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GPR Investigations in Upper Kama Potash Mines

by

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16. Abstract

This project is aimed at graduate research training of students interested in pursuing careers in transportation areas. Each year, financial support was provided to recruit eight new graduate students interested in pursuing a doctoral degree in a transportation area. These students could pursue doctoral studies in any department at Missouri S&T. In departments where a master’s degree is the highest degree awarded, students pursuing a master’s degree with a thesis option will be considered. Areas stated in the goals, interests and objectives of the State Departments of Transportation and Missouri Department of Transportation in particular were considered for support in this project.

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GPR Investigations in Upper Kama Potash Mines

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Summary

Geohazards posed by the surface subsidence accompany extensive exploitation of the potash deposits and cause serious damage to property, infrastructure and industry facilities on the surface. Undermined areas of the Upper Kama (Verkhnekamskoye) potash deposit within the cities of Berezniki and Solikamsk (Perm region, Russia) present an especial threat for their population safety. Large chemical and power plants, roadways, railroads and gas pipelines are located within the subsidence zone. The significant losses of company and state budget due to replacement the roadways and infrastructure objects from the risky area were reported after the catastrophic collapses at the mines BKRU-2 in 1988 (Fig. 1) and BKRU-1 in 2006 (Fig. 2).

Fig. 1. Collapse zone at the BKRU-2 mine.

Studying of deformation of the rock mass surrounding the mine openings is very important for safe mining, planning the methods of extraction of an orebody, and, especially, preventing the catastrophic water inflow in the potash mines. Geophysical methods have proven to be an effective, nondestructive investigative tool, providing mining engineers with continuous information about the structure and geomechanical properties of subsurface material.

Fig. 2. A salt collapse structure above the BKRU-1 mine.

Preliminary experiments in the Upper Kama potash mines show that the GPR (ground penetrating radar, georadar) method is capable of providing the most detailed and continuous information about the rock mass structure at the distances of up to 40 m from mine openings.

About 6 km continuous common-offset GPR profiles were collected in the potash mine of the JSC “Silvinit” located near the city of Solikamsk (Russia) in order to develop the site-specific methodology of data acquisition, processing and interpretation. Data were collected at the upper mining level where the tension vertical fractures were exposed by the workings as well as at the lower level to estimate an extent of the fracture zone.

Small portion of data comprised seven parallel 8 m long profiles spaced at 0.2 m was used to create a 3-D grid for imaging of the millimetric scale surface-exposed fracture.

The OKO (Logis, Russia) and RAMAC/GPR commercial georadar systems were employed for data acquisition. The software used for data processing and interpretation was REFLEXW (Windows OS) and OpendTect (Linux OS).

Although the GPR method has been used in German and Canadian salt and potash mines for long time, the geological and geotechnical environments of the German and Canadian deposits differ significantly from those of the Upper Kama deposit. Consequently, the appropriate GPR acquisition, data processing and interpretation methodologies were developed.

Because of intensive folding of different range, GPR data are significantly contaminated with diffractions and a migration is required to make the data interpretable.

The results of data analysis show that GPR method may be of great utility for detection of the small-scale fractures and the flexure folds at the depth up to 20 m. The 3-D imaging technique has proven to be an effective tool for studying the geometry of the fractures.

This study has the following results:

- the electrical properties of typical rock salt formation members were determined,
- the site-specific data acquisition technique and object-oriented data processing schemes consistent with the local geological and geotechnical environment are developed,
- the methodology of 2-D and 3-D GPR data interpretation using interactive modeling is worked out.

Introduction

Geology and Geotechnical Conditions

The Upper Kama (Verkhnekamskoye) potash deposit is situated to the west of the Ural Mountains in the northern part of the Perm kraj (Russia), about 250 km north of the city of Perm (Fig.3).

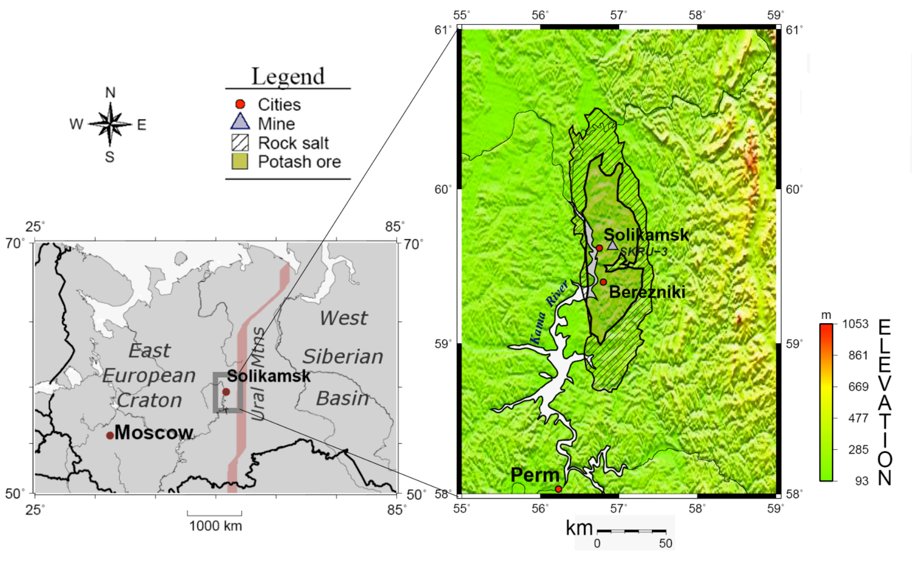

Fig. 3. Location of the Upper Kama (Verkhnekamskoye) potash deposit.

The joint stock corporation (JSC) Uralkali of Berezniki operates the southern part of the potash deposit, and joint stock corporation Silvinit of Solikamsk operates the northern area.

The term potash denotes a variety of mined and manufactured salts, all containing the element potassium in water-soluble form. Potash is a mixture of three minerals: sylvite (potassium chloride - KCl) with lesser amounts of carnallite (hydrated potassium magnesium chloride – $KMgCl_3$ $6H_2O$) and halite (sodium chloride – NaCl). Sylvinite, as the most sylvite-rich crude ore, is mined in the Upper Kama deposit. Some amount of carnallite is mined for the extraction of magnesium.

The Upper Kama potash deposit lies in central part of the Solikamsk (Solikamskaya) depression of the Pre-Ural margin basin. The Permian evaporite formation (Kungur subdivision, Middle Permian age) is up to 400 m thick, and is composed mostly of halite with substantial interbedded sylvinite, carnallite, clay, and anhydrite layers. The potash salts were deposited after the rise of the Ural Mountains in the late Carboniferous as a result of the continental collision between the East-European platform and West-Siberian plate (Warren, 1989).

The horizontally bedded rock salt is underlain by clastic Proterozoic rocks of 2-3 km thickness, Devonian reef sequence, Carboniferous and low Permian carbonate sediments of up to 1 km thickness. Clay marl, limestone, sandstone and siltstone beds of about 200 m thickness overlay evaporate formation (Fig. 4).

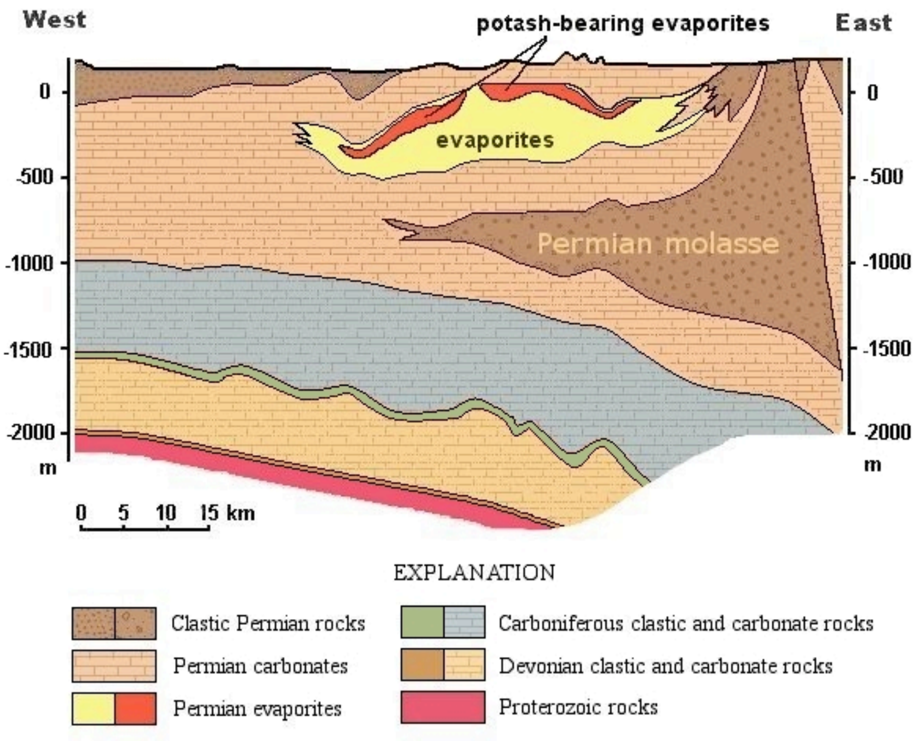

Fig. 4. Schematic geological section of the Solikamsk depression.

The uppermost 120 m of evaporite formation, termed the *productive formation*, contains economic deposits of potash, which include several beds of variable content of sylvite, carnallite and barren halite (Fig. 5). The sylvite-rich beds in lowest part of productive formation are the principal mining targets.

Tectonic and gravitational stress has caused within the evaporite formation extensive folding of different range (Jeremic, 1995; Kudryashov, 2001). Due to high plasticity of the salt beds a brittle deformation is not common in the rock salt formations but occurs when tectonic, gravitational or mine induced stress exceeds the strength of the rock mass (Brady, 2007). Widespread small-scaled fracturing in the Upper Kama potash mines is well documented (Kudryashov, 2004) mainly in thin-bedded clay seams. Open fractures occur rarely in productive formation, but they are a potential threat of inflow of external water into the mines (Fig. 6).

Mine openings are typically about 300 m below ground surface. A multiple-level room-and-pillar method is used to extract the potash ore. Mining is customarily done on 2 or 3 levels corresponding to the locations of the thickest potash-bearing beds.

The influx of water into a mine presents a significant danger because of the potential for dissolution of salt rock and gradual to catastrophic collapse. The upper part of *productive formation*, about 70–90 m thick is left un-mined along with the overlaying salt beds, to form a water protective barrier (Garrett, 1995; Kovin, 1997).

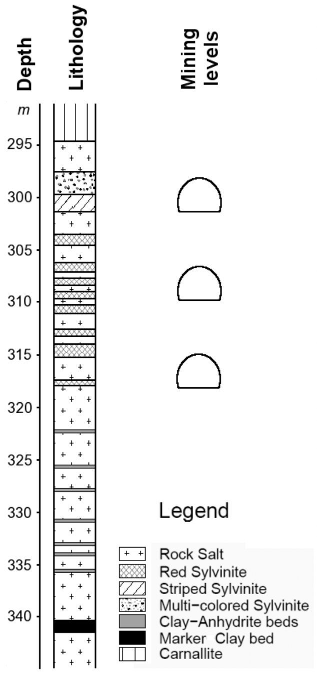

Fig. 5. Generalized geological section of interval of the productive formation available for GPR observation.

Mining problems

Geohazards posed by the surface subsidence are common in the areas of extensive exploitation of the potash deposits. Large sections of the cities of Berezniki and Solikamsk are undermined. The stability of the underground openings depends on factors such as the manner of mining, geomechanical properties of the pillars supporting the overlaying beds, and subsidence preventive measures employed (such as filling the mine workings with the potash ore post-processing wastes).

Abrupt changes in the geomechanical properties of the salt rock mass, caused by anomalous nature of the geological section (due to extensive folding, natural fracturing, lithology) can result in collapse of pillars, sudden surface subsidence, or even the flooding of mine due to water cover destruction.

Safety regulations on the operation in the potash mines require that all the high amplitude flexural folds and open fractures are considered as hazardous geological anomalies and should be thoroughly investigated. The flexure folding is considered as a prerequisite feature of presence of faults in the underlying basement rock salt.

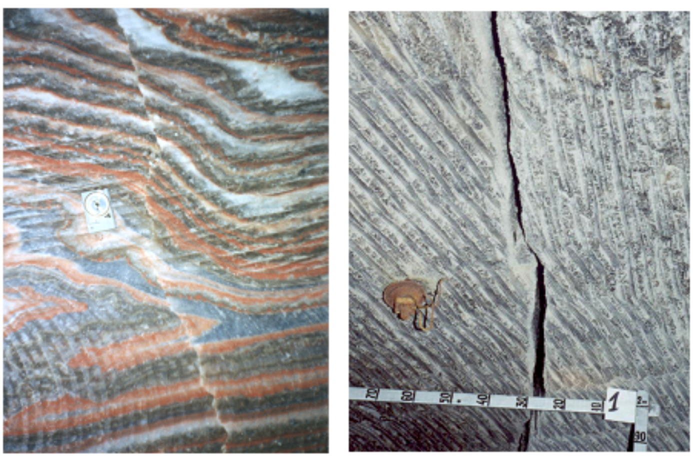

Fig. 6. Examples of the fractures exposed by the workings in the potash mine (Kudryashov et al, 2004).

Drilling into the salt beds above the roof is restricted due to potential damage to the water protective cover and its sampling rate does not provide detail information about subsurface structures. Consequently, the geophysical methods are considered as effective, non-destructive investigative tools, supplying geologists with continuous information about the surrounding rock mass structure along the mine workings.

The analysis of the geophysical data has shown that GPR provides the most accurate and detailed information about the subsurface at distances of up to 40 m from the mine openings (Kovin, 2000, 2002).

High-resolution, portable, easy-to-use and cost-competitive – the GPR method has proven to be most effective technology for detection and mapping of deformation features into the rock mass surrounding the mine workings (Kovin, 2004).

Method

Ground penetrating radar (georadar, GPR) method has a widespread set of applications in geology, civil engineering, archeology, construction industry and mining (Annan, 2002).

GPR method uses high-frequency (10–2500 MHz) short electromagnetic signal propagating through the medium with a velocity governed by the electrical properties of material. Energy reflected from the boundaries of materials with different electrical properties is recorded. Velocities, attenuation, amplitude and spectral parameters are typically used to estimate the properties of material (Orlando, 2003; Zeng, 2000).

Results of successful using GPR for the fracture detection and study of deformation are reported in numerous publications (Grandjean, 1996; Busby, 1999; Seol, 2001; Haeni, 2002; Orlando, 2003; Porsani, 2006).

Numerous recent publications showed great capability of 3-D georadar imaging to delineate the subsurface structures (Grasmueck, 1996, 2004; Gross, 2002, 2003, 2004; Christie, 2009).

It is known that the relatively low attenuation allows the electromagnetic signals to penetrate the substantial distance into the rock salt.

Information regarding the GPR mining application is rather scattered (Cook, 1975; Coon, 1981; Lang, 1996). First published GPR investigations of rock mass in salt mines environment have been reported by Holzer at al. (1972), Stewart and Unterberger (1976) and Unterberger (1978).

Recently, the GPR method has been extensively used to investigate mining problems in potash mines in Germany, Canada and Russia (Band at al., 1988; Annan at al., 1988; Kovin, 2000). Generally GPR method is applied for (Thoma, 2003; Maybee, 2004):

- mapping of geological interfaces and thickness of water protective layers
- investigation of fracturing in the vicinity of the mine workings
- detection of the unstable rock in the roof of openings for safety reasons
- evaluation of integrity of supporting pillars.

Detection of fractures in the potash mines was described by Annan (1988), Gregoire (2002), and Kovin (2003, 2006).

METHODOLOGY AND EQUIPMENT

Two GPR systems, OKO (Logis, Russia) and RAMAC/GPR (Sweden), were used for data acquisition in the potash mine. A set of the central frequency ranging 50 to 400 MHz georadar antennae was tested.

The principal objective of this survey was an investigation of the fracture zone exposed by mine workings at the upper mining level. 3-D georadar survey was conducted for testing the feasibility of the characterization of spatial geometry of the millimetric scale fracture. Although a few fractures at the lower mining levels were visually observed, the additional 2-D data were acquired at the conveyer drift to confirm the absence of fracturing in the underlying rock salt.

Continuous constant-offset mode is mainly used for the data acquisition. Step-mode measurements are used for the walk-away soundings in order to evaluate the velocity of the wave propagation in subsurface material.

Due to portability of antennae it is possible to pull them along the floor or carry along the wall for profiling (Fig. 7).

Fig. 7. Typical side-look profiling operations in Solikamsk mine 3 with OKO system.

For roof probing, antennas can be mounted on a special platform, but the surface irregularities and communications set on the roof do not allow using effectively any antennas bearing system. The testing of effectiveness of antennas depending on the position in the tunnel has proven that the signal reflected from the objects above opening is not affected if antenna is located near the floor.

The little signal directionality of the dipole antennae presents a considerable problem for interpretation of GPR data because of tunnel reverberation noise and side reflections. The usage of the shielded antennas considerably improves a quality of data acquired in the mine.

DATA PROCESSING

Common processing flow applied to both 2-D and 3-D data includes start time adjustment, "dewow" filtering to suppress the very low-frequency noise, 2-D filtering to remove the "ringing" and direct waves. Gain correction is needed to amplify week signals.

Analysis of the data revealed that for data acquired with the different georadar systems the different kind of noise dominates. It suggests applying the specific processing parameters to the each instrumentation used.

Usually the elevation of openings varies following the geometry of productive layer and a topographic correction should be applied to long survey lines.

Additionally the object-specific procedures can be applied. A result of *fk* filtering of 2-D profile along the sidewall of mine panel shows a valuable improvement of fracture detection (Fig. 8).

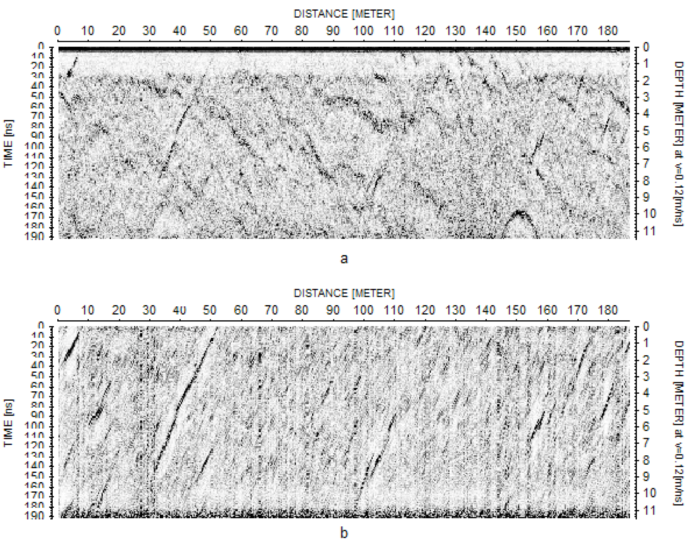

Fig. 8. GPR section before fk-filtering (a) and after (b). AGC gain correction and normalization data along the line are applied.

Band pass filtering commonly is not used but can be employed in case of noisy data or for correction the signal after some processing procedures.

Migration is used to remove diffractions from the records (Fig. 9).

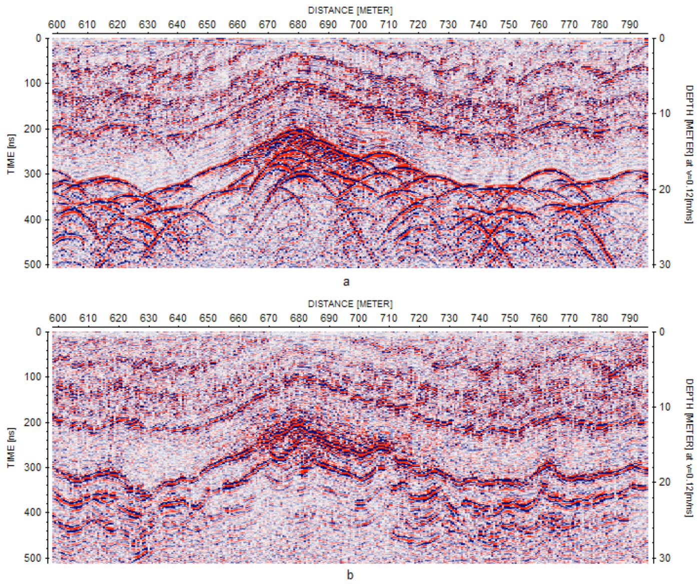

Fig. 9. Georadar section before (a) and after 2-D Kirchhoff time migration (b).

REFLEXW software was used for processing of 2-D data and preparing 3-D data set for three-dimensional migration and interpretation.

3-D data are further converted to SEG-Y format and loaded into the interactive system of data analysis OpendTect. Data are migrated using the Madagascar seismic data processing plugin. Fallowing 3-D Kirchhoff migration (Fig. 10), the data acquired at the pillar were analyzed and interpreted in order to define the spatial characteristics of the subsurface structure.

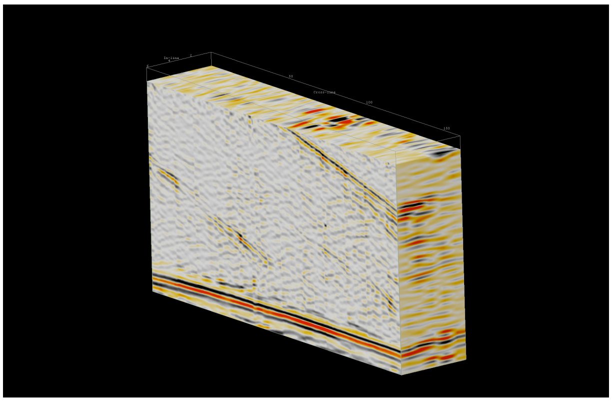

Fig. 10. 3-D data volume showing two fractures of dip angle of 25 degree.

DATA INTERPRETATION

Knowing the value of velocity of electromagnetic wave propagation in the material of subsurface is very import for correct interpretation. Laboratory studies of the samples of rock salt, walk-away soundings in the mine and information found in the publications suggested that velocity of 0.11-0.12 m/ns could be used for the time to depth conversion. The results of walk-away sounding of underlying rock salt are shown in the Fig. 11.

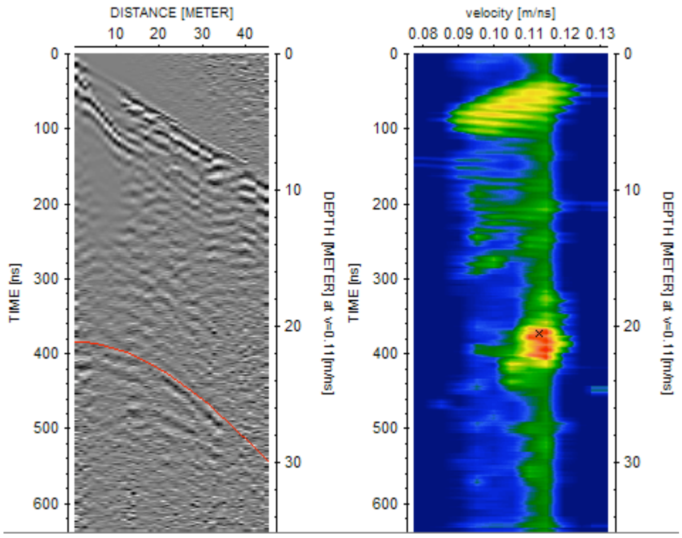

Fig. 11. Velocity semblance chart showing the velocity 0.11 m/ns for the underlying rock salt.

Constant velocity is used for all the calculations because the properties of the evaporite formation materials are significantly uniform.

Inversion of 2-D georadar data was done using iterative FD modeling. Initial model was derived from the migrated section (Fig. 12). Parameters of the marker clay layer were varied to fit to the row data.

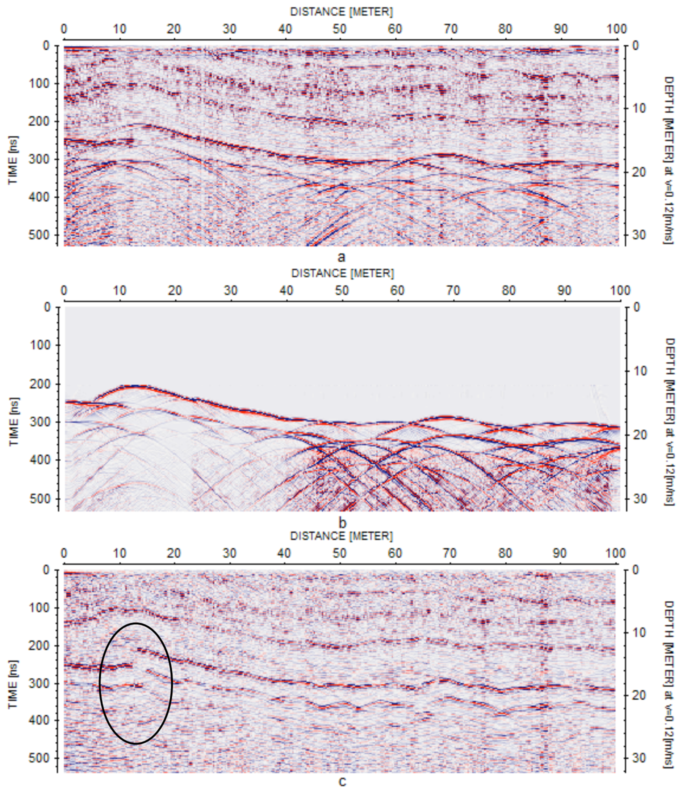

Fig. 12. GPR data inversion comprised the picking the desired horizon at the migrated section (c) to construct the initial model, iterative modeling (b) to fit the successive model to unmigrated data (a). In this case the resulting model of the marker clay layer complicated with a fault(identified by circle) clearly coincides with a raw record.

For identification of fractures the interpretation templates were worked out using such characteristics of exposed evident features as orientation, linear and continuous signature (see Fig. 8).

Previous modeling was performed to confirm the feasibility of GPR method to detect a millimetric scale fracture. The result of FD modeling is shown in the Fig. 13.

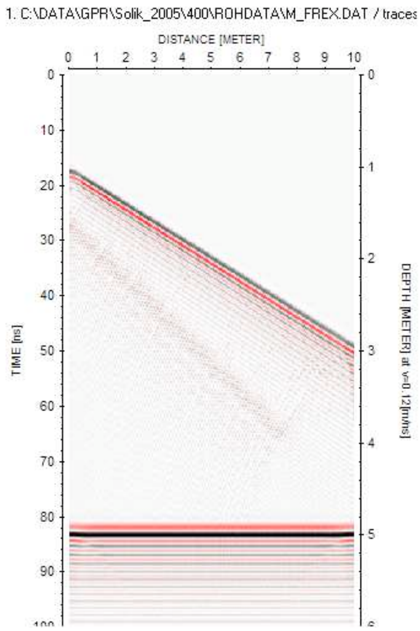

Fig. 13. Model of sounding of the mine pillar with millimetric scale fracture of dip angle of 25 degree.

3-D GPR data imaging allows significantly improve the detection and delineation of subsurface structures. 3-D image of the fractures in the mine pillar (see Fig. 10) is presented in Fig. 14.

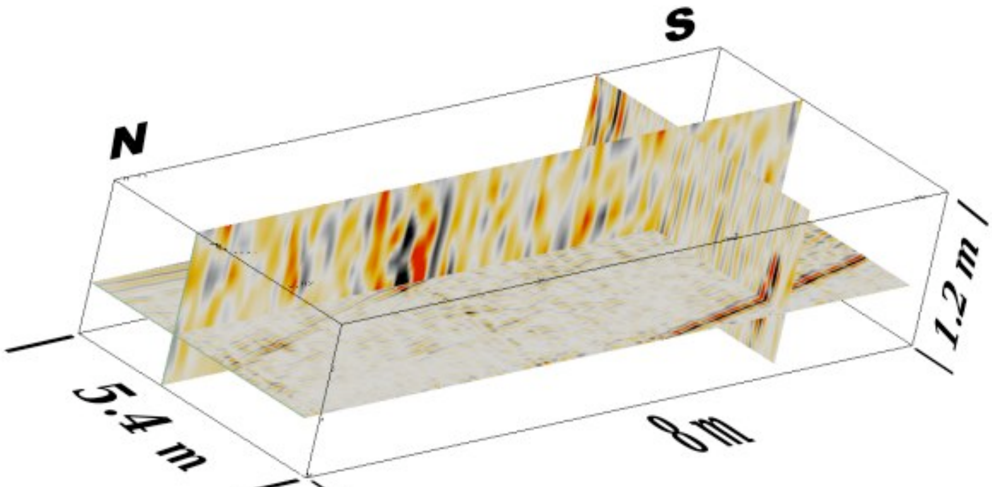

Fig. 14. 3-D image of two fractures. Orientation of the data volume corresponds to side-look direction of sounding.

Subsurface structures commonly are picked and the spatial model can be constructed (Fig. 15).

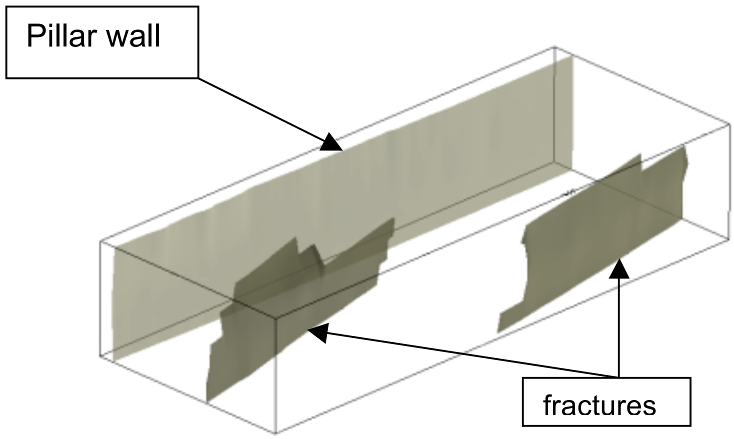

Fig. 15. Spatial model of two fractures into the pillar derived from the 3-D georadar data.

RESULTS

More than 6 km experimental GPR data were collected in the Upper Kama potash mines resulting in a comprehensive data base for studying the feasibility of georadar method to solve the potash mine problems.

Experiments conducted in the Upper Kama potash mines have shown that the probing depth of the electromagnetic signal of frequency range of 50 – 100 MHz does not exceed 40 m, because of high clay content and moisture condensate on surface of openings (Kovin, 2002). However, the penetration depth is still sufficient to achieve the exploration tasks.

Analysis of the acquired data has shown that the usage of georadar reflection method in potash mines of the Upper Kama deposit have some peculiarities that distinguish from those in the in German and Canadian potash mines. Interpretation of reflections from geological boundaries is significantly complicated because of multiple diffraction hyperbolae produced by the wide-spread multi-scale folding.

The object-oriented processing schemes were developed to effectively detect and delineate the subsurface structures.

Migration should be performed to improve the quality of the GPR image and to make the data interpretable. We can see on Figure 16, that the quality of mapping of reflection boundaries differs depending on the processing algorithm used.

The data shown in Figure 16 were acquired in the underlying rock salt using a 50 MHz unshielded antenna. The strongest reflector at the distance of about 20 m is a clay layer of thickness of about 2 m termed "marker clay". The weaker reflectors are presented by thin clay and anhydrite seems.

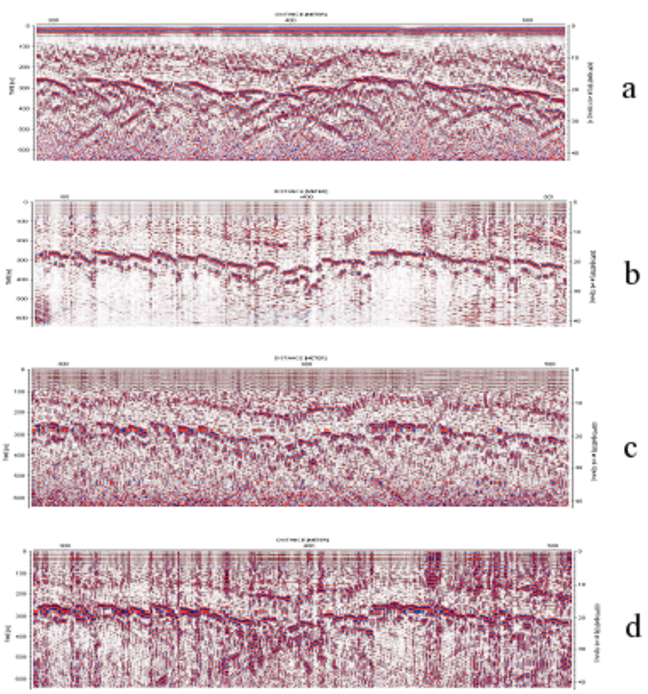

Fig.16. Comparison of quality of different migration algorithms: a – row data; b – diffraction stack; c – Kirchhoff migration; d – Stolt fk migration. It can be seen that the clearest image is produced with a simple diffraction stack, but Kirchhoff algorithm provides with more details. Stolt migration effectively restores the geometry of main boundaries but generates more artifacts at the noisy data.

The system of open natural sub vertical fractures directed NW-SE was exposed by workings in the upper sylvinite layer in Solikamsk mine 3 of the JSC “Silvinit” (Kovin, 2003; Kovin, 2004). Only a few open fractures were found in workings within the lower sylvinite layer. The GPR studies were designed to map the geological boundaries and determine an extent of the fracture zone above and below the openings.

Analysis of the radargrams obtained by side-look sounding of pillars shows that the open fractures of dip angles up to 25-30 degree can be clearly detected (Fig. 17).

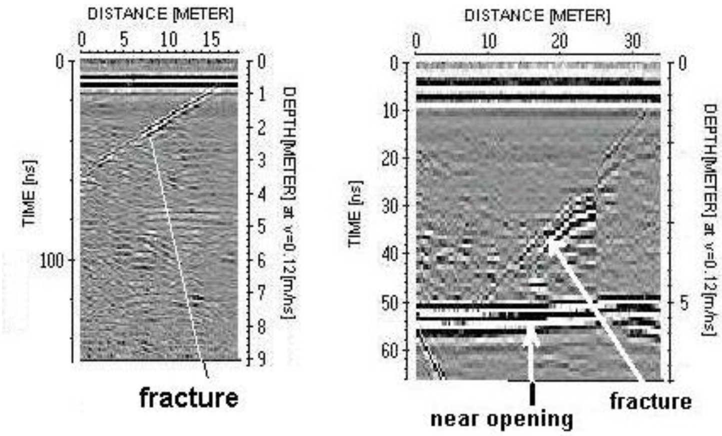

Fig. 17. Images of the open fractures into the pillars of room 166.

The location of these fractures was verified with visual inspection of mine workings. Interpretation templates of the fractures signature, developed by data analysis, were used for detecting the fractures inside the pillars (Fig. 18).

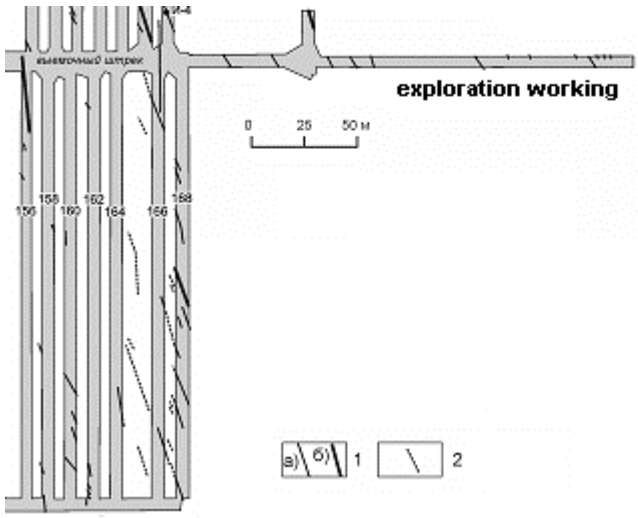

Fig. 18. Schematic map of fracturing distribution in the area of GPR survey: 1 – fractures detected by visual inspection of openings; 2 – fractures detected by georadar (Kudryashov et al, 2004).

As it is shown above, the 3-D imaging technique can significantly improve the effectiveness of georadar method to characterize the spatial parameters of separate fractures and fracturing systems.

It was found unfeasible to clearly define the geometry of sub-vertical fractures oriented perpendicular to the survey line and presented by column of separate diffractions generated in irregularities of the reflection surface or at the edges (Fig. 19).

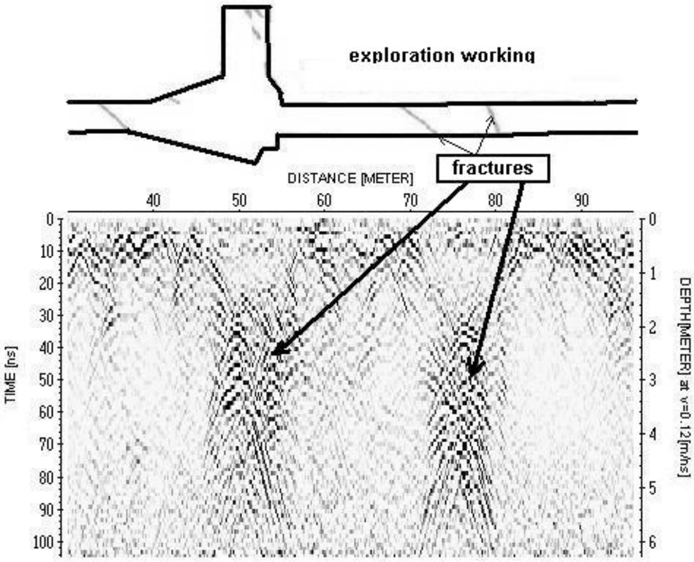

Fig. 19. 250 MHz GPR profile, acquired along the floor of exploration drift, shows the columns of diffraction hyperbolae that indicate the position of scattering points at sub vertical fracture surface.

Results of interpretation of the radargram obtained by sounding along the floor of the exploration drift suggest that maximum depth of fracture extent below this mine level is about 4 m. It is consistent with the fact of absence of fractures at the lower mining horizons.

GPR mapping of the geological boundaries below conveyer drift confirmed a widespread extent of flow folding in evaporate formation, which can cause the stretch strain and fracturing especially in case of flexure folds and overturned structures. The character of flow folding coincides with orientation of main regional tectonic and local gravitational stress (Fig. 20).

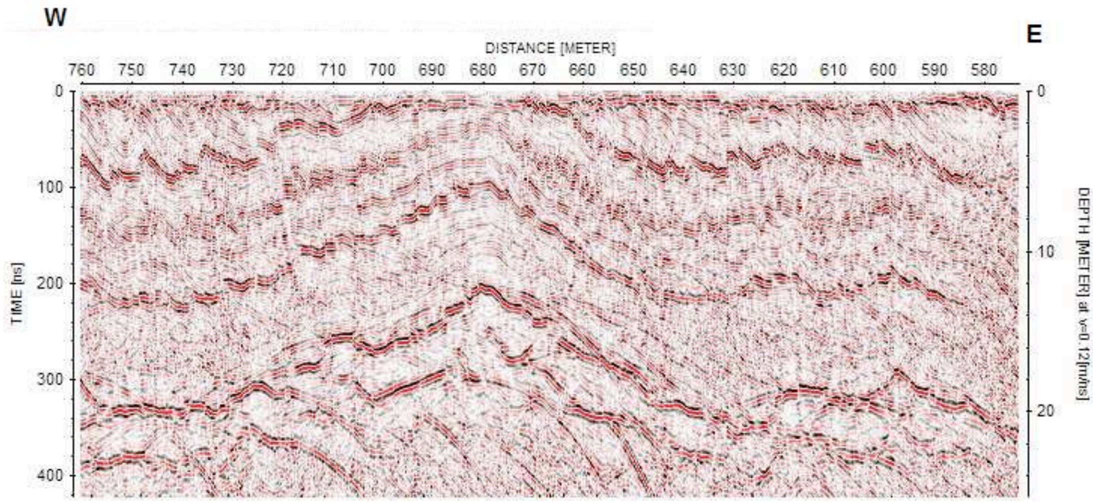

Fig. 20. Migrated georadar section shows the clear flow folding in the underlying rock salt beds. Note that the main tectonic stress is oriented from East to West.

CONCLUSIONS

Significant amount of experimental data acquired in the potash mine was analyzed. It made possible to develop an efficient methodology of GPR investigations in the Upper Kama potash mines that are capable to solve many problems in ore extraction planning and mining safety.

The obtained results of study confirm that GPR method has proven to be an effective tool for detection and delineation of deformation structures in local geological and geotechnical environment.

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