Chapter 13

Magnetotelluric Studies in Russia: Regional-Scale Surveys and Hydrocarbon Exploration

Mark N. Berdichevsky[*,1], **Valery Bubnov**[†], **Elena Aleksanova**[†], **Dmitry Alekseev**[**,†], **Andrey Yakovlev**[*,†], **and Denis Yakovlev**[†]

[*]*Faculty of Geology, Lomonosov Moscow State University, Moscow, Russia;* [†]*Geophysical department of Nord-West Ltd., Moscow, Russia;* [**]*Lab Geophysical Fields, Shirshov Institute of Oceanology RAS, Moscow, Russia*

Chapter Outline

13.1 INTRODUCTION

Electromagnetic (EM) geophysical methods (telluric current method, magnetotelluric (MT) sounding, frequency sounding, transient sounding) have been used in the USSR to study a deep structure of sedimentary basins and consolidated crust since 1950s. Tectonic schemes of the major sedimentary basins of the USSR were constructed and several large hydrocarbon deposits, for example, the Urengoy gas field, were discovered using telluric currents method and MT

[1]Deceased.

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soundings, in combination with other geophysical methods. A review of major results obtained up to 1990s is presented in (Berdichevsky, 1994), indicating substantial progress in this field.

In 1990s, because of economic difficulties, the rate of EM exploration dropped dramatically. However, a rapid expansion began in 2000, caused by the depletion of established resources and by hydrocarbon (and other mineral resources) price growth.

Nowadays, electromagnetic methods, used for subsurface conductivity imaging are widely applied in Russia in three areas: regional exploration; oil and gas prospecting; and solid mineral prospecting. Regional onshore geophysical surveys are performed along single profiles that are from a few hundred to several thousand kilometers in length and run through deep boreholes. Joint application of a variety of geophysical methods is characteristic for regional surveys. The combination includes common depth point (CDP) seismic, EM, gravity and magnetic prospecting, and other methods; such as geochemical. Seismic prospecting plays the leading role, in most cases it determines the location of geological boundaries rather precisely. Other methods, in particular EM, supplement this data with information about the physical properties of rocks, characterizing their lithology, fluid content, rheological state, etc.

This chapter represents an essential revision of the material published by Bubnov et al. (2007). In the subsequent sections, we briefly cover some results of recent regional-scale surveys, with primary target being Earth crust large-scale structure, and then consider a number of case studies, aimed at hydrocarbon prospecting.

13.2 MT SURVEY TECHNOLOGY IN BRIEF: DATA ACQUISITION, PROCESSING, ANALYSIS, AND INTERPRETATION

Since 2000, regional MT surveys in Russia have been conducted mostly utilizing Canadian-made instruments, designed and manufactured by Phoenix Geophysics Ltd. This equipment features high sensitivity and broad dynamic range, unattended operation, synchronization using the GPS satellite system, reliability, and simplicity. According to standard acquisition procedure, either all five components of the natural electromagnetic field (E_x, E_y, H_x, H_y, and H_z) or only the two electric field components (E_x and E_y) are measured at each station. In the latter case, magnetic field records taken at neighbor sites are used to calculate impedance tensor and other transfer functions. As a rule, a receiver at some reference site is operating synchronously with regular stations, which is used for remote reference processing. This approach is helpful for uncorrelated noise cancellation. In addition, robust statistical schemes are used to increase the reliability of results. Rejection of data values according to different criteria, such as dispersion relation between apparent resistivity and impedance phase, normally provides considerable improvement.

The background of MT data interpretation methods is essentially the Tikhonov's theory of ill-posed problems (Berdichevsky and Dmitriev, 2008). Acceptable dimensionality of inversion methods, usually 1-D or 2-D, is determined through analyzing measured responses. In regional-scale studies, 3-D inversion methods are rarely applied due to a specific configuration of the observation grids, usually implying that stations are spaced along a single profile, which makes 3-D inversion fairly tricky and unstable. However, to verify the accuracy of 1-D and 2-D models, 3-D forward modeling is often used allowing the study of 3-D effects and possible errors. Data interpretation is usually done in two steps. At the first step, smooth-structure inversion is applied. At the second step, the data is fitted by piecewise-uniform models in order to achieve higher detail in the resistivity structure. All MT data components are used for interpretation, although their simultaneous inversion is not always effective because of their differing sensitivity to resistivity structures and differing robustness against 3-D distortions.

13.3 REGIONAL-SCALE MT STUDIES

In recent years, a number of regional-scale MT surveys, aimed at imaging Earth crust and sedimentary cover structure have been completed in Russia (Figure 13.1).

We start the review with some results obtained at the East-European craton, where a large number of stations have been collected over the last decade. Essentially new data on the resistivity structure of Moscow syneclise, the largest tectonic structure of the craton, was obtained with magnetotellurics under so-called RIFEY exploration program. The profile, measuring 650 km in length,

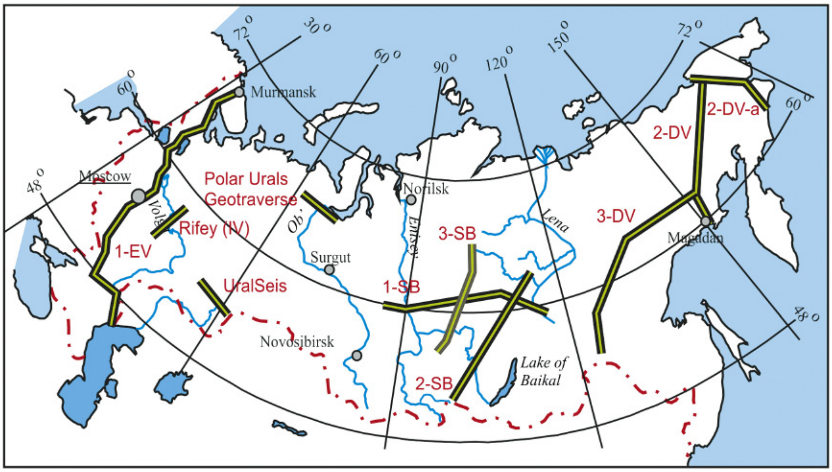

FIGURE 13.1 Major geotraverses in Russia.

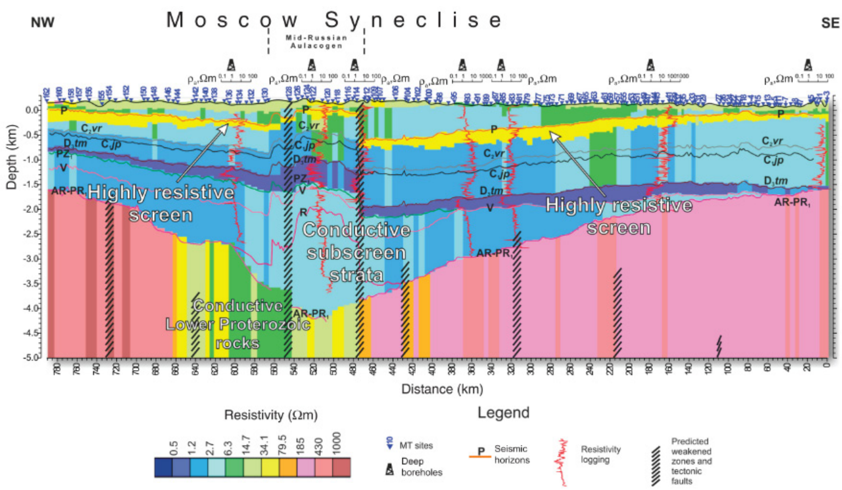

FIGURE 13.2 Resistivity image across the Moscow syneclise.

consists of 160 MT sites. The resistivity image, interpreted form MT, borehole, and seismic data (Figure 13.2), includes the basement depression – the Soligalich aulacogen and the superimposed uplift in sediments (Bubnov et al., 2003). Due to the resistive layer, redistributing the transverse electric current, this uplift strongly influences the transverse impedance (TM-mode) data. At the same time the longitudinal impedance (TE-mode) provides information about deeper layers and reveals conductive Meso- and Neo-Proterozoic and Devonian rocks. The total thickness of the sediments in the Soligalich aulacogen is about 2–3 km, and their low resistivity is the evidence for good reservoir properties. The resistive basement consists of large blocks of different resistivity. At the margins of the Moscow syneclise, the basement is presented by resistive, probably Archean rocks, while in its central part it is found to be more conductive, likely due to the presence of Proterozoic rocks.

Figure 13.3a shows a resistivity image for 800-km long part of 1-SB profile (Aleksanova et al., 2005). The model images the structure across east margin of West-Siberian plate, Enisei ridge, and Siberian craton. Within the limits of West-Siberian plate, the conductance of the sedimentary cover reaches 1000 Sm. This very conductive background does not allow imaging the structure of the underlying Earth crust in much detail. In the Enisei range, a conductive region of unknown nature is imaged beneath the resistive Proterozoic metamorphic rocks. MT data analysis demonstrated that it has complex 3-D geometry making neither 1-D nor 2-D inversions applicable here. At the Siberian craton within the Baikit anteclise, a conductive layer is clearly seen. Its resistivity is approximately 100 Ωm and its thickness is about 10–15 km. Possibly, the nature of this anomaly can be explained by fluid presence in disintegrated rocks in the brittle-ductile transition zone.

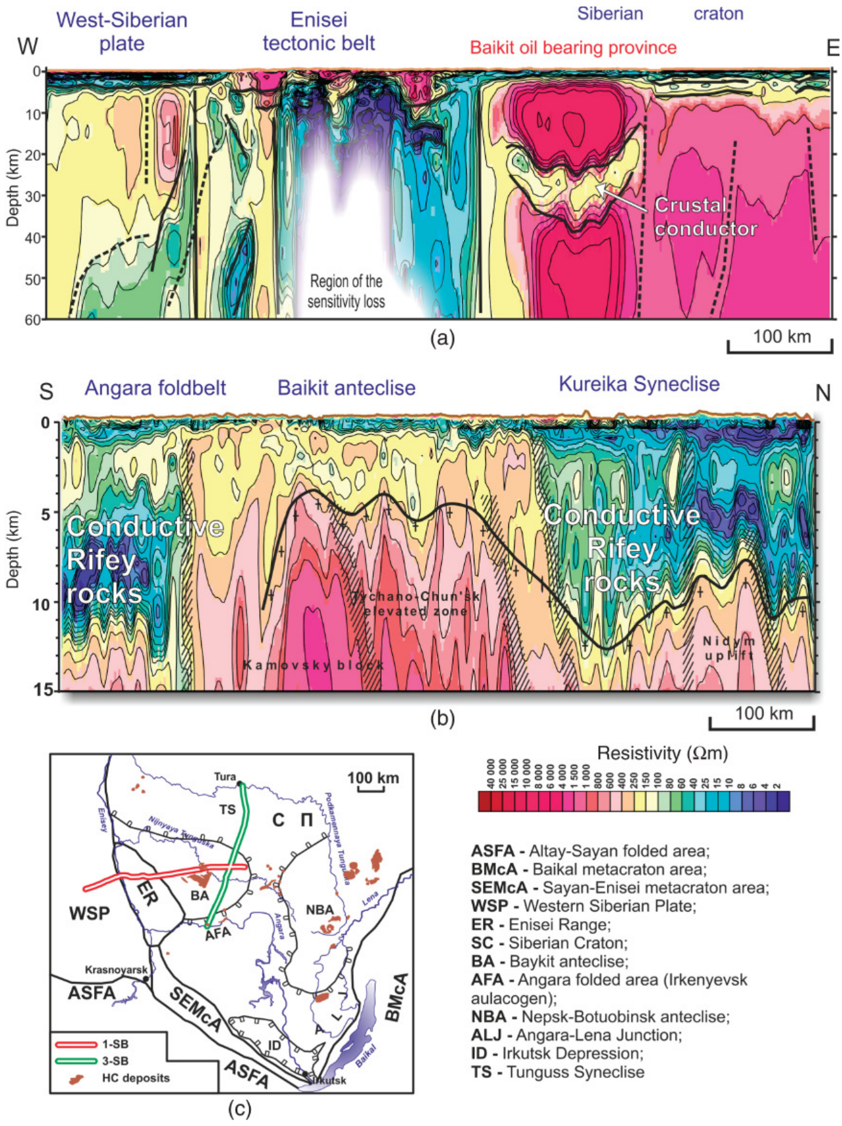

FIGURE 13.3 Resistivity images along 1-SB (a) and 3-SB (b) geotraverses. Location map is shown in (c).

Note that currently a special study of crustal conductivity structure in oil and gas provinces is being performed. In this connection, the mid-crustal conductive layer detected in the Baikit anteclise (containing Yurubchen-Tokhom oil field, the largest in East Siberia), and also in the region of the huge Romashkin field at the East-European craton, can be of great practical interest.

Another image indicating conductivity structure of the Siberian craton sedimentary cover (3-SB profile) is shown in Figure 13.3b. In the south of the profile, within the Irkenyev aulacogen, conductive Meso-Proterozoic rocks are identified at 7–11 km depth. According to borehole data from the adjoining Baikit anteclise, these are mainly carbonates. Their low resistivity is probably caused by high porosity and mineralized water content. Within the Kureika syneclise, conductive layers that could potentially include reservoir rocks have been also imaged.

The studies have revealed some interesting patterns of both sedimentary cover and crust structure, like highly conductive regions. In connection with hydrocarbon potential assessment, of great practical interest is the mid-crustal conductive layer detected within the Baykit Anteclise of the Siberian Craton (where the Yurubcensk-Tokhomsk deposit, the largest one in the East Siberia, is located) and in the region of huge Romashkinsky deposit within the East-European Craton.

The 2-DV and 3-DV profiles cross Sakha, Magadan, and Chukotka regions (Berzin et al., 2002). To date, more than 4000 stations have been collected. These vast amounts of data allowed mapping numerous tectonic structures of the region and revealing conductivity anomalies in the Earth crust. Figure 13.4 displays the resistivity image along some part of 3-DV profile.

General pattern suggests a strong correlation of conductive anomalies with areas in which the intensity of seismic reflections from the Moho boundary is small. This can be explained by connection of the conductors with connected with paleo-subduction zones and association with permeable rocks allowing the mantle fluids to migrate easily upwards to the Earth's surface. Major gold and silver deposits of the region are situated in the vicinity of these anomalies. In some areas, the conductors may also be related to graphitized rocks in the upper crust.

Joint interpretation of electromagnetic (MT) and seismic (CDP) data along with geological and airborne geophysical data enabled reconstruction of regional-scale resistivity image and creating a detailed geophysical model of the

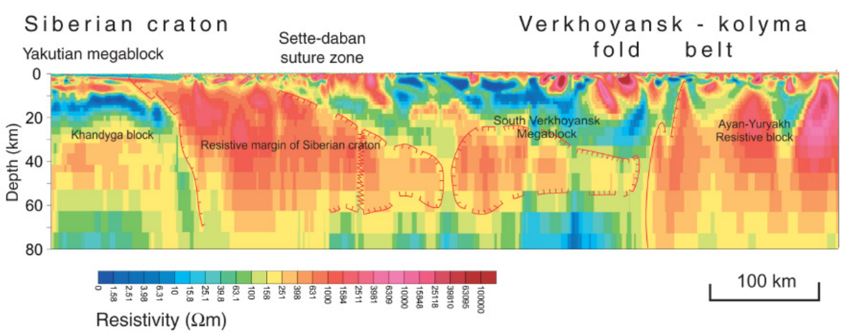

FIGURE 13.4 Resistivity image across Siberian craton and Verkhoyansk-Kolyma fold belt.

Earth crust. Treating MT and seismic data jointly greatly clarifies understanding of geological structure hierarchy and helps to recover the structure pattern at different depth levels. The main achievements of the constructed model are recovering the configuration of crystalline basement of Siberian Craton; discriminating between continental and oceanic crust type in numerous crustal blocks, revealing an elevated conductivity regions in lower crust and lithosphere, which are frequently found as associated with volcanic activity and/or hydrothermal metasomatism.

Besides that, an important result is imaging of a system of deep conductors and revealing their connection with shallow-depth prospective regions. Appearance of small-scale high-contrast conductive anomalies at shallow depth suggests occurrence of active hydrothermal metasomatism around them, which is usually found prospective in terms of mineralization. Characterization of tectonic structure in terms of conductivity pattern allows discriminating between consolidated blocks and active regions with presence of ongoing geological processes.

13.4 MT FOR HYDROCARBON PROSPECTING

13.4.1 Eastern Siberia

Based on seismic data, within some part of 3-SB profile (Eastern Siberia) a reef massif has been imaged, separating two regions, totally different in terms of sediment accumulation settings in lower and middle Cambrian. To the south of the reef, a salt-generation basin is located. $Э_{1–2}$ sediments are mainly halogenous carbonates with thickness of nearly 2 km and are considered a source rock (Kuonam formation). To the north of the barrier reef, this formation abruptly decreases its thickness to 600–800 m, while clays, siltstone–limestone packages and marls appear in the upper part of the section. In the study area, the principal targets in terms of hydrocarbon potential are the reefs and Vendian terrigenous sediments. Besides, the source rock itself is of specific interest.

With MT data, also available for this profile, we were able to recover lateral conductivity variations of each formation imaged by seismic and confirm a reef structure (Figure 13.5). This greatly helps the detailed exploration of the hydrocarbon prospective formations.

Following the dimensionality analysis, 1-D constrained MT inversion has been performed, with primary focus on resistivity values of the formations. Formation geometry has been prespecified according to seismic and borehole data. Though, in some parts of the profile additional resistivity layers were required to be introduced within a single seismic horizon. On the contrary, some seismic reflectors were found to be inconsistent with resistivity boundaries inferred from MT data. Nevertheless, the combined MT-seismic image obtained in this way provides more information than either MT or seismic models treated separately, and allow tracing the lateral resistivity variations within particular formations.

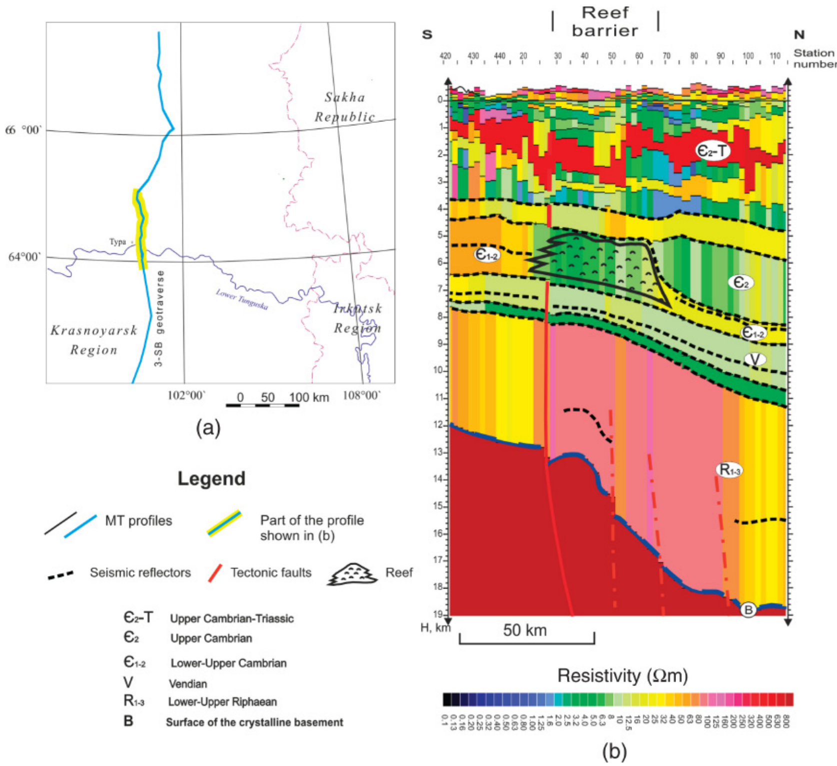

FIGURE 13.5 Reef barrier in East Siberia as interpreted from MT survey constrained by seismic data.

When compared with borehole data, the resistive layers imaged by MT in the upper part of the section were found to be associated with volcanic trap formation. As a result of joint MT and seismic surveys, a new data has emerged which is useful for characterization potentially prospective formations. In particular, the reef was found to be relatively conductive, which is the evidence for high porosity of reef material.

13.4.2 Taimyr Peninsula

The Taimyr Peninsula (Taimyr fold belt) is enormously rich in natural resources, including hydrocarbon material. Oil seeps and discoveries made in the adjacent Enisei-Khatanga basin suggest that the Taimyr fold belt has active petroleum systems. The existing geophysical data indicates that total thickness of Paleozoic-Mesozoic sedimentary cover locally may exceed 20 km. Until recently, vast territories with good prospects of oil and gas, the most part of which still remains undistributed, have been studied very poorly. At present, a new stage of geophysical regional studies performed both on land and in the

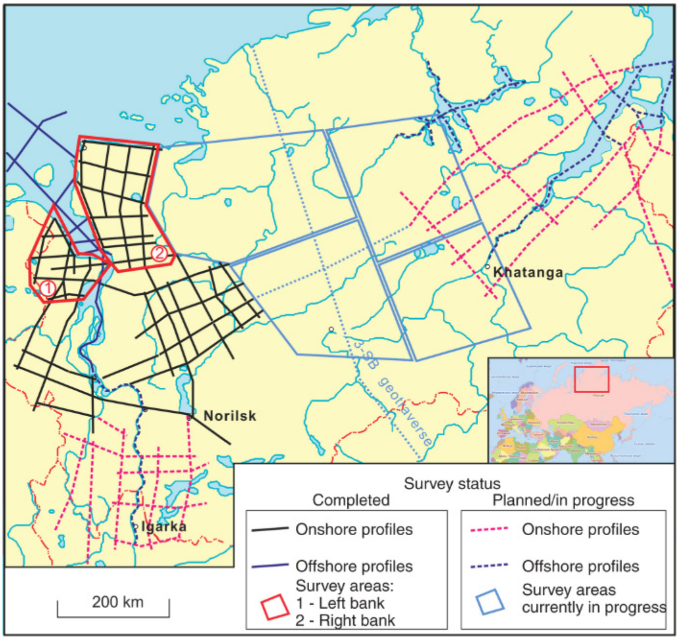

FIGURE 13.6 Map of the survey area in Taimyr region.

aquatic areas of rivers, bays, and seas, has been started. The applied technology of joint seismic and electric prospecting techniques provides a reliable level of studies of the entire sedimentary cover and in many cases of deeper horizons, as deep as the Moho surface. The primary goal of the exploration conducted in the Taimyr Peninsula was to discover large-scale oil and gas deposits with further preparation of the most prospective areas for licensing. The total length of the planned profiles is over 15,000 km. As the study objectives were not limited to understanding the structure geometry, but also its lithological peculiarities, seismic exploration was performed jointly with audio and broadband magnetotellurics.

At first, let us briefly consider electromagnetic survey results obtained at the Left-bank area of the Enisei river, the main objective of which was to study in detail the Jurassic and Cretaceous terrigenous sediments, lying in the depth interval of 0–7 km. MT data was collected along 12 profiles, spaced by 2 km distance between each other with total amount of stations being around 1000 (Figure 13.6).

Since the resistivity structure appears to be close to layered with smooth variations, inverse problem was solved utilizing 1-D inversion with constraints imposed on model geometry. That is the geometry of the layers was fixed according to available seismic data and only the resistivity values were evaluated. However, additional layer boundaries, not seen from seismic, were introduced

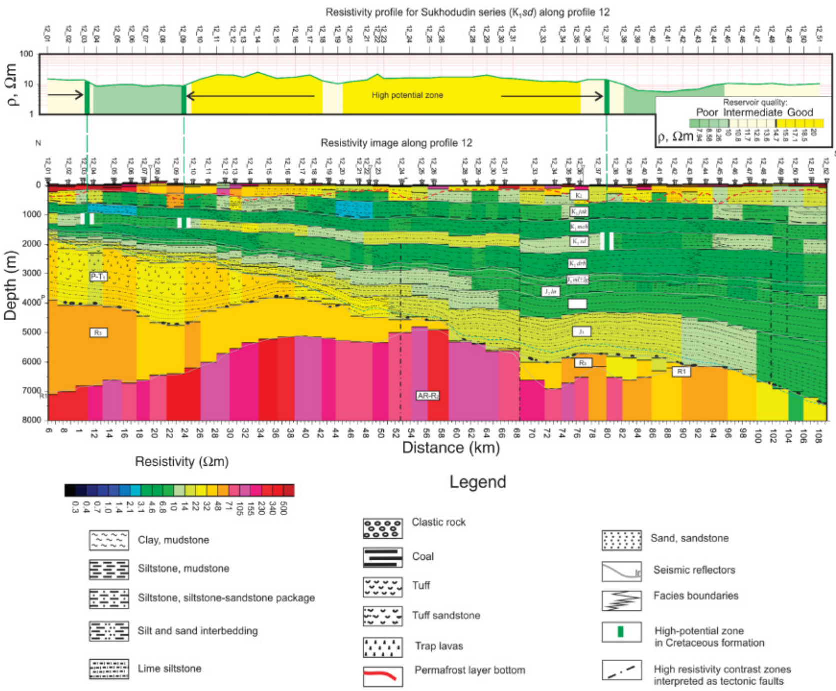

FIGURE 13.7 Resistivity image and reservoir quality distribution along profile 12.

when it was not possible to fit MT data under prespecified geometry. Well logging data from the nearest boreholes was also exploited to correct resistivity distributions. Such an approach made it possible to determine resistivity of the layers with a high degree of accuracy, which allowed us to come up with lithology models.

Thus, as a result of MT data interpretation, resistivity models have been constructed, imaging the structure down to 15 km depth. Those images not only contain information about the resistivity structure of the sedimentary cover and basement surface geometry but also indicate lithological properties of the major formations (Figure 13.7).

Along with resistivity images, the maps showing lateral resistivity variations within each formation have been produced. From those maps, the main peculiarities of the resistivity structure can be traced rather clearly. That enabled us to delineate the regions with high reservoir quality within the limits of the prospective formations. As a result, we were able to create a prediction map indicating the distribution of hydrocarbon prospects, with delineation based on the following criteria:

1. Relatively high resistivity (>15 Ωm, sometimes up to 100 Ωm). Taking into consideration that sediments in the area are commonly of terrigenous type,

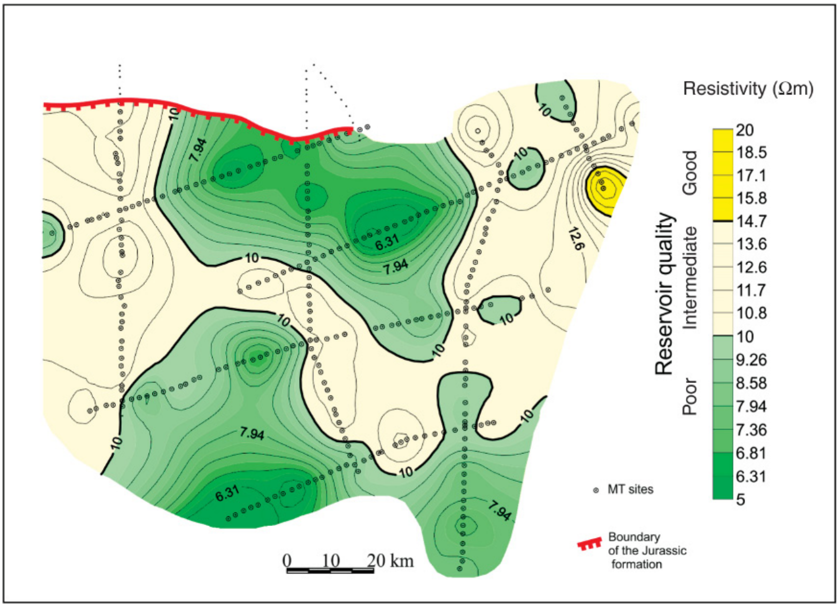

FIGURE 13.8 Reservoir quality distribution for Mid-Upper Jurassic sequence.

relatively high resistivities should be associated with sands or sandstones, both of which are believed to form reservoirs in the survey area;

2. The presence of impermeable formations (cap rock) is considered to be one more mandatory factor. In the area, the cap rock turns out to be argillaceous sediments with resistivity of 2–10 Ωm;
3. The structural factor like presence of anticlinal domes, swell-like structures, nonconformity of bedding.

The combination of the first two findings and the presence of an appropriate structural type made it possible to reveal regions of possible hydrocarbon accumulation. Figure 13.8 demonstrates an example of reservoir quality map for mid-upper Jurassic formation.

Another MT survey, with roughly 800 broadband stations acquired, was conducted in the area located at the right bank of the Enisei river. Unlike the study described earlier, the main aim of this survey was to image the resistivity structure and determine lithology of Paleozoic sediments. As the data had been found to be essentially 2-D, the resistivity images have been obtained from 2-D inversion of data. As the next step, taking available seismic data into account, the resistivity models were transformed into schematic lithological models. Since there is no single borehole in the area, the lithology prediction was made according to the results of the surface geological survey.

Resistivity distributions for the main structural levels compiled by interpolating 2-D resistivity models, reveal important data about deep structure

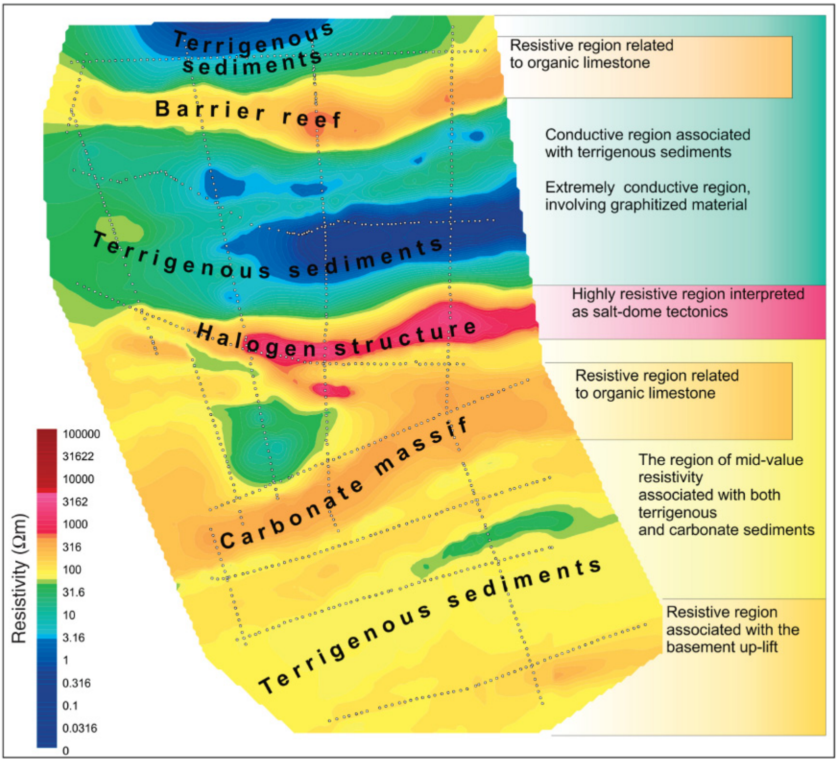

FIGURE 13.9 Major structure elements as interpreted from MT data.

(Figure 13.9). Paleozoic sediments in the survey area are divided (laterally) into three large blocks, which differ considerably from each other in terms of electric properties: the northern block is relatively conductive, the central one is a high-resistivity region, while the southern one is characterized by an intermediate resistivity values. This pattern can be seen from Figure 13.10.

The northern zone corresponds to Taimyr thrust system. The sedimentary cover within the limits of this region is fairly conductive, with average resistivity of 10–30 Ωm, and is associated with terrigenous sediments. Two types of anomalies are imaged in this region: extremely conductive bodies (less than 3 Ωm in resistivity) and a high-resistivity block (300–1000 Ωm), located at the northern end of the profile. Extremely low resistivities can only be explained by the presence of graphitized rocks, which is also evident from numerous coal outcrops found on the surface in this region. The coals could have been transformed into graphites in the process of dynamic metamorphism related to thrust formation. Thus, the low resistivity marks regions where coal rocks have been transformed in graphite as a result of tectonic movements. The high resistivity feature (300–1000 Ωm), traced within the considered region across 4 distinct

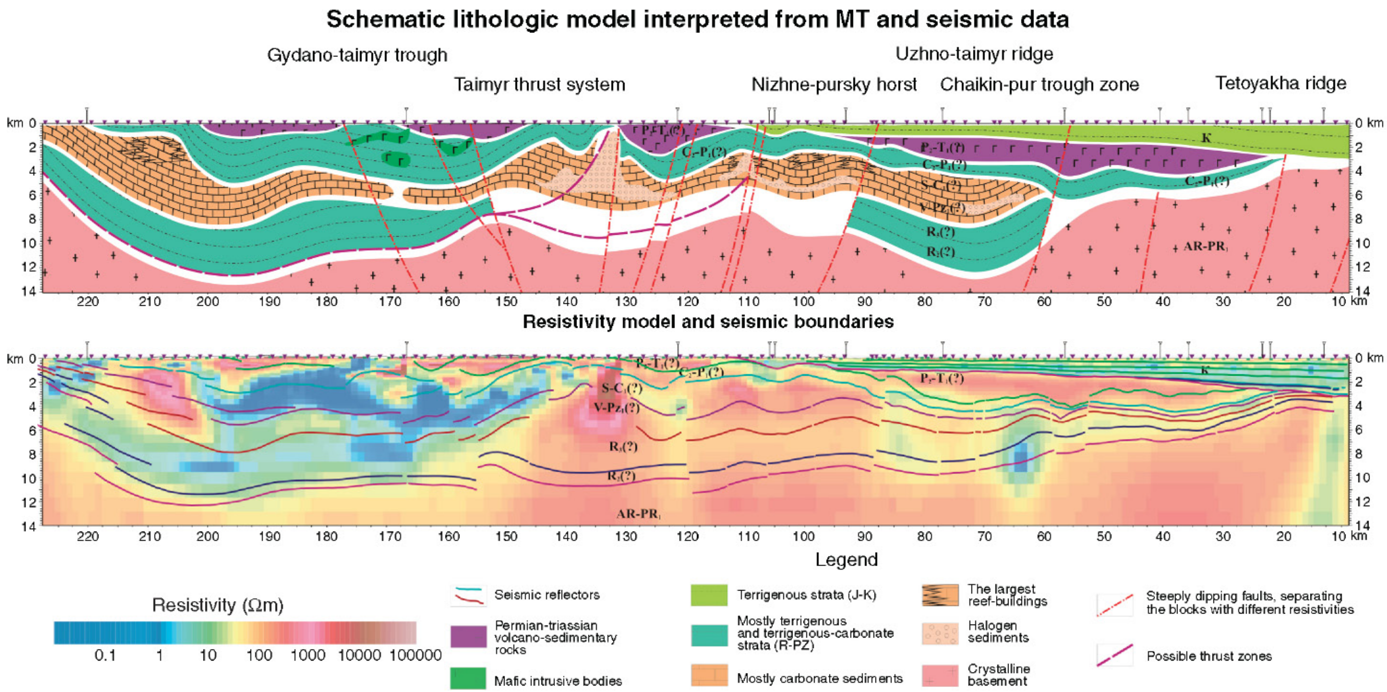

FIGURE 13.10 Geologic model and resistivity image across Taimyr Mountains.

MT profiles, is about 15 km wide and 5 km deep. It also has its signature in the gravity field as a positive anomaly with linear configuration and is interpreted as a barrier reef.

The central part of the survey area is characterized by quite a different correlation of geophysical fields. In highly resistive (up to several thousand Ωm) regions, the correlation between different geophysical fields is found to be poor, while amplitude and energy of seismic signal is low. In this case, taking into account the specific configuration of seismic reflectors, the observed anomalies are treated as the manifestation of the salt-dome tectonics. Thus, the entire central part having elevated resistivity is interpreted as the region of well-developed salt tectonics, which can be connected with hydrocarbon deposits.

Resistivity structure in the southern part of the survey area can be clearly discriminated from the northern and central parts due to the absence of impact of thrust and salt tectonics. In this part, the seismic reflectors are found smooth and consistent with resistivity boundaries. Positive anomalies of resistivity (100–500 Ωm) associated with upper and middle Proterozoic formations are interpreted as carbonate sedimentary layers.

Thus the application of a prospecting technology involving several methods, with primary role of seismic and MT imaging, enabled us to arrive at some important conclusions about the deep geological structure of the western part of the survey area, which would have been impossible to do by exploiting surface geology only. MT data provided consistent lithology models and made it possible to discover a number of carbonate structures as well as the salt-dome structure. Taking into account an extreme complexity of the geological setting with age of sedimentary formations ranging from late Proterozoic to Mesozoic, which contains elements like thrust system, trap magmatism, salt-dome tectonics, and reef structures, we can make a conclusion that MT method plays an essential role in the exploration.

Having provided subsurface resistivity background, MT data has permitted the development of more accurate subsurface interpretation. Large Devonian evaporite diapirs and zones of Paleozoic reefs were interpreted based largely on these MT data in the inner part of the fold belt for the first time. The latter may represent important exploration objectives. In the thrust belt front, the new data helped delineating potential exploration sweet spots in the Mesozoic clastic section and in buried Paleozoic highs. The results of the Taimyr fold belt study demonstrate high value-adding potential of implementation of the MT prospecting for licensing and petroleum exploration in the frontier areas.

13.4.3 Pre-Caspian Depression

Geological setting of the Pre-Caspian depression (Figure 13.11) is fairly complex due to the presence of the salt domes. MT is the only EM method capable of providing information on the electric conductivity of subsalt formation, hosted at the depth up to 10 km and more. Several case studies indicate that MT could

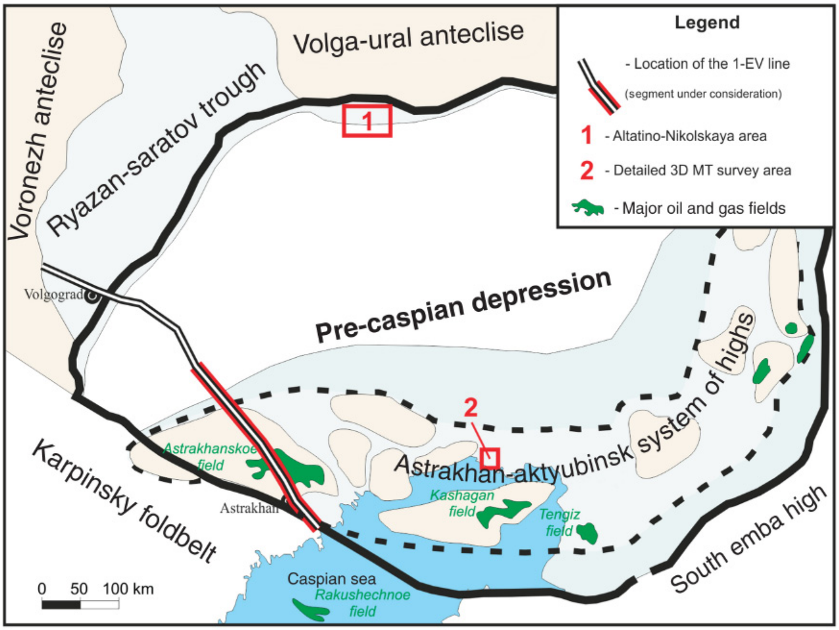

FIGURE 13.11 Tectonic map of Pre-Caspian depression and MT survey locations.

be efficient tool for subsalt imaging even in the presence of highly conductive suprasalt rocks (Aleksanova et al., 2009). Here, we briefly consider the results of 3 MT surveys, whose scale varies form regional (southern edge of the 1-EV geotraverse, Astrakhan region, Russia) to semi-regional (Altatino–Nikolskaya area, Saratov region, Russia) and local (imaging an isolated salt-dome structure in Western Kazakhstan).

13.4.3.1 Akhtubinsk–Astrakhan 1 – EV profile

Regional geophysical investigations along the 1 − EV profile were carried out under the framework of a government project initiated by the Russian Ministry of Natural Resources and included 2-D seismic, MT soundings, and some other techniques (Kheraskova et al., 2006). The southern edge of the 1 − EV profile goes within the Pre-Caspian depression, known as an area of salt-dome tectonics (Figure 13.11). The spacing between MT stations was about 1 km. Figure 13.12 shows a seismic-geological cross-section alongside with a resistivity image interpreted from the MT data acquired within the Akhtubinsk–Astrakhan segment of the 1 − EV profile. Resistivity model (15 km in depth) has been obtained by utilizing of 2-D inversion code (Rodi and Mackie, 2001). In general, the model obtained has four-layer structure and includes a conductive suprasalt horizon (P_2Q), resistive salt (P_1k), conductive subsalt horizon (PCm_3-P_1), and resistive basement (Archean).

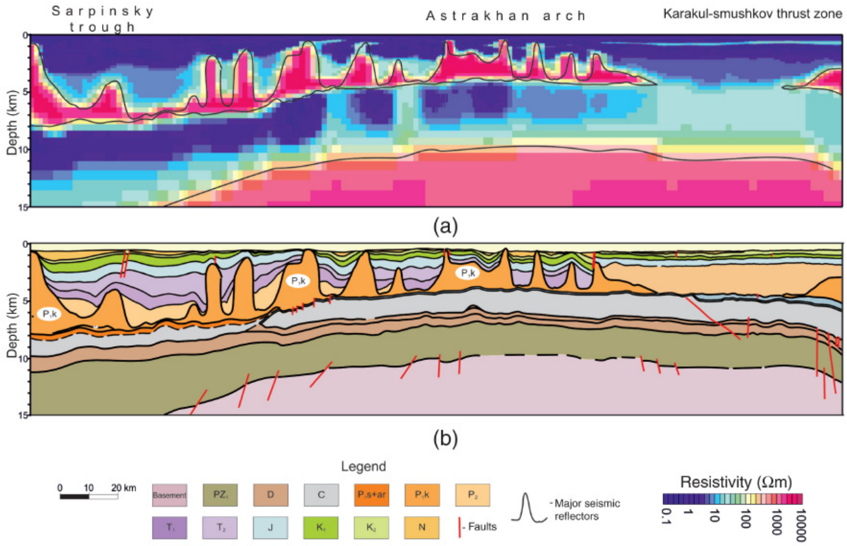

FIGURE 13.12 Resistivity image along the 1-EV profile obtained from 2-D inversion of MT data (a) compared to seismic-geological model (b).

Subsalt strata is of key interest in the context of the prospects for hydrocarbons. A complex resistivity structure doesn't allow imaging of the subsalt formation in much detail, because the latter is overburden by salt and suprasalt packages. Main features of the subsalt structure are as follows. The upper part of the subsalt horizon (from the bottom of Paleozoic and above) is less resistive in comparison with its lower part.

Within the Sarpin trough, the subsalt layer is characterized by relatively low resistivity and it increases significantly in the Astrakhan arch and Karakul–Smushkov thrust zone. However, in this area there are several conductive (4 Ωm or less) anomalies. The regional trend, reflecting this increase in resistivity, is probably due to change in subsalt lithology. In the Sarpin trough, the lower-middle Devonian is primarily terrigenous, while in the Astrakhan arch area it has carbonate composition. Another mechanism leading to low resistivity of the subsalt horizon in the Sarpin trough is an increase of ground water salinity. It's well known that water mineralization in a given horizon is lower when the horizon is located closer to the ground surface and higher when it's buried deeper. Local conductive inhomogeneities, mapped in the subsalt strata, seem to be related to the zones of high porosity or cracks concentration. Thus, these anomalies are promising for hydrocarbons.

13.4.3.2 Altatino–Nikolskaya Area

Altatino–Nikolskaya area is located at the northern edge of the Pre-Caspian depression (Saratov region, Russia). 3-D MT survey was carried out in this area in 2004. The observations were performed along several profiles with station

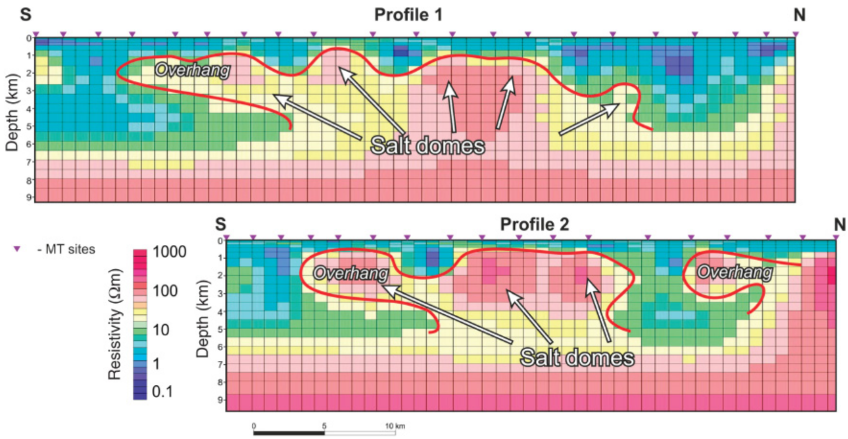

FIGURE 13.13 Salt-domes imaged by 2-D MT inversion in Altatino-Nikolskaya area.

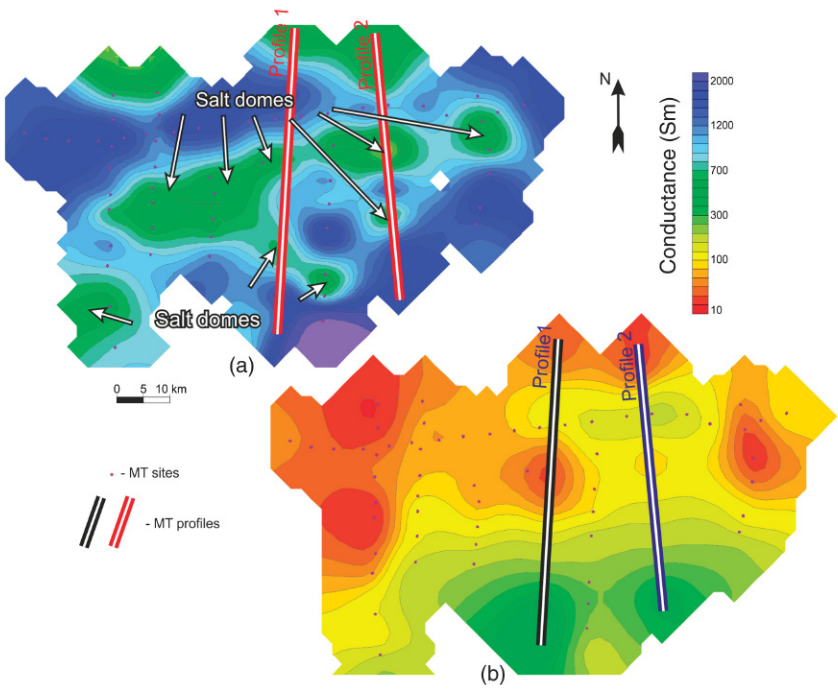

FIGURE 13.14 Signatures of the salt-domes in conductance distributions. (a) 0–4 km depth range; (b) 4–6 km depth range.

spacing of 1–5 km. A volumetric resistivity model was constructed by combing 2-D inversions into a consistent 3-D distribution. The model is presented in the form of (vertical) resistivity images (Figure 13.13) and maps of conductance, calculated for depth intervals of 0−4 and 4−6 km (Figure 13.14).

The sedimentary cover has a three-layer structure, including conductive suprasalt Mesozoic sediments; highly resistive Kungurian salts; and subsalt horizon (mostly also resistive). Suprasalt sediments are horizontally layered and their structure could be described utilizing a 1-D model. Resistivity of the Mesozoic rocks varies in the range of 1−30 Ωm and increases with depth. Thickness of the suprasalt strata varies in a wide range from 100 m to 300 m above the salt-domes, up to 4 km in deep sub basins.

From the images, it can be clearly seen that some of the salt-domes are forming overhangs and traps beneath them. The latter could contain hydrocarbons. Several relatively resistive zones are revealed in the subsalt strata. They may be related to local carbonate massifs.

13.4.3.3 *Detailed Imaging of an Isolated Salt Dome*

Another 3-D MT survey was conducted to image a single salt-dome structure; map the sediments, trapped in the salt, and obtain any information on the properties of underlying subsalt strata. Geological setting of the area is typical for the Pre-Caspian region. The observation grid includes 6 profiles with 200 stations in total. Data interpretation was performed using 2-D inversion; horizons geometry known from seismic was taken into account.

Main results are presented in the form of resistivity images, 10 km in depth (Figure 13.15), and out of those a 3-D model of resistivity distribution was constructed (Figure 13.16). Conductive suprasalt formation, resistive salt, and

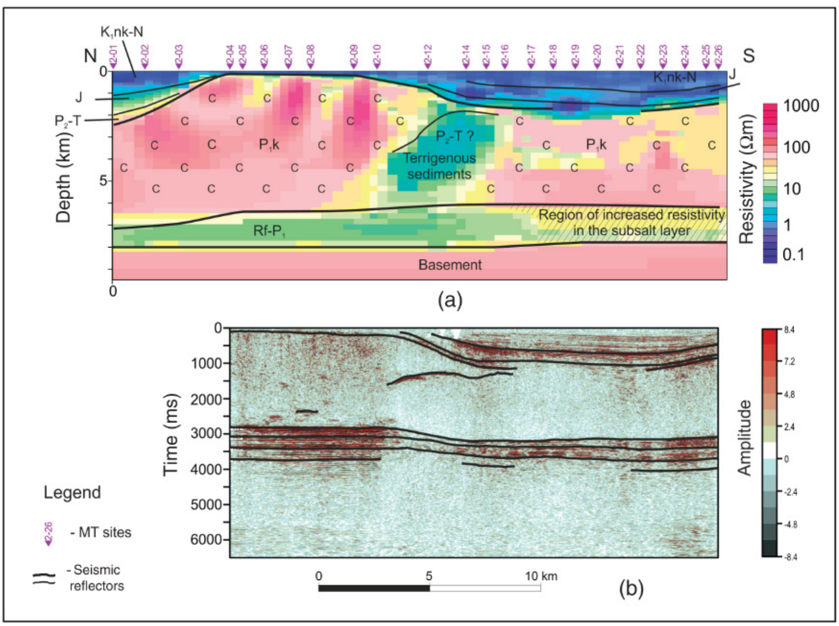

FIGURE 13.15 Salt-dome structure as imaged by magnetotellurics (a) and seismic survey (b).

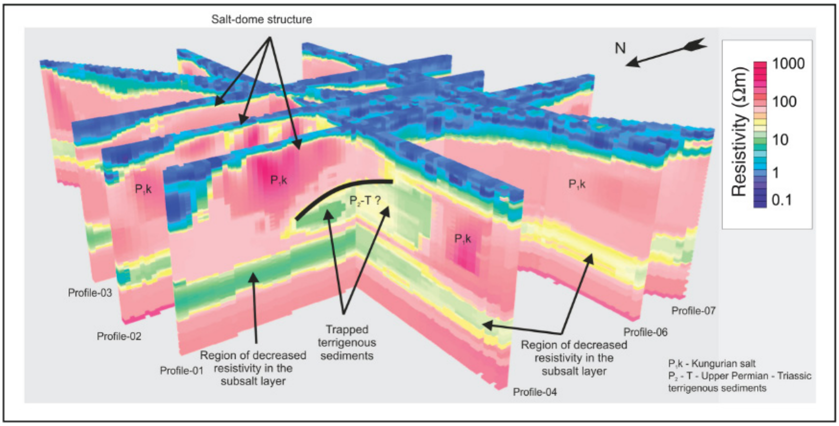

FIGURE 13.16 3-D resistivity model of the salt-dome structure.

conductive subsalt are main and already familiar elements of the resistivity structure. Meso-kainozoic suprasalt strata is of terrigenous nature and has resistivity of 0.1–10 Ωm. Its thickness varies from 200 m (above the salt-dome) to 3000 m (in deep sub basins). There are vertical contrasts of resistivity within suprasalt rocks. Its upper part is formed by clays and has extremely low resistivity (about 0.1 Ωm). The lower part (P_2-J) is less conductive (1–10 Ωm). It is important to notice that suprasalt sediments could be treated as the oil reservoir as oil migrates up there from the subsalt formations.

Kungurian salt is a highly resistive horizon with resistivity of 100−1000 Ωm and thickness of up to 6 km. Top of the salt-dome is located at the depth of 200−300 m. MT imaged a complex structure of the salt strata. It revealed conductive (5−15 Ωm) anomalies, located beneath salt traps, probably associated with terrigenous rocks of Upper Permian-Triassic age. The bottoms of these anomalies are determined rather inaccurate. However, their thickness is estimated to be up to 3.5–4 km. It should be mentioned, that overhang traps localized within the marginal parts of the salt-dome structure are of primary interest in terms of discovering oil and gas accumulations. In the study area, the reservoirs could be related to sandy layers of Permian and Triassic age.

Subsalt strata is formed by terrigenous sequences (Artinskian) and carbonate rocks (Upper Visean–Sakmarskian). With MT, it was possible to infer generalized characteristics of subsalt strata; vertical differentiation of resistivity within the strata is severely complicated. In general, subsalt rocks are rather conductive (3−80 Ωm) with thickness of 1.6−2 km. The pronounced lateral zoning of subsalt conductivity is observed. Southern, southwestern, and southeastern parts of the area are characterized by relatively high values of resistivity (over 20 Ωm), while the northern part is more conductive (3−20 Ωm). Resistive subsalt strata in the southern part could be associated with either carbonate sequences or effusive rocks.

It is important to say that seismic is often inefficient for the imaging of the subsalt strata. This problem arises because of the strong velocity contrasts within the salt formation. The application of MT techniques in such settings can provide more reliable information on the properties of subsalt sediments. According to modeled data, MT is able to image relatively low-contrast anomalies with lateral size of 10 km and thickness of 1 km.

With regard to suprasalt strata, MT allows its imaging in a great detail. In settings typical for the Pre-Caspian depression, characterized by high content of clay minerals in Jurassic and Cretaceous–Neogene rocks, MT is able to distinguish less conductive sandy layers from the highly conductive clays. These horizons could hardly be seen by seismic due to small contrasts in elastic properties. At the same time, their electric properties are substantially different, permitting their discrimination.

13.5 PROSPECTS FOR FUTURE

The further progress of MT method requires solving two groups of problems.

The first group is technical problems, which, although, seem to be fairly important for the development of practical magnetotellurics. These include the following:

- New instrument designs with main attention to portability and small cost. Similar to other geophysical techniques, the success of MT largely depends on the amounts of collected data, which requires reducing the costs paid for a unit measurement. Release of the cheaper instruments, would intensify exploration and, after all, increase the reliability of interpreted data.
- Development of marine MT systems. So far, the application of marine magnetotellurics has been very limited due to, first of all, unavailability of instrumentation in the market. Seafloor MT surveys are performed by 2–3 companies, which are not interested in spreading this technology making more cost-effective and available. Another problem is related to creation of MT equipment, designed specifically for acquiring data in shallow water transition zones.
- Further development of controlled source magnetotellurics (CSMT). The presence of cultural EM noise, particularly produced by electrified railroad and agricultural systems is drastically limiting the ability of MT to provide a reliable data/models. This issue results in inapplicability of the method in vast areas where significant cultural/industrial activity takes place. Use of the powerful transmitters, exciting the field at specific frequencies commonly provides high signal to noise ratio. However, interpretation of CSMT data assumes that measured field is consistent with far zone approximation and therefore appropriate conditions have to be satisfied to achieve consistency. Namely, large transmitter-receiver spacing is required which makes it challenging to accurately measure the response when the signal gets low.

Thus, the instruments should provide sufficient accuracy and sophisticated processing codes are required for treating the data.

- Development of software tools. Amounts of MT data collected in a single survey may reach as many as a few thousand stations. Respectively, the software used to store, process, interpret and visualize these huge amounts of data must be capable of handling them effectively and provide compatibility with existing geophysical software.

Among the second group of the challenges are following scientific problems:

- 3-D MT inversion. The primary trend of MT exploration is transition from single soundings and isolated profiles to 3-D grids. Availability of dense 3-D data would enable implementation of 3-D inverse codes, calculating the models from a complete transfer function datasets.
- The studies of the transfer functions sensitivity and resolution should be continued aimed at formulating the strategies of choosing optimal datasets for inversion. A number of transfer functions are currently used in magnetotellurics. They all exhibit different sensitivity and resolution to target objects. In particular, apparent resistivity (or impedance magnitude) is often severely distorted by galvanic effects, while magnetic transfer functions are not. An important result would be a creation of interpretation technique using the advantage of each transfer function.
- Anisotropy and model scaling. Anisotropy is a common feature of subsurface structure and it may be caused by sedimentary layers sequencing or existence of subvertical fault systems. Thus, the model parameterization in terms of anisotropy is required and appropriate forward/inverse codes should be used to handle anisotropic models.
- Joint interpretation of various geophysical data. A relatively new, fast developing field is producing geological models from joint inversion of, for example, MT and gravity or MT and seismic data. This approach allows one to take interpretation to entirely new level.

13.6 CONCLUSIONS

1. MT exploration essentially expands the existing ideas about structure and geodynamics of the Earth's interior, based on the results of drilling as well as seismic, gravity, and magnetic surveys. MT studies provide unique information about the structure and reservoir properties of sedimentary formations, the state of tectonically active regions, the graphitization and fluid regime in the consolidated crust, and the permeable and fluid-saturated crustal zones. MT methods supplement other geophysical data with characterization of rock lithology and fluid content. With modern survey technology, data acquisition, processing, and interpretation methods, MT turns out to be a powerful tool for subsurface imaging and mineral exploration.

2. Regional studies discovered many features indicating some specific processes and signatures of past tectonic activity. One example is the uplift structure mapped in the Moscow syneclise. Also, with deep MT soundings, the mid-crustal conductive layer has been detected beneath the large Yurubchen–Tokhom oil field, the largest in East Siberia, which can be of great practical interest. Outstandingly long 2-DV and 3-DV geotraverses, crossing the Far North-East of Russia and counting thousands of MT stations, allowed mapping numerous tectonic structures of the region and revealing conductivity anomalies in the Earth crust, which can have either fluid or graphite nature.
3. The detailed mapping of the reef structure in the Eastern Siberia has found it had been relatively conductive, which is the evidence for high porosity of reef material. The massive MT survey in Taimyr area, with an inversion of acquired data under constraints inferred from seismic exploration, yielded a high-detail resistivity model and allowed assessing the hydrocarbon potential over vast areas within the western part of Enisei-Khatanga trough. Recent studies conducted in the Pre-Caspian region end up with delivering important information on both the geometry of particular salt domes and the regional-scale patterns of subsalt resistivity. An important point is related to the fact that the reservoirs trapped in the salt, as well as those laying beneath it are frequently unreachable by seismic method, yet being fairly important in terms of hydrocarbon exploration.
4. The case histories presented in the chapter cover only some fraction of much larger material collected and interpreted over recent years in Russia. The generalization of all electromagnetic data, obtained in its territory, is currently underway. The regional-scale maps of sediments' conductance and other parameters of the resistivity structure have been compiled and are being updated as new EM data become available (Sheinkman et al., 2003; Feldman et al., 2005).

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