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ABSTRACT: Geophysics has been used for at least a century to discover new orebodies, including significant deposits such as the West Wits line discovered by Krahmann in the 1930s. It is only since the mid 1980s, though, that geophysics has become an important tool for mining itself.

The paper discusses the rise of various geophysical techniques for in-mine use in South African tabular gold and platinum orebodies, from 3D seismic reflection, used for feasibility studies; to techniques that are applied in-mine, particularly radio and electrical methods, including borehole radar and electrical resistance tomography. Barriers to adoption are discussed, including the lack of skilled clients, the need for reliability and the need for good integration with mining operations.

INTRODUCTION
The Early Days
Geophysical techniques have been used in South Africa for discovering new orebodies almost since the discovery of the techniques themselves. The Witwatersrand Basin, the world's largest known gold deposit, outcrops on surface for 58 km, east and west of Johannesburg. However, further west, it is covered by younger rocks. Boreholes had shown the existence of gold "reefs," as they are known locally, in the West Wits but it was not until 1930 that Dr Rudolph Krahmann was able to show that the position and extent of the reefs could be determined using a magnetometer, and the West Wits Line was born (Krahmann 1936, Walker 1950). It has a strike distance of 64 km, and is home to what was once dubbed the world's richest gold mine, Driefontein, which poured its 100-millionth ounce of gold in 2005 (Anon, 2005).

Later that decade, gravity measurements were used to identify a potential portion of the Witwatersrand Basin about 200 km to the south of Johannesburg. Drilling confirmed the find, which later became the Free State goldfield. Almost all of the other remaining gold fields in the Witwatersrand were eventually discovered by geophysics—magnetics or gravity, alone or in combination (Roux 1967).

While geophysics is well known as a technique for discovering new orebodies, its use is less well known in the later stages of mining.

The Mining Life Cycle
For our purposes, the life cycle of a mine, as defined by Hartmann and Lacy (1992) and others, can be simplified to:

- Exploration
- Feasibility
- Construction
- Operations
- Closure

In this paper, we discuss the application of geophysics at each stage in the life cycle, in order to make mining safer and more productive. Our discussion is largely limited to the tabular hard-rock deposits of South Africa, particularly its gold and platinum mines. The first step of exploration is discussed above, and does not come into the realm of in-mine imaging.

FEASIBILITY
As the mine gets closer to production, the risk in the project drops, so information that lowers risk is most valuable early in the life cycle. For this reason, it is at the feasibility stage that the greatest use of geophysics takes place—to reduce the risk of a poor mining decision.

In the feasibility stage, the mineral resource manager needs to determine that there are sufficient resources in the ground to make mining a financially
successful proposition. The two factors to be considered are the size of the orebody and the difficulty of mining. In South Africa, exploration techniques are being successfully applied at a higher resolution for feasibility studies, particularly to map dislocations to reef. In particular, magnetics and electromagnetics have been used to map and characterise dolerite dykes and faults in platinum and coal prospects (Campbell 2006, du Plessis and Saunderson 2001). More recently, testing of a Full Tensor Magnetic Gradiometer has shown that it is particularly sensitive to dykes, and can also characterise non-magnetic dykes for Bushveld platinum prospects (Rompel 2009). Knowing the true thickness of dykes is an important part of calculating geological losses.

It is in the use of seismic reflection techniques for hard rock mining that South Africa has been a pioneer, with "what is probably the most extensive use of reflection seismics in the hard rock mining environment globally." ( Pretorius 2009). 2D seismic lines proved that the major economic horizons in the Witwatersrand Basin and the Bushveld Complex are seismic reflectors or have suitable proxies. With the introduction of 3D imaging came the resolution that would enable mine planning. Early surveys such as those at Oryx (de Wet and Hall 1994) and Vaal Reefs (Pretorius et al. 2000) showed the quality of data that could be achieved, and later surveys prevented at least one mine planning disaster.

Pretorius (2009) states that “today, at least one phase of 3D seismic imaging would be considered mandatory on Anglo-managed mine developments in the Witwatersrand Basin and Bushveld Complex.”

CONSTRUCTION

During mine construction, the most important need is for high resolution geotechnical information. The construction risk is highest at the shaft, and lowers as the development moves towards the edges of the mine. For shaft sinking, a combination of seismic surveys done during feasibility, geological logging from the shaft borehole, and geophysical wireline tools applied in the shaft borehole, provide near total coverage of the volume to be excavated for a shaft (Kaldine 2007). Borehole radar and acoustic or optical televiwer are both good tools for mapping structure near the shaft borehole: borehole radar can map out to tens of metres away from the borehole (Mabedla and Trofimczyk 2009) while a televiwer maps structure in the immediate vicinity of the borehole (Mahlati and Krynne 2009). In one case, the shaft was relocated on the basis of geotechnical evidence, including geophysical logging, that it would run within 15 m of a low strength lamprophyre dyke (Trofimczyk and du Pisan 2009).

The other mining risk is in the positioning of surface mine infrastructure. Here, typical geophysical tools for geotechnical applications can be applied, such as gravity, electrical resistance tomography (ERT) or ground penetrating radar (GPR) to look for voids below preferred building locations. This would only be done if there were good geotechnical reasons to do so. Techniques such as gravity or ERT are also useful for determining if voids such as sinkholes are developing near or under existing buildings (Van Schoor 2002), and could prevent disasters such as the sinkhole that swallowed the reduction works at West Driefontein gold mine and killed 29 people in 1962 (de Bruyn and Bell 2001).

OPERATIONS

The cost and inconvenience of doing in-mine geophysics are barriers to its use, despite the obvious value of the information that can be obtained. Once mapping is underway, the typical information requirements are for orebody grade and geometry, and for geotechnical information about the host rock. In many environments, the location of the orebody is not well known, and in-mine geophysics provides excellent guidance for mining operations, for example finding sulphide occurrences in typical distributed massive sulphide deposits. For these problems higher resolution versions of standard exploration tools can be used such as electromagnetics, magnetism or even gravity.

In South African gold and platinum mines, the overall geometry of the tabular orebody is well known, and the orebody is continuous on a large scale for kilometres in both strike and dip. Mine operators are therefore sometimes overconfident in their understanding of the geology. Mine operators, particularly on platinum mines, also have a very long life-of-mine, and are less concerned by geological losses than operators close to the end of the life of mine.

However, operators are now beginning to appreciate the value of in-mine geophysics, and are starting to introduce some techniques on a routine basis. The change has occurred as particular tools have become more reliable and easier to apply, and as mining pressures have changed. For example, GPR is particularly suitable as a tool for determining hangingwall conditions and the likelihood of hangingwall failure, and hence in determining the need for the appropriate support. In an industry increasingly concerned with safety, GPR is becoming a routine tool, and is likely to be written into the codes of practice for some mines in the near future.

A good review of high resolution techniques for in-mine use is contained in Van Schoor et al. (2006).

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Ground Penetrating Radar

GPR is a high resolution technique that reflects short radio pulses off target horizons in rock that have different electrical properties to the host rock. The transmit and receive antennas are usually co-located in a single box. Data is collected by moving the antennas along a survey line, and presented in an image such as that in Figure 1, where position along the survey line is along the x-axis, and time of the reflection into the rock is on the y-axis. If the velocity is known, the depth of the reflection can be calculated. The colour scale in the image represents the strength of the reflectors. The image in Figure 1 is inverted, as it represents a radogram looking up into the roof of an excavation. Usually, the time and depth scales start at 0 on the top of the image, increasing downwards.

GPR works best in resistive host rocks that contain reflective target horizons. The quartzites of the Witwatersrand Basins and anorthosites of the Bushveld Complex are both highly resistive and very suitable for radar use (du Pisani and Vogt 2003). Radar resolution and range are linked to the operating frequency. At a frequency of 500 MHz, the resolution is better than 10 cm, with a range of 5 m to 8 m. At higher frequencies, better resolution comes at the cost of decreased range, and vice versa.

A good application of GPR is in the hangingwall of the Bushveld Complex (Vogt et al. 2006). There are a number of thin chromitite layers that occur in the hangingwall of the UG2 reef that are subject to weakness and that can fail if unsupported. The chromitite is an excellent reflector, making GPR a very effective tool for mapping the potential parting planes. In Figure 1, the distance to the horizon is clearly visible. If the distance to the horizon is known accurately, it can be used to confirm that roofbolts used for support are long enough to reach the solid rock above the unstable ground in the immediate hangingwall.

In Bushveld Complex mines, additional hazards to hangingwall stability are caused by flexural slip structures, often known colloquially as domes. GPR can detect flexural slip structures if the fault contains infill that is different to the host rock. Figure 1 shows some evidence of flexural slip structures, labelled as curved joints.

GPR is also useful for determining the location of voids in rock. In mining, one of its most practical ad-hoc uses is to find lost boreholes. When drilling from one level to another, for a drain hole, or raise bore pilot hole, or for any other purpose, if the borehole does not end up where it is expected, GPR can be used to find it easily in the sidewall, footwall or hangingwall. The conventional alternative is to drill many short holes in an attempt to reach the lost borehole. For this application, GPR can greatly reduce the search time and in an application like a raise borehole, it can save significant costs by bringing the raise into operation more quickly.

In Figure 2, a GPR survey has been used to find a lost raise bore hole. The modelled response is illustrated, together with the measured response, and the excellent correlation can be seen. The measured radogram is not of particularly good quality, with many other reflectors present due to the fractured nature of the sidewall. However, the coherent hyperbola that is characteristic of a cylindrical target is clearly visible against the noise. The hyperbola is not
symmetric about its axis because the raise bore hole that it is imaging is not parallel to the survey line.

GPR is also sensitive to fractures. Often the fractures are not imaged individually, particularly if they are small and closely spaced, but the character of the GPR image changes when fracturing has occurred. In one study (Grodner 2001), GPR was used to determine how much fracturing was caused by preconditioning. Preconditioning is the practice of setting off small explosive charges ahead of the mining face, to transfer stresses away from the immediate face area. It is normally undertaken where the mining face is under high stress, as it is in deep level gold mines. In Figure 3, the character of the GPR survey before and after preconditioning shows how the fractured the rock is clearly visible. If GPR is used for fracture density determination, it must be calibrated at sites with known density, but it is particularly effective at mapping changes in fracturing, for example as in this case after blasting.

Borehole Radar

While GPR works well for geotechnical hazards, it has two problems in determining the geometry of reef geology in tabular orebodies:

- To achieve significant range of tens of metres, the frequency has to be dropped below 100 MHz. At this frequency, antennas become impractically long for use underground.
- Radar, in common with seismic reflection, works best when applied parallel or sub parallel to the horizons of interest. For perpendicular targets, only the top of the target returns a radar
response, as illustrated in Figure 4. In South African tabular orebodies, there is no convenient access-way where GPR can be applied to easily map the topography of the reef.

The solution is borehole radar—GPR applied in a borehole. Once the antenna is in a borehole, its physical size ceases to be important, and the borehole can be drilled exactly where it is required to map a reef horizon. Figure 5 shows how a borehole drilled under the reef and approximately perpendicular to it can map features that are not visible using GPR from the face.

Borehole radar was first applied in South Africa in 1995, when trials were run with the Swedish Malå system. These trials showed that there are strong reflectors associated with the Venterdorp Contact Reef (VCR) in the Witwatersrand Basin, and with both the Merensky and UG2 reefs in the Bushveld Complex. Other significant gold reefs are often associated with reflective markers, for example the Carbon Leader often has a shale layer a metre or two above in its hangingwall. The Malå system was not capable, at the time, of operating at the high temperatures found deep underground in gold mines, and also had some logistical problems, leading to the development of two competing borehole radar systems, the South African CSIR Aardwolf (Vogt 2006), and the Australian-South African Geomole (Bray et al. 2007). Both are in regular use on South African platinum and gold mines, and Geomole is active in mine elsewhere (e.g., Kemp et al. 2009).

In both gold and platinum, the most immediate use for borehole radar is to identify dislocations to the planar reef: faults, dykes, and potholes. These dislocations are of a size that is too small to be easily identified in 3D seismic images, but that can significantly hinder day-to-day mining operations. In particular, it is very useful to know whether the throw of a fault is less than 3 m, where mining can continue through the fault, or greater than 3 m, when redevelopment will be required. If this information can be supplied at least a month before the working face reaches the fault, planning can take into the account the stoppage that will occur when the working face reaches the fault.

In gold, the topographic information provided by borehole radar can also be used to refine the gold
grade model (Figure 6). For example, in the VCR, the gold is associated with terraces and with low lying areas, and there is little mineralization in the slopes or "rolls" as they are known. The rolls are also associated with bad ground conditions, so borehole radar can enable planning that allows for the rolls not to be mined, making mining safer, and lowering dilution (du Pisani and Vogt 2004).

In the Bushveld Complex, potholes cause significant loss of ground, and are also associated with poor ground conditions. The potholes are slumps in the reef horizon that cut across the normal order of the stratigraphy. Borehole radar can be used to delineate the edges of known potholes. It is not straightforward to discover potholes using borehole radar, because a single radar survey gives just a single line of elevation on the reef, meaning that several boreholes have to be drilled underneath a block of ground to ensure that no potholes escape detection. However, if a pothole is known or suspected, borehole radar can easily determine its depth and horizontal edges. Just the saving caused by not mining into a pothole unnecessarily, with related costs and dilution, is often enough to justify the use of borehole radar. A thorough examination of the financial benefit of using borehole radar in the Bushveld was undertaken by du Pisani (2007).

Electrical Resistance Tomography

ERT is a modern adaptation of the well known electrical resistivity method that uses inversion theory to produce images of conductivity versus depth for lines on surface. On surface it is relatively cheap to acquire, and usually works very well. CSIR has been

Figure 5. How borehole radar applied under the reef and sub-parallel to it can map undulations in the target, where GPR signals from the mining face are deflected away (Vogt et al. 2006)

Figure 6. A three dimensional reconstruction of the VCR, delineated by borehole radar results from five boreholes, and from survey results along two raise lines. The scale is in metres (du Pisani and Vogt 2004).
experimenting with the application of ERT underground and between boreholes. When using ERT on surface, electrodes are placed on one side of the body to be imaged. In mine, electrodes can be placed on two or more sides, improving resolution.

In the Bushveld Complex, if all the electrodes can be placed on the reef horizon, the apparent resistivity will increase if the reef slumps into a pothole, because the paths taken by current between the electrodes will be longer as they follow the reef horizon (Van Schoor 2005b).

A case study from Van Schoor (2005a) is illustrated in Figure 7. A block of unmined ground about 85 m long and 32 m wide was thought to be reachable on all four sides. In fact, the bottom tunnel, marked SPD on the figure was not accessible. The mine plan on the left of Figure 7 shows inferred targets based on available geological information. 24 electrodes were placed around the block, and an ERT survey was conducted. The resistivity image is on the right of Figure 7. The resistive anomaly marked A correlates well to the observations from which the pothole in the mine plan was inferred, and appears to correlate with the pothole occurrence in the mined out area at the northeast corner of the survey. The extremely resistive anomaly B is interpreted as the combined effect of the small pothole near electrodes 16 and 17, the large pothole in the southeast, and the Iron-Rich Ultramafic Pegmatoid (IRUP) in the southwest. The fact that the IRUP extends further north than indicated in the mine plan was confirmed by a post survey underground visit.

ERT delivers images that are not of a high resolution, but for targets like potholes, it can scan a large area on reef, so it can be used for discovery. It promises to be an excellent way of quickly determining whether a mining block contains a pothole. If it does, follow-up work can be done using borehole radar to determine the details of the pothole.

Seismic Methods and Seismology

In the 1990s in-mine seismic methods were tested for use underground in South African mines. A number of techniques, including seismic refraction (Wright et al. 2000), seismic reflection, seismic tomography and an in-mine implementation of vertical seismic profiling, called mine seismic profiling or MSP were used. Unfortunately, many of the experiments do not appear to have been reported in the literature. Today, none of these techniques are in regular use, because of the logistical problems that were encountered. MSP in particular (Goldbuch 2007) showed promise as a method of providing information about the reef from existing development, but was very slow and difficult to conduct. There appears to be no theoretical reason not to use these techniques, and if small and easily deployed equipment is developed, the techniques may be revisited.

Seismic monitoring is undertaken routinely in deep gold and platinum mines to determine

Figure 7. A case study of ERT use. The prior information and electrode locations are plotted on the geological map on the left, with the ERT image of conductivity plotted on the right (van Schoor 2005).
where seismic events occur, and to estimate risk. Seismology is not considered further here, as it is a subject in its own right and has evolved somewhat separately from the in-mine geophysics discussed here. It is reviewed extensively in a paper by Durheim in this volume, or see Linzer (2007).

MINE CLOSURE
At the end of the life of a mine is the closure phase. In the case of good record keeping, required on mines currently operating, there is little need for geophysics, except to monitor waste dumps or slimes dams. For this purpose ERT (Rucker et al. 2009) and airborne radiometrics (Coetzee and Larkin. 2009) are particularly useful. Where older mines stopped operating without filing closure documents, there is often uncertainty as to their location. If they are shallow, ERT is an excellent tool for mapping the workings (Chirenje and Dip, 2009; Chambers et al. 2007).

The geophysics used in mine closure is not unique to mining, but uses the tools and techniques developed in other fields such as geohydrology and engineering geophysics to detect targets of interest after a mine has closed.

CHALLENGES
Pretorius (2009) raises the lack of skills in mining companies. Even at head office level, most mining companies have lost their entire geophysical skills base. This makes it very difficult to sell geophysical services to a knowledgeable client, which is a requirement when introducing a new technique. CSIR’s experience is that the initial stages of developing a new technique for in-mine use require a high level of commitment from the mining company, but also some level of technical expertise to appreciate the use, limitations and problems of the technique.

As techniques become more mature, for example GPR, they become part of routine operations on the mine. At this point, the reliability of the instruments becomes important. Many geophysical instruments are not developed with the harsh in-mine environment in mind, and quickly become unreliable. In addition, the in-mine market is not sufficient to set up local support for instruments, so time is lost shipping instruments back to their overseas manufacturers for repairs. For in-mine geophysics to become viable, it is essential that manufacturers set up support infrastructure in South Africa particularly as there are local operations that do repair geophysical equipment.

Related to the challenge of reliability is the challenge of logistics. For example, during the developmental phase, a survey might take several days. While that is acceptable as part of an experiment, it is not possible in a production environment. As tools come close to production use, it is essential that the logistics behind them become as simple as possible, and preferably that they match the mines’ current mode of operation.

CONCLUSION
In-mine geophysics is building on the platform created by 3D-seisics, and is starting to provide high-resolution mapping of in-mine features such as reef geometry and potentially grade, and host rock mechanical properties. The challenge for further uptake of in-mine techniques is to provide the information cost effectively and quickly enough for mining decisions to be made on the data. As service providers refine their operations, geophysics will become part of the standard arsenal of the modern mining company, at all scales from fracture mapping over metres to mapping geological structures for shaft positioning over kilometres.

REFERENCES


Durrheim, R.J., 2009. "Mitigating the risk of rockbursts in the deep hardrock mines of South Africa," this volume.


