High-resolution, short-range, in-mine geophysical techniques for the delineation of South African orebodies

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The economic horizons (also referred to as orebodies or reefs) of the two major precious metal ore deposits of South Africa, the Bushveld Complex (platinum) and the Witwatersrand Basin (gold), exhibit remarkable lateral continuity on a regional scale. Consequently, the geometry of the respective planar orebodies is relatively easy to predict ahead of mining. On a local, in-mine scale, however, the geometry of these orebodies is far less predictable because of the presence of disruptive geological features such as faults, rolls, terraces, potholes, dykes, and iron-rich ultramafic pegmatite (IRUP) bodies. The occurrence of these features compromises mine planning, production and safety. This paper illustrates how the integrated use of three high-resolution geophysical techniques can provide valuable geological and rock engineering information ahead of mining, making mining operations more cost effective and safe. The geophysical techniques considered are electrical resistance tomography, borehole radar, and ground penetrating radar.

Introduction

The economic horizons of the two major precious metal ore deposits of South Africa, the Bushveld Complex (platinum) and the Witwatersrand Basin (gold), have one thing in common — these thin, tabular orebodies, or reefs as they are locally referred to, are relatively non-undulating and laterally continuous on a regional scale. Conventional ore extraction and tracking of the reef horizon ahead of mining are therefore fairly straightforward from a regional perspective. Where major structural alterations to the reef exist, these can be detected through the use of geological mapping or three-dimensional (3D) surface seismic reflection. If one zooms in to local areas within individual mines, however, the continuity of the reef is often unexpectedly disrupted by geological features that are not detected prior to mining. Some of the important small-scale disruptive geological scenarios for gold and platinum mining are briefly described in this section.

Gold mining: abrupt reef topography variations, rolls and terraces

The gold of the Witwatersrand Basin occurs within a series of conglomerate bands or reefs hosted within a sequence of quartzites and shales. One of the most important gold-bearing reefs, the Ventersdorp Contact Reef (VCR), occurs at the contact unconformity between the sedimentary, terraced palaeo-landscape and the overlying lavas.[1] The palaeo-landscape consisted of a complex drainage pattern comprising braided streams confined by terraces (Fig. 1). The gold is concentrated in palaeo-river channels situated on the terraces. The terrace slopes also contain gold, but this gold is of lower grades. Accurate information about reef topography prior to mining is advantageous, as mining can then be planned so that higher-grade areas are accessed first. Also, sterilization of gold is reduced if supporting pillars can be placed in low-grade areas. Sterilization occurs where a gold-bearing area becomes impossible to extract, for example, because of safety considerations. Abrupt changes in reef topography cause further problems for mining, as was previously outlined. For example, if the change in reef elevation is less than approximately 3 m, the change can easily be mined through. If, however, the elevation change is significantly more, adaptive mining may be required, which will result in delays in production. Advance knowledge of such elevation changes would enable mine planners to mitigate the effects of the loss of production by developing alternative areas. A further potential mining problem occurs at the transition between a terrace and slope, which is also known as a roll. Rolls are often related to unstable hangingwall (roof) conditions and collapses. Advance knowledge of rolls would thus contribute to counteracting poor ground conditions, thereby contributing to safer mining conditions.

Platinum mining — potholes and iron-rich replacement pegmatoids

On the platinum mines of the Bushveld Complex, the continuity of the reefs is often disrupted by slump structures, locally

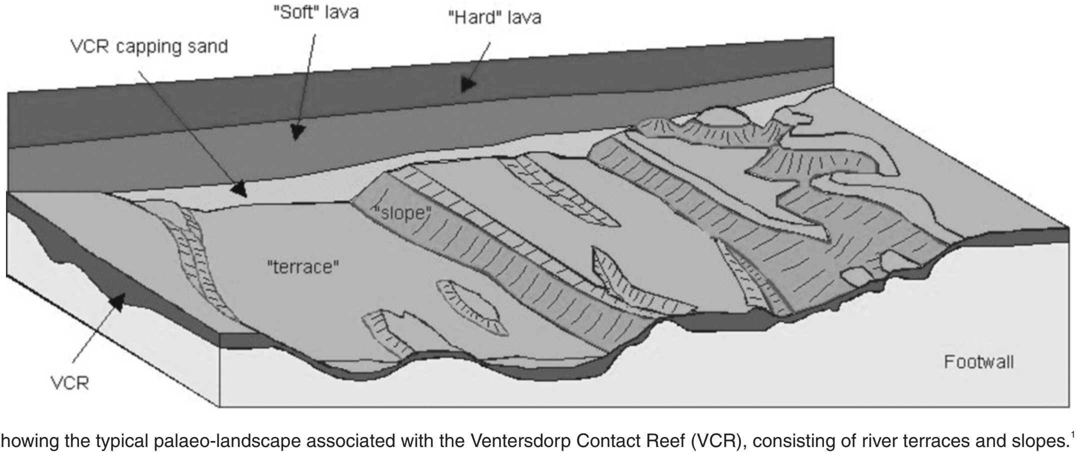

Fig. 1. Diagram showing the typical palaeo-landscape associated with the Ventersdorp Contact Reef (VCR), consisting of river terraces and slopes.[1]

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referred to as potholes, and by iron-rich ultramafic[‡] pegmatite bodies (IRUPs). Mine-scale potholes and IRUPs may vary in size from only a few metres to several tens of metres across and can result in local distortions or discontinuities in the reef horizon, with inevitable adverse economic implications. Pothole occurrences also result in poor ground quality, which increases support requirements and impacts adversely on safety. The detailed extent and geometry of potholes and IRUPs are often very unpredictable. The reef could, for example, either be distorted (slumped) or interrupted (pinched out). IRUPs and dykes would also have the latter effect on the reef. The implication for mining is either a loss of mineable ground or the need for unplanned and expensive adapted mining practices to negotiate the slumping reef. As in the case of gold mining, there is thus a definite need for a routine geophysical tool that can predict changes in the reef topography ahead of mining for the assistance of short- to medium-term mine planning.

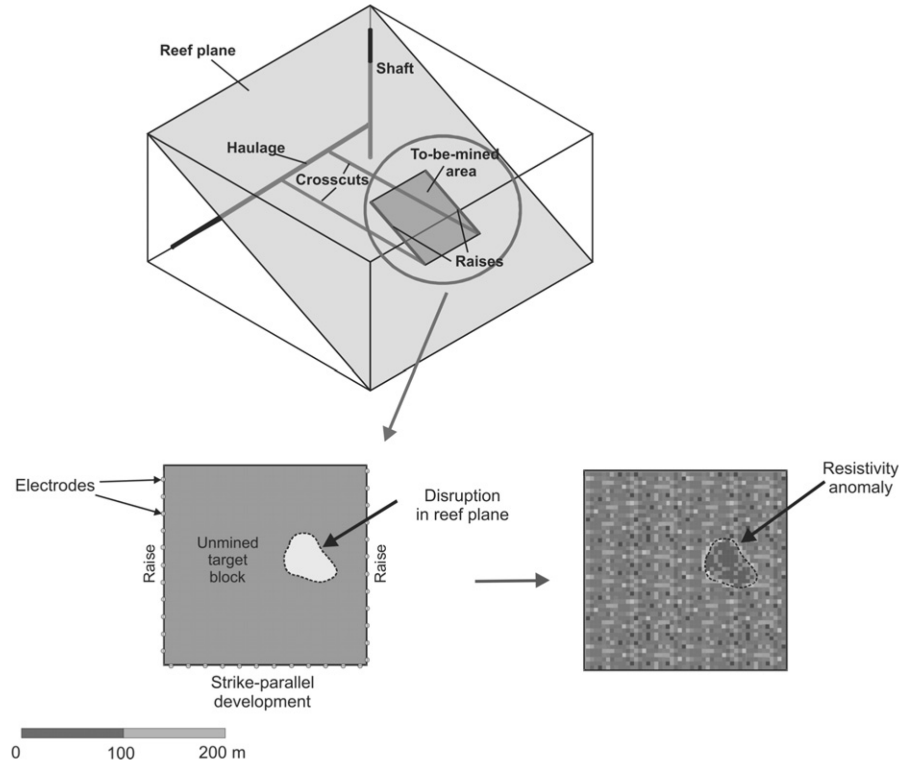

Fig. 2. Schematic representation of the concept of in-mine ERT.

Mining layout

Typical gold or platinum working occurs at depths from a few hundred metres to a few thousand metres below the surface. Access to the mineralization is provided by a system of tunnels, including haulages or main travelling ways, cross-cuts, and raises that are developed from the main vertical shaft to positions within the plane of the tabular reef (Fig. 2). Strike-parallel haulage tunnels are developed from the shaft along the orebody, at different levels above and below the orebody. A series of parallel cross-cut tunnels branch out perpendicularly from these haulages in the dip direction, and intersect the plane of the orebody. From these intersection points, raises are developed in the plane of the orebody, in directions perpendicular to the strike (up-dip and down-dip). Mining activities, such as drilling and blasting, are started from within these raises and the virgin block between two adjacent raises is gradually mined out in segments called panels. The spacing between raise tunnels and, consequently, the dimensions of the to-be-mined area is a function of factors such as the mining method and the dip of the orebody. However, a typical block width, or raise spacing, may vary from as little as 35 m to more than 200 m.

The challenges of applying in-mine geophysical methods

The successful application of in-mine geophysical methods poses a far greater challenge than in conventional surface geophysical exploration. There are several unique obstacles associated with the in-mine environment that have to be overcome in order to make routine, in-mine, geophysical surveys a reality, and ongoing research at the CSIR is dedicated to optimizing in-mine geophysical methods. The key obstacles associated with the application of in-mine geophysical methods are as follows:

- *Environmental conditions*: the humid and corrosive in-mine atmosphere combined with frequent and sporadic surplus water occurrences compromises the effective functioning of electrical and electronic equipments.
- *Limited access to the survey area*: limited access close to an intended survey area often causes geometrical constraints on survey design. Limited access may also impair the mapping accuracy of geophysical techniques.
- *Production-related constraints*: the first priority in mining is undoubtedly production. The obvious precedence that mining activities take over, for example, research, combined with the rigid scheduling of resources, often causes delays, interruptions and sometimes even the abrupt termination of geophysical surveys.
- *Impact of mining infrastructure*: in-mine, geophysical surveys are conducted within tunnels, other excavations or in-mine boreholes. The effect of these excavations and the associated infrastructure (e.g. ventilation pipes and other utilities) needs to be taken into account. In some cases, data corrections are necessary.
- *3D full-space vs 2D imaging*: the 3D nature of geological targets as well as of interfering infrastructure can lead to spurious 2D imaging results. Because underground access constrains all the geophysical techniques discussed in this paper, the third dimension has to be taken into account when interpreting the images.

Proposed geophysical solutions

The evolution of in-mine geophysics in South Africa

In the 1990s, CSIR Mining Technology was involved in several research efforts aimed at introducing high-resolution geophysical methods to the South African mining industry.[2–5] These efforts were only partially successful for reasons that are summarized below:

- The application of in-mine, geophysical methods was usually commissioned because of some short-term, pressing mining

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[‡] The term ultramafic refers to a class of rock that crystallizes from silicate minerals at the highest temperatures when the magma cools.

problem — consequently, in-mine surveys were usually conducted sporadically.

- The mines had access to a fairly limited range of geophysical tools that were either relatively immature or not well adapted for in-mine use.
- There is a historical culture of resistance from mines to embrace emerging technologies and to the inevitable trial-and-error nature of experimental surveys.

In the last decade, however, great advances have been made in relevant geophysical tool and technique developments. Research efforts have also benefited from a closer working relationship with the mining industry, especially through highly successful collaborative research initiatives such as DeepMine, Coaltech 2020 and PlatMine. These positive changes have enabled mining geophysicists to employ a more calculated and integrated strategy, taking high-resolution in-mine geophysics a step closer to becoming a routine part of the mining cycle. This paper describes and advocates a generic, three-pronged approach to in-mine geophysics in which the emphasis is on integration with mining.

Electrical resistance tomography (ERT)

ERT exploits on-reef developments (raise lines and strike-parallel developments) surrounding a virgin block to probe for disruptive features within the block.[6–8] Electrodes are attached to the sidewall at intervals along the developments. Electrical current is applied by means of a pair of electrodes, while the resulting potentials are measured between various other pairs of electrodes (Fig. 2). These four-electrode measurements are repeated in a systematic fashion for many different source–receiver electrode combinations. The resulting set of resistance data is then used as input to a tomographic inversion algorithm that iteratively reconstructs the likely resistivity distribution that is responsible for the observed resistances. The output is a two-dimensional colour-coded image of the reef plane showing spatial variations in the electrical resistivity. A disruption or distortion of the economic horizon will manifest as a resistivity anomaly on the output image. Consequently, both known features, intersected by developments or boreholes, and unknown features can be delineated. The ERT technique is applicable to blocks of up to 200 m × 200 m at a resolution of approximately 5 m. To date, in-mine ERT has been tested only in South African platinum mines and of the three techniques described in this paper it is the least mature.[8] Even though the technique has shown a lot of promise, it still requires some significant research and development before it reaches the same level of maturity and acceptance that ground penetrating radar and borehole radar have achieved.

Ground penetrating radar (GPR)

GPR is a high-frequency electromagnetic technique for imaging in the earth.[9] An antenna transmits pulses into the ground that are reflected from geological discontinuities. The reflections are detected and can be displayed in real-time and stored for later analysis. The output from a GPR survey resembles that of a seismic record, which makes it possible to determine the distance between the target and the antenna at points along the radar profile. The typical operating frequency for in-mine GPR applications is between 250 MHz and 500 MHz, which equates to a maximum range of approximately 5 m to 10 m in typical hard rock environments. The associated resolution is of the order of a few centimetres.

The niche application for GPR is the probing of the immediate hangingwall to determine distances to specific interfaces, layers or partings for support design for rock engineering purposes. GPR can also identify hazardous geological features such as angled joints or faults and can thus play a key role in monitoring hangingwall integrity. Where roofbolts are applied, GPR is particularly useful for determining whether they are adequately supporting the required beam.

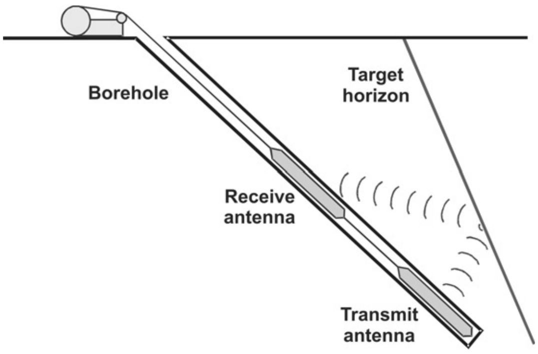

Fig. 3. Schematic representation of a borehole radar system.

Borehole radar

Borehole radar is an in-borehole application of ground penetrating radar. A closely spaced radar transmitter and receiver operate along the length of an exploration borehole (Fig. 3). The borehole radar tool can be employed in boreholes of any orientation. The fundamental principles of data acquisition are similar to those of GPR except that a much lower operating frequency is employed. Geological interfaces will reflect some of the transmitted radar energy back to the receiver, making it possible to determine the distance between the target and the tool at points along the profile defined by the borehole. The CSIR's Aardwolf BR40 system operates at a centre frequency of 40 MHz, which implies a maximum range of up to 50 m in hard rock environments, with a resolution of 1 m. The major advantage that borehole radar has over GPR is the artificially extended range provided by the borehole, making it possible to target areas well ahead of mining, where discontinuities are expected.

Case studies

ERT surveys at Impala platinum mine

An ERT trial survey was conducted at Impala's number 9 shaft and was aimed at delineating known pothole features developed on the UG2 reef horizon. At this particular site, access was available from three sides of the target block. The spacing between the two adjacent raises was approximately 110 m. The output image from this survey is shown in Fig. 4. Warm colours (red and orange) indicate electrically resistive features, while cold colours (blues) represent conductive features. Disruptions to the reef horizon caused by potholes are expected to manifest as resistive anomalies on ERT images.[6] A number of resistivity anomalies can be seen on the output image. Most of these anomalies (A, B and C) were correlated with known pothole intersections in the raises, strike parallel development, and an abandoned stope. Anomaly D appears to have been caused by a smaller pothole. A follow-up site visit shortly after the ERT survey did not reveal any evidence of such a pothole or other anomalous geological feature being present. The most likely explanation for this anomaly is that it is caused by a geological feature that lies just outside the image plane. In other words, the anomaly may be the manifestation of the 2D simplifying assumptions used in the tomographic algorithm being violated by 3D geology.

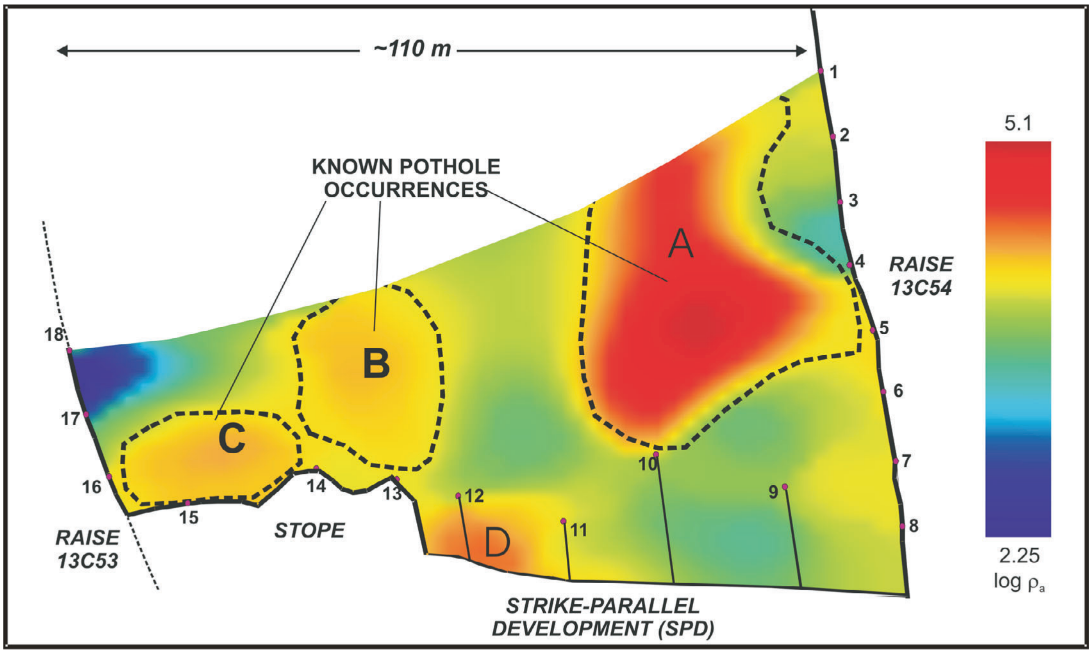

Fig. 4. ERT survey result from Impala platinum mine. Electrodes 1–8 were located along raise tunnel 13C54. Electrodes 9–12 were located at the ends of short exploration tunnels branching out from the strike-parallel development. Electrodes 16–18 were located along the raise tunnel 13C53.

The source of the unmarked dark blue (relatively conductive) anomaly located between electrodes 17 and 18 is also uncertain, but may be related to a localized increase in mineralization. mm

Borehole radar survey at Mponeng gold mine

Five boreholes were surveyed at AngloGold Ashanti's Mponeng mine through the use of the CSIR's Aardwolf BR40 borehole radar system in 2004.[1,10] The surveys were conducted in boreholes drilled from opposing cross-cuts into the hangingwall lava, and designed so that they would run approximately parallel to the VCR, between 30 m and 50 m above it (Fig. 5). The dip of the VCR is 22° in a southerly direction, with the boreholes drilled at various inclinations so as to remain parallel to the reef target. The five boreholes covered an area of approximately 200 m × 200 m and the borehole radar information from these boreholes, together with additional *a priori* information from cross-cut and raise intersections, was used to construct a 3D model of the orebody in this mining block.

Figure 6 shows the typical radargram obtained during this survey; this particular radargram is for borehole 3. The distance along the borehole from its collar is given along the *x*-axis of the radargram; time in nanoseconds is given on the primary *y*-axis, while converted depth is shown on the secondary *y*-axis. A summary of the interpretation presented by Du Pisani and Vogt[1] follows: the prominent reflector seen approximately 20 m from the borehole collar position is interpreted to be the contact between the lava and the footwall shale, exactly where the VCR is expected. If the borehole is rotated into its true orientation of –25°, slopes and terraces can be distinguished on the VCR. Results from the other four boreholes showed that slopes, terraces and disruptions to the VCR, such as rolls and faults, could be detected with borehole radar. A 3D visualization package called Fresco, developed under the Platmine Research Initiative, was used to model the borehole radar data in three dimensions for the elimination of the directional ambiguities associated with borehole radar data. The 3D coordinates for the reef elevation lines above the boreholes produced in Fresco were then imported into the mine's own reef modelling software to

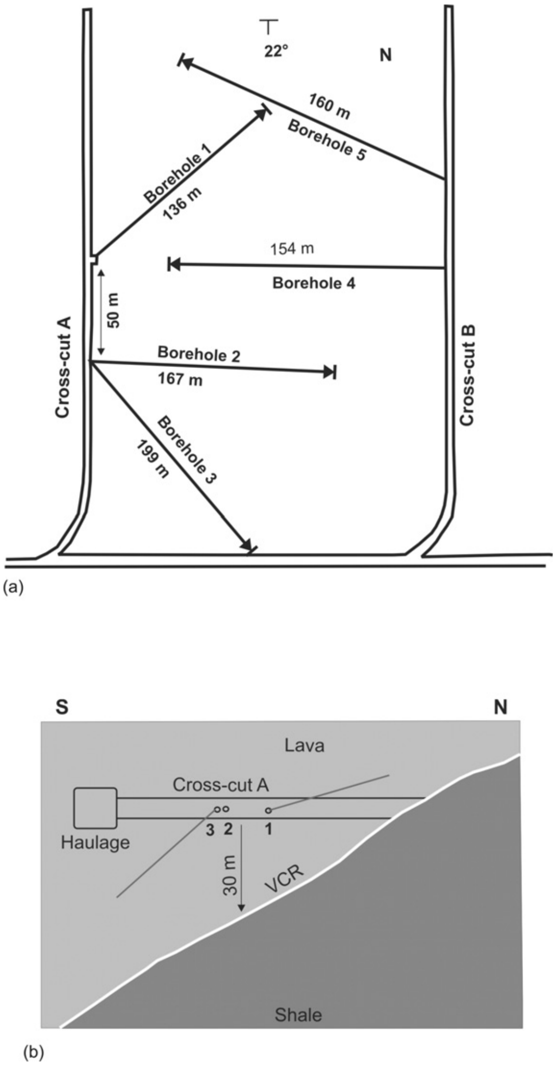

Fig. 5. Borehole radar case study geometry in plan (**a**) and in section (**b**), showing boreholes 1 to 5, drilled from cross-cuts A and B. The VCR is below the boreholes, dipping in a southerly direction at 22°.[1]

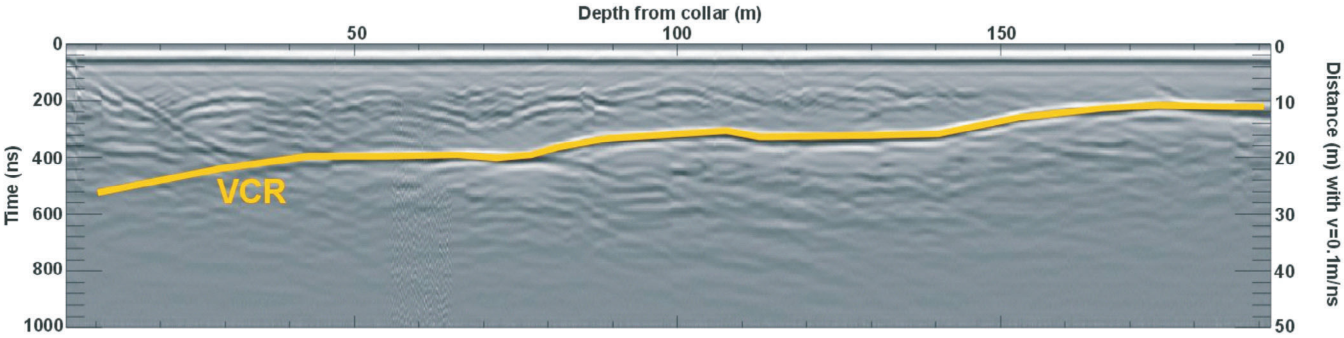

Fig. 6. Radargram for borehole 3. The VCR reflector is seen 28 m below the borehole at its collar. It moves closer to the borehole and is located approximately 8 m below the borehole, where it ends.[1]

produce a reef elevation model for the mining block between the two cross-cuts (Fig. 7).

The outcome of this case study was that the existing geological model of the mining block was improved, leading to improved mine planning and resource evaluation. The financial implications of accurate reef topography were briefly discussed by Du Pisani and Vogt[1] and they concluded that the application of borehole radar can lead to significant cost savings. The success of the surveys conducted at Mponeng in 2004 has led to a continuing relationship between the CSIR and Anglogold Ashanti for the provision of borehole radar surveys in 2005 and 2006.

GPR survey at Waterval mine

A GPR survey was conducted at Waterval Shaft (Rustenburg Platinum Mines), in which the primary aim was to determine whether GPR could accurately map the position of the Leader Seam, a marker horizon that occurs approximately 1 m above the UG2 reef.[11,12] A secondary, but equally important, objective was to assess the capacity of the technique for detecting curved joints. These joints sometimes cut across the immediate hangingwall, compromising its stability. A GPR profile was acquired directly over a set of known curved joints. The resulting radargram is shown in Fig. 8. Several curved joints can be identified as indicated. In this particular case the radargram indicates that the joints do not extend beyond the Leader Seam. The apparent disruption of the Leader Seam at about seven metres is due to antenna-positioning errors on the highly irregular hangingwall surface, rather than changes in structure. The result proves that GPR can be used to map the topography of Leader Seam, while curved joints and their vertical extent can also be mapped.

The integrated approach to applying in-mine geophysical methods

ERT, borehole radar and GPR can be applied in an integrated fashion to optimize mining by improving mine planning and safety, and such an approach has already been advocated for mechanized mining operations.[11] The application of each geophysical technique depends on the stage of mining and the type of information required at each stage:

Stage 1: Development of haulages and cross-cuts to define mining layout/grid. During this stage, mine planners could benefit from reef elevation and reef continuity estimates in areas where on-reef developments (raises) are planned. Advance warning of major reef disruptions can be obtained in this way, and raises can be optimally placed to minimize the impact of any detected features. The type of information required during this initial stage of mining can be provided through the application

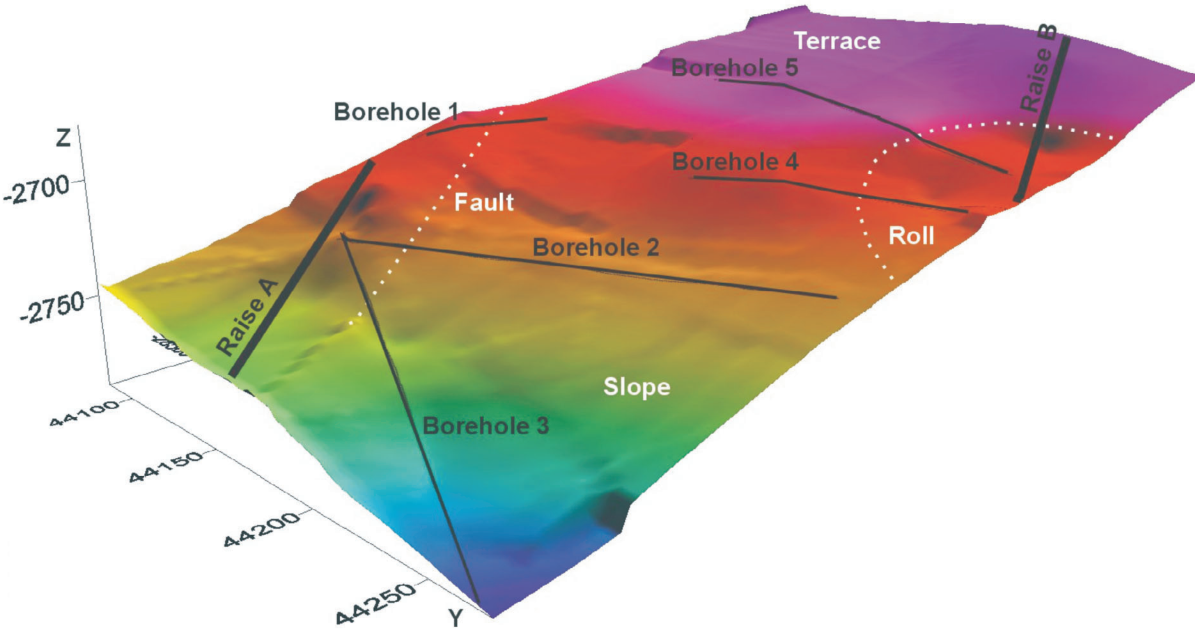

Fig. 7. 3D model for the mining block between cross-cuts A and B using the borehole radar data from boreholes 1 to 5, as well as prior information supplied by Mponeng mine.[1] Plot axes show relative position in metres.

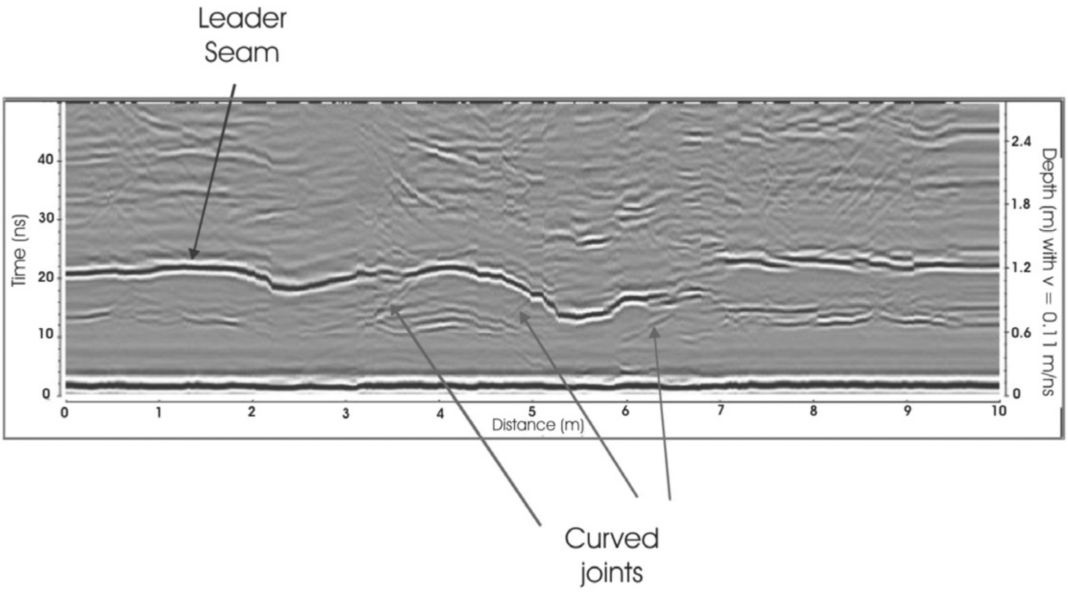

Fig. 8. Mapping the Leader Seam and known curved joints at Waterval Mine, Rustenburg Section.

of borehole radar in selected exploration boreholes.

Stage 2: On-reef development of raise lines and strike-parallel developments. During this stage, mine planners would want to obtain higher-resolution maps of reef topography and continuity within the to-be-mined blocks defined by adjacent raises. The detection and accurate delineation of disruptive features can be achieved by applying tunnel-to-tunnel ERT after development of raises, but prior to the start of mining. Once the spatial extent of disruptive features has been determined, follow-up borehole radar surveys may be used for accurately determining the vertical extent of reef topography variations and the degree of reef continuity related to the disruption.

During the on-reef, development stage, hangingwall stability plays an increasingly important role and rock engineers are particularly interested in the relative position of key marker horizons within the immediate hangingwall. This type of information is typically obtained through the drilling of numerous boreholes and by interpolating between these boreholes. GPR can be used to map marker horizons accurately along continuous profiles. In the process the quality and quantity of information regarding the immediate hangingwall structure can be vastly improved and the cost associated with drilling a large number of hangingwall boreholes can be significantly reduced.

Stage 3: Ore extraction. Once mining begins, accurate knowledge regarding hangingwall structure and condition continues to be of critical importance from a safety perspective. GPR can be used routinely to monitor hangingwall conditions and to optimize support requirements.

Conclusion

Historically, the potential of high-resolution in-mine geophysical methods has not been fully exploited by the South African gold and platinum mining industry. However, closer cooperation between researchers and the mining houses, combined with significant technological advances made in recent years, has resulted in positive changes in this regard. Mine geologists, rock engineers and mine planners are starting to realize that geophysics can add immense value to the mining cycle by contributing to more cost-effective ore extraction, while at the same time improving safety. The strength of the geophysical techniques described in this paper lies in the fact that they provide additional quantitative information that can reduce the risk associated with unexpected changes in geological and geotechnical conditions ahead of mining. Each geophysical technique has its own niche application, with associated strengths and limitations. For example, the range of the respective techniques varies from only a few metres at centimetre resolution to a few hundred metres at metre-scale resolution. This variety enables geophysicists to address short (day-to-day) and medium- to long-term mine planning issues. Furthermore, when applied in an integrated fashion, as is outlined in this paper, valuable information can be added to all stages of the decision-making process that will result in more cost-effective and safer mining.

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