Assessment of the Prospective Water Inflow Hazards Using Georadar: Case Study of Upper Kama Potash Deposit

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Abstract

The problem of prevention of the water influx in the potash mines is vital for proper planning of the safe ore extraction and timely collapse hazard mitigation action. Geophysical methods provide with the effective tools for studying the fractures, which are the possible water passageways into the mine. Previous works showed that usage of georadar might be a valuable solution for fracturing investigation in salt rock. The investigations were conducted in the Solikamsk Mine #3 (former JSC Silvinit), where the wide fracture zone was encountered during ore extraction. This study allowed delineation of single fractures and their systems including the hidden features inside the surrounding rock mass.

Keywords: potash mines, water inflow, fracture delineation, georadar.

Introduction

The Upper Kama (Verkhnekamskoye) potash deposit is situated to the west of the Urals Mountains in the northern part of the Perm krai (Russia) at about 250 km north of Perm (Figure 1). The stratabound salts of about 500 m thick were deposited in the Late Carboniferous at the centre of Solikamskaya Depression of the Pre-Urals Foreland Basin. The Upper Kama is the second currently mined after the Prairie Evaporite Deposit (Canada) in size. Mining is conducted with room-and-pillars mode.

The problem of ground water influx is principal for the potash mines because salt is very soluble material. Dissolution of the water protective salt beds leads to flooding the mines, losses of reserves, catastrophic surface subsidence, collapse features, and consequent contamination of ground water, and damage of the buildings or different infrastructure objects (Figure 2).

As a rule, some portion of salt rock is left above the potash mines to provide the water protective cover. In mines of the Upper Kama Deposit, the impermeable strata composed of thick carnallite, and overlaying interbedded halite, marl, anhydrite, gypsum, and carbonate beds of total thickness of 70-90 m is used to prevent the water inflow into the workings.

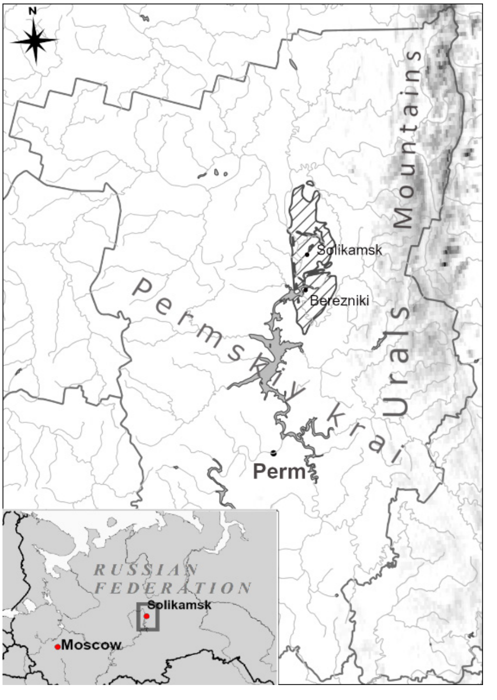

Figure 1 Upper Kama deposit location map. Hatch filled contour indicates the extent of the potash beds.

Because of salt high plasticity and healing capability, the natural open fractures have been rarely encountered in the mine workings. A few number of stand-alone

Figure 2 Large collapse structure occurred at Berezniki mine #1 in 2007 after the water influx initiated in 2006. The size of structure achieved 446 to 335 m in 2009. Sinkhole cut the railroad Perm - Berezniki that is seen in the front of sinkhole (Berezniki 2009).

natural fractures and fracture systems of various scales have been observed during mining operation, especially, in a central part of deposit. Most fractures within the salts are healed and visually are observed only in the clay/anhydrite layers. However, the open fractures are of the most concern for miners. In contrast to the stress relief cracks around the openings, natural fractures usually are related to the large zones of strata failure that may affect the whole water protective cover. The increased attention must be paid to vertical and subvertical fractures as the primarily possible pathways for water influx.

The largest set of open fractures discovered in the Upper Kama potash deposit was eventually exposed at the eastern edge of mining field of the Solikamsk mine #3 at the sylvinite beds level (Figure 3). Upward exploration boreholes and visual observation of the roof showed that the fractures die out within overlying carnallite layer or interlayer clay seams (Figure 4).

To determine the spatial extent of the fractured rock, the special exploration drift of about 200 m length was made. The extensive drilling is limited in the salt mines due to the safety of the impermeable strata and economic reasons. Therefore, non-invasive and economic geophysical methods are used currently for investigation of the anomalous geological features (Thoma 2003). Georadar (ground penetrating radar, GPR) method has proven by previous research to be an effective geophysical tool providing with detail images of the salt rock structure (Annan 1988) and

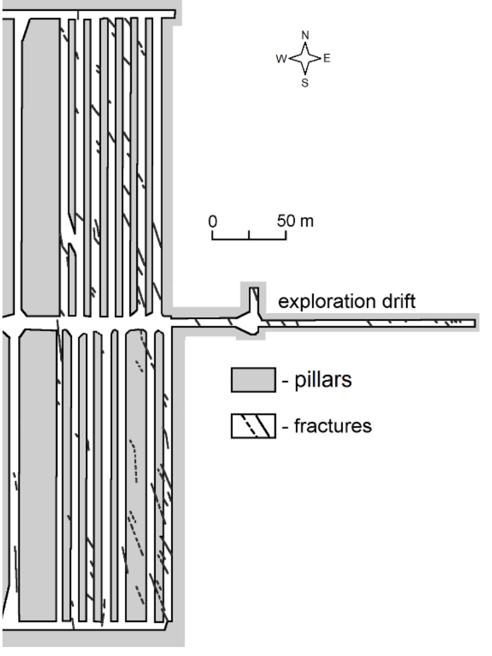

Figure 3 Schematic fracture zone encountered in the Solikamsk mine #3 (modified from Kudryashov et al. 2004).

was chosen for study. Presented in the paper experimental works were conducted in 2003 and 2005 in order to delineate fractures and estimate their extent outward the mine workings.

Method

Method georadar is based on emitting the short high frequency electromagnetic impulse and receiving the signal reflected on the subsurface interfaces between materials with different electrical properties (Utsi 2017). The electromagnetic properties of medium (mainly dielectric constant or relative permittivity) control the georadar signal parameters such as velocity and attenuation. The velocity v and dielectric constant ε are connected by following relationship:

$$v = c/\sqrt{\varepsilon} \quad (1)$$

where c is a light velocity in vacuum. Knowing the velocity, one can obtained the distance *h* to the reflection object as:

$$h = \frac{vt}{2} \quad (2)$$

Figure 4 Exploration borehole intersects a fracture exposed in the roof at the sylvinite mining level, Solikamsk mine #3.2004).

where t is a signal travel time to the interface and backward. The amplitude of the recorded signal from the target depends on the reflection coefficient R:

$$R = \frac{\sqrt{\varepsilon_1}-\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1}+\sqrt{\varepsilon_2}} \quad (3)$$

where ε_1 and ε_2 are dielectric constants of two contacting media.

The signal attenuation is frequency dependent parameter. The higher frequency, the higher signal attenuation and, consequently, the lower penetration depth. Critical parameter for signal ability to resolve the reflections from both walls of the fracture is a resolution Δr:

$$\Delta r \geq \frac{\lambda}{4} = \frac{v}{4f} \quad (4)$$

where λ – wave length, f – central frequency of antenna. Therefore, selection of proper operation frequency providing with most details about certain object is trade off between spatial resolution and depth of penetration of the signal. Previously, it was shown that the detection (not resolution) is available for fractures of thickness under threshold of resolution depending on their geometry and properties of filling material (Kovin 2011).

Average velocity of 0.12 m/ns was defined for salt rocks on the results of laboratory and in-situ testing (Kovin 2011, 2017). Reflections in the uniform salt rocks strata relate mainly to the clay/anhydrite thin (centimeter scale) layers having the contrast electrical properties against the contacting rocks.

The Ramac (Mala GeoScience AB, Sweden) and OKO (Logical Systems, Russia) georadar systems with 250 and 400 MHz antennas were employed for data acquisition. Operating frequencies were chosen according the results of previous tests as showed the optimal relationship between resolution and penetration depth. Radargrams were recorded using continuous common offset mode. Data were acquired sounding into the back, walls, and floor of exploration drift. The main attention was paid to the subvertical (especially upward) direction of investigation.

Reflexw (Sandmeier Geophysical Research) software was used for processing and interpretation of obtained radargrams. Common processing flow applied to all the GPR data included start time correction, "dewow" filtering, background or "ringing" noise removal, and gain correction for visualization of weak signals.

Results and discussion

Orthogonal orientation regard the traverse line make challenging obtaining the prominent reflections from the fractures plane. The radargrams recorded on the roof and floor of exploration drift are shown in Figures 5 and 6 respectively. Sounding in the

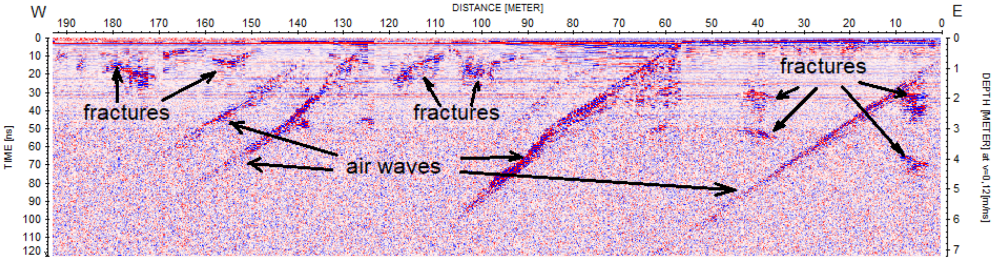

Figure 5 Radargram obtained on the roof upward profile using RAMAC 250 MHz antenna. Air waves (reflections from the surface objects) pose the noise patterns to the records that complicate identifying the target signals from fractures.

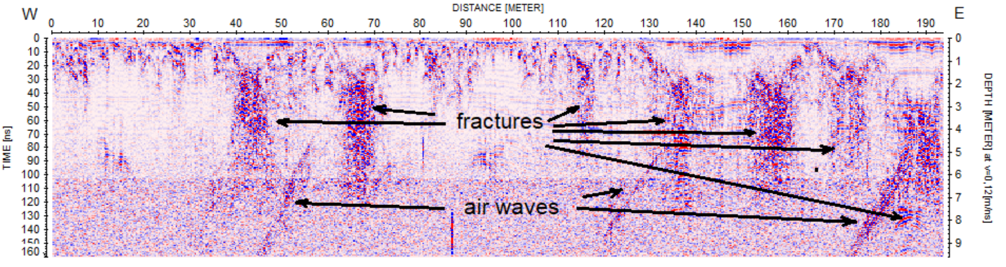

Figure 6 Results of downward sounding in the floor using OKO 400 MHz antenna.

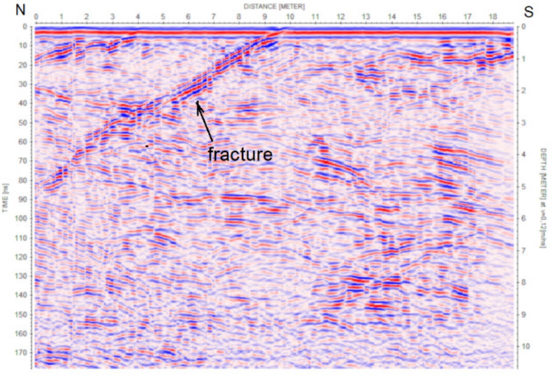

Figure 7 Radargram of sounding in a mine pillar with OKO 400 MHz antenna. Reflection from the fracture visually observed on a wall is clear.

wall (in horizontal plane), when the fractures cross the observation line under relatively small angle (Figure 3), the clear reflections could be easily identified (Figure 7). In contrast, the subvertical fracture plane does not produce reflections when the common antennas configuration is implemented. However, the fractures were traced by the series of diffraction patterns that could be generated at the plane irregularities or in case of plane rotation to a favorable reflection angle (Figure 5, 6).

Analysis of radargram in the Figure 5 shows that failure concentration is observed at the fracture intersection with the bedding interface presented usually by weak clay or anhydrite thin layers. In addition, it was established that a coalescence fracture and interface is observed in place of intersection (Zhang 2007) and the fracture plane changes the trajectory and rotates to the favourable for reflection angle.

Results of georadar study shown that extent of fractures does not exceed 4-5 m above the mine level and 7-8 m in underlying beds, thus suggesting that the observed fractures do not form the crosscutting pathway for ground water. However, the further mining at this area was stopped and workings were backfilled.

Conclusions

The results of this study demonstrate that georadar might be a useful tool for investigation of the mine hazardous features such as fractures and possible ground water pathways they may provide. Georadar allowed studying a substantial area in non-invasive, cost and time effective manner, and obtaining the most detail information provided by geophysical methods. The study revealed the problem of imaging the subvertical fractures that require the development of new instrumentation and methodology of the field work.

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