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DETAILED STUDY OF STRUCTURE AND COMPOSITION OF WATERPROOF STRATA BY MINE SEISMIC SURVEY AT THE VERKHNEKAMSKOE SALT DEPOSIT

The key objective in salt mining is preservation of the waterproof strata integrity which is a guarantee of accident-free operation of mines. Until recently, for the Verkhnekamskoe Salt Deposit, there were no reliable tools to study the waterproof strata at the interwell distance. This article continues publishing new data obtained by mine seismic on shear waves with separation of reflections. For the first time in history of geological exploration at the Verkhnekamskoe Salt Deposit, this method developed by the Geophysics Laboratory of VNII Galurgii has allowed the explicit detection of geological section elements previously only revealable by the direct methods. Within the framework of the article, the possibility of identifying the rhythm stacks in the waterproof strata, the areas of spreading, wedging and replacement of carnallite rocks in the waterproof strata, and the possibility of tracing the folding behavior of these rocks is evaluated and exemplified. It is shown that the developed method makes it possible to significantly increase the detail and reliability of geological models. Implementation of the method of mine seismic survey using shear waves with separation of reflections in modern practice in mining significantly reduces the risks of emergencies and loss of mines.

Keywords: *Verkhnekamskoe Salt Deposit, mine seismic survey, reflected wave method, common depth point, shear wave method with separation of reflections, geology, sylvinite, carnallite, waterproof strata, replacement zone*
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Introduction

One of the largest Verkhnekamskoe Salt Deposit (VKSD) occurs on the left bank of the Kama River in the Perm Krai. This complex deposit produces sylvinite for manufacturing potash fertilizes and carnallite for magnesium–titanium alloys. The well-stratified salt is divisible bottom-up into underlying rock salt (URS), potash strata composed of sylvinite and carnallite sequences (SS and CS, respectively) and overlying rock salt (ORS). The commercial-value strata occur at the bottom of the potash accumulation, and are represented by the strata KpII, АБ and, in a lesser degree, by В. The bottom of URS contains *marker clay* (MC) which is well detectable both geologically and geophysically. The salt table are overlaid with the salt–marl strata (SMS). The SMS bottom containing the salt-bearing rhythm stacks (RS) is called a transition stack (TS). SMS are overlaid with the terrigene–carbonate strata (TCS), variegated soils (VS) and quaternary deposits (Q). Furthermore, there is a conventional (nonstratigraphic) boundary named a salt table (ST)—this is a surface composed of the first top layers of salt [1, 2].

Research relevance and goal

During undeground mining of the commercial-value strata at VKSD, water ingress in mines is prevented by waterproof strata (WPS), which consists, when fully cut, of alternating commertial-value layers and rock salt table, ORS and RS rhythms. The total thickness of WPS is taken as a vertical distance from the top drifts to the salt table. The safety of WPS, as a guarantee of safe mining, is a top priority in all phases of mining.

Any intersection of the salt table by a surface borehole means salt loss in the borehole pillars and a risk of water ingress in the salt production drifts. For this reason, the number of such boreholes is minimized. As a consequence, the structure of WPS and its roof position (salt table) at a great interwell distance can only be judged from a wide well spacing pattern, and from the ill-reliable indirect methods, which sometimes leads to accidents up to the loss of whole mines [3, 4]. After 2018, development of the method of *seismic survey* using shear *waves with separation* of *reflections* (SWSR) enabled the detailed modeling of salt table towards the higher safety of mining. The higher detail imaging provided the earlier unavailable geological information which required systematization. In this manner, the goal of this research is the detection and geological justification of new details on the geological structure and tectonics of VKSD using the method of SWSR.

Research method

The world practice of studying mineral occurrences on the whole and salts in particular commonly uses geophysics, both electromagnetic [5, 6] and seismic methods [7–12]. The geophysical methods to solve ore provblems are widely applied both in Russia [13–17] and in the near abroad countries [18–19]. In 2018 the specialists of the Geophysics Laboratory at VNII Galurgii developed the method of *seismic survey* using shear *waves with separation* of *reflections* (SWSR) [20–24]. This method is based on the widely known common depth point (CDP) seismic exploration. The theoretical and the full-scale research show that SWSR enables separation of reflections incoming from different half-spaces, and allows tracing firmly the salt–not salt interfaces, examining the structure of the whole salt table and solving problems of mining geology.

The geophysical profiles are laid in gate roads in the commercial-value strata (АБ, KpII) and in URS. When it is necessary to examine the overlying strata, the drifts driven in the upper seam are preferred as in this case noise is reduced in the upper half-space which is the objective. Likewise in case of studying the underlying strata, the drifts driven in the bottom seam are chosen.

Detailed study of structure and composition of WPS

The generalized geological structure of the seismic survey areas and the obtained comprehensive information on geology is on the whole typical of the VKSD. The generalized cross-section of the deposit in the area of geophysical surveys is depicted in **Fig. 1**.

Starting from 2018, a huge amount of work was accomplished using SWSR on different operating sites of VKSD. The geological interpretation of the geophysical survey data using the above-mentioned methods points at the sharp difference in the behavior of the same reflection horizons in WPS in different areas. In some areas, the boundaries between WPS layers generate expressed reflections, and in the other areas, these boundaries produce either weak or indistinguishable reflections. Sometimes, that is caused by the complex mining technical conditions, but the major reason is the difference in geological structure.

Figure 2 superimposes two seismic profiles from different areas of the deposit. In the larger profile, the interval CS is geophysically *mute*, without clear reflection horizons. The profile distinctly shows the blanket salt roof and rhythm stacks (RS), but the whole series, from the drift where the profile is laid to the ORS roof, is seismically uniform and contains no distinct reflection horizons. The white-framed insertion shows a fragment of the seismic profile from another site of the deposit, mated with the underlying profile with respect to the ORS roof and MC layer. The apposition demonstrates that the information content of the superimposed profile in the CS interval is much larger than the lower-lying profile has—it is possible to identify a few carnallite seams, and to determine the nature and parameters of their folding. Furthermore, the salt table have the same thickness in the shown profiles, while the absolute altitudes differ appreciably—by 125 m. The dip angles of the seams also differ. Therefore, we had to rotate the superimposed profiles for the full-fledged superimposition.

From the drilling data in the area in the underlaid cross-section with the *mute* WPS, the interval of CS contains not carnallite but sylvinite. And, vice versa, from the drilling data in the area of the superimposed cross-section, with the reflection horizons in WPS, carnallite is present.

As known, carnallite has sharply different physical and mechanical properties than the other VKSD salts have; for this reason, rocks with high content of carnallite are highly contrast in the seismic profiles and are definitely traced in the areas of gentle folding. So, the SWSR-based seismic survey enables detecting the zones without carnallite-bearing rocks in the cross-section of WPS. Earlier, detection of such lithological characteristics was only possible using the direct methods.

For another thing, the rhythm stacks (RS1–RS3) are detectable in the large cross-section and are absent in the inserted cross-section. The number of the rhythm stacks depends on the rate of dissolution of their salt component. The dissolution is more active in the uplifts. The rhythm stacks belong in WPS, and their integrity favors the safety of mining of the commercial-value strata.

Let us discuss another example. It is seen in **Fig. 3** how the distinct reflection horizones within the limits of survey stakes 50–730 wedges out eastward against the background of the general decrease in the thickness. Geologically, in the cross-section in Fig. 3, it is seen how the carnallite-bearing rocks pass into the non-carnallite rocks. The non-carnallite rocks in the interval of the potash strata in VKSD may only be sylvinite or rock salt. The thickness of the carnallite seams (H_1) is approximately two times the thickness of the sylvinite cross-section (H_2). Such consistent pattern, at the simultaneous reduction in the thickness of the sylvinite cross-section as compared with the carnallite cross-section, is usually observed in production roadways.

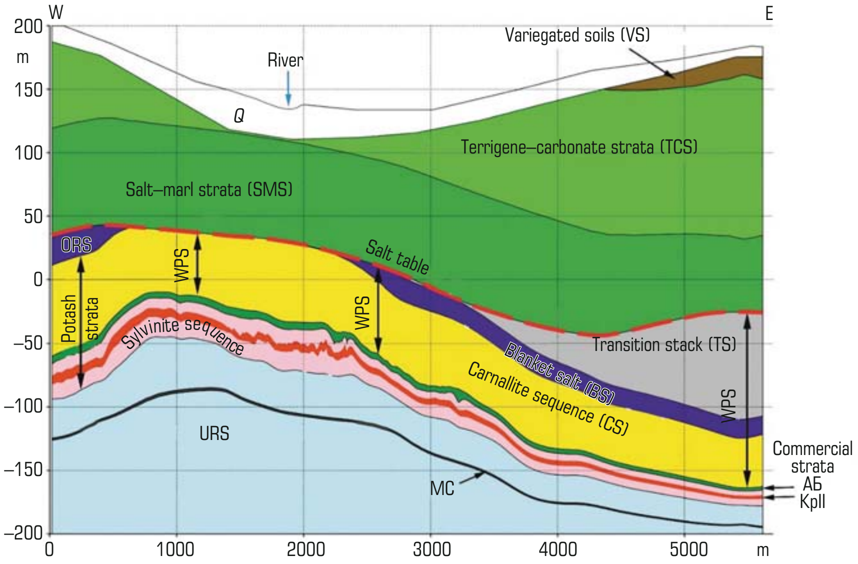

Fig. 1. Generalized geological cross-section in geophysical survey area of VKSD

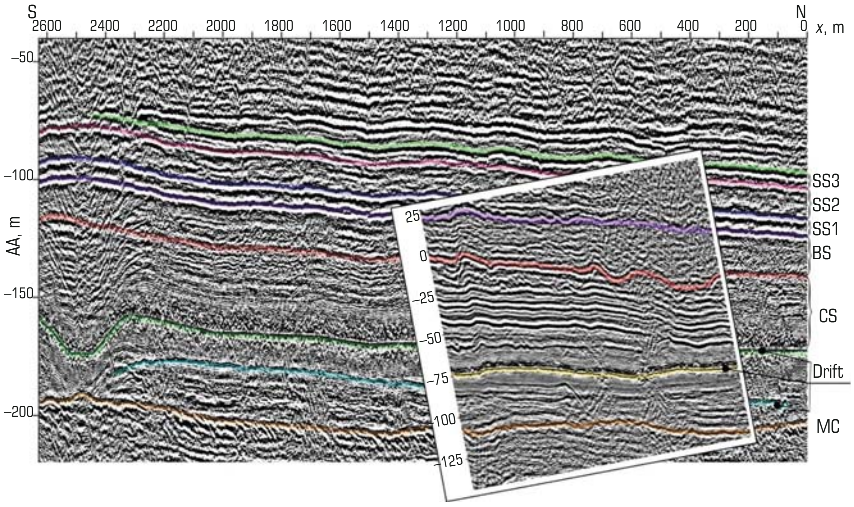

Fig. 2. Superimposed seismic profiles in different areas

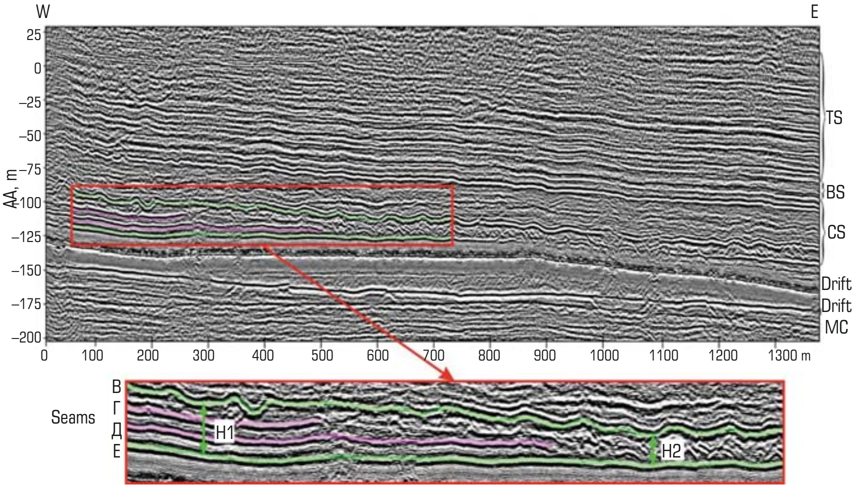

Fig. 3. "Wedging" of carnallite seams Д and Г

Because of similar physical and mechanical properties of sylvinite and rock salt, the seismic survey is incapable to clearly differentiate between them. However, there is a high probability that carnallite rocks are absent eastward of the reflection horizon wedging out. Stratigraphically, the interval of the wedged-out reflection horizons coincides with the seams Г and Д,

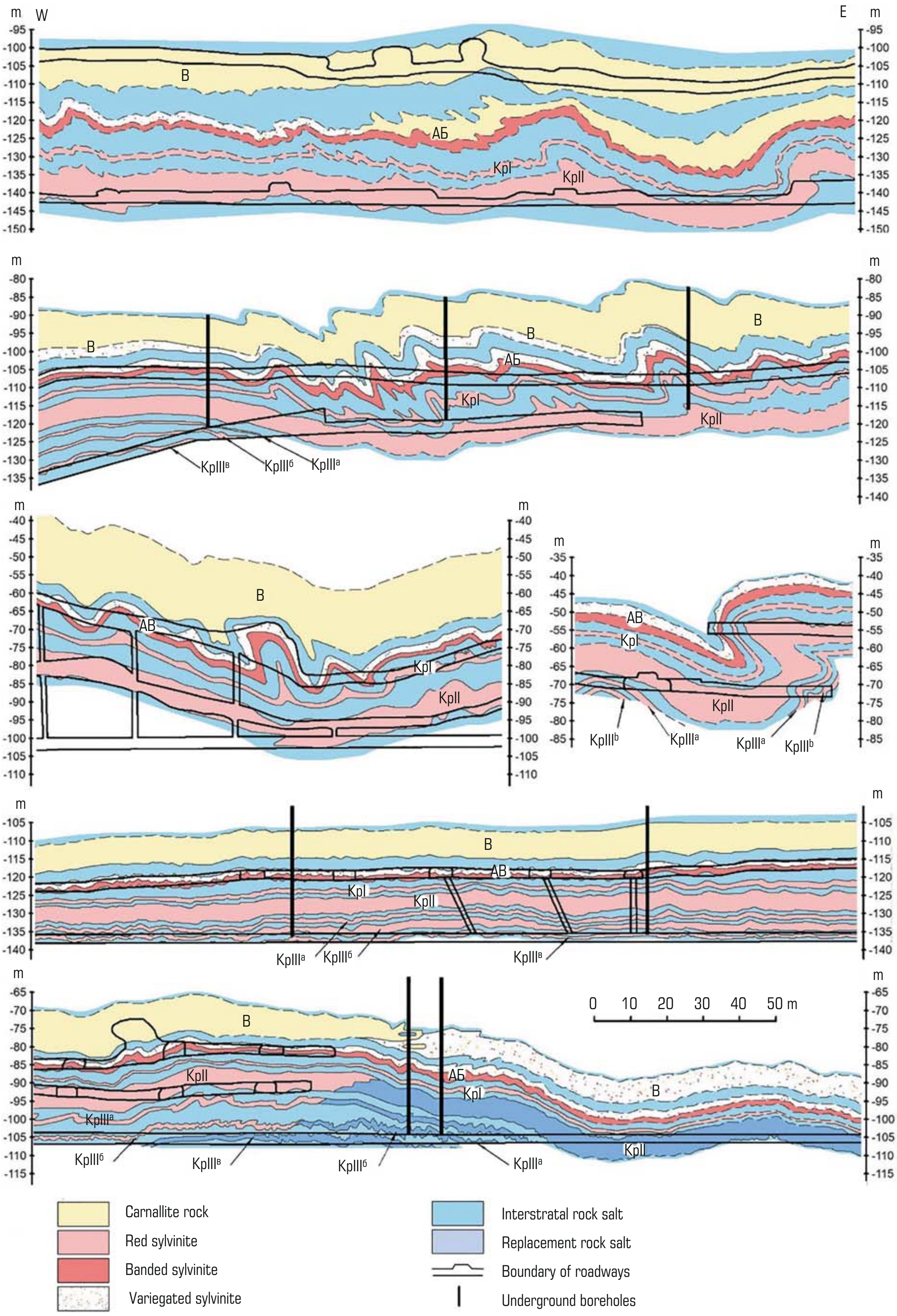

Fig. 4. Folding in the interval of commercial strata

which are prohibited to be accessed by boreholes or, moreover, by the other underground openings.

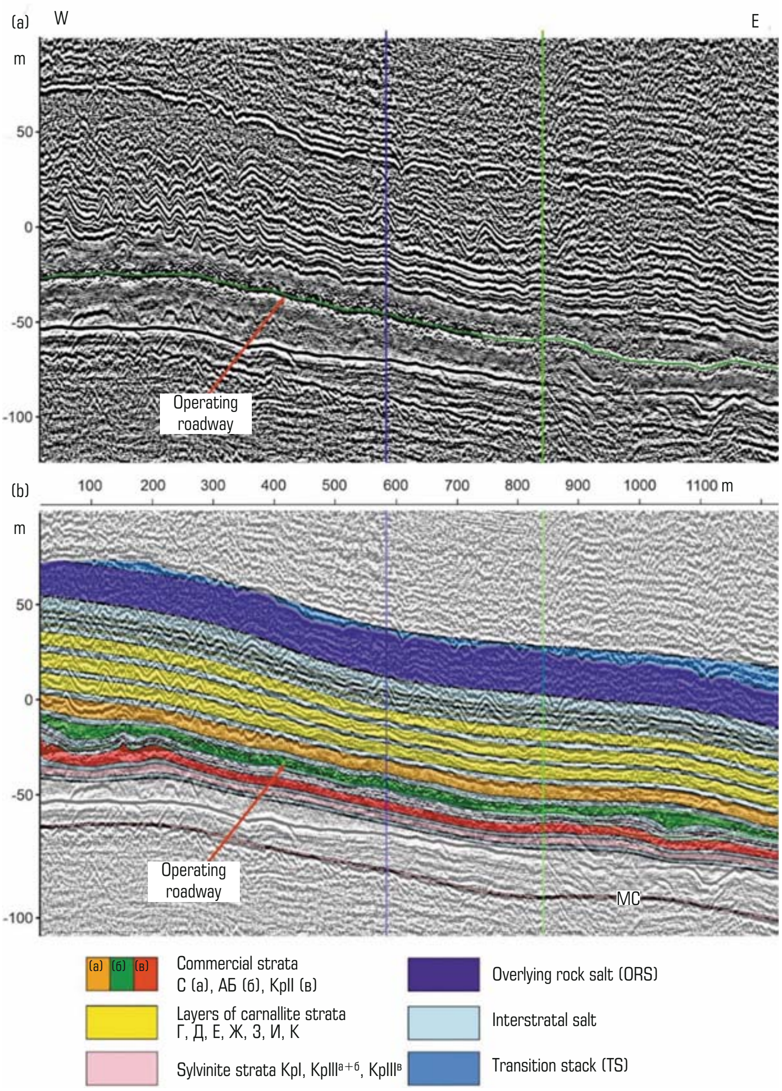

Fig. 5. Fragment of seismic cross-section without (a) and with (b) interpretation

Together with the traceability of carnallite rocks in the WPS interval by the behavior of the reflection horizons, it is also possible to predict the intensity of folding of these carnallite-bearing layers. The VKSD folding is multi-scale [2], often disharmonic and features higher intensity at uplifts. The folding behavior is visually observable in the interval of the commercial-value seams under mining (**Fig. 4**), but in the above-lying WPS, such observation is impossible as it is forbidden to cause damage to WPS. Single intersections with mine shafts are the exceptions.

Seismic surveying with SWSR makes it possible to study folding in WPS. For example, according to the reflection horizons in **Fig. 5**, the west part of the cross-section features a more intense folding than the east part. Eastward of the uplift, the folding becomes gentler or vanishes all together, which is observed actually in the roadways being mined and is proved by the reflection seismics in the upper-lying carnallite-bearing strata. At the same time, intensive folding is traced over the overlying reflecting horizons of the potash deposit at a greater distance than over the underlying horizons.

Given the complex folding (overfolds, dipping folds, isoclines, etc.) in VKSD, the reflection horizons image the folding with distortions because of the interference and dissipation of the reflections from the folds. Furthermore, in profiles laid along the axes of the folds, the interference of the reflections coming to the observation line from different directions is observed.

Figure 6 shows the interpreted seismic section combined with a geological drawing based on the actual underground observations. It is seen in fig. 6 that above an overfold observed in the roadway, there are traceable simpler folds (0–100 m from the beginning of the profile), which is reflective of the flattening of the folding bottom–up the section.

Figure 6 depicts one more interesting anomaly. Above the fold mapped in the roadway, the WPS roof contains a canyon-like erosion wedging-out expressed in terms of an abrupt subsidence of the reflection horizon associated with the blanket salt roof as against its expected position. The data interpretation allows supposing that in this case, together with the transition stack salt, much salt from the blanket is also dissolved. The erosion wedge, its mechanics and impact on the mine safety were in detail considered in the previous study on geological features discovered by the SWSR-based seismic survey.

The SWSR method provides a higher-level analysis of rock masses, and allows the well-to-well adjustment of the positions of critical components in the geological section of the salt table, affecting the mining safety, which was impossible earlier.

Furthermore, it is seen in fig. 6 that the folding intensity grows toward the uplift, which is a typical feature of dome structures in the conditions of salt tectonics.

Summing up, the SWSR method makes it possible to study salt table, and occurrence and folding of rocks bearing carnallite. Carnallite is the most brittle salt in VKSD, and is readily solvable with water; for this reason, it is excluded from the calculation of water-resistance properties of WPS and calls for a greater care.

It should be mentioned that each reflection horizon is formed at the interface of rocks having different physical and mechanical properties but it is not always that the horizon position agrees with the actual lithological and, the more so, stratigraphical boundary. For example, in figs. 5 and 6, it is seen that the salt interbeds between the thick strata В, Г, Д, Е merge into a single horizon, most probably, since the thin interbeds are at the limit discriminability of the SWSR method. There is a chance that the reflections from the roof and floor of the same seam, or of a group of thick carnallite seams merge into the same horizon. Furthermore, there are cases when carnallite seams are partly replaced by sylvinite or have interseam layers of rock salt, which complicates geological interpretation of geophysical data. Eventually, a reflection horizon in the potash strata points at the presence of carnallite-bearing rocks in the section of WPS, and allows judging on the behavior of folding in this interval.

The further research should focus on sensitivity of the SWSR method to the minimum content and distribution of carnallite and insoluble residue in rocks, capable to form an independent reflection horizon.

In the seismic profiles laid in parallel to the folding axes, the reflection horizons show up worse and less unambiguously than in the profiles across the folding. This agrees with the theory of seismic exploration— a 2D profile is incapable to provide a better quality image of folding which is parallel to the profile. In this case, the way out is the use of the three-dimensional field geometry. Summing up, the SWSR method, as any other geophysical method, should always be attended by an expert geological interpretation and supported with drilling data.

The method SWSR drastically improves investigation of the structure and composition of the waterproof strata at an interwell distance, which directly contributes to the enhanced mining safety. The application of this method in the forward underground exploration greatly helps select and optimize mining patterns and flowcharts.

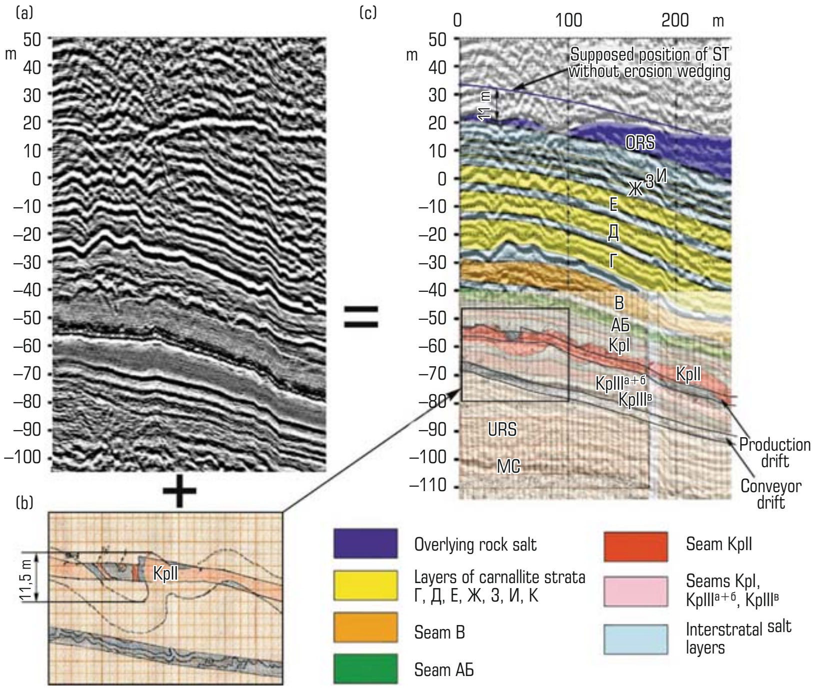

Fig. 6. Seismic section (a), geological drawing of drift sidewall (b) and geological interpretation of potash strata interval (c)

Conclusions

The underground seismics using the SWSR method has for the first time provided the interwell seismic data which enable:

- finding signs of carnallite replacement by other salts;
- delineating areas of spreading and replacement of carnallite-bearing rocks in WPS;
- tracing the folding behavior in carnallite-bearing rocks in WPS;
- identifying signs of presence / absence of rhythm stacks inside WPS;
- adjusting position of the roof of WPS at the interwell distance.

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