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Review

Electromagnetic Surveys for Petroleum Exploration: Challenges and Prospects

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Abstract: Transient electromagnetic (TEM) surveys constitute an important element in exploration projects and can be successfully used in the search for oil and gas. Different modifications of the method include shallow (sTEM), 2D, 3D, and 4D (time-lapse) soundings. TEM data allow for solving a large scope of problems for estimating resources and reserves of hydrocarbons, discriminating reservoir rocks, detecting tectonic features, and characterizing drilling conditions. TEM surveys are applicable at all stages, from initial prospecting to production, and are especially efficient when combined with seismic surveys. Each stage has its specific objectives: estimation of net pay thickness, porosity, and fluid type during prospecting, optimization of well placement and prediction of drilling conditions in exploration, and monitoring of flooding during production. Electromagnetic soundings resolve permafrost features well and thus have a high potentiality for exploration in the Arctic petroleum province. At the first reconnaissance stage of regional prospecting in East Siberia, electromagnetic and seismic data were used jointly to map the junction of the Aldan basin (part of the Aldan-Maya foredeep) with the eastern slope of the Aldan uplift and to constrain the limits of Neoproterozoic sediments. The TEM-based images revealed reservoir rocks in the Upper and Middle Neoproterozoic strata. TEM data have implications for the amount of in-place oil and gas resources in prospects, leads, and plays (Russian categories D_{1-3}) at the prospecting and exploration stages and contingent recoverable reserves (C_2) during exploration (latest stage). The contribution of the TEM survey to oil and gas evaluation is quantified via economic variables, such as the value of information (VOI) and expected monetary value (EMV).

Keywords: oil and gas fields; resources and reserves of hydrocarbons; reservoir properties; transient electromagnetic soundings; seismic survey; processing and inversion; East Siberia; Arctic

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1. Introduction

Resistivity surveys for imaging the subsurface date back to the activity of the Schlumberger brothers in the late 1920s [1]. Since then, large progress has been achieved in the theoretical justification (e.g., [2]), methodology (e.g., [3–5]), and instrumental implementation (e.g., [3,6,7]). Resistivity surveys have become progressively more specific and differ in penetration and onshore/offshore applications [8,9]. Direct current (DC), shallow transient electromagnetic (sTEM), and ground penetrating radar (GPR) measurements focus on shallow subsurface (hundreds of meters), while time-domain TEM, frequency induction (FI), and magnetotelluric (MT) soundings cover km-scale depths.

In Russia, electromagnetic soundings have been largely used for petroleum exploration since the 1980s. TEM surveys have a good success history in East Siberia, where exploration is challenging because of climate and terrain conditions. Seismic exploration alone is often poorly efficient in faulted high-velocity rocks with salt beds, heterogeneous lithology, depositional traps, and thin reservoirs [10–12]. A good solution in this respect is to combine seismic and resistivity surveys [13]. The integration approach has already led to important discoveries in East Siberia: Upper Chona oil field, Middle Botuobia oil-gas field, Kovykta gas-condensate field, Yarakta oil field, Danilovo oil field, and others.

The results of TEM surveys become increasingly more informative due to instrumental advances [6,7]. As such, they are currently applicable at all stages of oil and gas evaluation, from reconnaissance prospecting to well placement, drilling, and successive operations. Surveys at each stage require special design, loop configuration, source and receiver parameters, as well as approaches to data acquisition and processing. Appropriate organization of workflow can help in choosing the best exploration and development strategy.

We demonstrate the potentialities and prospects of using TEM surveys for petroleum exploration purposes, with examples from Siberia, one of the most complex and problematic regions in terms of local geology, climate, and landscapes. In such regions especially, the use of seismic surveys alone has strict limitations associated with conditions at shot points, high-velocity sections, active faults, poor contrasts of target intervals, hardly identifiable fluid type, etc. Therefore, seismic evidence requires additional checks from geophysical methods based on different physical principles.

2. Materials and Methods

2.1. Transient Electromagnetic (TEM) Surveys: Historical and Physical Background

Transient electromagnetic (TEM) soundings are performed using a controlled pulse-like source and record the transient process (voltage decay) as a response of the earth to transmitter current turnoff [2,14]. The signals are transmitted and received by multi-offset arrays with ungrounded square loops. TEM surveys are advantageous by high resolution, sufficient depth penetration, low sensitivity to anisotropy and shallow heterogeneities, lack of galvanic distortions in the absence of grounding, and the possibility of operating in any climate, weather, and season (which is especially important in Siberia), as well as by loop sizes smaller than the target depth. The TEM method ensures much better depth resolution than other resistivity techniques that use galvanic sources or natural electromagnetic fields [15]. Furthermore, the quality of TEM responses to magnetic excitation is insensitive to the presence of high-resistivity zones, including salt beds (50,000 to 100,000 Ohm·m) or permafrost (thousands of Ohm·m).

The use of induction methods for subsurface imaging is based on the correlation of resistivity with porosity, saturation, pore space structure (rocks), salinity, and temperature (pore fluids) [16]:

$$R_t = aR_w\phi^{-m}S_w^{-n} \tag{1}$$

where R_t is the total resistivity of fluid-saturated rock, R_w is the resistivity of the fluid itself (w meaning water or an aqueous solution containing dissolved salts with ions bearing electricity in solution), ϕ denotes the porosity, S_w is the water saturation, or more generally the fluid saturation, of the pores, m is the cementation exponent of the rock (usually in the range 1.8–2.0 for sandstones), n is the saturation exponent (usually close to 2), and a is the tortuosity factor.

Resistivity varies largely in different rocks with water- or oil(gas)-filled porosity: from 0.2 to 15.0–20.0 Ohm·m (0.5–5.0 Ohm·m on average) in sand and silt aquifers, depending on porosity and pore water salinity, or from a few Ohm·m to 100–200 Ohm·m in hydrophilic reservoirs [5]. Non-reservoir silicate clastic rocks are relatively resistive, from tens to hundreds of Ohm·m depending on porosity, though the resistivity depends less on fluid salinity. Carbonate (limestone and dolomite) non-reservoir rocks reach resistivities of n·1000 Ohm·m. Aquifers are slightly less resistive than the host rocks. The resistivity of carbonate reservoirs falls in the same range as that of non-reservoir clastics: from a few Ohm·m in chalky limestones to hundreds of Ohm·m in more porous oil-saturated limestones and dolomites.

TEM soundings are sensitive to porosity and fluid type of reservoir rocks, which was demonstrated, for instance, as net-pay thickness dependence of resistivity for a Cenomanian sand-silt gas reservoir in West Siberia [17].

2.2. Features of TEM Techniques for 2D/3D/4D and Shallow Surveys

Various TEM techniques have the same physical background but differ in technology. The most broadly used techniques are shallow (sTEM) soundings, acquisition along profiles (2D), irregular (low-density) or regular (high-density) networks (3D), and time-lapse (4D) monitoring (Table 1).

Table 1. Comparison of sTEM, 2D TEM, 3D TEM, and 4D TEM surveys. Adapted with permission from Ref. [18]. Copyright 2021, Geodynamics & Tectonophysics [18].

TEM Technique	sTEM	TEM 2D	TEM 3D	TEM 4D
Maximum penetration depth [1], m	500	4000	4000	4000
Acquisition configuration	Arbitrary (sometimes by walking)	Profile (regular or irregular)	High-density, regular, coupled with 3D seismic profiling	High-density, regular, coupled with 3D seismic profiling, fixed stations
Density, points per m^2	16–33	1–2	5–12	8–30
Transmitter loop size [2], m	25–200	500–1200	500–1200	500–1200
Current [2], A	40	200–250	200–250	200–250
Instruments	FastSnap, 16, 24 bit	SGS-TEM, 32 bit	SGS-TEM, 32 bit	SGS-TEM, 32 bit
Number of vehicles in a field team, piece	1	5	10	10

[1] Penetration in poorly conductive (e.g., Paleozoic) rocks may reach 5–6 km or more [18]. [2] Transmitter loop size and current depend on penetration, resistivity pattern, terrain, river network, infrastructure, etc.

The survey design has to be chosen with special care among the diverse TEM techniques (Table 1) [3,19,20], especially when seismic and resistivity measurements are run jointly within the same season and along the same profiles [17].

The optimal survey design choice is critical for several reasons. It is important to

- run the TEM and seismic surveys along the same profiles in order to ensure that resistivity and acoustic anomalies that represent the same targets are precisely located;
- tailor the spacing of TEM stations or density of measurements (Rx/sq.km) to the specific geological objectives at different stages of the workflow (reconnaissance, evaluation, exploration, and production);
- choose the loop geometry (size) and current transmitter corresponding to the required penetration.

Namely, 2D CMP seismic and 2D TEM surveys with profile (1D) acquisition are more suitable for the initial (reconnaissance) stage, while 3D CMP and 3D TEM measurements along two horizontal directions are used at later exploration stages.

3. Results

The whole process of oil and gas search and evaluation consists of three main stages: (1) regional-scale reconnaissance and appraisal, (2) exploration, and (3) development [21,22].

3.1. Reconnaissance (Initial Prospecting)

A reconnaissance survey implies the prediction of petroleum potential and zoning on the regional scale. First, potential oil and gas reservoirs and fields are delineated, and the possible amount of undrilled resources in leads and plays (prospective in-place resources, categories D_2 and D_3, respectively, in the Russian classification [23]) is estimated qualitatively and quantitatively in order to choose further exploration strategy. At the step of zoning, the largest oil and gas traps are detected, and the exploration objectives are prioritized.

Surveys at this stage are performed by various magnetic, gravity, seismic, and resistivity methods. Induction resistivity surveys are commonly either TEM or MTS soundings. MTS can see to depths of 6–10 km or more during TEM data image the subsurface within the upper 3–4 km. TEM soundings are especially advantageous in the presence of carbonate and salt beds, volcanic, and cratonic complexes. Reference TEM profiles are commonly spaced at 10 to 50 km, and the density of measurements increases to 0.5–1 km/km^2 in geologically complex areas such as the Angara-Lena Fault Step, the Nepa-Botuobia uplift, and the Tunguska basin in East Siberia [24].

It is reasonable to run resistivity surveys before seismic reflection profiling, especially in areas with a network of roadways, as TEM data can be used to optimize the design of seismic surveys. Integrated seismic and resistivity data can better resolve large tectonic features (faults) and provide constraints for sediment thickness as a basis for good placement [25]. Surveys of this kind were conducted, for instance, in the Aldan-Maya Basin in 2015 [26] (Figure 1), where the junction of the basin with the Aldan uplift and the limits of Neoproterozoic sediments were mapped from abrupt resistivity changes. The low-resistivity layers revealed in the basin sediments may store hydrocarbons. Low-resistivity middle Late Neoproterozoic sediments (PR2) that potentially store hydrocarbons are clearly traceable in the TEM-based conductivity pattern till a depth of 5000 m (Figure 1A).

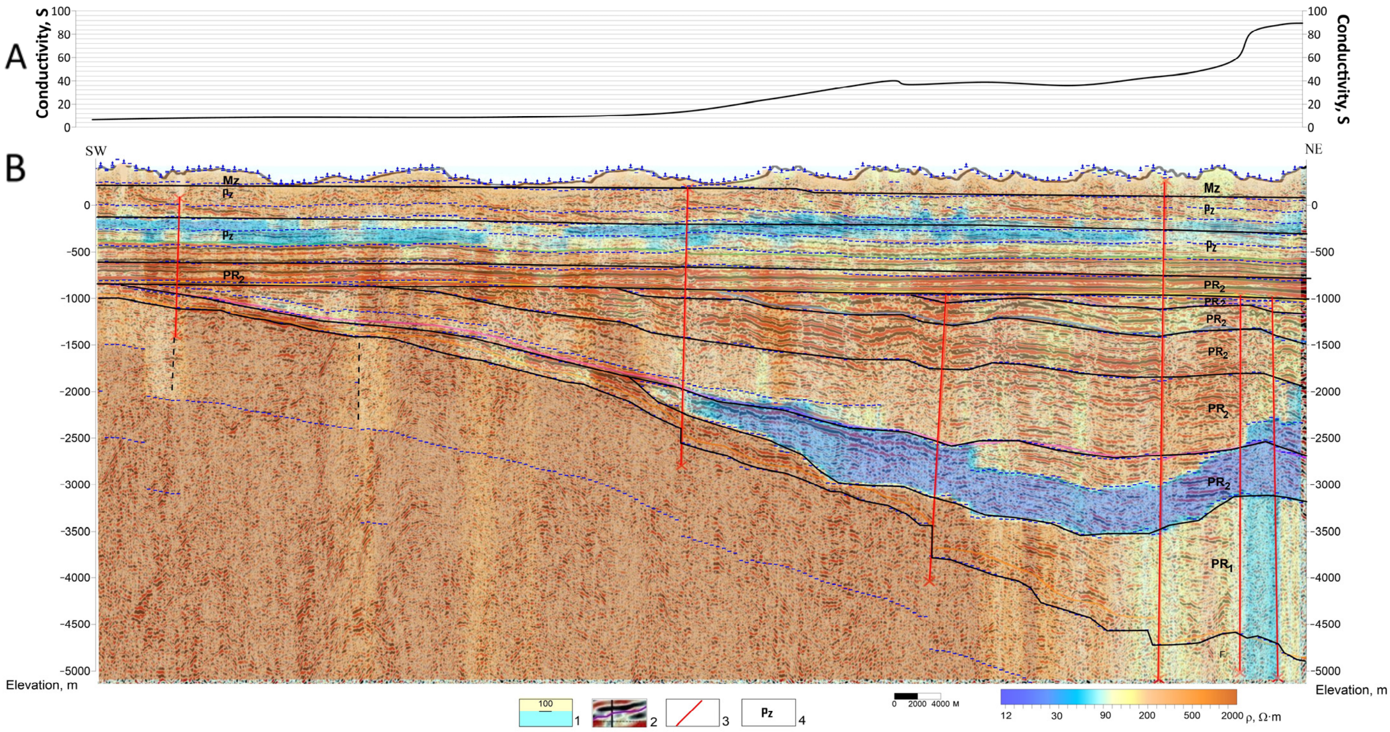

Figure 1. Total conductivity pattern from 2D TEM data (**A**) and combined seismic-resistivity cross-section of Aldan-Maya Basin from 2D TEM and 2D CMP data (**B**). 1 = resistivity layers and their resistivity in Ohm·m; 2 = seismic time section; 3 = faults inferred from seismic data; 4 = wells.

The regional surveys follow the national subsoil use program, in which electromagnetic surveys make an indispensable part of East Siberia and some other regions of Russia. This stage maintains the initial geological background for further exploration of the respective private subsoil users.

3.2. Appraisal

The appraisal substage of the initial prospecting stage focuses on yet undrilled localized recoverable resources in oil and gas traps detected within leads and prospects (resources of categories D_2 and D_1 in the Russian classification). The appraisal is based on the data of high-density seismic, resistivity, and gravity surveys which detect traps, anticlines, stratigraphic unconformity, faults, out pinch, and facies change. At this stage, a resistivity survey can resolve faults and local features with amplitudes at least 10–15% of reservoir depth. TEM soundings are better applicable to petroleum exploration than the classical DC methods of telluric current (TC), vertical electric sounding (VES), or frequency induction (FI) [27]. Specifically, imaging of the subsurface below 300–500 m by VES, with penetration depending on cable length, is hardly feasible and economically unreasonable.

TEM surveys are advantageous over seismic surveys for salt-bearing formations with salt beds sandwiched between nonsaline sediments [28]. Seismic data are often distorted near steep slopes of salt domes, while the highly resistive salt beds are clearly detectable in TEM images. Thus, joint use of resistivity and seismic data substantially improves the exploration results.

Anticlinal traps associated with reef systems (barrier reef systems or isolated fringing reefs and shelf organic buildups) likewise show up clearly in TEM images. For example, the properties of a reef system in the Lower Cambrian Osa reservoir in East Siberia predicted from TEM data were confirmed by time-lapse (4D) measurements at a large oil field in the Irkutsk region [29]. Furthermore, TEM surveys resolve lithofacies boundaries and erosion cutouts which make detect depositional traps (more frequent than anticlinal traps in East Siberia).

TEM soundings outcompete the multichannel reflection profiling combined with gravity survey and remote sensing [30] in search of targets within fold-thrust belts and other complex geological features. Namely, TEM data from the junction of the Anabar uplift and the Verkhoyansk foredeep in the Siberian craton clearly resolve the Sololi uplift within the Olenyok dome (Figure 2), where high-resistivity Archean and Proterozoic rocks crop out [18]. The boundary between the resistive Proterozoic basement and conductive Mesozoic sediments, as well as exposed Proterozoic rocks and older igneous bodies, are clearly traceable in the TEM images based on conductivity data till a depth of 6000 m (Figure 2A).

The choice of geophysical methods for the detection of oil and gas fields has been challenging since long ago [10]. Reservoirs are commonly detectable in seismic data according to reflections from the oil-water contact and greater attenuation in oil- or gas-bearing intervals. However, sometimes the approach is poorly workable in heterogeneous geologically complex areas of East Siberia with high velocities, thin layering, poorly expressed small accumulations and large target depths. TEM surveys may be a good alternative in this respect due to resistivity contrasts between oil and gas accumulations and the host formations. Again, the exploration efficiency may be far greater if several methods are integrated, especially seismic and TEM surveys [11].

The TEM method is applicable to various geological objectives associated with appraisal, from imaging tectonic features to prediction of drilling conditions. It is compared with the seismic method in Table 2.

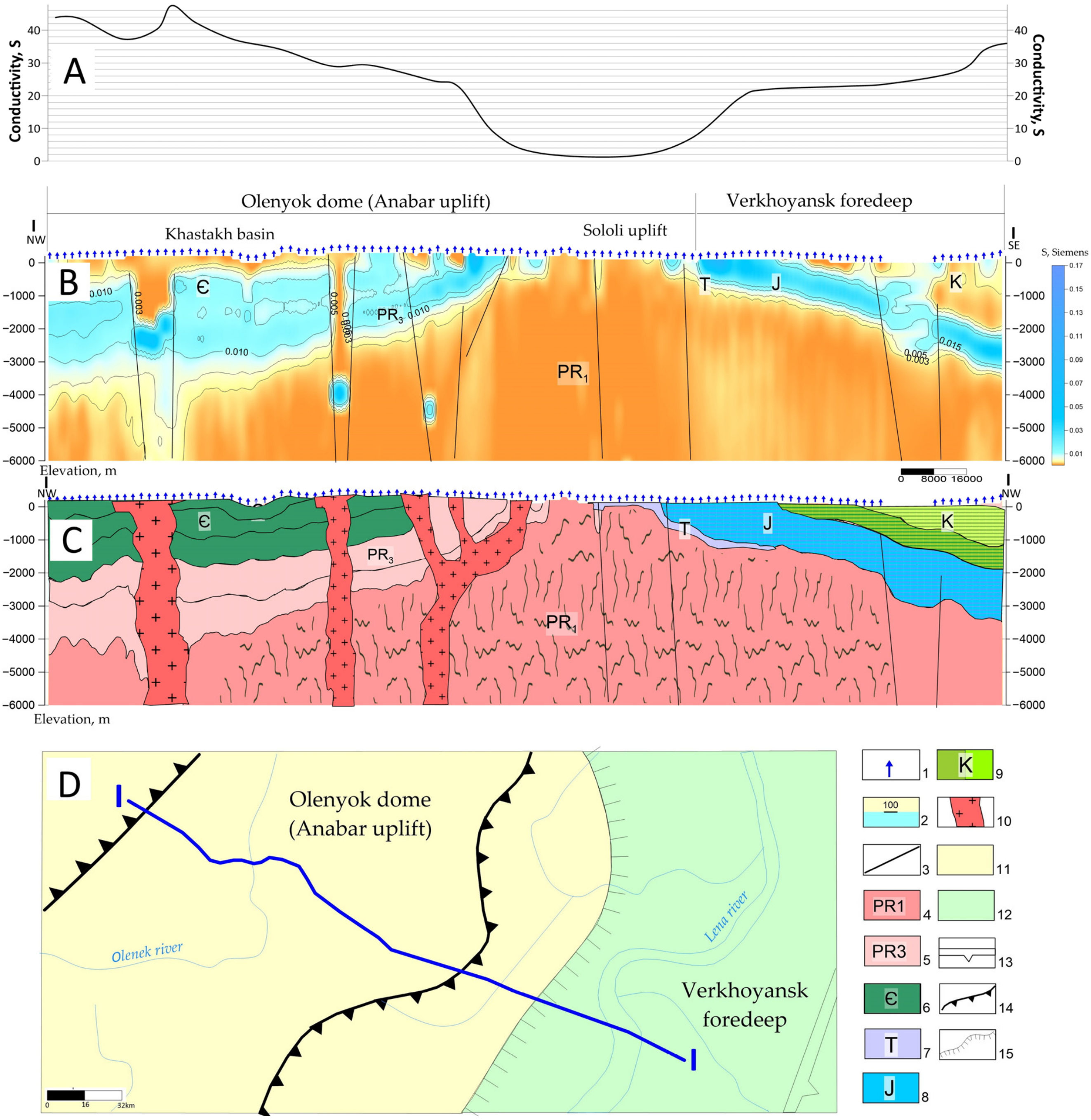

Figure 2. Total conductivity pattern from 2D TEM (**A**); differential conductivity (**B**) and geological (**C**) cross sections imaging the junction between the Olenyok Arch and the Verkhoyansk Foredeep, according to 2D TEM data; simplified local tectonics (**D**). 1 = TEM stations; 2 = resistivity layers and their resistivity in Ohm·m; 3 = inferred faults; 4 = early Proterozoic metamorphic rocks; 5 = Upper Proterozoic clastic and carbonate rocks; 6 = Cambrian carbonate sediments; 7–9 = Triassic (7), Jurassic (8), and Cretaceous (9) clastic sediments; 10 = Early Proterozoic intrusions; 11 = Siberian Craton; 12 = Foredeep; 13 = Lena suture; 14 = boundary of the Olenyok dome core; 15 = boundary of basins on the Early Cretaceous base surface.

Table 2. Seismic and TEM surveys for petroleum exploration. Adapted with permission from Ref. [18]. Copyright 2021, Geodynamics & Tectonophysics [18].

Stage	Objective	CMP Seismic Profiling	TEM Survey
Reconnaissance and appraisal	Tracing layer boundaries and faults	Maximum resolution for contrasting acoustic interfaces. Precise structural modeling	Tracing boundaries of resistivity layers and acoustically mute units (e.g., granitic basement/Neoproterozoic sediments). Moderate resolution
	Detecting reservoir rocks	Estimating reservoir potential with reference to well logs. Imaging carbonates problematic	Detecting resistivity-contrasting reservoirs, including clastic or vuggy carbonate reservoirs, without reference to well logs
	Appraisal	Estimating in-place localized resources: leads and prospects (categories D_2 and D_1)	
Exploration	Estimating reservoir properties	Estimating net pay thickness and porosity (H_{eff} and ϕ), with reference to well logs	Discriminating between reservoir and non-reservoir rocks. Estimating H_{eff} and ϕ when integrated with CMP data, with reference to well logs (using Archie relationship)
	Identifying fluid type	Identifying fluid type in favorable geological conditions; problematic in East Siberia	Identifying fluid type, with reference to well logs. Estimating S_{w} with reference to petrophysics (using Archie relationship)
	Mapping faults	Accurate mapping of strike slip faults. Estimating permeability of fault zones impossible	Mapping resistivity-contrasting faults; estimating permeability of fault zones and secondary effects (carbonation, salinization)
	Imaging near-surface	Imaging near-surface with standard acquisition systems problematic	Imaging near-surface to 500 m depth: detecting aquifers and gas hydrates; velocity modeling; imaging permafrost and pingoes; geo-environment monitoring, etc.
	Appraisal of in-place reserves	Evaluating in-place contingent recoverable reserves (category C_2)	

The use of TEM and seismic surveys at different stages of prospecting and exploration can be presented as a workflow chart (Figure 3) [18,31,32]. At stage 1, TEM surveys can be run either before or simultaneously with seismic profiling. In the former case, TEM soundings commonly follow the existing road network and profiles of previous campaigns to avoid cutting and laying new profiles, which would take from six to twelve months. The designed TEM profiles should cross the main target structures and wells (if available). The available road/profile network permitting, profile spacing is reduced as much as possible within presumable prospects. The field campaign may last two or three months, depending on the amount of work, and is followed by three months of laboratory analyses. Thus, the whole process of obtaining TEM data commonly takes about six months. The zoning based on TEM data is used for the placement of the more expensive seismic profiles.

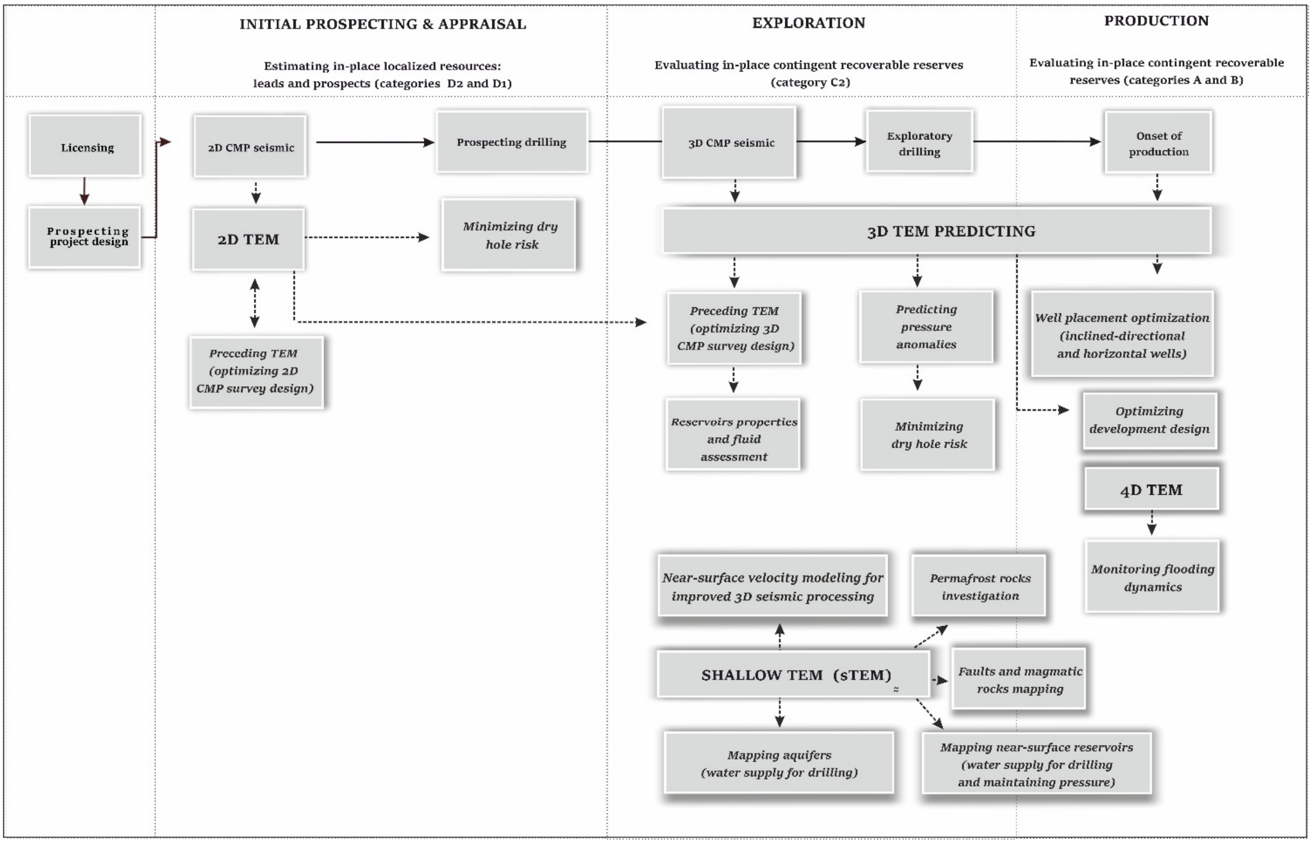

Figure 3. Workflow of seismic and TEM surveys, modified after [31].

The TEM surveys simultaneous with seismic exploration are performed along the same profiles in one season, which saves logistic and maintenance costs. The information on tectonic features and reservoir-related anomalies provided by integrated results of the two methods allows detection and imaging of reservoir rocks to depths from 100 m to 3–4 km. The geological and geophysical evidence is used further for good placement.

It is important to obtain appropriate design specifications and estimates for the exploration work [32–34] with reliable justification and planning (resistivity surveys, successive or simultaneous seismic surveys, exploratory drilling, and appraisal). The planning ensures efficient use of new data and a good choice of exploration and development strategy.

3.3. Exploration

Exploration proper aims at characterizing oil and gas fields and updating the distribution of reservoir rocks as a basis for development design [30]. The work commonly includes geological and geophysical surveys on the surface, well logging, and high-density 3D seismic survey. In the recent decade, shallow 3D TEM soundings, which are performed together with CMP seismic profiling, on the same profiles and by the same field team [17], became an indispensable cost-efficient element of exploration and development operations (Figure 3).

The objectives of the exploration stage are:

1. Saving costs by reducing the amount of expensive 3D seismic survey and optimizing its placement.
2. Optimal well placement due to reducing uncertainty as to the presence of reservoir rocks and type of fluid.
3. Estimating drilling conditions to avoid emergencies.

Preliminary characterization of leads and plays, with discrimination between the reservoir and non-reservoir rocks by 2D TEM surveys at the prospecting stage, saves costs at the exploration stage. 3D TEM surveys provide baseline data for time-lapse (4D) TEM measurements for subsequent monitoring of the advance of flooding [29]. Integrated 3D seismic and resistivity data from the same profiles provide information on porosity, permeability, and the fluid type and thus minimize the risks of drilling dry holes. TEM soundings can reveal zones of over- and under-pressure, aquifers supplying water for drilling and maintenance (sTEM), and permafrost features.

The use of sTEM for the detection of aquifers in East Siberia was successful at the Middle Botuobia oil-gas-condensate field in the Nepa-Botuobia uplift [35], at the Kovykta gas-condensate field within the Angara-Lena Fault Step [17,36], and in other fields of the Irkutsk region and Yakutia. Water-saturated reservoirs with resistivities from 60 to 90 Ohm·m likewise stand out clearly in resistivity against the >150 Ohm·m host Cambrian clastic and carbonate sediments and <40 Ohm·m shales (Figure 4). Wet zones in East Siberia are often associated with zones of unfrozen rocks (open taliks).

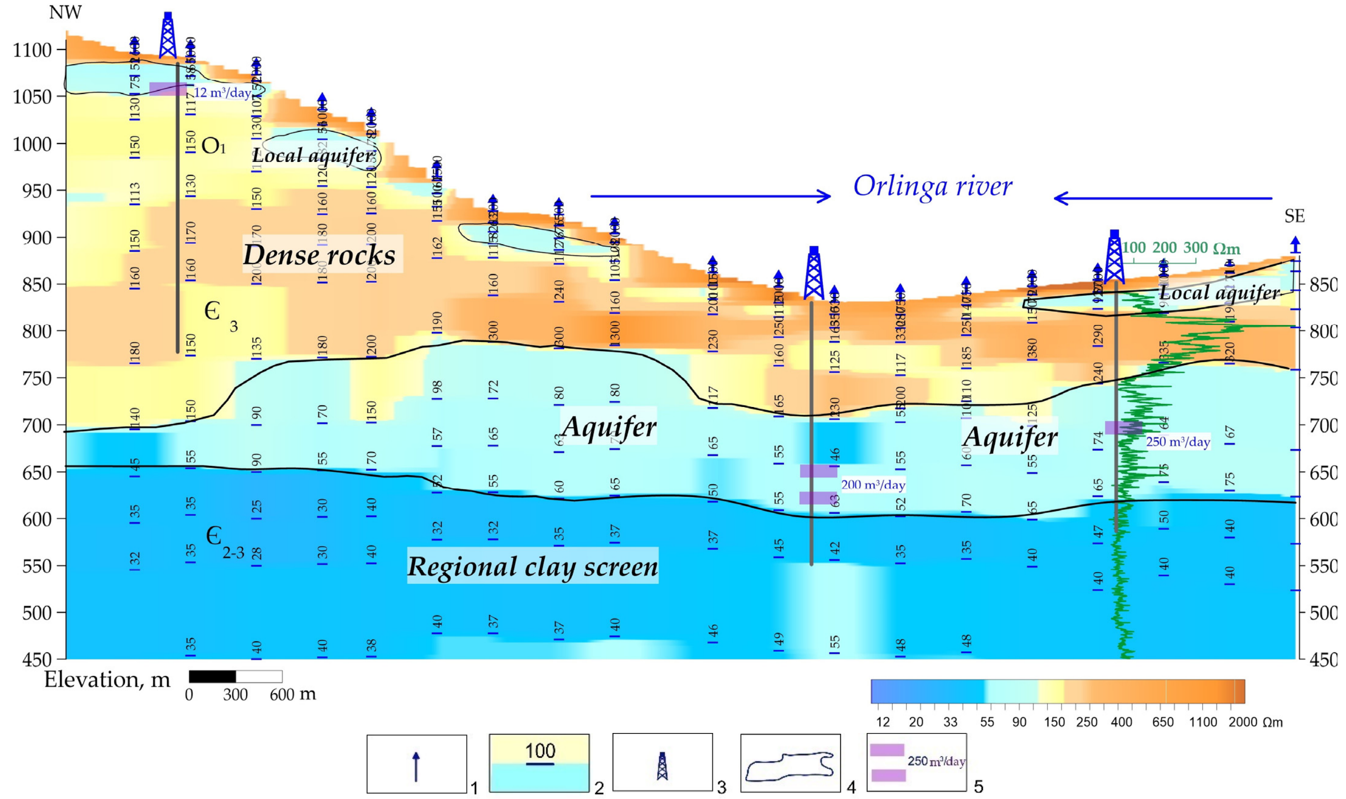

Figure 4. Resistivity pattern based on sTEM data from East Siberia. 1 = TEM stations; 2 = resistivity layers and their resistivity in Ohm·m; 3 = water test well; 4 = water-saturated reservoir inferred from sTEM data; 5 = water intervals and flow rate.

The knowledge of geocryological conditions in high-latitude petroleum provinces is required for subsequent infrastructure design. TEM surveys have been used broadly for permafrost mapping in West [37] and East [38] Siberia. Being markedly different from unfrozen rocks in resistivity (low resistivity and high induced polarization), permafrost is clearly detectable in TEM responses [4], which is crucial for high-latitude regions.

The Russian Arctic stores extremely rich resources of hydrocarbons, but the complex climate conditions pose problems to geophysical surveys prior to exploratory drilling. Induction methods, such as TEM, require no grounding and thus can make a workable alternative to DC, frequency-domain EM, and MT measurements with grounded systems, which are problematic in the Arctic.

Combining seismic profiles with easily configured TEM arrays (Table 1) saves the logistic costs for building camps considerably, and laying winter roads. Note that surveys with joint resistivity and seismic teams were practiced broadly in the Arctic three decades ago.

The objectives of TEM surveys in the Arctic (Table 2) include mapping reservoir rocks (mostly clastic sediments); estimating permeability of fault zones; predicting fluid type (using integrated TEM, seismic, and well log data in special software such as *Petrel* (Schlumberger) or *RMS* (Roxar). The experience of large-scale exploration TEM works by our team was described in a number of publications [5,7,35–37,39–45]. Specifically, sTEM and 3D TEM surveys were performed in the Yamal-Nenets Autonomous District in 2017 (Figure 5) to compile prediction maps of Cretaceous sediments. The zone of inferred paleo channels were hypothesized to be quite a rich reservoir, e.g., [39–44].

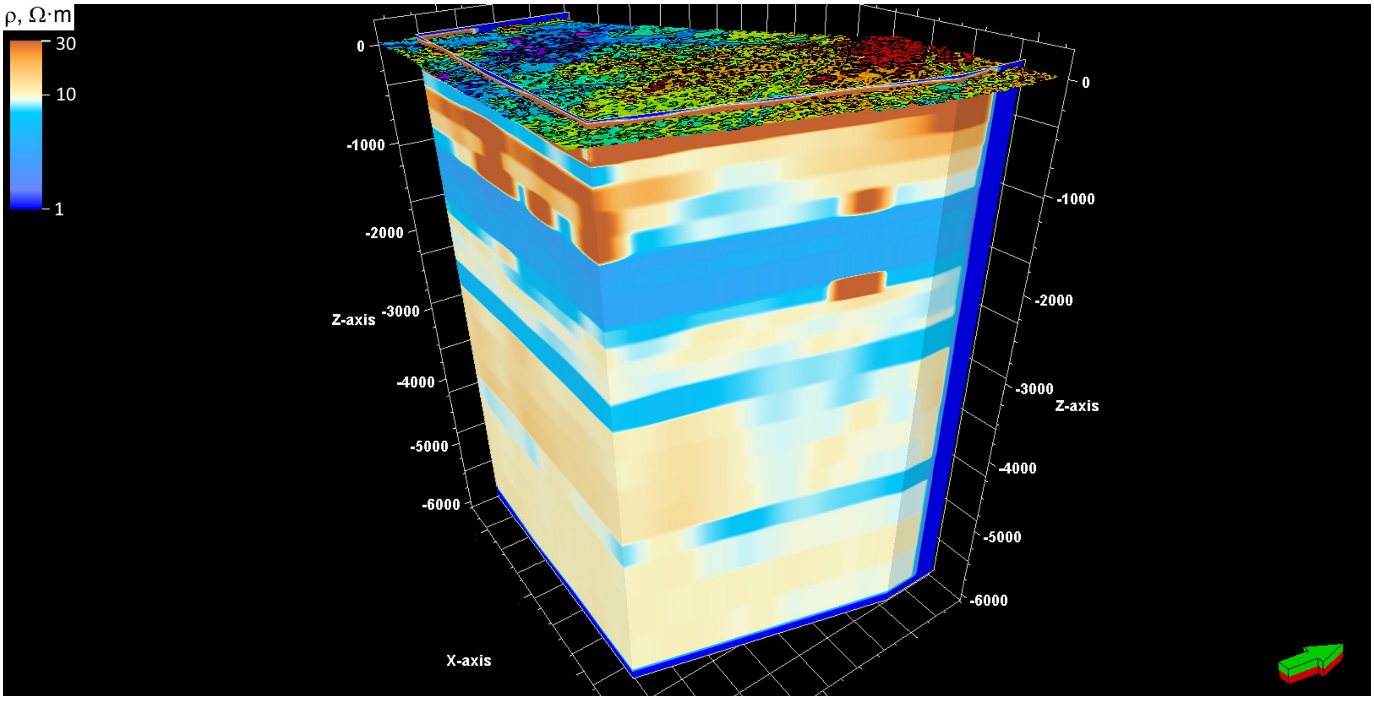

Figure 5. Example of Shallow TEM and 3D TEM results from Arctic region: composite sTEM + 3D TEM resistivity cube.

TEM surveys provide high-quality, high-resolution images of the near surface within 500 m, where seismic data are especially noisy. Ice-rich low-temperature modern permafrost and ice-poor pale permafrost appear in TEM data as layers of high and elevated resistivity, respectively. The base of pale permafrost in the Yamal Peninsula lies at a depth of 330 m. TEM images also reveal frost mounds (pingoes) over thick modern permafrost and gas conduits (e.g., [43]). Thus, TEM surveys make an advantageous tool in Arctic studies.

Characterizing the reservoir in terms of net pay thickness (H_{eff}), porosity (ϕ), and fluid type (S_w) is the main objective of petroleum exploration. The fluid type can be predicted from integrated resistivity and seismic data. For this, the water saturation coefficient is estimated from TEM-based longitudinal conductivity [46] and seismic-based net pay thickness (H_{eff}) and porosity (ϕ) using the Archie equation [5]. The method can be applied to a whole reservoir rather than too thin layers.

The water saturation coefficient is estimated using a 3D TEM survey, with porosity and net pay thickness constrained from seismic 3D data as [5]

$$S_w \approx \left(\frac{H_{eff}}{S \cdot a \cdot \phi^{-m} \cdot R_w} \right)^{\frac{1}{-n}} \quad (2)$$

where S_w is the water saturation coefficient; S is the longitudinal conductivity obtained by inversion of TEM data; H_{eff} is the net pay thickness; ϕ is the porosity parameter; R_w is the pore water resistivity; n is the constant that refers to reservoir type, and a is the tortuosity factor.

This information is useful to update the geological models of oil and gas fields which make reference for the evaluation of resources and reserves and subsequent development. Note that seismic and resistivity surveys (Figure 6) are not alternative but complementary methods to be applied jointly, taking full advantage of each (Table 2).

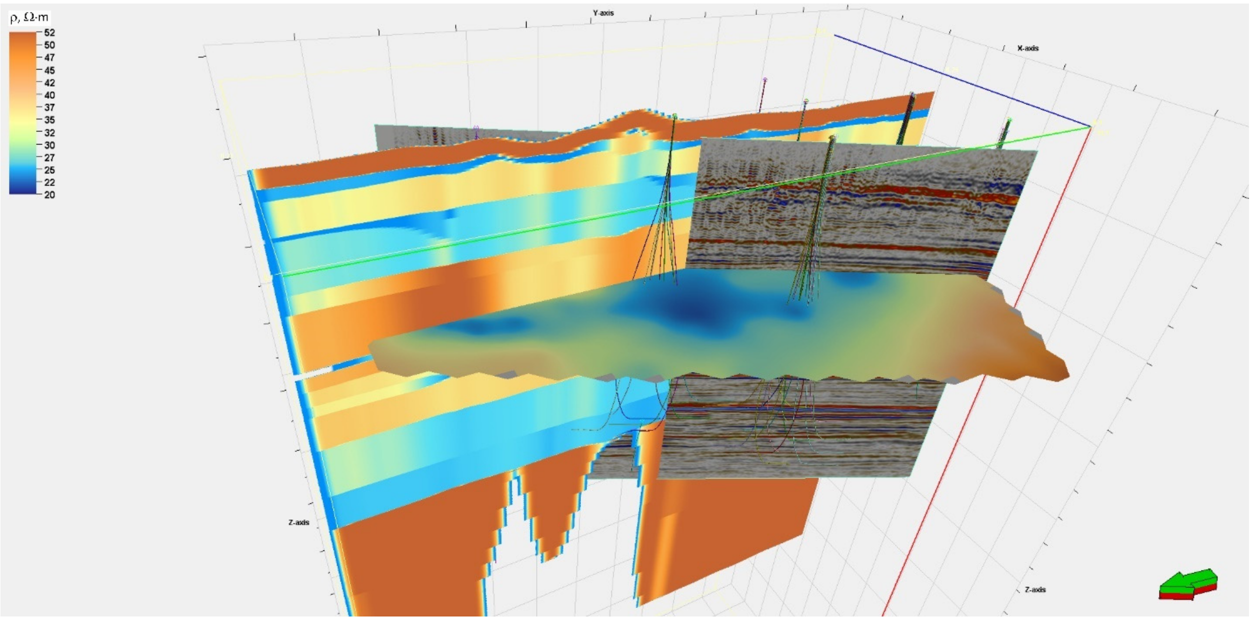

Figure 6. Example 3D seismic-resistivity model (East Siberia).

3.4. Production

The main objectives of the development (production) stage are:

(1) choosing the design of good clusters;
(2) estimating drilling conditions in order to minimize emergency risks;
(3) providing water supply for drilling and maintaining pressure;
(4) monitoring of flooding dynamics.

High-density 3D TEM data collected jointly with 3D CMP reflection patterns can reveal pressure anomalies and allow optimizing the development strategy [47,48]. TEM surveys conducted in producing fields can trace the advance of flooding in reservoirs by time-lapse (4D) monitoring [29]. sTEM imaging of aquifers can provide the supply of groundwater for drilling operations and pressure regulation [35].

The best approach is to use TEM soundings successively, from reconnaissance to production. The geological models obtained at each previous stage make reference for the following stages and create a solid basis for effective development solutions.

4. Discussion

4.1. Challenges and Limitations

Although the physics behind the electromagnetic methods applied to petroleum exploration, as well as multiple success examples, have been known since long ago and require no additional proof, several issues remain to clarify.

1. Numerous guidelines for geological prospecting require combining several geophysical methods (seismic, resistivity, gravity, and magnetic surveys). However, in practice, this combination is limited to the stage of reconnaissance, whereas oil and gas evalua-

tion and exploration (including detection of faults and other tectonic features, as well placement) is most often performed using seismic surveys only.

2. Many geologists and petroleum people still doubt the applicability of non-seismic methods to exploration. Meanwhile, the modern TEM surveys not only provide resistivity models but allow for characterizing the reservoir properties, identifying the fluid type, detecting faults and estimating their permeability, etc. It is the joint use of several geophysical techniques that can successfully challenge these problems, though most the oil companies prefer limiting themselves to conventional seismic surveys.
3. Oil and gas evaluation is most often based on drilling and seismic data, while other geophysical methods are overlooked. This underestimation is especially improper in East Siberia and similar geologically complex regions where TEM surveys can constrain the lateral extent of reservoirs.
4. There is also much misunderstanding about the choice of methods for specific geological objectives. For instance, predicting the fluid type (oil, gas, or water) with TEM data is workable only during exploration when 3D TEM, 3D seismic, and well-log data are integrated but are unsuitable at the reconnaissance or appraisal stages.

As a result, TEM surveys are often either neglected or misused.

On the other hand, the TEM method has its limitations. It is superior over magnetotelluric or frequency domain soundings but still inferior to seismic surveys in a number of aspects. That is why it is crucial to integrate data from different methods, e.g., use more precise seismic and well-log data to fix framework models in an inversion of TEM responses.

Other limitations are associated with poorly contrasting low-resistivity young rocks. The induction-based TEM responses sample the bedding-parallel conductivity preferably and are more sensitive to conductors in high-resistivity sections. Meanwhile, it is more reasonable to measure transversal resistivity across the bedding as oil and gas are resistive up to hundreds and thousands of Ohm·m. Furthermore, imaging >4–5 km thick low-resistivity sediments by the TEM method is too costly because very large loops and long stacks of pulses with >10 s long responses (3–4 h or longer acquisition time) are required to achieve good S/N ratios. Therefore, MT soundings are more viable in this case.

Another problem is that the simulation of a highly heterogeneous subsurface (different horizontally layered earth) is possible using 3D inversion of TEM responses acquired on a dense survey grid, which is likewise money-consuming.

Therefore, the use of any geophysical method, including the TEM electromagnetic survey, will be successful if the geological objectives have been well formulated, the local geology is known, and the advantages and pitfalls of each method are properly estimated. That is why the integration of physically different methods is especially efficient.

4.2. Requirements for a Priori Information

The work at each stage, from reconnaissance to production, has its specific aims and objectives. At the regional prospecting stage, the characterization of license areas is most often limited to scarce irregular 2D seismic reflection (CMP) and TEM data and a standard set of good logs from one or two exploratory wells. Such amount of a priori information is only sufficient for approximate zoning of reservoir rocks and ranking the zones as a basis for preliminary recommendations for the placement of exploratory wells. Thus, regional prospecting aims at obtaining reliable resistivity images of reservoir rocks. More substantial data are collected during the subsequent exploration by high-density 3D seismic (CMP reflection profiling) and 3D TEM surveys. These data, together with logs and core data from a greater number of wells, are, as a rule, sufficient for geological modeling. sTEM results complement seismic data, making reference in velocity modeling of the near-surface. Thus integrated geological and geophysical data of the exploration stage provide constraints on reservoir properties, fluid type, drilling conditions, and intervals of fluid loss and pressure anomalies [47,48].

At the stage of development, the information gained during exploration is extended with rock mechanics and fluid dynamic models and can be checked against data from operation wells. With this additional evidence, the placement design of good clusters can be substantially improved. The advance of flooding in producing reservoirs is monitored by time-lapse (4D) TEM surveys at fixed stations of high-density networks, with sampling every six to nine months.

It is important to choose appropriate geological objectives at each stage. For instance, identifying fluid type would be an invalid objective for the stage of initial prospecting when the amount of geological and geophysical data is yet insufficient.

4.3. Oil and Gas Evaluation with Reference to TEM Data

Different exploration methods and instruments have to be reasonably combined to provide reliable oil and gas evaluation [49,50]. A preliminary evaluation is commonly based on seismic and drilling data, but TEM surveys are useful in this respect as well [51]. The TEM-based contouring of reservoir rocks provides reliable geological information at the prospecting and exploration stages. The surveys of the prospecting stage can provide an appraisal of predicted in-place resources in leads and plays (Russian categories D_1 and D_2, respectively).

Contingent recoverable reserves (Russian category C_2), equivalent to SPE probable and possible combined [49], including those inferred from seismic or other measurements data and confirmed by independent geological and geophysical evidence and well tests of the exploration stage [49,50].

TEM soundings are highly sensitive to variations of porosity and saturation [5,17,46] and thus have implications for the reservoir continuity and contours of reserves at new and explored fields. The best accuracy of prediction for the reservoir properties and fluid type is achievable by combined use of TEM and seismic data and their correlation to good logs and core analysis results. In some cases, lithofacies in undrilled areas can be inferred from data on adjacent drilled zones, which allows mapping the reserves as well.

4.4. Contribution of TEM Surveys to Exploration: Economic Estimates

Exploration results are evaluated stage by stage (e.g., [49,50]), with reference to the classifications of oil and gas resources. Economic evaluation in subsoil use is mainly based on the value of information (VOI) depending on the expected monetary value (EMV) and chance (probability) of success [52–54]. The success chance is estimated proceeding from the probability that the area stores source rocks, has fluid migration paths, high saturation, and good conditions for the preservation of oil or gas accumulations. The higher the probability for each criterion, the higher the chance. The constraints on these criteria are provided by seismic exploration, drilling, and logging. In this respect, TEM data can provide additional evidence on the proxies of reservoir properties and conditions.

The VOI and EMV variables, as well as other economic parameters, can be used to estimate the contribution of TEM soundings to the saving of costs and improving the project viability.

5. Conclusions

The efficiency of exploration depends strongly on planning and prioritizing the geological objectives according to successive stages. Random use of expensive geophysical surveys brings no success, whereas a well-organized workflow from prospecting to exploration and on to production ensures that concise information at each stage makes solid background for the following stage. According to the principle of increasing complexity, TEM surveys change from 2D at the first stage to 3D and finally to 4D at the final stage.

The properly chosen sequence of seismic and TEM resistivity surveys offer many advantages: saving costs for 3D seismic, reducing risks of drilling dry holes, minimizing emergencies caused by pressure anomalies, improving the development design, and monitoring the production process.

The use of TEM surveys allows for estimating localized in-place resources in prospects and leads (Russian categories D_l and D_2) at the prospecting stage and contour contingent recoverable reserves (C_2) in new and tested fields at the exploration stage. The efficiency of TEM surveys can be estimated quantitatively using economic parameters, such as the value of information (VOI) and expected monetary value (EMV).

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