

Borehole Radar as a Tool to Optimize Mine Layouts and Production

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Abstract

The major gold and platinum deposits of South Africa are thin, typically less than 1 m thick, shallow dipping, typically 5° – 30°, and of huge lateral extent. On a regional scale, they appear flat, but on a local scale there is significant topography. In the Bushveld platinum mines, potholes disrupt the orebody, known locally as a reef. In the Witwatersrand gold mines, structures such as faults, dykes and rolls disrupt the reef.

On a scale of tens of metres, these disruptions can be measured using reflection seismic techniques adapted from the oil industry, and 3D seismic surveys are now routine prior to developing new gold or platinum mines. While reflection seismics from surface provides excellent information for mine layout, the information is too coarse for day-to-day mine planning.

There is a great need for a tool that can predict disruptions to reefs on a scale of metres, over ranges of tens to hundreds of metres. Borehole radar can meet this need. Borehole radar is a reflection technique where radio wave pulses are transmitted into rock from tools in boreholes. The pulses reflect off discontinuities in the electrical properties of the rock. The typical Bushveld and Witwatersrand host rocks are nearly ideal for borehole radar, as they have high resistivity, allowing good radar range, and they have a good contrast to significant targets.

This paper reviews the impact of the CSIR developed Aardwolf BR-40 radar system, both in its own right, and as a technology demonstrator that assisted in selling the technique of borehole radar to South African gold and platinum miners. It reviews the technology briefly, discusses applications to typical economic targets, and discusses new developments, particularly in the field of directional radar. A new high-frequency

directional radar antenna and tool is undergoing field trials at present.

1. Introduction to the geological problem

The major gold and platinum deposits of South Africa occur in the Witwatersrand Basin (gold) and Bushveld Complex (platinum) (Henning et al., 1994; Carr et al., 1994; Cawthorn, 1999). While the origins and geology of the two structures have almost nothing in common, the resulting orebodies, known locally as reefs, share a number of physical similarities:

- they are thin, typically centimetres to a metre thick;
- they are shallow dipping, typically with dips of 5° to 30°;
- they are of great lateral extent; and
- they are tabular in geometry.

In both cases, the reefs appear flat on a regional scale, but have significant topography on a local scale. Bushveld platinum mines are particularly disrupted by potholes and iron-rich ultramafic pegmatoids or IRUPs, gold mines have to contend with rolls and channels, and both types of mining face the usual geological challenges of faults, joints and dykes.

The similar topography of the two types of orebodies leads to similar mining methods being used. The conventional manual drill and blast approach is discussed here. While some mines are mechanizing, conventional methods still dominate the gold and platinum industries.

A conventional mine is laid out to access the orebody through a vertical shaft and horizontal haulages that run parallel to strike, and cross-cuts that run perpendicular to strike to reach the shallow dipping reef (Figure 1). Raise lines are then mined up-dip. Mining proceeds out from the raise line in one of a number of different layouts.

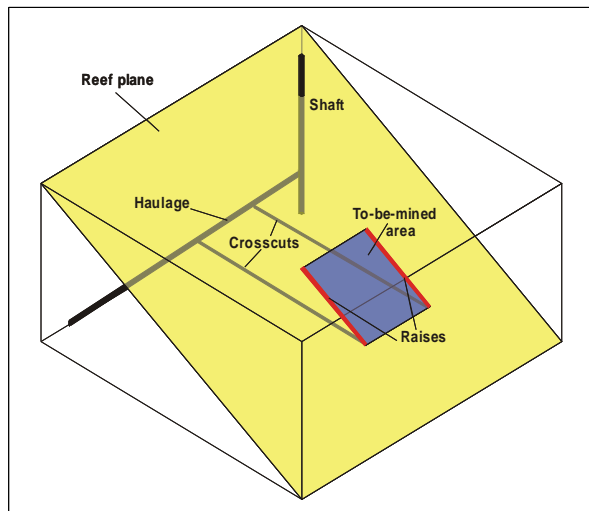


Figure 1: The geometry of a typical deep-level conventional gold or platinum mine (Van Schoor et al., 2006)

The overall mine layout can be designed from an understanding of the regional geology. Originally, this came from drilling, but it is now routine to undertake 3D seismic surveys across areas that are to be mined. The 3D seismics typically offers a picture of the structure of the reef with a horizontal resolution of 25 m and a vertical resolution of about 8 m. At that resolution, it is a routine matter to site the shaft and the main developments such as the haulages. It is when it comes to actual mining of the reef that higher resolution is required.

The problem to be addressed by borehole radar is to determine reef topography from available development, prior to mining. The available developments are the haulage, parallel to reef, and the cross-cut, running in to the reef horizon (Figure 2).

2. Geophysical approaches

To detect structures using geophysics, the chosen technique must be able to penetrate through the host rock to the target, and there must be a contrast in a physical property between the target and the host rock. For the Ventersdorp Contact Reef (VCR), an important gold-bearing target, and for the Merensky and UG2, the two main platinum-bearing targets, the host rocks are relatively transparent to radar pulses, and there is a good

contrast in the velocity of propagation between the host and the target, hence radar is ideally suited for imaging the target reefs.

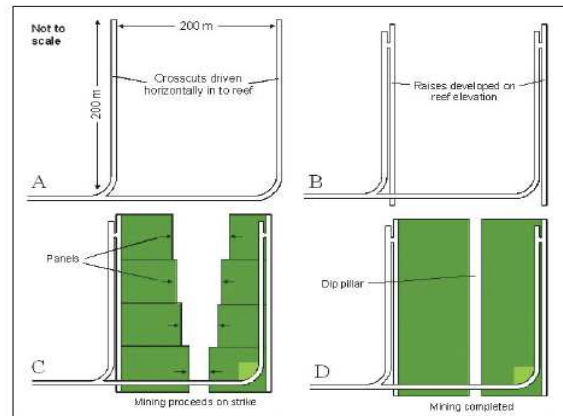


Figure 2: Access geometry available for reef imaging (Du Pisani and Vogt, 2004)

The first attempts were made using Ground Penetrating Radar (GPR), looking up from the haulage or cross-cut to the reef horizon. The results were promising, but the range was insufficient. The range of GPR can be increased by using lower frequencies, but the size of the antenna also needs to be increased. To consistently achieve ranges of greater than 30 m, it would be necessary to use frequencies lower than 100 MHz, resulting in antennas about the size of a large suitcase, which are impractical for routine use underground.

In addition, not all the power in the GPR pulse goes into the rock, some is able to travel in the air in the haulage or cross-cut. At longer ranges, unwanted reflections in the air along the tunnel overpower wanted reflections from within the rock, reducing the effective range.

Borehole radar was proposed to overcome the problems with handling a large antenna, and with air reflectors. In 1995, a Malå RAMAC borehole radar was brought into South Africa to conduct a test campaign. The results at a surface test site showed conclusively that ranges in excess of 30 m could be achieved for imaging the VCR (Vogt, 1997). Unfortunately, underground tests showed that the RAMAC borehole radar was not capable at the time of operating in high virgin rock temperatures, above about 50°C.

From 1998 to 2000, the DEEPMINE collaborative research programme funded further investigations of borehole radar, using an experimental system developed originally at Oxford University, with development following key staff to Sydney University. One particularly impressive result showed the topography of the VCR at distances of up to 70 m from the borehole (Trickett et al., 1999). In 2001, the CSIR embarked on development of the Aardwolf BR40, a robust, mineworthy borehole radar system, with a bandwidth of 40 MHz, ideal for long-range imaging of important geological targets. The first system was delivered in record time in October 2001 (Vogt, 2001, 2002, 2006), and was used in a number of DEEPMINE trials.

The DEEPMINE work showed that borehole radar for the gold industry worked very well for the VCR, where there is a marked contrast between the gold-bearing quartzite conglomerate and the lavas deposited above. For other quartzitic gold reefs, which are hosted in quartzites, there is no contrast between the reef and the host rock, so direct imaging is not possible. However, in many cases, the gold reef is associated with a marker. For example, the Carbon Leader reef is usually associated with the Green Bar shale, a few metres into its hangingwall. The shale is an excellent reflector compared to the quartzite host rocks. Borehole radar can be used to determine the structure of the Green Bar, which is then used to infer the structure of the Carbon Leader reef.

Following the success of borehole radar in gold applications, it was trialed by a number of platinum mines under the PlatMine collaborative research programme. It was an immediate success, because the major platinum reefs are excellent radar reflectors.

3. Directional ambiguity

Most borehole systems are rotationally symmetrical. They can identify the distance to a reflector, but not its direction in azimuth (Figure 3). During the PlatMine trials, a program called Fresco was written to assist in interpreting borehole radar data that applied fast forward modelling within an interactive environment (Vogt, 2004).

Within Fresco, four windows are displayed (Figure 4). The first window shows the 3D model. The borehole is located in 3D space, using coordinates from a borehole survey. Candidate reflectors are

located in 3D space, positioned initially based on geological knowledge, with the typical dip and strike of the targets known to exist in the rock near the borehole.

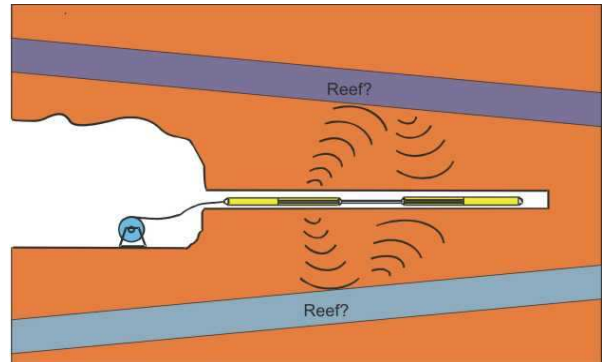


Figure 3: The directional ambiguity inherent in borehole radar

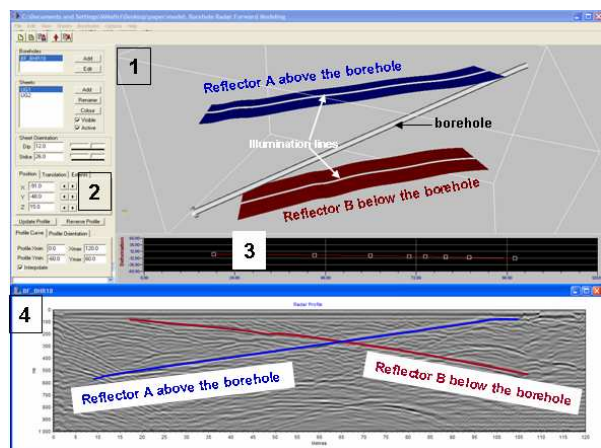


Figure 4: The Fresco BHR modelling and interpretation environment

The second window displays controls that allow candidate reflectors to be created and manipulated in dip and strike. Topography can be added to the candidate reflector using the profile display in the third window. Topography can only be added in one dimension, to limit the number of degrees of freedom available to the operator.

In the fourth window, the recorded radargram is presented, with lines superimposed, showing the modelled result from candidate reflectors. As reflectors are manipulated using the controls in windows two and three, the position of the

modelled reflector changes. The interpreter can then manipulate candidate reflectors based on what is reasonable from knowledge of the geology, until the modelled reflector is superimposed on the measured result.

The system resolves the directional ambiguity by letting the interpreter choose reasonable solutions, based on a priori knowledge of the geology of the target. The product of the interpretation is the 3D coordinates of the illumination line on the candidate target. These coordinates can then be fed to other geological interpretation software for further use.

4. Borehole radar in-mine applications

4.1 Platinum reef imaging

Borehole Radar has been successfully used in delineating the topography of the platinum reefs (UG2 and Merensky) in the Bushveld Complex because of the good contrast in permittivity between these reefs and their host rocks (Vogt et al., 2005).

A borehole radar survey was conducted in borehole A in a platinum mine, using the CSIR's Aardwolf BR40 radar system. Borehole A was drilled approximately 20 m below the UG2 reef in the norite, along the strike of the UG2 reef. The borehole deflected up and intersected the UG2 reef at 148.37 m.

Figure 5 shows the radargrams from borehole A; without interpretation (a) and with interpretation (b). A simplified geological log of the borehole is shown between the radargrams. The horizontal scale at the top of each radargram indicates the distance along the borehole from its collar, in meters. The scale on the left-hand side is the two-way travel time for the radar pulse in nanoseconds. The scale on the right-hand side of the images shows the distance of reflectors from the borehole in meters based on an assumed velocity of 0.105 m/ns.

Data processing consisted of applying a time offset correction, then band pass and automatic gain control (AGC) filters respectively.

The surveyed borehole was drilled below the UG2 reef and the furthest reflector from the borehole is located furthest above the borehole. There are no significant targets expected below the borehole. The interpreted position of the UG2 reef is indicated by a dashed yellow line. The UG2 Reef

reflector started at approximately 20 m above the borehole and was imaged for the entire length of the borehole with no interruptions of more than a meter. However, there is slight slump in the UG2 reef between 85 and 97 m along the borehole (enclosed in the white dotted line ellipse). Other reflectors detected by borehole radar are also indicated in Figure 5(b).

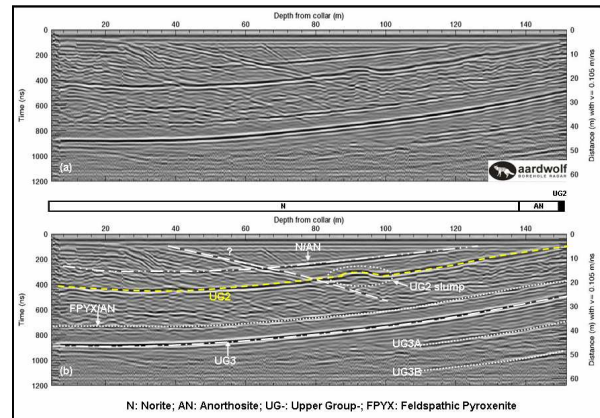


Figure 5: Radargrams for Borehole A: (a) without interpretation and (b) with interpretation. A simplified geological log of the borehole is shown between the radargrams

The directional survey information as well as the radargram for borehole A were imported into the CSIR's Fresco software, in order to determine the elevations of the UG2 reef reflector in the mine coordinate system in 3D (as in Figure 4). As a starting point, in this visualization the correct strike direction of the strata was used and it was assumed that the strata dipped at an angle of 12°.

Fresco requires the directional survey coordinates (XYZ) of the borehole, correct depth of the borehole and the correct dip of the targets. The only results that come from the Fresco model are the illumination line coordinates that represent the target in 3D. The illumination line coordinates are used by the mines to improve their geological model of the reef.

A more detailed 3D surface of the reef topography can be obtained by applying borehole radar in a group of boreholes. The illumination lines from the boreholes are then incorporated with the geological knowledge of the reef to build an improved geological model (Figure 6).

The red lines in Figure 6(b) are the illumination line coordinates calculated from individual boreholes. The length of the red lines correspond to the portion of the reef (approximately 120 m long) detected by borehole radar from each borehole. The topography of the UG2 reef was defined successfully and the reef was found to be mineable.

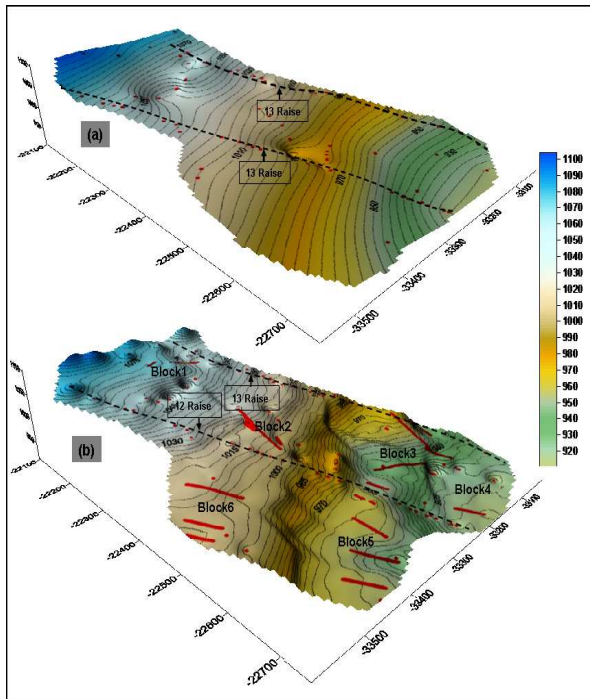


Figure 6: 3D model developed in Surfer showing: (a) the surface map before borehole radar application and (b): the surface map merged with illumination line coordinates results from 22 boreholes (red lines) and all points (from exploration drilling and geological mapping) used to build the reef topography (red dots). The black dashed lines represent the positions of the raises

4.2 Gold reef imaging

Several borehole radar surveys were previously conducted in the gold mines to delineate the topography of the VCR. The contrast in permittivity between the VCR and the overlying lava produces a radar reflector. The VCR was deposited on terraces and slopes (Henning et al., 1994). It is important to define the terraces and slopes because they determine the grade of gold.

Terraces contain higher gold grades than the slopes, and hence are preferentially mined.

The Aardwolf BR40 radar system was deployed in five boreholes in order to image the VCR in 3D geometry (Du Pisani and Vogt, 2004). The boreholes were drilled from two adjacent cross-cuts, at 30 - 50 m above and sub-parallel to the VCR (Figure 7).

Figure 8(a) shows the radargram for borehole 3 and is representative of results obtained in all the boreholes.

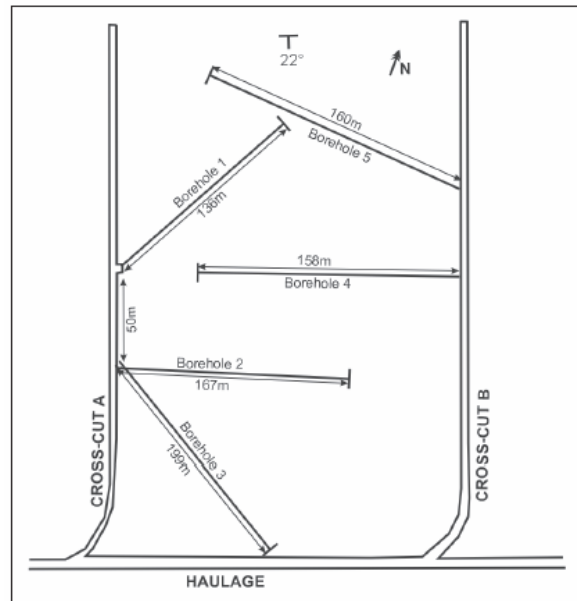


Figure 7: The geometry in plan, showing boreholes 1 to 5. The VCR dips 22° to the south, below the boreholes (Du Pisani and Vogt, 2004)

The interpreted position of the VCR is shown in Figure 8(b); slopes and terraces can be distinguished by rotating the radargram to its correct orientation (borehole 3 was drilled at inclination of -25°).

The illumination line coordinates for the VCR from five boreholes were then incorporated with the geological information (supplied by the mine) to build an improved 3D model as indicated in Figure 9. The VCR was successfully defined and geological structures can be seen on the 3D geological model, including slopes and terraces.

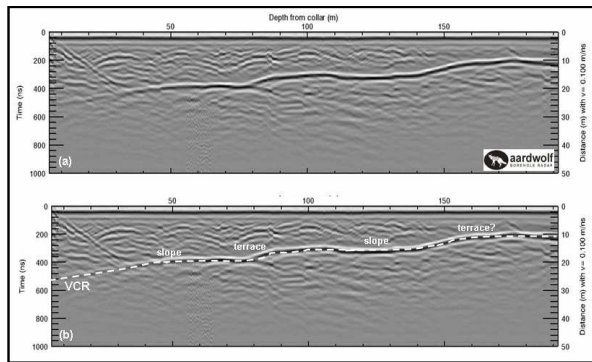


Figure 8: Radargrams for borehole 3, (a) without interpretation and (b) with interpretation (Du Pisani and Vogt, 2004)

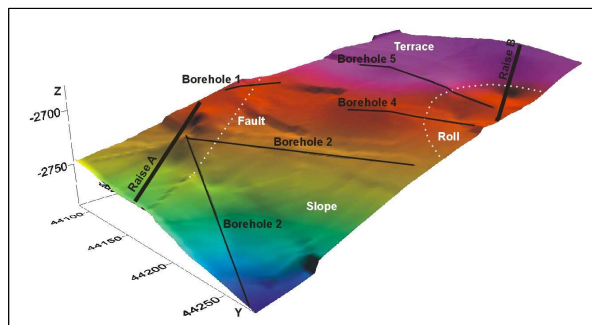


Figure 9: 3D Model for the VCR built in Surfer, using the illumination line coordinates from all the boreholes and geological information (Du Pisani and Vogt, 2004)

4.3 Financial benefits of using borehole radar

The financial benefits of using borehole radar have been analysed in detail by Du Pisani (2007), for platinum mining projects on the Bushveld Complex. The objective of the cost-benefit analysis that she carried out was to ascertain if borehole radar could minimise unnecessary development and improve productivity across all phases of a mining cycle. In general, borehole radar was expected to result in increased productivity by reducing the geological risk associated with features such as potholes, faults, dykes and IRUPs.

From one of the case studies, involving the mapping of the topography of the Merensky reef the cost-benefit analysis results revealed that it costs 23 times more to define a reef intersection point by drilling than it costs to obtain a set of

illumination line coordinates by using borehole radar. In addition borehole radar gives a continuous line of points about the reef topography (Turner et al., 2000). Mapping is limited by available access, and to obtain additional points by drilling would require more drill holes (assuming the holes are at an angle to the reef).

Overall borehole radar greatly outweighed the high costs of drilling and directional surveying, and much improved the knowledge about the geological model of the reef. It is, therefore, recommended that borehole radar be used to minimise excessive and unnecessary cover hole drilling, and that the latter only be employed as ground truth to complement the former.

5. On-going and future research

5.1 Directional borehole radar

Most borehole radar techniques used in the mines can determine the distance to the target reflector relative to the borehole, but cannot determine the direction of the target reflector, as discussed in section 3. A borehole radar system measures the travel time of an electromagnetic signal travelling from the transmit antenna to the receive antenna via a target reflector. The distance to the target reflector is determined from the travel time information. As shown in Figure 3, it is not clear whether the target reflector is above or below the borehole. Therefore, for some targets, a borehole radar system with directional capabilities is essential.

Directional antennas and direction finding techniques have been used in radio for several decades. Most of these techniques are based on the Watson-Watt technique and employ the Adcock direction-finding antenna (Adcock, 1959). All these techniques rely on antenna elements that are of the order of a quarter of a wavelength apart.

For borehole radar, a novel direction-finding antenna has been developed, consisting of an array of four dipole antennas placed symmetrically in the receiver probe of the borehole radar system. The direction of a target reflector is determined from the time of arrival of the electromagnetic wave at the four antennas placed in the receiver probe.

The typical diameter of an exploration borehole in South African mines is 48 mm. The 48 mm

diameter constraint implies that the four antenna elements are much closer than a quarter of a wavelength, and are therefore affected by mutual coupling (Balanis, 1982). Therefore, it is important to investigate if it is feasible to determine direction from an array of four antennas constrained to a borehole of diameter 48 mm.

Nyareli and Vogt (2007) used a numerical modelling method to determine that it is feasible to determine direction from an array of four antennas only 20 mm apart, using the GprMax3D electromagnetic simulator.

The numerical modelling was followed up by physical scale modelling undertaken in a water tank. Mutual coupling affects the time delay between received signals on different antenna elements. The symmetrical arrangement of the four antenna elements means that as long as the coupling effect is constant, it disappears when ratios of the time delay are taken. By following a simple calibration procedure it was found possible to determine the direction of incoming waves to within $\pm 15^\circ$ (Vogt and Nyareli, 2007).

A borehole radar system that implements an array of four dipole antenna elements has been built at CSIR. Figure 10 shows the borehole radar system with the four dipole antenna elements in a receiver probe. Tests are currently being undertaken to determine if the system can determine the direction of real target reflectors as is predicted from numerical and scale modelling.

5.2 Electrical property measurements

The application of radar technology is more successful when an a priori understanding of the geological conditions of the area where it is applied exists. Therefore, when using borehole radar it is important to have a prior knowledge of the electrical properties of the rocks in which the target to be imaged is hosted (Rütschlin et al., 2007, Simmat et al., 2006). Between 1980 and 2003 electrical property measurements were done at the

CSIR on about 4 500 rock samples from most of the major mining rock types in Southern Africa, including the two major platinum horizons found in the Bushveld Complex (Du Pisani and Vogt, 2003). Radar velocities are calculated from the same database. The radar wave velocity is used to convert radar wave travel times to distance. It has been observed that the measured values may not

be representative of the specific geological conditions encountered in every mine.



Figure 10: Direction borehole radar receiver

The CSIR has, therefore, resumed research on electrical property measurements. The result of this research is expected to improve data interpretation and modelling prior to undertaking field surveys.

5.3 Data analysis and presentation

To derive the maximum information from radar images, data processing and interpretation has to be optimized as far as possible. The interpretation turnaround time needs to be as short as possible in order for radar to be routinely applied in the underground mining production environment. At present, GPR and borehole radar data analysis is mostly done by skilled users (Yelf and Al-Nuaimy, 2004).

Further work in design of data processing and analysis methods that could simplify interpretation such as computational and mathematical tools that enable automatic picking of reflectors or de-noising of images prior to interpretation (Ngwenya et al, 2007) is in progress. Radar images usually show many reflections from targets that are not the objective of the survey. There is a need for new techniques that separate genuine targets from undesirable reflectors. Forward modelling (computer simulations) incorporating a priori information from drilling or geology is useful in determining the anticipated result in the field, by removing interpretation ambiguity. Developing and simplifying automated modelling and interpretation

are likely to make borehole radar a more user-friendly technology that can be operated by mine personnel, for routine underground application, for smooth integration into the production cycle.

5.4 Other related research

For surveying of underground borehole radar holes, the current technique used by the CSIR is to push an anchor into the borehole. The anchor supports a pulley that is used to pull the borehole radar tool along the borehole. The process of installing the anchor requires about four people and takes about 45 minutes to do. The anchor is abandoned after each survey. Research and development are currently under way at CSIR to design an automated crawler that will move to the end of the borehole and remain fixed (self-anchored) during the survey. It is then recovered at the end of the survey. A prototype has been constructed and will be tested in due course.

Further local mining problems that are yet to be successfully addressed using geo-radar include geotechnical and geological characterisation of underground mine tunnels where geological information is inadequate. Reconstruction of target geometries in such difficult environments still presents challenges in terms of data interpretation. Development and application of directional radar, 3D borehole radar imaging, and cross-hole radar tomography may offer some advantages in such cases (Osman et al., 2002). In cross-hole geo-radar, the radar transmitter and receiver are placed in separate boreholes and used to image the rock mass between the boreholes (Zhou and Fullager, 2001).

6. Conclusions

Borehole radar has proved to be a valuable geophysical tool to optimise mine layouts and production. The application of borehole radar prior to and during mining is cost-beneficial. During mine planning, costly development is avoided since knowledge of reef geometry and obstructing structures and features is greatly improved. However, there are limitations that need to be well understood to optimise suitable positioning of the boreholes for borehole radar. Knowledge about the position of the reflectors, other possible radar target in the area and a good understanding of the mine rock layering is required in order to get maximum benefit from borehole radar data.

The topography of South African gold and platinum mine reefs can be defined to a meter accuracy using borehole radar. A radar penetration of 30 m is typical for both gold and platinum mine environments in South Africa at a frequency of 40 MHz, although longer ranges have been achieved under ideal circumstances.

The CSIR's Fresco software assists in interpretation and in removing the directional ambiguity of the data.

Antennas operating at 250 MHz with a spacing of 20 mm are susceptible to mutual coupling, but time-delay information can still be obtained despite the coupling. It is possible to determine the direction of incoming waves to within $\pm 15^\circ$ of the correct angle.

There still remains a need for radar research in the following areas: electrical rock properties, modelling radar wave propagation in rocks, and data analysis especially for optimizing information extraction and application of the technique in geotechnical characterisation of mine tunnels.

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8. Endnote:

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