges módszert a Kaspi-süllyedékből, Kelet-Szibériából és a Fekete-tengerről vett példákkal mutatja be.

A frekvencia tartománybeli gerjesztett polarizációs szelvényezést sikerrel alkalmazták a szénhidrogének kimutatására az Eszak-Kaspi-süllyedéken. Végül a mély földmágneses és magnetotellurikus szondázás fizikai hátterét és néhány eredményt (Kelet-Európa és Oroszország, részletesen Kamcsatka) tárgyalja.