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R. I. TSAREV [1, 2], Head of Direction, Associate Professor, Candidate of Engineering Sciences, Roman.Tsarev@uralkali.com
A. M. PRIGARA [1, 2] Head of Direction, Chair of State Examinations Commission, Candidate of Engineering Sciences
A. A. ZHUKOV [1], Head of Laboratory, Candidate of Engineering Sciences
A. A. MITSKEVICH [1], Engineer

[1]VNII Galurgii JSC, Perm, Russia
[2]Perm State National Research University, Perm, Russia

MONITORING OF GEOLOGICAL ENVIRONMENT DURING MINING USING LAND AND IN-MINE SEISMIC SURVEYS

This research aims to assess feasibility of control over geological environment in the course of mining operations with the help of land and in-mine seismic and detection of possible changes in hypsometry of geological boundaries and in physical and mechanical properties of rocks in time (monitoring). The subject of research is the salt strata and overlying rocks at the Verkhnekamskoye Potash Deposit situated in the area of the Berezniki and Solikamsk towns in the Perm Krai. The line of the land seismic survey coincides in plan view with one of the underground seismic lines. The land seismic study involved excitation of spherical waves by blasting explosive charges embedded in blastholes and the reflected wave method of the common depth point (RWM CDP). In the in-mine seismic study and monitoring at the inner points of the test environment, the point force was excited by an impact directional source with recording of shear waves using RWM CDP with separation of reflections (SWSR). As known, stopping operations induce subsidence of ground surface which may cause changes in properties of rock mass above stopes. Within the research framework, the data of land and in-mine seismic are correlated with each other and with the acoustic logging (AL) and underground testing results. The results prove a good agreement between the recorded data on locations of the main reflecting boundaries and on temporal thicknesses of the main lithologic types. Within the research, the major advantages and limitations of the discussed geophysical methods are determined. Land seismic is convenient to study geological structure and detecting large changes connected with strong subsidence and deformation, and is suitable for monitoring critical sites of the geological environment, with a complex geological and tectonic situation, after mine closure– with a view to controlling solution of salt strata. In-mine seismic allows highly detailed monitoring sensitive to even minor changes in the geological environment.

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Introduction

The object of study is a geological environment between ground surface and the floor of the salt strata at the Verkhnekamskoe salt deposit which is located in the north of the Perm Krai and is one of the largest formations of potassium salts in the world. The salt deposit has a shape of a lens striking approximately north–south. The geological structure is complex and in downward direction consists of: quaternary deposits, speckled strata, terrigene–carbonate strata, salt–marl strata and salt strata. The salt strata are the thin-bed alteration of rock salt, sylvinite, carnallite and clay. The salt strata occur at a relatively shallow depth of 250 to 650 m on average, and the pay zones of potash lie at a depth of 350 m approximately. The upper part of the section (UPS) is an quaternary system composed of disperse unconsolidated rocks of different genesis (sand, sandy clay, loam, clay), variable thickness and at different ratios. The quaternary deposits thickness reaches 80 m at the deposit and ranges from 5 to 20 mm at the test site [1–3].

In conformity with the federal norms and internal production procedures of subsoil users, the mining system applied at the test deposit involves stiff pillars to preserve integrity of the impermeable waterproof strata. The stiffness standards imposed on the rib pillars and on the general mining system are governed by the rate of loading and density of backfill, and are set to ensure stability of stopes with regard to geological and geotechnical conditions.

As experience of salt mining in Russia (USSR), Germany, Canada, Belarus and Congo shows [4, 5], rib pillars have propensity to convergence and spalling, and stope roof — to bending and caving. These processes can provoke cracking in overlying rocks of the waterproof strata (WPS), which, in its turn, can lead to inflow of above-salt water in stopes. Water intrusion in underground openings at water-soluble mineral deposits often results in mine flooding.

The major causes of loss of a mine are, first, the lack of reliable information on geological structure and location of fault zone in the mining area [4] and, second, the underestimate of field experience of accidents and floods in mines [5].

The aim of this study is to assess feasibility of geological environment control in the course of mining operations using the methods of land and in-mine seismic, and potentiality of detection of alterations in hypsometry of geological boundaries and in physical and mechanical properties of rocks within the monitoring time. The impellent for the research is the risk of subsidence and deformation of ground surface and geological strata above the mining area.

The seismic monitoring was carried out in an operating mine, and included both ground and in-mine observations.

Method

The research consisted of three stages:

– in-situ study of the geological environment (before starting mining operations);
– study in the course of mining operations;
– study after completion of stopping and backfill.

The geophysical exploration included:

– RWM-CDP land seismic acquisition [6–11];
– RWM-CDP SWSR underground seismic prospecting [12–14].

The land seismic line coincided in plan view with one of the underground prospecting lines. The observation ground represents a rough topography. The ground seismic signal source was an explosive charge placed on the bottom of a hole. In the ground survey, a spherical wave was generated, and P-waves were recorded by vertical seismometers. The in-mine excitation conditions were nearly perfect as elastic vibrations were excited and received directly in dense rocks. The underground source of seismic signals was a club hammer which generated a point and directional impulse. The subject of study was horizontally polarized shear waves SH.

The observations were carried out from sides to center. On ground surface, the observations were carried out at a spacing of 5 m for receiving points (RP) and 10 m for source points (SP) at the spread length of 715 m, which conformed with 144 channels. The in-mine observations had RP spacing of 2 m and SP spacing of 4 m at the spread length of 190 m, with recording in 96 channels. The seismic lines were straight. In the study, year in year out, RP and SP laid at the same places traced by highly precise topographic and geodetic surveying. The monitoring period lasted from 2020 to 2023. Ground survey was carried out once a year, underground survey — twice a year. The analysis of the ample obtained theoretical and practical knowledge is presented in this article.

Results

A feature of the recorded seismograms in ground survey is the presence of high-amplitude surface noise waves that interfere with useful signals in the target interval. The dominant frequency was 60 Hz in ground survey and 500 Hz and above in underground survey. The in-mine data are characterized by the presence of high-frequency microseisms with the frequency over 1000 Hz and low-frequency noise in a range to 100 Hz, which are effectively removed by frequency filtering.

For comparing detail of the methods, on the basis of average velocity in the section and dominant frequency, it is possible to determine vertical resolution in the given conditions. It is 12 m in ground survey and 1.25 m in underground survey. Vertical resolution shows a stratum thickness value allowing outlining the roof and floor of a stratum.

The seismograms of both ground and underground survey contain hyperbolic time curves of reflected waves (**Fig. 1**). The in-mine seismograms also include linear curves connected with reflections from cross-passages between a drift, where the line of excitation and receiving is located, and stopes. A common feature of ground and underground survey is reflections from the transient stratum roof (rTS), carnallite stratum roof (rCS), marking clay (MS) and from the lower transient stratum roof (rLTS).

In the time sections of land seismic (**Fig. 2*a***), reflections from rTS (WPS roof or salt table), rCS, MC and rLTS (upper layer of marl in the lower stratum of underlying rock salt URS) are well traced. The dynamic intensity of the reflections is high, the bedding is sub-horizontal and the strata have a consistent interim thickness. Plicative dislocations intrinsic to salt tectonics [15, 16] are

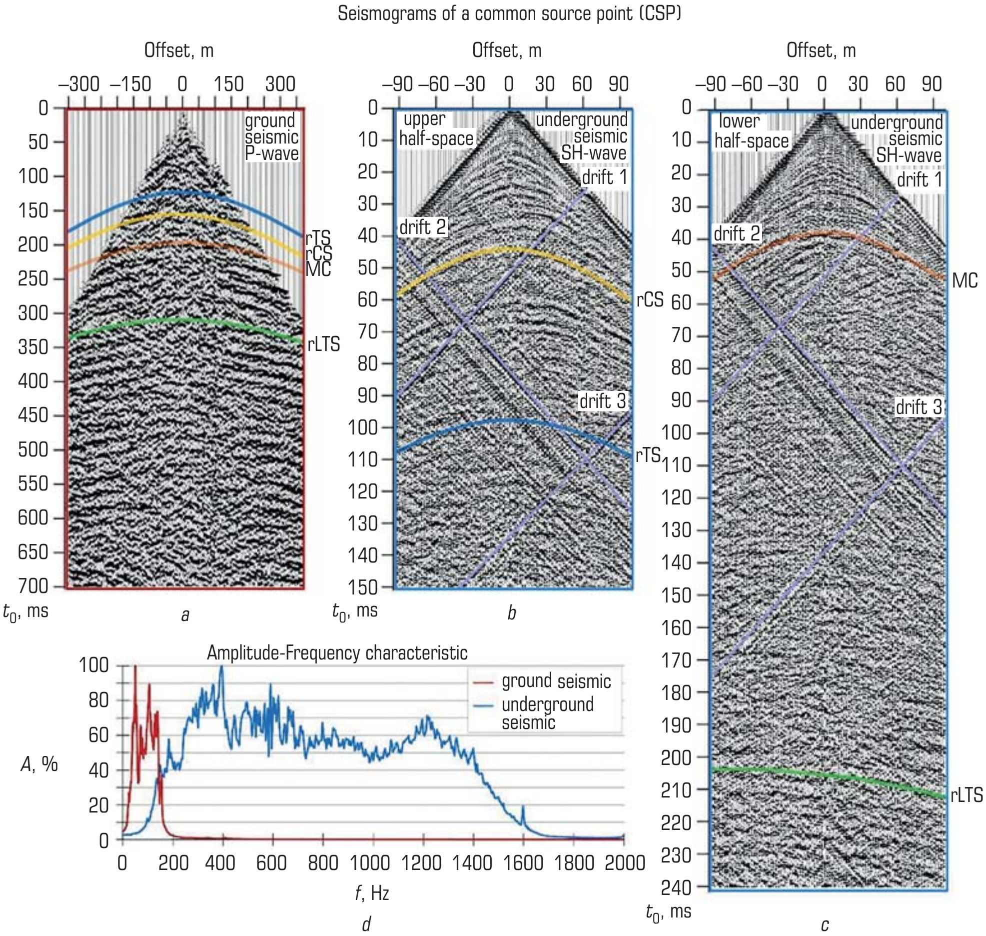

Fig. 1. Seismograms and their amplitude–frequency characteristic:
a – ground seismic survey; *b* – underground seismic survey upper half-space; *c* – underground seismic survey lower half-space; *d* – amplitude-frequency characteristic

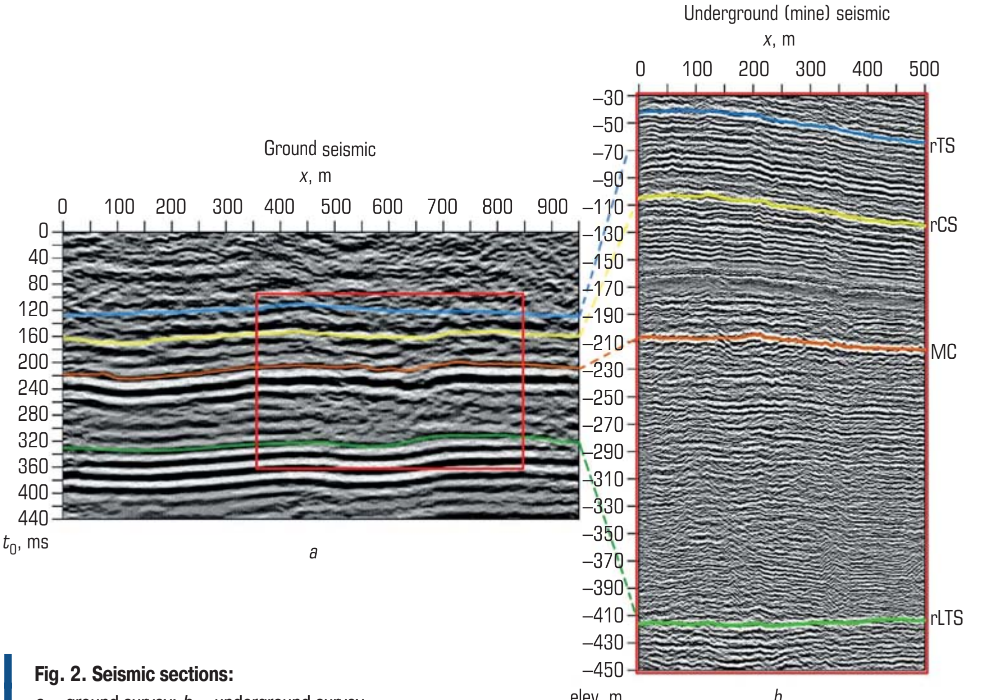

Fig. 2. Seismic sections:
a – ground survey; *b* – underground survey

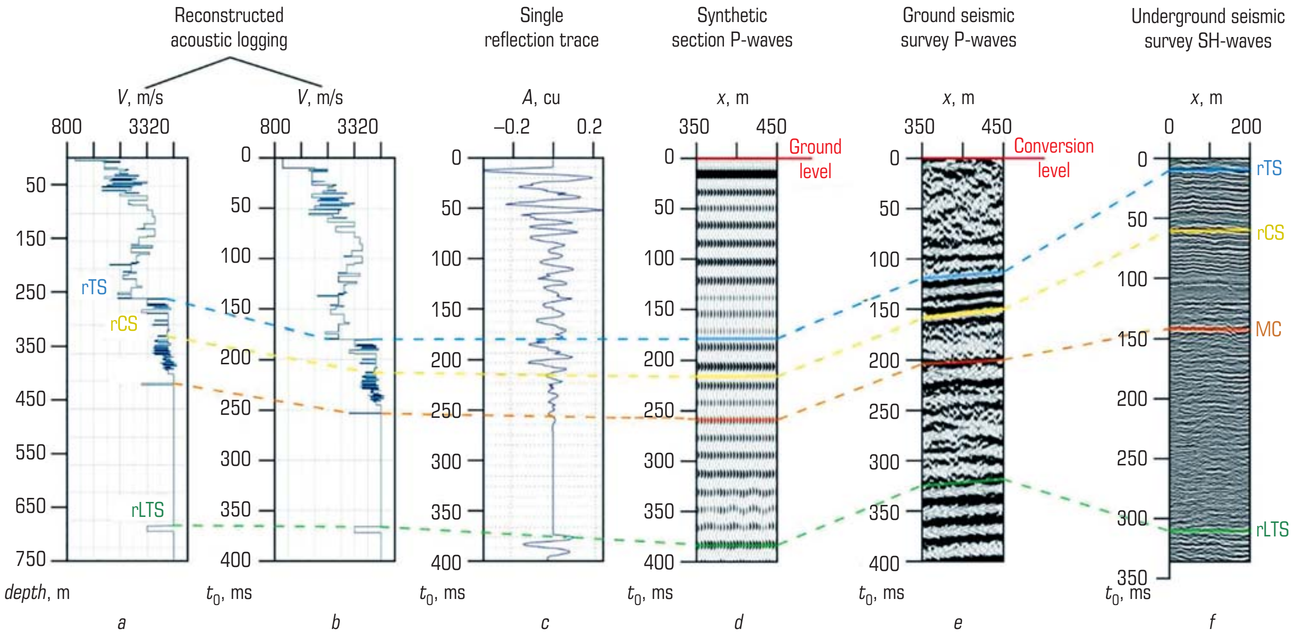

Fig. 3. Data binding tablet:
a – reconstructed acoustic logging in depth; *b* – reconstructed acoustic logging in time; *c* – single reflection trace; *d* – synthetic section; *e* – ground seismic section; *f* – underground seismic section

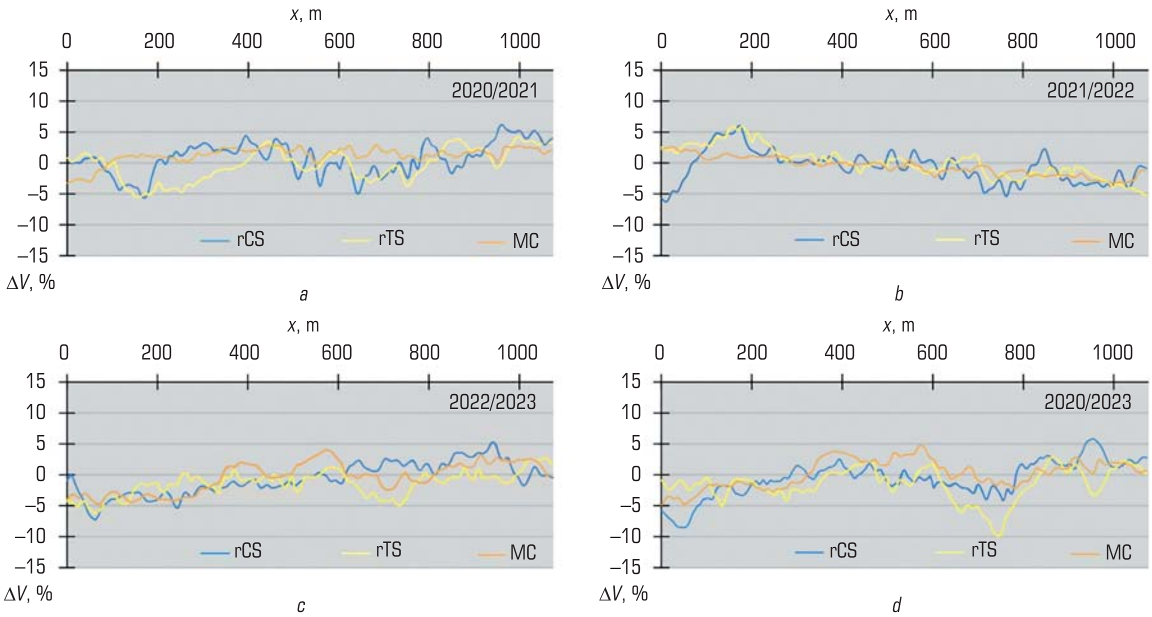

Fig. 4. Graphic charts of variation in average velocities:
a – 2020 to 2021; *b* – 2021 to 2022; *c* – 2022 to 2023; *d* – 2020 to 2023

unrevealed by ground survey since their sizes in the test area are smaller than the horizontal resolution.

The in-mine SWSR seismic produces the depth sections (**Fig. 2*b***) which display the geological structure of the test area in considerable detail. Such comprehensiveness allows identifying local intra-salt deformations, folding, variation in thickness of WPS and exhaustiveness of the section.

The land and underground seismic data were bound with the acoustic logging (AL), in-mine tests (positioning survey of stopes and drifts, sketching of strata on walls of stopes and boreholes) and seismic modeling [17–21]. From the binding results, the recorded data on position of the main reflecting boundaries and on interim thicknesses of the main geological strata were correlated (**Fig. 3**).

For the quantitative evaluation of local changes, deviations from average velocity were calculated using the test results from 2020 to 2023. The calculations assumed the same (unaltered) positions of geological boundaries matching the natural geological structure as per 2020. Later surveying showed no significant subsidence of ground surface and geological layers in WPS. With such approach, the temporal variation of the wave arrival time is only connected with the change in the physical properties of rocks in the above-salt strata.

Figure 4 shows the graphic charts of P-wave velocities which vary in a range of ±5% in ground survey. At the average velocity of 2800 m/s, the changes are ±140 m/s, which is commensurable with a measurement error for the depth of 500 m. The results prove high consistency of the study data on the geological environment.

The major difficulty in ground survey is determination of velocities in UPS and calculation of static corrections. Since the unconsolidated (disperse) rock strata are very thick and the terrain is cut with narrows and creeks, there are errors in true hypsometry of strata, which can only be reconstructed using the data of in-mine seismic.

Interpretation of underground exploration reduced to detection of structural features of WPS, i.e. the interval between the roof of the upper stratum being mined and the roof of the upper salt layer in the geological section. During interpretation, the reference reflecting strata rTS and rCS were identified inside WPS, and their positions were correlated with the investigation holes. The noticed consistency of the results obtained during the monitoring tests talks of the reliability of structural imaging based on the in-mine SWSR seismic survey data.

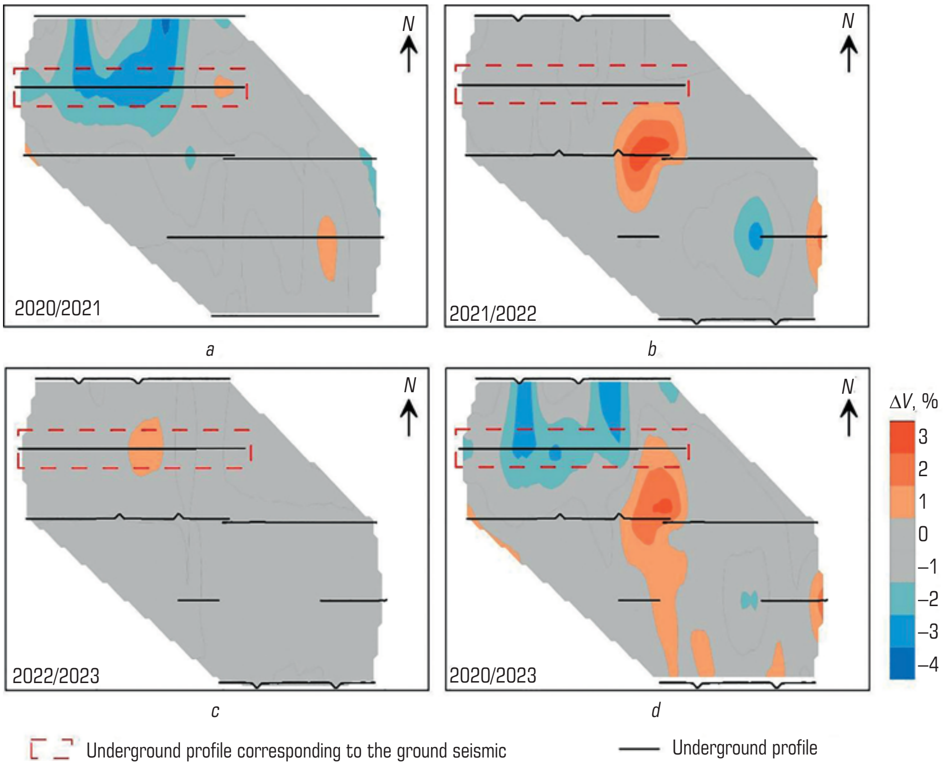

Fig. 5. Maps of relative change in average velocities in waterproof stratum:
a – 2020 to 2021; *b* – 2021 to 2022; *c* – 2022 to 2023; *d* – 2020 to 2023

For the quantitative evaluation of local changes, deviations of the average velocity were calculated from the test data from 2020 to 2023 (**Fig. 5**), and the maps of the deviations were plotted starting from the velocity level of 2500 m/s with the assumption of constant thickness of WPS. The deviations of the average velocity are not higher than 4%.

The underground monitoring completed in 2023 showed that neither composition nor structure of WPS changed since the initial estimation of its condition in the beginning of monitoring in 2020. Accordingly, by the time of the last cycle of monitoring observations in the second half of 2023, no changes in WPS higher than observational error were revealed.

It is worthy of noting that the major changes occur nearby dynamic mining operations which affect the quality of the recorded signals. In the natural occurrence analysis, when the mine field only represented development drifts, the quality of the recorded signals was high. Stopping resulted in formation of voids in rock mass. As a consequence, the dynamic equilibrium was violated, and deformation processes were actuated, which induced cracking and convergence of pillars, as well as roof caving and floor buckling in stopes. Aiming to weaken the deformation effects, hydraulic filling of stopes was carried out, with the mouths of stopes at cross passages (intersections) with stopping drifts remained unfilled, i.e. with the conveyor drifts cut with the cross passages.

As a consequence, the recorded seismic field contains some artefacts (**Fig. 6**) associated with the missed points of excitation and receiving and, accordingly, with the reduction of the repetition factor of observations. For another thing, the adjacent rock mass becomes nonuniform, which causes dissipation of elastic waves and leads to a general decrease in the quality of the acquired data.

Figure 6*a* contains three domains of reduced coherence, which coincide with the intersected stopes. When the extraction panel was totally mined-out (**Fig. 6*b***), the number of stopes increased, which resulted in even greater degradation of the acquired data.

The adverse effects in the wave pattern because of the geotechnical conditions make seismic attributes (variations in amplitudes, frequencies, phase characteristics and their derivatives) totally uninformative. The geological structure (depth and incline of geological interfaces, thickness of strata) is reconstructed satisfactorily.

Discussion

Processing of land seismic uses procedures of automatic amplification or correction of amplitudes (AGC) which distort dynamic characteristics of reflecting boundaries and even the recorded field. On the other hand, the AGC procedures help reconstruct structural features in a thin-bedded section and amplify (compensate) low-amplitude reflections from weakly contrast reflecting boundaries.

Underground seismic exploration is complicated by various cross-cuts, declines and multi-strata mining, which distort the recorded signals. If a seismic profile is located nearby a site with varied geotechnical conditions, the distortion of amplitudes, frequencies and phases is unavoidable. For this reason, interpretation of dynamic characteristics is only possible in case of ideal conditions of receiving and recording, which is achievable in single mine drifts without any other underground openings in enclosing rock mass.

Conclusions

The monitoring investigations implemented within three years revealed neither subsidence of ground surface and nor deformation in the waterproof strata and in the above-salt rock mass. The strata occur relatively consistently and subhorizontally. The deviation of the average velocities of wave reflections from the reference boundaries rTS and rCS is never higher than 4%. The accomplished research proved feasibility of geological environment monitoring both on ground surface and in mine using the seismic exploration methods of different comprehensiveness.

The authors have for the first time ever correlated the land seismic, underground seismic and acoustic logging, and determined the main limitations of these methods on this basis. In land seismic, adverse effect is mostly exerted by the presence of unconsolidated and disperse rocks in the upper

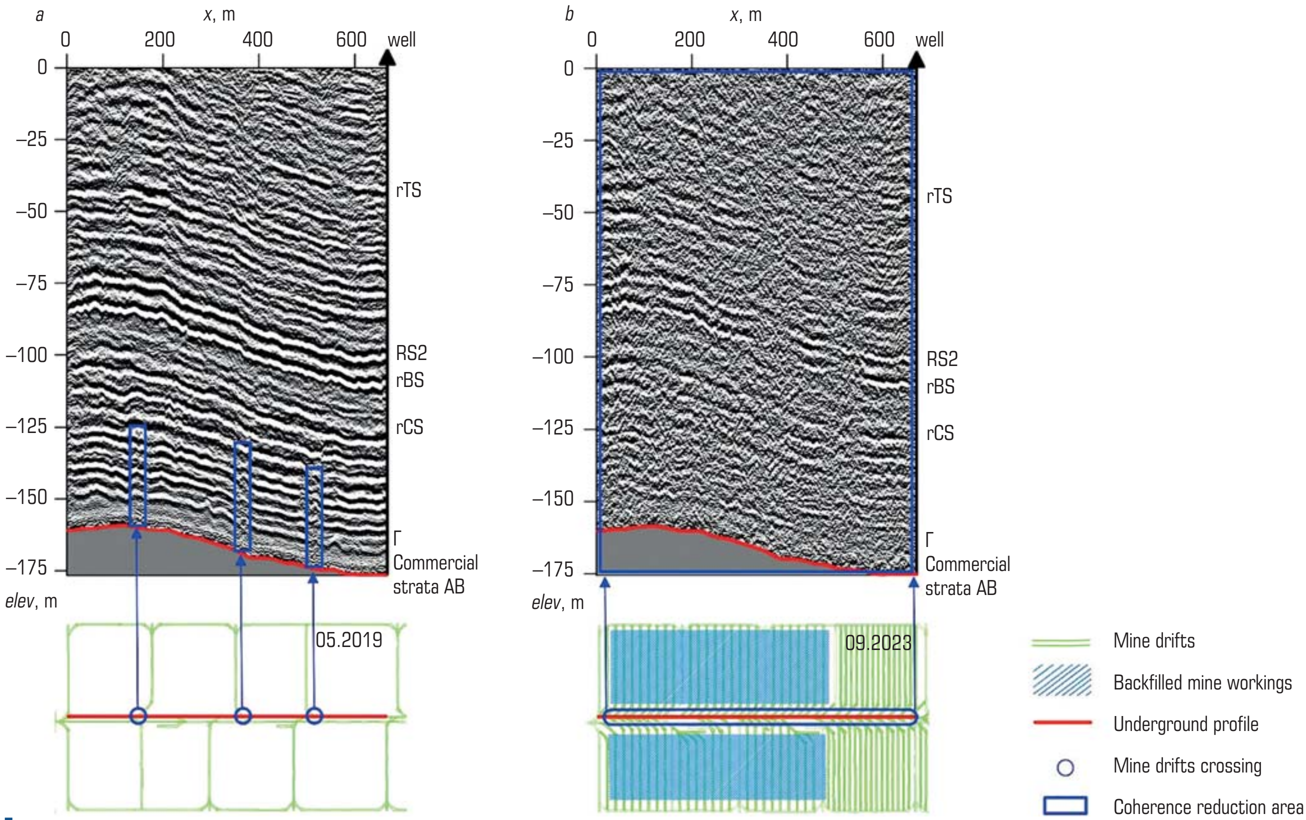

Fig. 6. Geophysical profiles:
a – before stoping; *b* – after stoping and backfill

part of the cross-section, by the rough terrain and relatively low frequency of recorded signals, which inevitably reduces resolution. In in-mine seismic, the low quality of data ensues from geotechnical conditions of a test site (a few strata being mined, many cross-passages, operation of transport machines). The main limitation is feasibility of seismic studies only in driven drifts.

The package of the ground and underground seismic exploration surveys proposed by the authors can be considered as a promising approach.

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