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Shallow velocity model from the transient electromagnetic method data: results of application in Eastern and Western Siberia

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Abstract. The geological section of Eastern and Western Siberia is a complex object for a seismic exploration. The reason for this is the extremely high variability of the upper part of the section lithology, rough terrain, and permafrost rocks. This paper delivers an alternative approach to predicting the velocity model of the upper part of the section. The approach based on the original method of restoring the elastic-velocity characteristics from the data of transient electromagnetic method (TEM) in the near field zone.

Research devoted to test the methodology of the shallow section velocity model calculation based on TEM data in a number of fields in Eastern and Western Siberia. Derived results aimed to improve the accuracy of the geological model building and the reliability of the hydrocarbon plays prediction.

Synthetic modeling and field data confirm the high level of the proposed methodology effectiveness. It was shown that for the Eastern Siberia settings, an improvement in the quality of processing of seismic data consists in a significant increase in the dynamics and coherence of seismic recordings. In Western Siberia, it is possible to take into account the velocity anomalies associated with the permafrost rocks and zones of transit from the onshore part of the survey area to the sea.

Keywords: velocity model, seismic exploration, reflected wave method, common depth point, transient electromagnetic method, upper part of the section, permafrost rocks, static corrections

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Introduction

When interpreting seismic data in areas with complex surface settings and heterogeneous upper part of the section, it is necessary to take into account its influence. The source of this influence is the velocity anomalies concentrated in a relatively thin, but heterogeneous in thickness, near-surface interval of the section.

Underestimation of the influence of these anomalies on the character of seismic reflections can lead to significant mistakes in structural constructions, a deterioration in understanding the nature of the recorded reflected waves and other components of the wave field (Bondarev et al., 2005, 2013), and also entails large uncertainties in traveltime inversion.

In this work, we propose a method to obtaining the values of the elastic characteristics of the upper part of the section, based on the data of transient electromagnetic method (TEM) in the near field zone in a shallow modification (sTEM).

Due to the growing volumes of 2D and 3D seismic surveys, the problem of correct reconstruction of the shallow velocity model is quite acute. There are a number of conventional techniques for predicting the shallow velocity model, calculating static corrections, including clarifying the structure of the permafrost, using multiwave seismology data (Kuznetsov et al., 2014).

Applying small anomalies of the upper part of the section is associated with a number of difficulties. As a rule, this problem is solved approximately (Armstrong, 2001; Armstrong et al., 2001). The propagation geometry of the rays of all reflected waves in the area of the upper part of the section anomaly is distorted. The zone of influence of the upper part of the section anomaly is approximately half the length of the spread from each boundary of the anomaly. Naturally, the zone of influence of the upper part of the section extends even further due to the Fresnel zone, because it is a case of the passage

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of the wave front, and not hypothetical rays. In addition, standard velocity analysis methods and data processing in the time domain provide processing of all traces on the seismogram of the common depth point/common mid point (CDP/CMP), using the same velocity function 1D, therefore, standard methods of processing in the time domain do not always solve the problem of the influence of the upper part of the section.

Within the framework of this problem, there is an urgent need to attract third-party sources of information about the upper part of the section in areas where seismic exploration is not able to cope "on its own".

The proposed method for calculating velocity models based on data of shallow modification of the TEM (sTEM), and makes it possible to reduce the uncertainties of the seismic depth-velocity model and, as a consequence, to increase the accuracy of structural model, which was confirmed by the results of mathematical modeling (Shelokhov et al., 2018a).

The experience of using EM studies to restore the velocity characteristics of the upper part of the section

The experience of using EM studies data to predict the shallow velocity model includes a number of both domestic and foreign works. For example, the technique proposed by V.V. Kiselev (Kiselev et al., 2009), as well as studies (Kaplan et al., 2019): the method using the Faust's equation have been tested on one of the areas of the Taimyr Peninsula, the velocity model has been successfully applied, calculated according to the sTEM data, and an informative seismic section has been obtained.

One of the foreign examples is the work of (Colombo et al., 2017). In the mentioned study, the way of predicting a shallow velocity model based on the method of joint inversion performed by means of cross-gradient regularization is considered.

Materials and methods

The method of calculating a shallow velocity model

In order to switch from the geoelectric properties of rocks to acoustic, it is possible to use empirical dependencies. For the first time, the relation between electrical resistivity and P-wave velocity have been presented by L. Faust (Faust, 1953),

$$v = \alpha(ZR)^{\frac{1}{6}} \tag{1}$$

α – constant; Z – the depth; R – electrical resistivity.

The authors analyzed the possibility of using this empirical equation (1) to reconstruct the acoustic properties of the section based on the sTEM data.

The schematic diagram of the calculation of the shallow velocity model based on the sTEM data through the empirical Faust dependences is shown in Fig. 1.

The experimental data, observed in the field, are used for geophysical inversion. Quantitative inversion involves numerical model study (geophysical inversion) of a horizontal layer structure, the parameters of which are linked to well logging and drilling data. In order to minimize the influence of the equivalence principle, the quantitative interpretation of the TEM data is carried out in several steps, each of which contributes to the quality of the result obtained. The first step in the interpretation of EM exploration data is the collection of a priori geological and geophysical information. At this step, information on deep drilling wells located in the study area is analyzed, well logging data are studied, regional conducting and high-resistivity marker horizons are determined, and lithological-stratigraphic linking

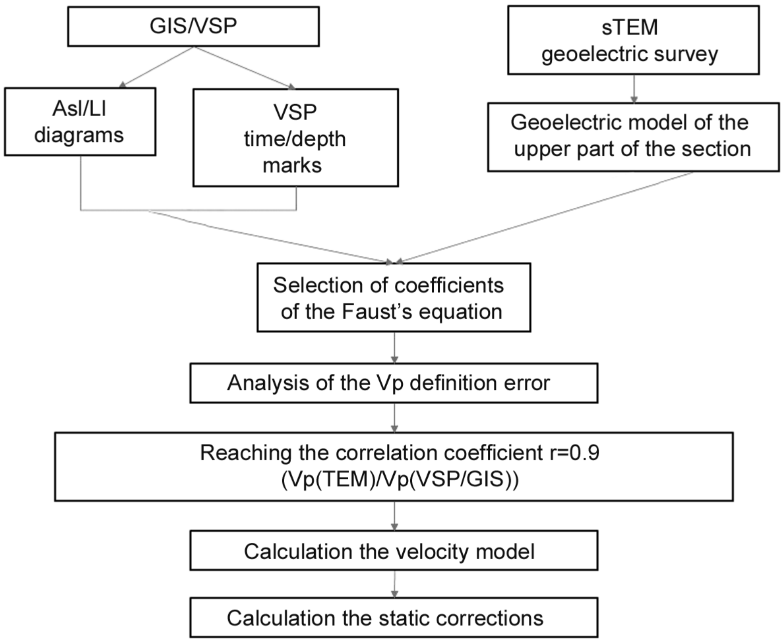

Fig. 1. Schematic diagram of the calculation of the shallow velocity model based on the sTEM data through the Faust empirical dependences. VSP – vertical seismic profiling, Asl – acoustic well logging, LI – lateral logging.

of layers is carried out. Consistency in thickness and strike of reference horizons is determined along the well network. Occurrences of magmatism and tectonic activity are being studied, which affect the structure of the study area, the nature of the electromagnetic field. The hydrogeological characteristics of the work area are determined.

At the second step, structural maps are constructed using marker horizons, the position of known geological structures and faults is determined. The electrical characteristics distribution of the section of the work site is also evaluated, the structure of the initial geoelectric model is selected in accordance with the constructed structural maps. This stage is designed to help link the main horizon obtained as a result of drilling wells and achieve lithological and stratigraphic binding of the geoelectric layers of the model.

The third step involves the inversion of the transient signal and the construction of geoelectric sections. At this step, the geoelectric parameters of the section are determined using the Model 3 interpretation program (Surov et al., 2011).

To proceed directly to the conversion of geoelectric models into velocity models, it is necessary to calculate and calibrate the empirical coefficients of the Faust's equation. The method has been discussed in detail in previous works (Shelokhov et al., 2018b), and therefore it is further presented in an abridged version. A reference well was used to calculate the coefficients. The main requirement for such a well is the presence of acoustic logging in the widest possible range of depths, starting from the first meters. An alternative is the use of vertical seismic profiling (VSP) data.

In the case when it is possible to achieve the maximum convergence of the observed and calculated values of V_p. It is necessary to achieve such combinations of coefficients that would satisfy the conditions within the framework of one lithological difference, but at the same time ensure the maximum convergence of the observed values and calculated V_p over the entire depth of the model. To assess the convergence, in this case, the correlation coefficient of the power function (the Faust equation) is used, which in this case acts as a kind of residual function.

After setting up the equation, a mass recalculation of geoelectric models and the formation of a cube of the upper part of the section velocities are performed.

The TEM method

The TEM method is one of the geophysical methods typically used in Russia to solve a wide range of geological problems: from studying the upper part of the section to prospecting and exploration of hydrocarbon deposits. Scientists A.N. Tikhonov, L.L. Vanyan, S.A. Sheinmann, B.I. Rabinovich, G.V. Keller, J.R. Wait, L. Buselli, C.H. Stoyer et al. have made a great contribution to the development of the theory of the method, methodology of field work and processing of the results of TEM.

This method belongs to the group of induction survey with control sources of electromagnetic fields. Among the various options for sources and receivers of the electromagnetic field, the most common are "loop-loop" or "loop-in-a-loop" templates. This is due to the high technology of such installations, which do not require grounding devices, which allows conducting research at any time of the year.

The TEM surveys using the "FastSnap" electrical prospecting station are carried out applying an inductive installation consisting of ungrounded square generator and receiving loops of various sizes. An installation with inductive source is of two types: with a transmitter receiving loop (Q-q) removed outside the limits and coaxial receiving-generating loops, the so-called «loop-in-loop» setting (Qq). Typically, in practice, it is recommended to use a combined coaxial-spaced setup, when the signal is measured from one transmitter loop on the coaxial and offset receive loops. In the course of the studies carried out in this article, the length of the side of the transmitter (Tx) loop was 100 m, the receiving (Rx) loop – 10 m (Fig. 2). Offsets equal to 100 m were used. The current strength in the generator loop was varied from 1 to 40 Amp.

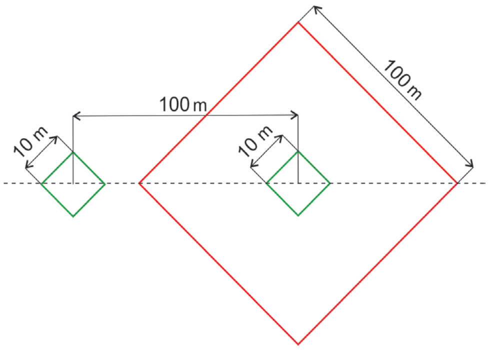

Fig. 2. sTEM template: red – Tx loop; green – Rx loops

This configuration of the template ensures reliable restoration of the geoelectric section to a depth of 700 m. The starting depth of sounding is 10 m. The EMF and apparent resistivity curves typical for the geological settings of Eastern and Western Siberia are shown in Figs. 3, 4.

The developed technique was tested in various geological conditions of Eastern and Western Siberia, where high-density studies of the sTEM were carried out.

Eastern Siberia. Angara-Lena step

The geological section of Eastern Siberia is an extremely difficult object to study by the main tool of exploration geophysics – seismic exploration. The reason for this is the extremely high variability of the lithology of the upper part of the section, rough relief, the presence of permafrost rocks, irregular aquifers along the strike, tectonic faults, and other factors that extremely complicate the processing of seismic survey materials (Kochnev et al, 2009; Pyankov, 2016).

In this context, it is relevant to develop a method that makes it possible to increase the accuracy of the shallow velocity model and the structural model of the prospective horizons of the section. When conducting seismic surveys using the common depth point (CDP) 3D method within the Verkhnelensky bending fold (Vakhromeev et al., 2019), field data were obtained, confirming the relevance of the above problems. As can be seen in the seismic section, in the eastern part of the profile, there is a complex composite wave pattern, which is explained by the presence of velocity anomalies in the upper part of the section (Fig. 5). Underestimation of these factors in the shallow velocity model will inevitably lead to errors in traveltime processing.

This paper proposes an alternative method to predicting the shallow velocity model. The method is based on an original technique for restoring elastic-velocity characteristics from TEM data using well logging and vertical seismic profiling (VSP) materials (Shelokhov et al, 2018a,b,c).

The research area is located in the south of the Siberian craton (Fig. 6). The section is characterized by complex tectonic settings: the presence of folding and numerous faults. The CDP survey has been carried out according to the following technique, the step between the receiver lines has been 150 m and the step between the receiver point – 25 m. The distance between the source lines – 300 m, between the source points – 50 m. The source type is explosive, setting: central, symmetrical, "cross". The upper part of the section of the study area is composed of rocks of the Middle and Upper Cambrian, Ordovician deposits. The Middle-Upper Cambrian includes the Verkholensk and Ilginsk formations, composed of red-colored terrigenous-carbonate rocks overlying the rocks of the Litvintsevskaya formation (Deev, 1972).

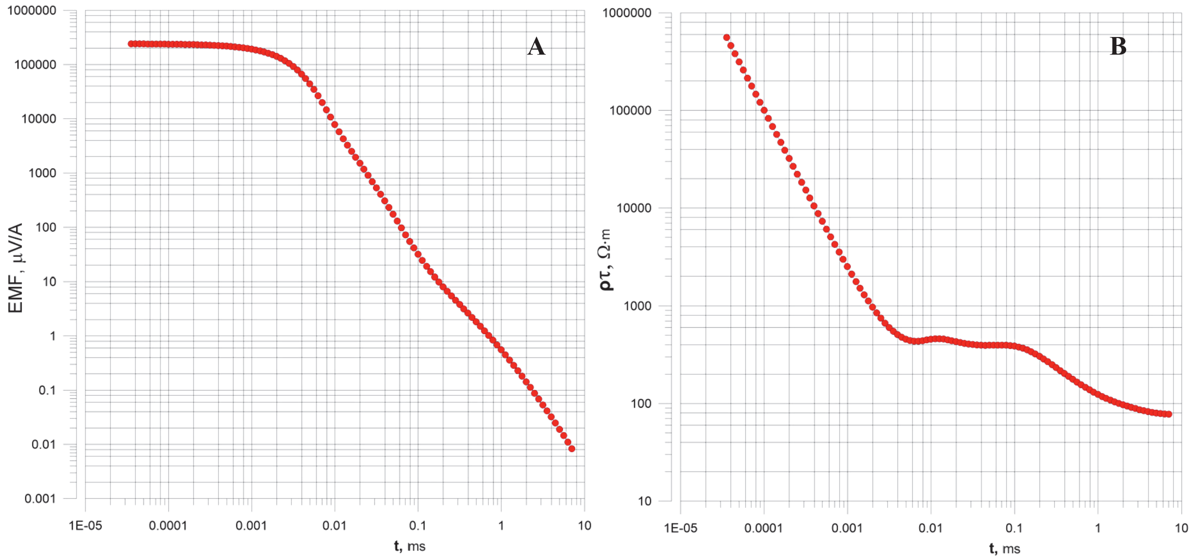

Fig. 3. The sTEM curves, obtained in Eastern Siberia: A – EMF; B – $\rho_\tau(t)$

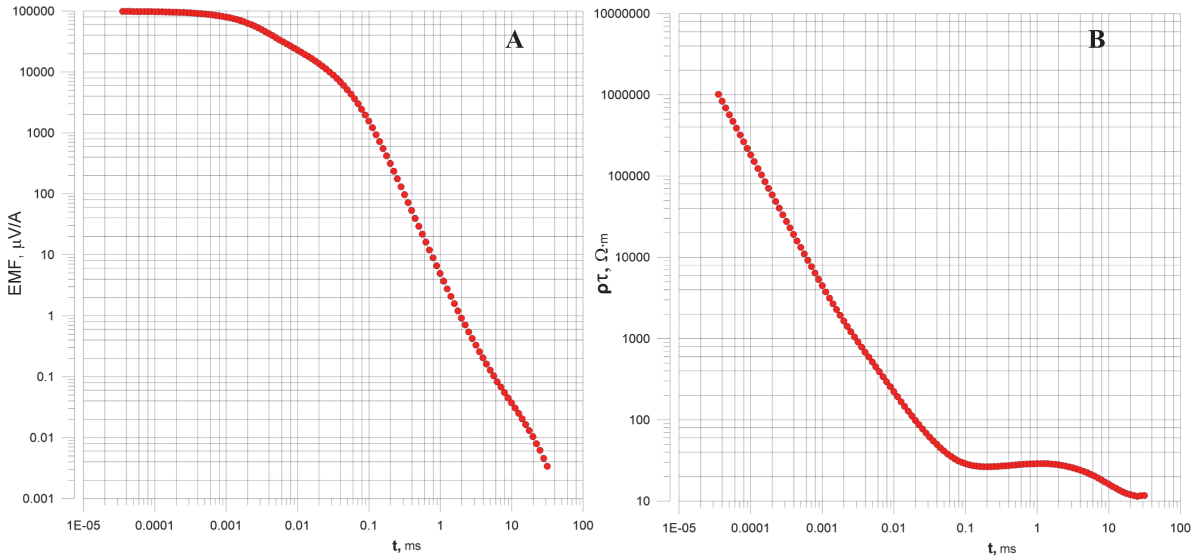

Fig. 4. The sTEM curves, obtained in Western Siberia: A – EMF; B – $\rho_\tau(t)$

The lower Ordovician is represented by undivided Ust-Kut and Iisk formations. The sediments are consistently overlaid on the red rocks of the Verkholensk Formation. In the lower part, the section is represented by dolomites with interlayers of greenish gray, dark gray limestones, gray, light and yellowish gray sandstones. Sediments have a limited distribution, composing the upper parts of the slopes of valleys and most watersheds.

According to the geocryological zoning scheme, two provinces are distinguished based on the degree of permafrost distribution:

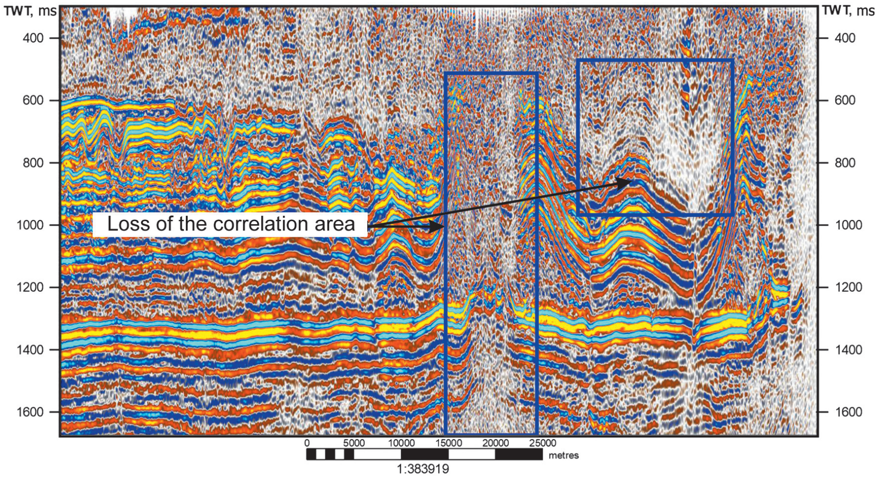

Fig. 5. The example of the seismic section, complicated by the influence of the upper part of the section

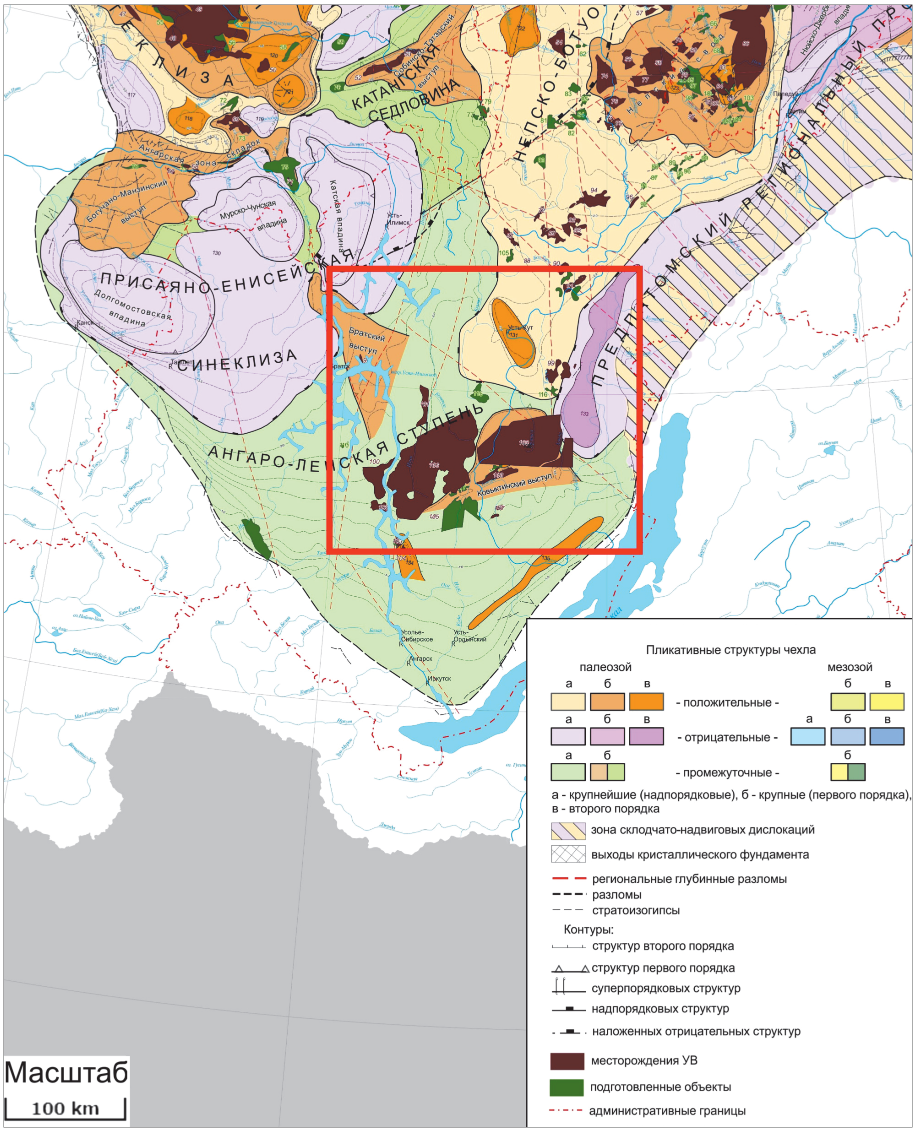

Fig. 6. Scheme of the survey area on a structural-tectonic map (ed. V.S. Staroseltsev)

A) The island distribution: islands of frozen rocks are confined to swampy areas of watersheds, to river valleys, creek valleys, to the foot of the northern slopes and occupy up to 10–25 % of the area;

B) Sparsely insular and sporadic distribution: occupying up to 30 % of the area and spreading on watershed flat surfaces, high and middle terraces of the Lena River and its tributaries, slopes of creek valleys and cleavage.

The frozen thickness within the study area varies eastward from 20 to 30 m. The thickness has a single-layer structure and is represented by permafrost of various genesis, strong, compacted, monolithic and fractured, covered with eluvial and deluvial rocks of low thickness (up to 3 m) of various ice content. Cracks and voids are partially or completely filled with ice.

In the region, cryogenic relict formations of Middle Holocene thermokarst forms are quite widespread on ice-wedge casts, mainly confined to the lower parts of the slopes and to the bottoms of the valleys. Seasonal thawing in the study area does not exceed 0.4–1.5 m.

The upper part of the section, composed of terrigenous-carbonate sediments of the Verkholensk and Ilginsk formations of the Middle-Upper Cambrian, as well as Ordovician and Quaternary formations, is poorly differentiated in terms of acoustic properties. Its thickness reaches the first hundred meters. With a shallow occurrence of this thickness in its uppermost part, a smooth increase in velocity from 1800–2000 m/s at a depth of 20–30 m, up to 4000 m/s at a depth of 200–300 m is observed. In general, the average values of the P-wave velocity in the upper part of the section are quite stable and vary within the range of 3880–4840 m/s (Fig. 7).

In terms of geoelectric characteristics, the first horizon from the surface is characterized by a high resistivity of 500–2000 Ohm·m and is identified with the rocks of the Quaternary system. Further along the section, the rocks of the Ust-Kut formation of the Lower Ordovician occur with resistivity values from 60 to 500 Ohm·m. Deposits of the Verkholensk and Ilginsk formations are characterized by relatively low resistivity values of 50–150 Ohm·m.

The settings of the south of the Siberian craton are characterized by several main inhomogeneities in the upper part of the section (Pyankov, 2016). The main one is a sharply interrupted relief with canyon-like river valleys (mountainous, highly dissected), which has very steep slopes, which create unfavorable surface seismogeological settings for conducting seismic survey. The study area is characterized by a difference in subsea depths from 700 to 1350 m, which corresponds to an extremely sharply dissected relief.

An important role is played by the variability of the low-velocity layer thickness. It can be reliably determined by the up-hole velocity survey the coverage area of which is not always sufficient for a reliable restoration of the low-velocity layer thickness, and therefore the low-velocity layer thickness is approximated by a kind of smoothed layer.

Analyzing the wave pattern, it is noted that the morphology of the reflecting horizons corresponds to the boundaries of the change in velocities in the velocity model, which correspond to the morphology of the relief surface.

The VSP data for the reference well have been used to calculate the coefficients. First of all, the values of the interval time are obtained for each depth mark, and secondly, multiple recalculation of the TEM model, obtained at the well point, into an acoustic model is performed; the calculation is performed until the maximum convergence is reached.

Fig. 7. Physico-geological model of the upper part of the section: Eastern Siberia

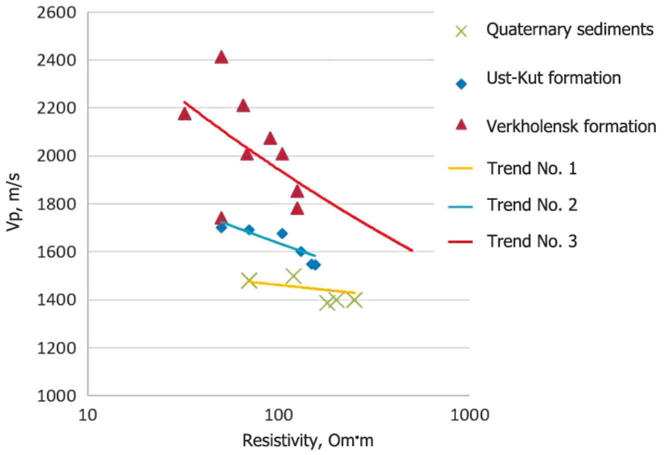

Fig. 8. The trends for velocity model calculation

As a result of the selection, 3 coefficients sets have been obtained – 3 trends (Fig. 8). Trend No. 1 (first group of coefficients) corresponds to Quaternary sendiments, trend No. 2 (second group of coefficients) corresponds to carbonate rocks of the Ust-Kut formation, trend No. 3 (third group of coefficients) corresponds to carbonate rocks of the Verkholensk formation.

The stability of the obtained trends has been assessed using a verification well at the site of operations. The average relative differance between Vp obtained from the sTEM data and Vp from the VSP data has been 7 % (Fig. 9). This fact allows us to conclude that the trends are stable and can be used to calculate the shallow velocity model.

The resulting models have been used to calculate static corrections. The static corrections obtained from the data of the first breaks vary from 10 to 110 msec. In its turn, the corrections obtained from the model based on the sTEM data are more differentiated and vary from 10 to 200 msec. The distribution of static corrections obtained by both methods over the area is very different. It is clearly seen that according to the first breaks data in the central part of the area, the corrections are maximum, while according to the data of the sTEM in the central part of the area, they are minimal (Fig. 10).

Comparison of the velocity models, obtained using different processing options, shows that the model, obtained from the sTEM data, reflects a significantly lower low-velocity layer thickness, and there are also high-velocity anomalies in the section that are not detected by the first breaks model.

Analysis of the time section (Fig. 11) shows that at the stage of taking into account the statics for the relief and average-period corrections, there is a significant improvement in the traceability of the reflecting horizons when using the model based on the sTEM data. On the section, obtained using the first breaks model data, the presence of foot print, passing through the entire section is noted. In the section, obtained from the sTEM data, such anomalies can be partially suppressed.

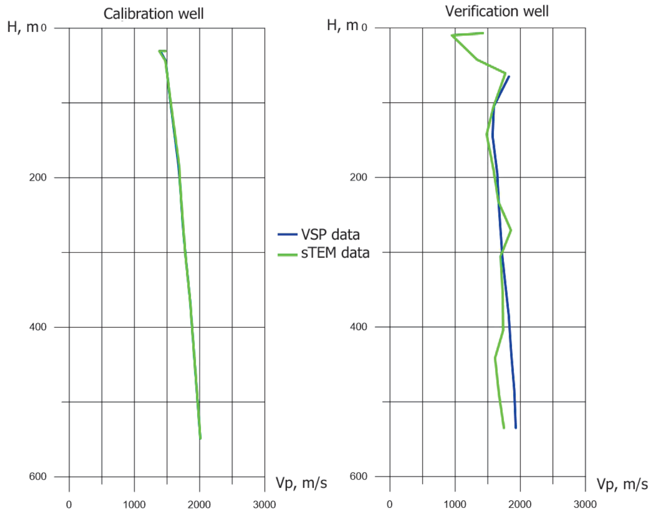

Fig. 9. Verification of the obtained coefficients

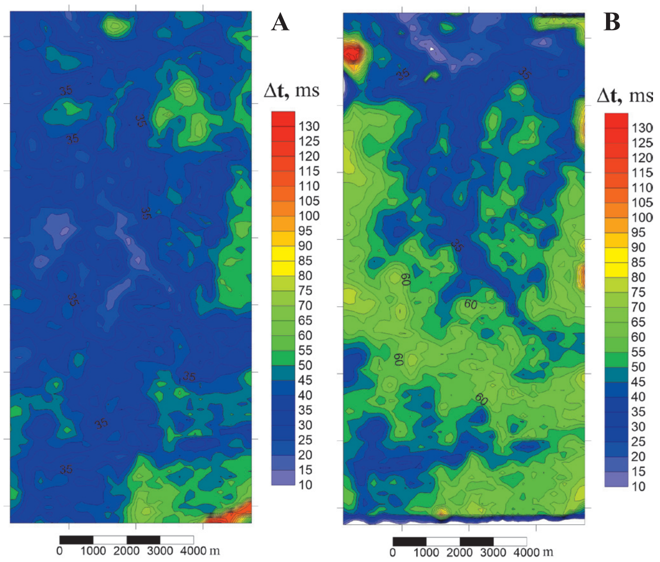

Fig. 10. Comparison of maps of static corrections: A – according to the data of the first breaks; B – according to sTEM data

The results obtained indicate an improvement in the quality of the seismic sections before taking into account the short-period component when using the velocity model based on the sTEM data.

The pattern of the RMS attribute for reflecting horizon H2 clearly shows (Fig. 12) an improvement in the dynamics on the section according to the sTEM data.

For a more visualization of the improvement in the quality of the sections, the RMS and Variance attributes (dispersion, an analogue of coherence) have been built. On the sections of the RMS and Variance attributes, it can be seen that the data, obtained taking into account the model, based on the sTEM data are distinguished by a higher level of the RMS amplitude and an increase in the quality of the reflecting horizons traceability by the Variance attribute than the data, obtained taking into account the model, based on the tomography of the first breaks (Fig. 13, Fig. 14).

Analyzing the coherence maps (Fig. 15), it can be noted that according to the sTEM model, anomalies are identified, reflecting the nodular-thrust tectonics

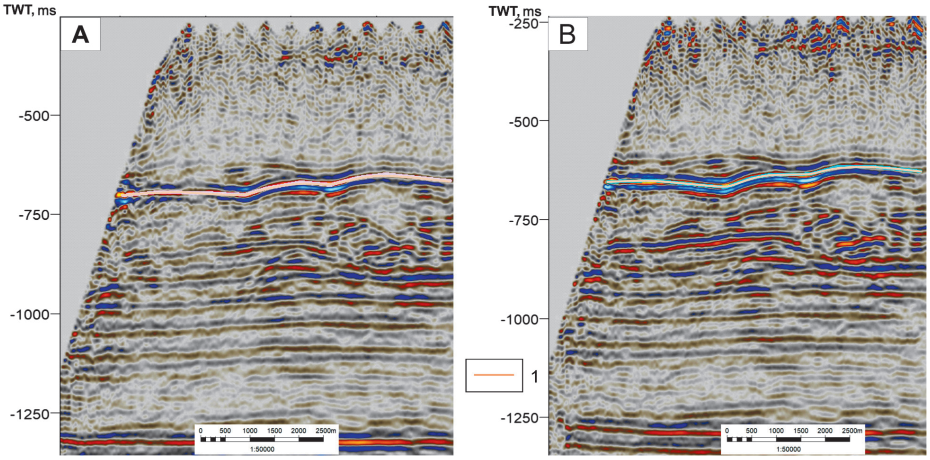

Fig. 11. Comparison of the seismic sections taking into account the short-period component: A – according to the data of the first breaks, B – according to the sTEM data. 1 – reflecting horizon H2.

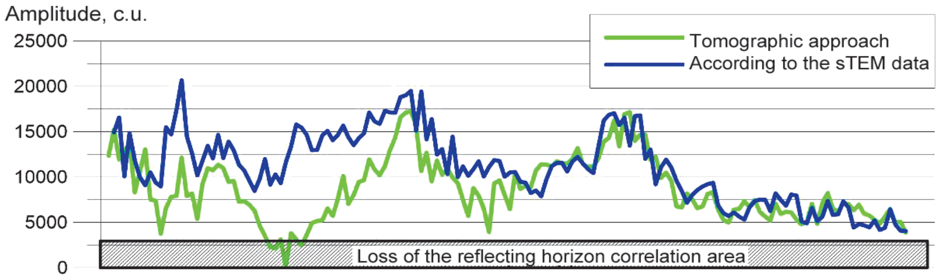

Fig. 12. The RMS amplitude attribute charts

characteristic of this area. On the left map (Fig. 15 A), the dynamic interval is poorly expressed, reflections are complicated by numerous interference zones. In the areas where salt deposits are developed, the wave pattern changes to a chaotic one, with separate, multidirectional, curved, short, uncorrelated reflections, which does not allow assessing their morphology.

On the right map (Fig. 15 B), there is an improvement in the quality of seismic reflections traceability. There are strong reflections due to the presence of acoustic contrast. The morphology of gross structures is pronounced. The folds of gravity sliding are mapped. Thus, it can be concluded that the use of sTEM in the processing of 3D CDP data allows improving the traceability of horizons and the dynamic characteristics of the seismic record both at the stage before taking into account the high-frequency component and at the final stage of processing.

Western Siberia. Sredne-Yamalsky megaswell

The studies of CDP 3D and sTEM were carried out on an area of 726 sq.km., using a combined observation network (Fig. 16). The 3D CDP survey was carried out according to the following technique: the step between the receiving lines has been 150 m, between the receiving points – 25 m. The step between the source lines – 300 m, between the source points – 50 m. The source type is vibratory, setting: central, symmetrical, “cross”.

According to the data of the sTEM exploration, there is a high differentiation of the upper part of the section to a depth of about 500 m. Up to a depth of 200–250 m, there is a high-resistivity layer associated with the spread of permafrost (Fig. 16). The continuity of the permafrost in the research area is interrupted by taliks, cryopeg lenses. Under the riverbeds and lakes there are thawing zones, characterized by low resistance according to the sTEM data. The boundary of the transition of rocks from a frozen state to a thawed state is clearly recorded. There is a significant reduction, up to the complete absence of permafrost, during the transition to the transit zone (water area). In general, there is a sharp variability of the permafrost base.

The upper part of the section of the study area is complicated by the presence of an uneven permafrost thickness with a high degree of ice content. The permafrost thickness is complicated by the spread of through and non-through talik zones. Part of the study area passes through the transit zone. An important fact is the presence of cryopeg lenses in the permafrost thickness.

All these factors are reflected in the time sections by the areas of complete or partial loss of the reflecting horizon correlation, as well as the distortion of the trend of the structural surfaces.

To build a shallow velocity model, the calculation and calibration of the empirical coefficients of the Faust’s equation are performed. To calculate the coefficients, the presence of acoustic logging or VSP data is required.

The first step is to form a lithological-generalized model, a multiple screening of the empirical coefficients

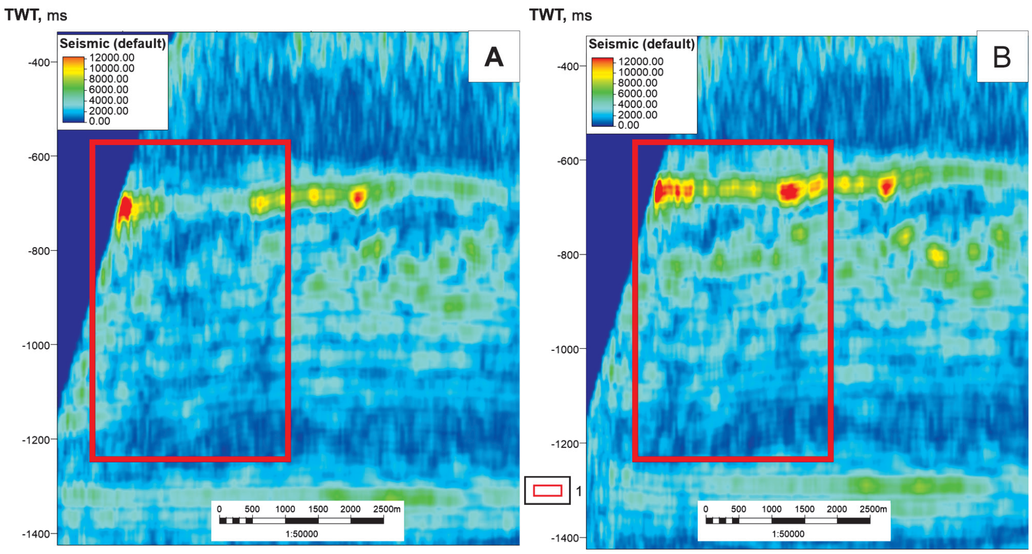

Fig. 13. Comparison of the RMS attribute sections: A – according to the data of the first breaks, B – according to the sTEM data. 1 – seismic amplitude improvement area.

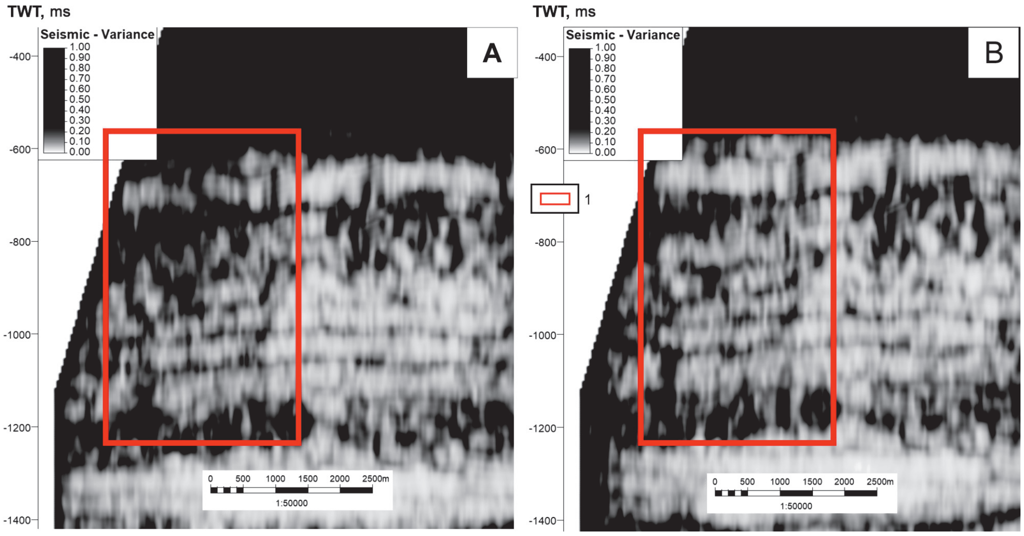

Fig. 14. Comparison of the Variance attribute sections: A – according to the data of the first breaks, B – according to the sTEM data. 1 – coherence improvement are

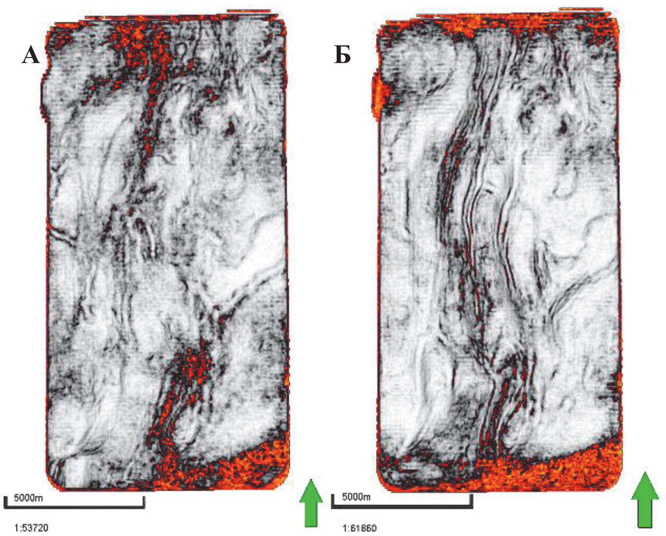

Fig. 15. The cutoff of the "coherence" attribute in the interval of -650 msec (top of the Litvintsevskaya suite): A – according to the data of the first breaks, B – according to the sTEM data

of the equation is performed within the framework of each lithological variety. The result is a unique pair of coefficients for each lithological variety. When the correlation coefficient r = 0.9 or more is reached, the coefficients are considered fitted. There are 3 VSP wells in the work area. Initially, the calculation and calibration of the coefficients have been carried out for one calibration well. However, using the results of selection at the verification well, a significant discrepancy between the observed and calculated velocities has been obtained.

After analyzing in detail all the existing VSP wells in the work area, it has been concluded that they reflect radically different conditions in the upper part of the section (Fig. 18). Based on this, it has been decided to use all the existing VSP wells for calibration.

To use wells with VSP, it has been necessary to perform zoning of the area. When comparing the position of the wells with the VSP and the resistivity map of the upper part of the section, according to the sTEM data,

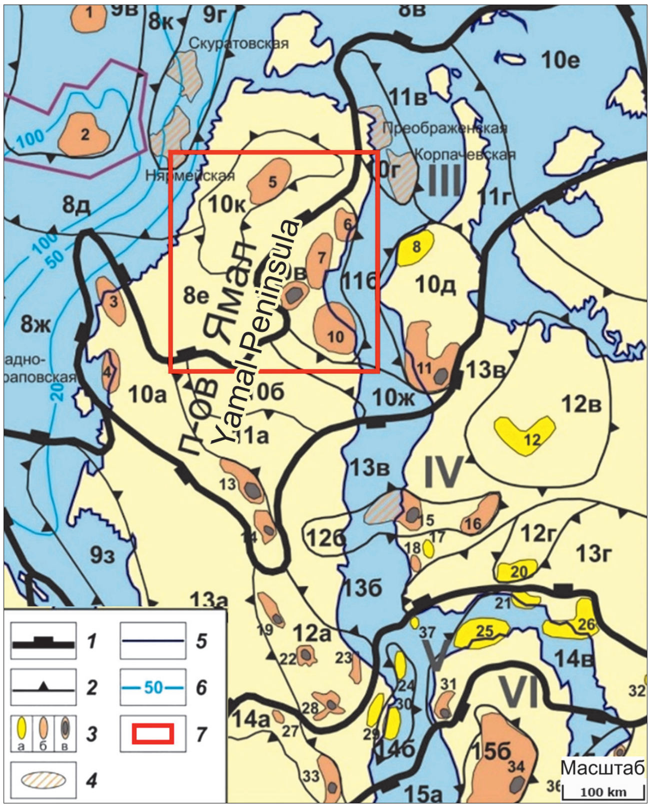

Fig. 16. Scheme of the survey area on a structural-tectonic map (according to «VNIGNI»). The legend: 1 – boundaries of the largest tectonic elements (syneclises and saddles); 2 – boundaries of tectonic elements of the 1st order (folds ,swells, depressions); 3 – fields (a – gas, b – gas condensate, c – oil and gas condensate); 4 – some prospect trap structures; 5 – coastline; 6 – isobaths, m, 7 – contour of the research area. The fields: 1 – Rusanovskoe; 2 – Leningradskoe; 3 – Kharasaveyskoye; 4 – Kruzenshternskoe; 5 – Malyginskoe; 6 – Tasiyskoe; 7 – Severo-Tambeyskoye; 8 – Shtormovoe; 9 – Zapadno-Tambeyskoe; 10 – Yuzhno-Tambeyskoe; 11 – Utrennee; 12 – Gydanskoe; 13 – Neitinskoe; 14 – Arkticheskoe; 15 – Geophysicheskoe; 16 – Soletsko-Khanaveyskoe; 17 – Trehbugornoye; 18 – Vostchno-Bugornoye; 19 – Sredne-Yamalskoe; 20 – Minkhovskoe; 21 – Yuzhno-Tota-Yakhinskoe; 22 – Nurminskoe; 23 – Khambateiskoe; 24 – Severo-Kamennomysskoe; 25 – Aderpayutinskoe; 26 – Antipayutinskoe; 27 – Malo-Yamalskoe; 28 – Rostovtsevskoe; 29 – Kamennomysskoe-susha; 30 – Kamennomysskoe-more; 31 – Parusnoe; 32 – Zapadno-Messoyakhinskoe; 33 – Novoportovskoe; 34 – Yamburgskoe; 35 – Nakhodkinskoe; 36 – Yurkharovskoe. Tectonic elements: III – Paykhoi-Taimyr saddle (10a – Nurminsky swell; 10b – Tsentralno-Yamalsky swell; 10c – Sredneyamalsky fold; 10d – Preobrazhensky swell; 10d – Yuratsky fold; 10e – Severo-Gydanskaya step; 10g – Severo-Seyakhinsky depression ; 10k – Severo-Yamalsky swell; 11a – Bolshetamboyakhinskaya depression; 11b – Arkticheskaya depression; 11c – Beloostrovsky depression; 11d – Vostochno-Gydansky depression), IV – Yamalo-Gydanskaya syneclise (9z – Poetayakhinsky swell; 12a – Yuzhno-Nurminsky swell; 12b – Geophysichesky swell; 12c – Gydansky fold; 12d – Minkhovsky high; 13a – Seyakhinsky depression; 13b – Tadibeyakhinsky depression; 13c – Toramyuyakhinsky depression; 13d – Antipayutinskaya depression), V – Yuzhno-Yamal-Messoyakhinsky saddle (Yuzhno-Yamalsky swell; 14b – Kamennomyssky swell; 14c – Nizhnemessoyakhinsky swell), VI – Nadym-Tazovskaya syneclise (15a – Parusovy dedepression; 15b – Yamburgsky swell; 15c – Nakhodkinsko-Yurkharovsky swell).

it has been concluded that each well is confined to a separate area of the resistivity.

Thus, the study area has been divided into three zones (Fig. 20): the first zone (red polygon) – the resistivity range of more than 50 Ohm∙m, rocks with the highest ice content – the area of using the VSP-3 well as a reference; the second zone (green polygon) – resistivity range from 25 to 50 Ohm∙m, less icy rocks – the area of use of the VSP-2 well as a reference; the third zone (blue polygon) – resistivity range less than 25 Ohm∙m, thawing zones – the area of using the VSP-1 well as a reference (assumed talik zones).

Based on the obtained dependencies, a 3D shallow velocity model has been made. Based on the acquired

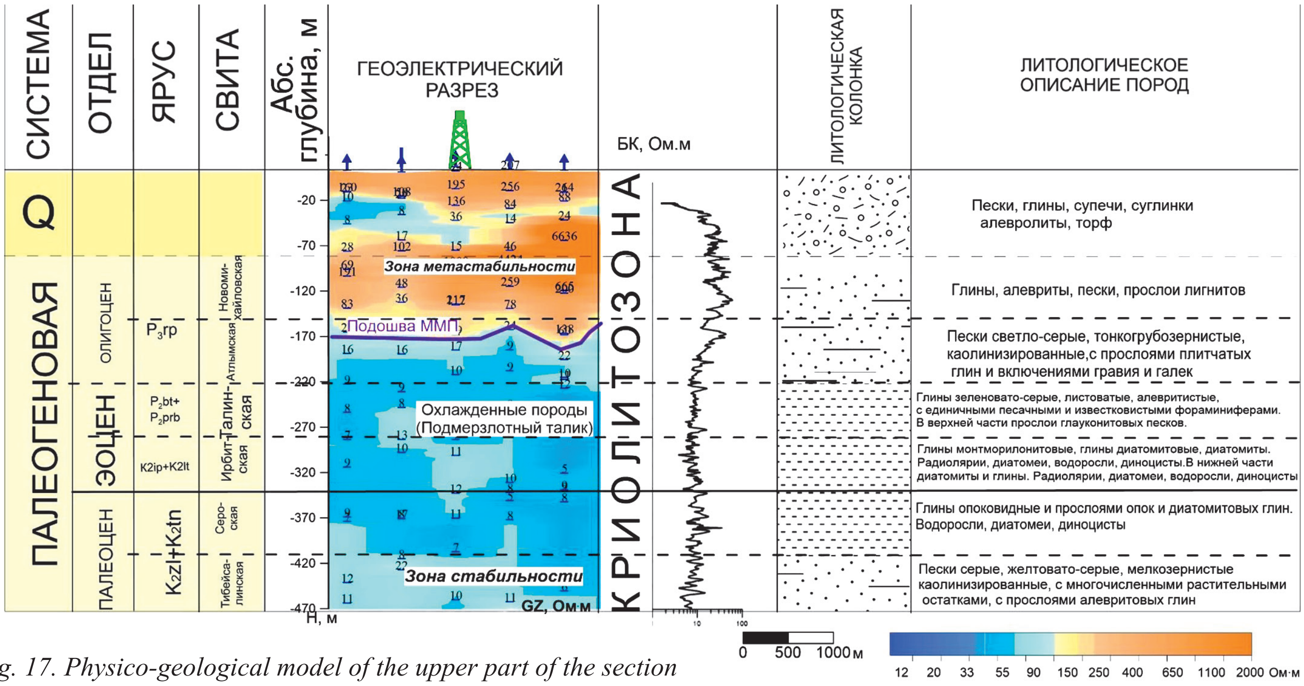

Fig. 17. Physico-geological model of the upper part of the section

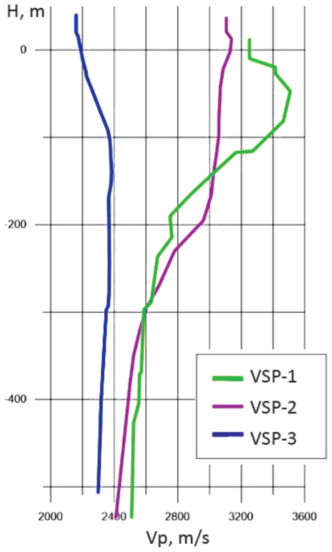

Fig. 18. P-wave velocity curves according to VSP data. 3 sets of trends (equation coefficients) have been obtained. For each well, Vp-resistivity trends have been obtained for three main types of section: 1 – sandy section, frozen rocks, 2 – clay section, chilled rocks, 3 – unfrozen section.

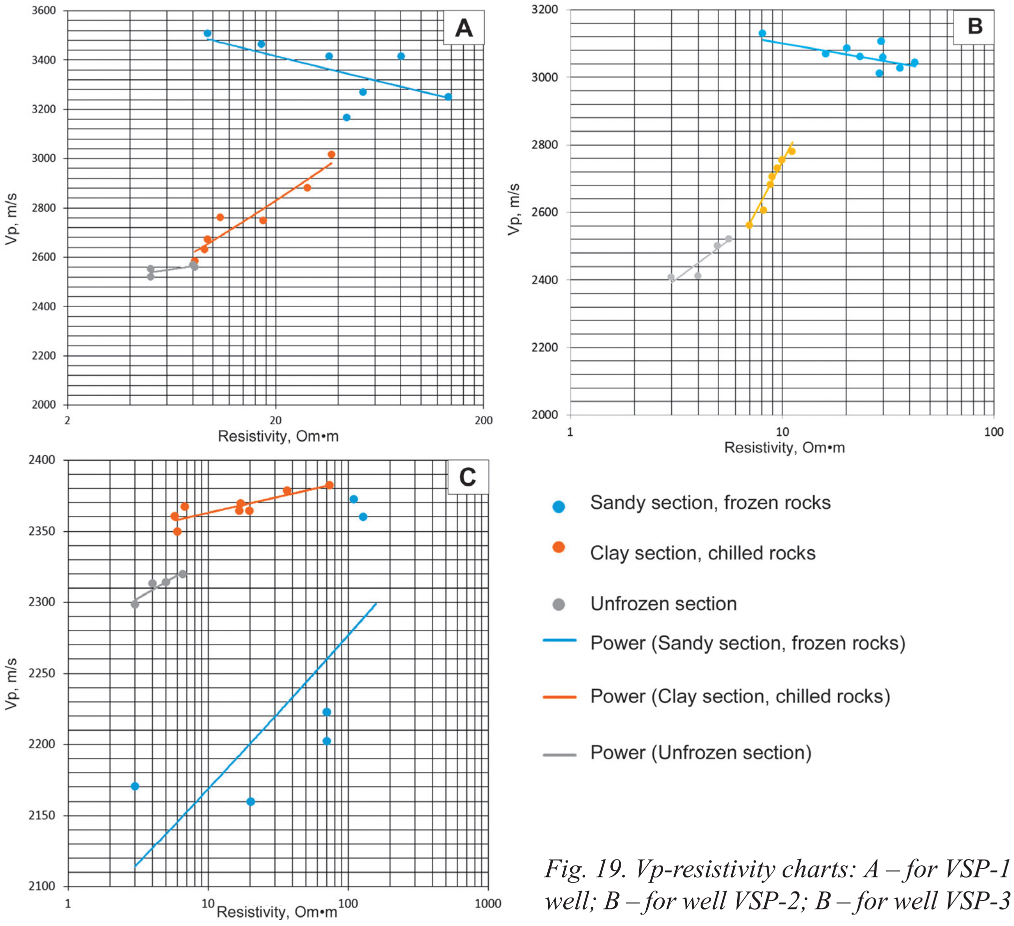

Fig. 19. Vp-resistivity charts: A – for VSP-1 well; B – for well VSP-2; B – for well VSP-3

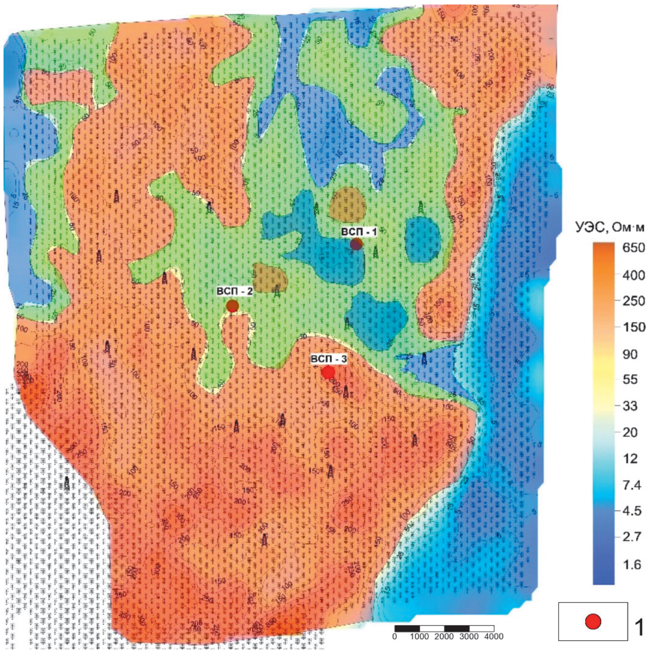

Fig. 20. The map of an area depending on the resistivity distribution. 1 – wells with the VSP

shallow velocity model, static corrections have been calculated and the obtained corrections were introduced into the total time sections.

For comparison, two options for calculating corrections have been used: from the values of the relief and from the data of the sTEM (Fig. 21).

On the sections, obtained without taking into account the sTEM data (Fig. 22 A, B), there is a phase correlation misfit - artificial synclines in the area of transition from the continental part to the transit zone. When using the sTEM model, these velocity anomalies can be taken into account (Fig.22 C).

Thus, it can be concluded that the application of the sTEM method to refine the model of the upper part of the section made it possible to take into account the velocity anomalies, associated with the transition from the continental part to the transit zone.

Conclusions

The main results of the conducted research are the development of an approach to the use of non-stationary electromagnetic soundings to refine the shallow velocity model and then take it into account when processing seismic data, as well as its approbation at a number of fields in Eastern and Western Siberia.

A methodological approach has been developed, the application of which increases the information content of seismic data due to the sTEM survey.

By applying this technique, it was possible to improve the dynamic characteristics and accuracy of structural model, as a result, to increase the precision of constructing geological models of oil and gas fields.

For Eastern Siberia, the developed technique makes it possible to increase the dynamic characteristics and

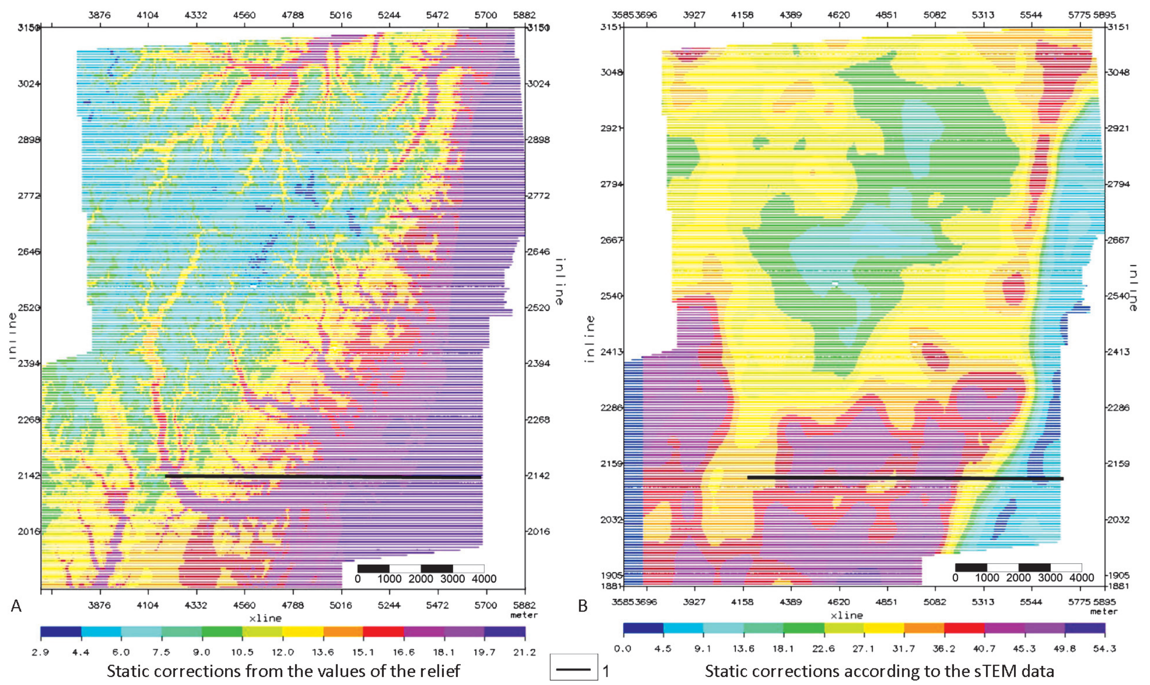

Fig. 21. Maps of static corrections: A – static corrections from the values of the relief; B – static corrections according to the sTEM data. 1 – traverse line.

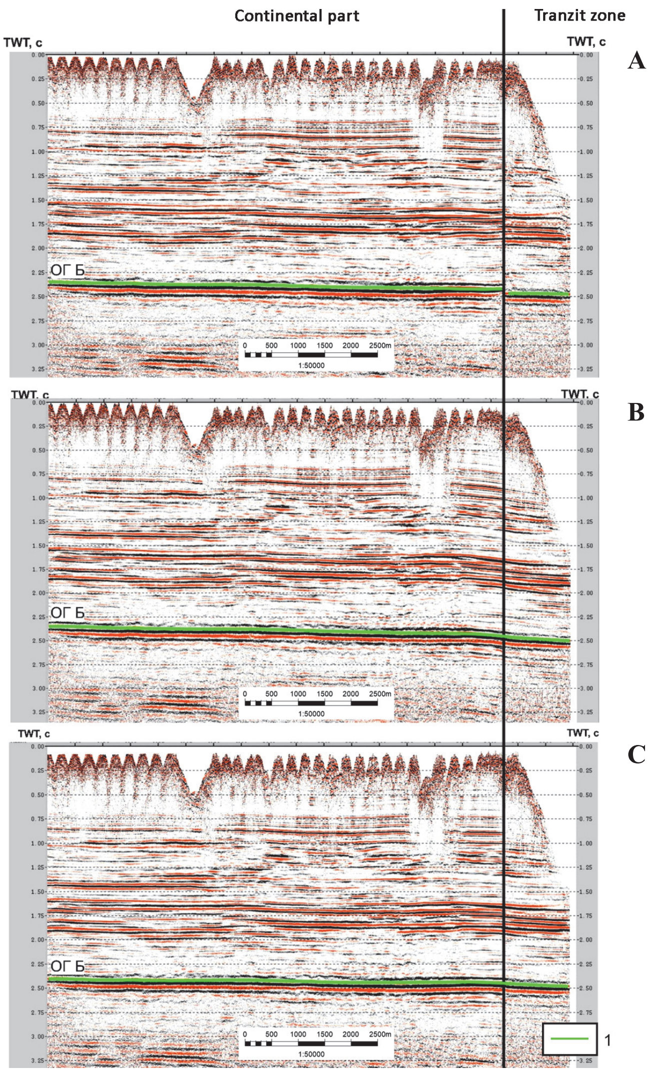

Fig. 22. Results of static corrections input: A – velocity model based on the first breaks of refraction waves, B – static corrections from the relief values, C – velocity model based on sTEM data. 1 – reflecting horizon B.

the level of seismic recording coherence. These factors make it possible to improve the quality of the final seismic-geological model.

In Western Siberia, it has been possible to achieve more accurate model by taking into account the velocity inhomogeneities of the upper part of the section, associated with the transit zone.

The geological efficiency of the conducted research consists in improving the accuracy of the geological model reconstruction and the reliability of the prediction.

The main conclusions of the study can be useful in industrial and scientific companies carrying out activities in the processing and interpretation of seismic data. The use of the developed methodology allows, at minimal cost, to improve the quality of seismic data processing and to increase the precision of the geological section mapping based on the nature of the problem being solved.

In general, the conducted research makes it possible to expand the field of application of shallow EM studies. Taking into account the results of the research carried out, the following ways of using EM data to improve the quality of seismic data are outlined:

Using the shallow velocity model according to the sTEM data to minimize the uncertainty of the upper part of the section during the traveltime inversion of the CDP data.

Velocity model building, based on the TEM data and its subsequent consideration during depth migration and construction of a velocity-depth model.

Joint inversion of the velocity model based on the sTEM data and ray tomography for complex refinement of the upper part of the secion.

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