An Apparatus for Collecting Upward-looking GPR Surveys in Potash Mines

C. W. Funk, R. Brehm, A. F. C. Errington
Potash Corporation of Saskatchewan Inc.
122 1st Avenue S Saskatoon, SK Canada
craig.funk@potashcorp.com

K. Backstrom
Kinemek Design Works Inc.
410 Downey Rd, Suite 17, Saskatoon, SK, Canada
kirk.backstrom@kinemek.com

***Abstract*—GPR has been used routinely in Saskatchewan, Canada, potash mines for nearly forty years. In general, the purpose for GPR surveys in potash mines is to map the salt-bed stratigraphy above and below the mined-out rooms. The stratigraphy in the Saskatoon, Saskatchewan area mines consists of a series of salt and potash beds separated by well-known and regionally distributed planar clay seams. The salt-beds have very low electrical conductivity, which makes GPR highly effective for imaging the clay seams.**

Collecting downward-looking GPR data in potash mines is straightforward, as the mine personnel can use standard off-the-shelf GPR equipment (push carts for example). Successful and safe collection of upward-looking GPR data is considerably more challenging. The terrain is uneven, there are numerous obstacles, and room heights are quite variable. Typical Saskatchewan potash mines are very large, with 100s of kilometers of operational mine rooms, so a solution which permits seamless collection of upward-looking GPR data was needed.

This paper presents the evolution of various apparatus used for collecting upward-looking GPR data in potash mines. The work eventually led to the development of a Kubota RTV mounted light-weight floating lift. This apparatus is known as a GPR-RTV, and it successfully overcame the many challenges to routine upward-looking GPR data collection in potash mines. Some data examples are presented to illustrate the effectiveness of the GPR-RTV. Finally, although this discussion focuses on applications in potash mines, it is envisioned that the GPR-RTV could be used safely in a variety of conventional mining and tunneling environments.

***Index Terms*—potash, safety, mining, tunneling**

I. Introduction

Innovation in a variety of safety systems is a high priority for all international mining companies at present. Potash Corporation of Saskatchewan Inc. (PotashCorp) has made the reduction of serious injury or fatality (SIF) rates a top priority. A SIF potential of concern for the Saskatoon, Saskatchewan Canada potash mines are unanticipated falls of ground (back falls).

GPR is an excellent technology for identifying some of the conditions that can lead to back fall hazards in potash mines. Use of GPR as a safety device in potash mines has been in development for the past two decades. In early 2013, PotashCorp developed a vehicle mounted GPR solution that addressed usability issues, instrumentation vulnerability and data quality problems. An operating prototype was successfully installed and tested at the PotashCorp Lanigan Mine on a Kubota RTV 1140 (GPR-RTV). Following refinement of the prototype, subsequent installations have been made at a number of mine sites in the Saskatoon area. GPR-RTVs will not eliminate back fall hazards; however, it is envisioned that as this project progresses and matures, the additional information provided by GPR will reduce back fall hazards in the potash industry.

II. Geology and Mining

Conventional underground potash mining in the province of Saskatchewan, Canada occurs within a narrow, 500 km long corridor running from the Saskatoon area to the southern border with Manitoba (Fig. 1). This corridor roughly parallels the shallow northern sub-crop edge of the Prairie Evaporite salts which host potash deposits at depths of 925 to 1050 m. Currently eight mines in Saskatchewan extract potash using conventional underground mining techniques. Within about a 100 km radius of Saskatoon there are five such mines, of which three: Cory, Allan and Lanigan, are owned and operated by PotashCorp. These mines produce potash from the Upper Patience Lake Potash member of the Prairie Evaporite formation, where continuous boring machines (miners) are used to cut the potash out of the flat-lying host rock. Mining methods and equipment are described in [1].

The Upper Patience Lake Potash member is mostly composed of potash and salt which, relatively speaking, makes for a very soft mine rock. In response to mining, room failure comes from steady creep rather than the sudden explosive breakage. Numerous horizontal, laterally continuous, sub-parallel clay seams occur throughout the geological formation and compound the plastic behavior of the ore body. Under certain conditions, these clay seams can serve as planes of weakness within the flat-lying host rock and lead to unexpected back falls characterized by the delamination of thick sheets of roof rock. Small localized geological anomalies that disrupt the normal bedded rock sequences are routinely encountered (Fig. 2). These anomalies often result in a thinner-than-normal beam in the salt-back. In these circumstances, ground conditions can become hazardous and rock bolting is often relied upon to help stabilize the salt-back. Mining crews are trained to identify such geological conditions, but not all back fall hazards can be identified visually since they occur in rocks above the actual mining rooms. For these

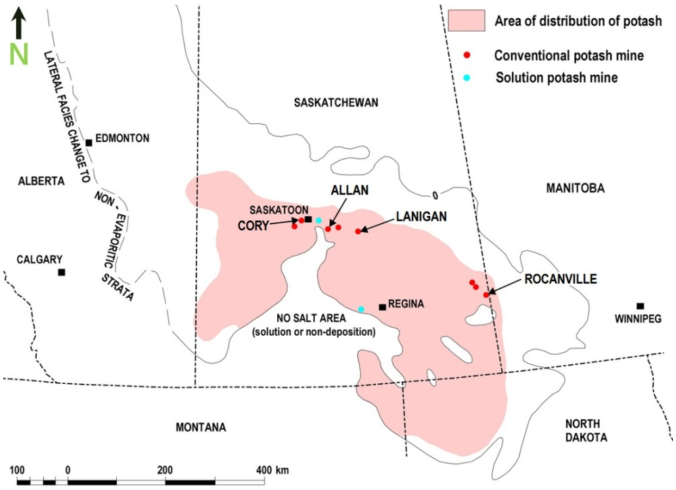

Fig. 1. Map of western Canada showing the potash rich zones in the Prairie Evaporite formation.

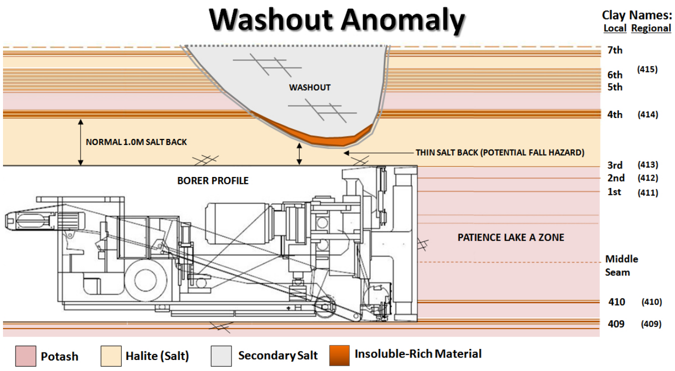

Fig. 2. Illustration of a potential backfall hazard created by mining underneath a washout anomaly.

situations, GPR has proven to be an effective back fall hazard identification technology.

III. Use of Upward–Looking GPR in Potash Mines

A. History

GPR has been deployed actively in potash mines for almost 40 years. Initial uses were primarily focused on mapping the geological stratigraphy and assessing hazards associated with water influx. Applications of the underground GPR method at potash mines began in 1976 by Dr. Don Gendzwill (University of Saskatchewan) and Dr. Peter Annan (Sensors & Software). The initial trial results were very promising and reported in [2].

Beginning in 2002, the Saskatchewan potash producers collaborated with Kali und Salz (K+S), Germany, for the purpose of developing GPR technology to be used for routine detection of delaminations in the clay seams in the salt-back. In the industry, this is known as Loose Detection: when the salt-back becomes loose it eventually leads to a fall of ground. In 2005, Kelly et al. [3] reported on encouraging progress at potash mines operated by the The Mosaic Potash Company (Mosaic), in Saskatchewan, where they were able to successfully detect and map loose areas in the salt-back. Likewise, in Germany at a K+S mine in Germany, Grégoire et al. [4] discuss promising developments in applications of GPR for use in fracture and loose detection.

B. GPR Equipment

A range of GPR systems and frequencies are used in potash mines. In the salt-back, thickness of the salt-beam ranges from 0.5 m to 1.3 m; nominal thickness is 1 m. The salt is dry and fairly homogeneous, with a typical dielectric constant of 5 to 6. Although the salt is known to have small isolated pockets of clay in the salt-back, in general it is quite homogeneous, so a constant velocity of 0.12 m/ns is used to convert the radargrams to depth. The 414 clay seam above the salt-back has a typical thickness of 10 cm to 15 cm (Fig. 2). Due to the substantial thickness of the 414 clay, frequencies of 250 MHz and higher do not image the strata above the seam because the signals are either reflected or completely absorbed. A variety of GPR antenna configurations have been investigated for imaging of the salt-back [3]. Because the salt–back is the imaging zone of interest and it is normally 1 m thick, the higher frequencies are best suited form imaging the zone (i.e. greater than 500 MHz). At PotashCorp mines, 1000 MHz ground coupled Sensors & Software (http://www.sensoft.ca/) antennas have been used for the past 10 years to image the salt–back.

C. Acquiring Upward–Looking GPR

The challenge of collecting upward looking GPR surveys in Saskatchewan potash mines has been a hindrance to routine use of GPR as a salt-back inspection tool. For quick GPR assessments of an area, the simplest solution was to mount the 1000 MHz antenna to a pole (see Fig. 3). Typically, a Sensors & Software Noggin system was used, although other systems have also been used from time to time. One person would walk along the mining drift holding the pole upright and keeping the antenna in contact with the back as they walked. The antenna was connected to a digital video logger (DVL) mounted to a cart with a standard distance encoder. In order to record distance traveled, another person would push the cart, keeping pace with the first person. Nominal room height can be upwards of 4 m, making the task of collecting GPR using a pole-mounted antenna physically challenging for survey lengths of more than 20 m. With this method, it is nearly impossible to maintain a constant speed, causing spatial compression and stretching in the GPR data. Besides data quality, the collection method itself raises several safety concerns: the floor of the rooms can undulate and small ledges (floor-heaves) are common. Such features are tripping hazards for the person carrying the pole, making it difficult to focus both on maintaining antenna contact with the salt-back and avoiding tripping on hazards. Furthermore, the person holding the pole is directly under the antenna, such that any loose rocks, or the antenna itself, will fall onto the person (in the line of fire). Given the potential for fatigue, tripping hazards,

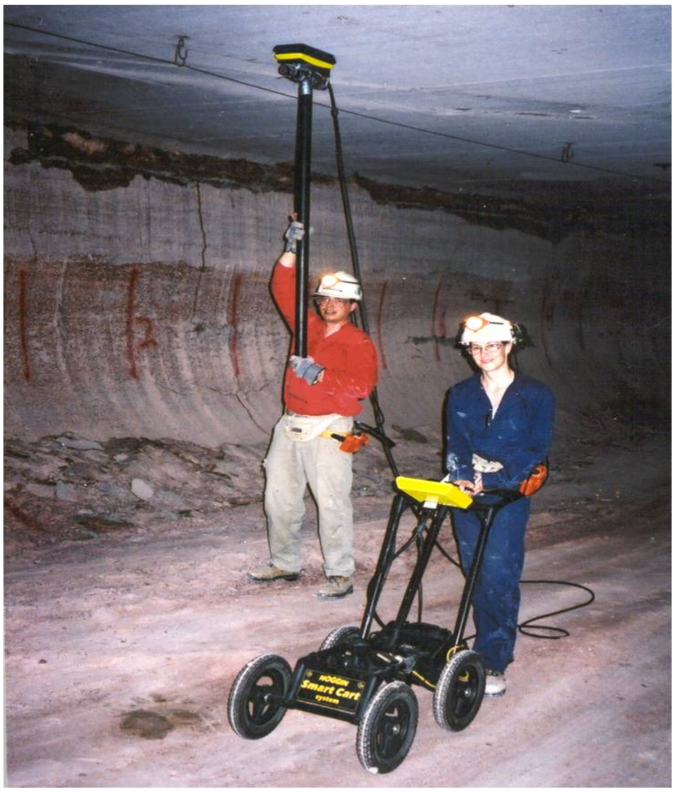

Fig. 3. Collecting upward–looking GPR in a potash mine using a pole.

Fig. 4. A GPR aluminum cart mounted tower.

and exposure to falling objects, collecting GPR with a pole mounted antenna became unacceptable. Rather than collect GPR with the pole mounted antenna while walking, a person (or two people) holding the antenna could stand in the back of a jeep while another person operated the DVL and acted as an additional spotter. A third person was the driver. Although riding in the jeep eliminated the tripping hazards, it did not make it any easier to hold up the antenna for any period of time nor did it remove exposure to falling objects. The data quality would be inconsistent as it was impossible to keep the antenna in contact with the salt-back. Eventually, with the evolution of safety standards at the mines, this data collection method in a moving vehicle was no longer permissible.

During trials at PotashCorp Lanigan mine it was found that the mine jeeps could not drive slow enough to collect the desired density of trace spacing (20 cm) and frequency of trace stacking (32). That led to development of an aluminum cart mounted tower which could be pushed at about 3 km/hr by an operator (see Fig. 4). The tower is easily mounted to an off-the-shelf Sensors & Software cart. The height of the tower is adjustable, and the antenna mounts to a pivot arm that holds the antenna in contact with the salt-back and is kept under tension by elastic cords. The quality and consistency of the GPR data collected using this tower was very good. However, it was a physically demanding task, requiring three people. The apparatus was rather unstable when pushed, so another person was needed to pull the cart from the front, and a third person was needed to keep the tower from tipping sideways. Tripping hazards were a concern, but the DVL operator was also exposed to falling debris from the salt-back. At best, a team could expect to collect about 1.6 km of data per shift. Other variations of the tower were tried, but in general, the surveys were physically challenging and the data collection rates low. These limitations motivated investigation into vehicle mounted solutions.

Several existing vehicle mounted systems for acquiring upward-looking GPR in potash mines are described in the literature. Both K+S [4] and Mosaic [3] have installed booms or hydraulic lifts on modified jeeps. The challenge for such mechanical systems is how to compensate for undulations in the salt–back and sudden changes in room height. To compensate for smaller undulations, the antennas were allowed to have an air gap of 0.5 m to 1 m. Larger height variations were accommodated by changing the antenna elevation while the jeep was moving via hydraulic functions. In [4] and [3] they acknowledged that the quality of the GPR data was compromised somewhat by the air gap, however the quality was still considered to be acceptable for their purposes. Our philosophy has been to collect the highest quality data possible. The time and effort required collecting the GPR data underground in a mine is a consideration, but other factors (mine operations, room closure, geotechnical factors, etc.) can significantly limit access to the rooms. Therefore, in our opinion, when an area in the mine is available for acquiring GPR surveys, it is best to collect the highest quality data possible as another opportunity may not be available.

A variety of trailer apparatus for collecting upward-looking GPR were built and tested (see Fig. 5). Trailer configurations included: counter-weighted arms, an extendable tower, and a scissor lift with height compensation. The trailers worked as intended; however they lacked the maneuverability that a single vehicle has, which is a significant drawback for an underground mine. The potash mines are very large: some survey locations where 20km from the shaft. Due to the terrain in the mines, the trailers had to be pulled to the locations at low

Fig. 5. Various trailer configurations used to collect upward–looking GPR surveys.

speeds (10km/hr), which added hours to the total time in some cases. Furthermore, three persons were required to conduct GPR surveys: one to drive, one to act as an observer for the trailer (communication with driver and avoid obstacles), and one person to operate the GPR DVL. Even with three people, several GPR antenna and trailers where severely damaged when they struck obstacles (rock bolts, suspended cables, etc.). After reviewing these failures, we began to consider vehicle mounted options.

D. The GPR–RTV

In early 2011, we started pursuing development of a dedicated vehicle for collection of upward-looking GPR surveys in potash mines. The requirements for the GPR vehicle and apparatus were as follows:

1) accommodate room heights from 2.1 m to 4.3 m;
2) maintain average speeds of 40 km/hr driving to survey locations but also operate at very low speeds of 3 km/hr when surveying;
3) the performance and safety features (roll-over protection, etc.) of the vehicle must not be compromised;
4) the drivers line-of-sight must not be impaired at any time;
5) the driver should be able to see the antenna at all times during the surveys;
6) antennas stay coupled to the salt-back during surveys;

Fig. 6. The first version of the GPR–RTV; a Kubota RTV1140 with a front mounted large hydraulic lift and aluminum control arm assembly.

7) antennas deflect under obstacles 10 cm or smaller without having to adjust apparatus height.

These requirements necessitated an apparatus that mounts on the front of the vehicle, which also has a mechanism that automatically adjusts for room height changes and small obstacles. A Kubota RTV1140 was chosen because it is the only vehicle of its class that has a low range hydrostatic transmission and dedicated hydraulic functions. These vehicles are able to drive smoothly at very low speeds. The first version of the GPR-RTV is shown in Fig. 6. Large height adjustments could be made with the hydraulic cylinder. The antenna was mounted on an aluminum control arm assembly which accommodated smaller height variations via the gas springs. The aluminum was found to have minimal impact on the data quality. The assembly behaved in a similar fashion to a weather vane when the vehicle turned. The hydraulic cylinder was permanently mounted to the Kubota, but the aluminum assembly was removable and only in place for the duration of the survey. Because the antenna was always visible to the driver, significant obstacles on the salt-back could be avoided easily by either steering around them, or lowering the assembly. However, there were several deficiencies to the design: the hydraulic cylinder was heavy, which negatively impacted vehicle handling and was also found to cause premature wear on the front suspension and tires; the height of the cylinder made it difficult for the operators to mount and dismount the aluminum assembly; the drivers line of sight was partially blocked by the hydraulic cylinder; finally, the low volume output of the Kubota hydraulics resulted in very slow cylinder height adjustments.

A second revision of the GPR-RTV (Fig. 7), developed in 2013, addressed all the design requirements and has been a considerable success. The basic principal incorporated into the design is a counterweighted arm, which is slightly unbalanced such that the antenna scrapes along the salt-back with just enough force to remain in contact. The antenna is mounted inside a non-conductive UHMW and phenolic composite skid-plate assembly. The lift remains permanently attached to the Kubota, while the aluminum counterweighted arm and weights are removable. For transportation to and from survey locations, the counterweighted arm can be folded up such that it fits in a large duffle bag in the back of the Kubota. The aluminum lift is very light, at about 70 kg, having no noticeable impact on the vehicle performance. Furthermore, when the lift is retracted it does not block the driver's line-of-sight. The lift is designed for an operational load of 113 kg with a factor of safety of 7.7. The hydraulic function is responsive, being able to reach full extension in about 5 seconds. This design has proved to be versatile and reliable for typical conditions encountered in potash mines and permits operators to collect up to 10 km of GPR profiles per shift (standard work day).

E. GPR–RTV: Improving Mine Safety

Beginning in 2014, GPR-RTVs were being used for GPR collection at the three PotashCorp mines which mine the Patience Lake A-zone: Cory, Allan and Lanigan mines. In general, the quality of the data collected at these mines is excellent (see Fig. 8). As more areas in the mines were surveyed with GPR, areas were found where the salt-back was thin but stratigraphy in the room looked normal. This was surprising, because normal ground-control procedures assumed that hazardously thin salt-back would have a visual signature of the anomalous condition in the mine rooms. If no anomalous conditions were observed, the areas would not be dealt with appropriately (i.e. rock-bolts installed or area abandoned), risking possible exposure to elevated hazard levels.

To better quantify salt-back thickness variations, comprehensive GPR survey campaigns were completed at the Cory, Allan and Lanigan mines. The salt-back thicknesses in bolted and unbolted areas were compared on histograms (Fig. 9 gives results from Allan mine). This analysis confirmed that areas of thin salt-back were not consistently rock-bolted. For example, at Allan mine only 50% of areas where the salt-back was 45 cm or less were found to be bolted (Fig. 9). In response to these findings, PotashCorp decided to change their policy and proactively install rock-bolts in areas where the salt-back is found to be thinner than 60 cm at Cory and Allan mine, and thinner than 50 cm at Lanigan mine (salt-back is more stable at Lanigan). This is a major change in ground control policy for potash mines; previously areas would have rock-bolts installed if the salt-back was known to be either thin or delaminating (referred to as loose).

Some 10 years ago, potash mines were pursuing GPR as a loose detector which could image delaminating clay seams [3]. PotashCorp has decided that GPR is not a reliable loose detector. Clay seam GPR anomalies can also be caused by changes in mineral content. However, it is very easy to map salt-back thickness with GPR (Fig. 8), so GPR is now being used routinely to map salt-back thickness.

Fig. 7. The second revision of the GPR–RTV. The light weight aluminum lift is easy to use and has no impact on vehicle performance or handling. The counterweighted arm maintains just enough force on the antenna to stay in contact with the salt–back, but still permits the skid plate to easily deflect under obstacles.

F. Future Direction

In parallel with development of the GPR-RTV, PotashCorp started development of continuous mining-machine mounted GPR systems (GPR-on-borer) so that images of the salt-back could be acquired during continuous mining operations. It is not possible to use the GPR-RTV in parallel with continuous mining operations due to the infrastructure in place. However, the GPR-RTV's were a critical component of the GPR-on-borer development process. They were used to test the GPR software systems and interfaces to the borer controls. The

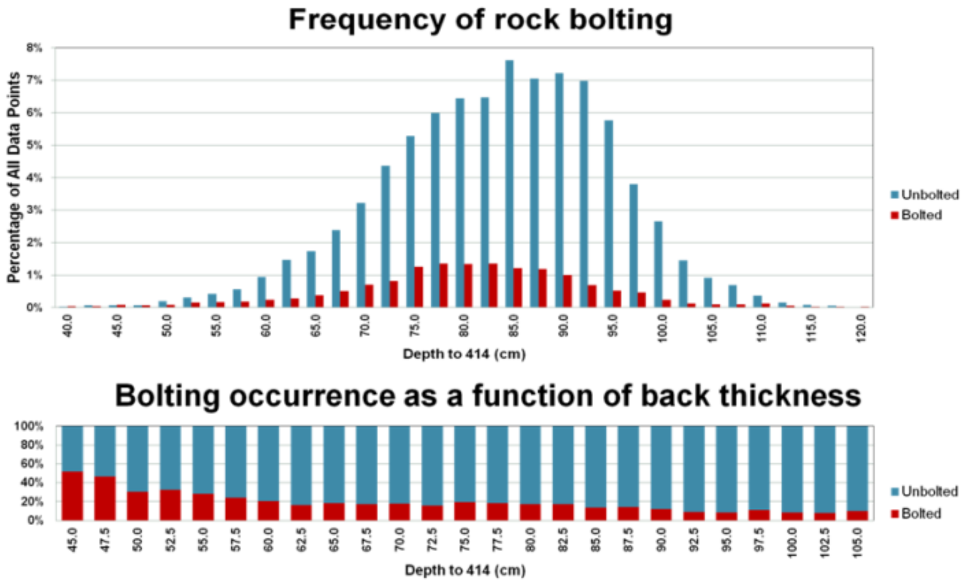

Fig. 9. Comparison of salt-back thickness as mapped by GPR, at the Allan mine, in bolted and unbolted areas. The likelihood of a fall–of–ground occurring increases considerably for areas in the mine where salt-back thicknesses is 60 cm or less. We where surprised to find that for very thin salt-back areas (45 cm) rockbolts were installed only 50% of the time.

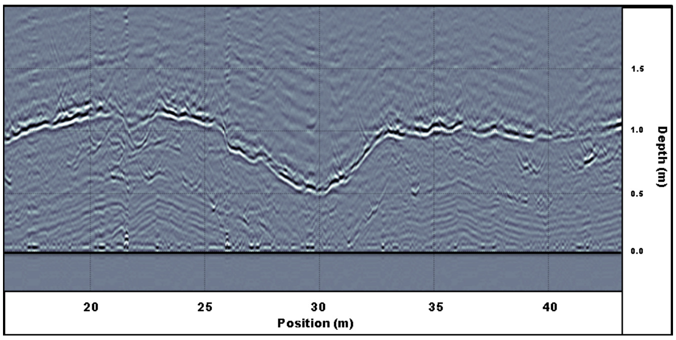

Fig. 8. An example of a washout feature clearly imaged in an upward–looking GPR profile collected in a Saskatchewan potash mine. The quality of the GPR data is excellent. The strong reflector is the 414 clay seam.

GPR-RTVs were also used as training vehicles for the borer operators. By the end of 2015, PotashCorp has installed GPR-on-borer equipment on 26 continuous mining-machines in use at Cory, Allan and Lanigan mines.

IV. Conclusion

The GPR-RTV has been a major success and was critical in enabling routine collection of upward-looking GPR surveys in mines. This has led to a better understanding of the salt-back in the Patience Lake A-zone, which in turn made a significant contribution to the development of improved ground control (rock bolting) policies. The GPR-RTV is safe, easy to use and versatile. The speed of GPR data acquisition with the GPR-RTV in potash mines is limited by the high trace density collection rate. At lower trace densities, it is possible to conduct upward-looking surveys at speeds of 10 km/hr to 15 km/hr. Although the GPR-RTV has only been used in potash mines, it should work well in a variety of conventional mining and tunneling applications.

Acknowledgment

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