



# The application of radar techniques for in-mine feature mapping in the Bushveld Complex of South Africa

by D. Vogt\*, M. van Schoor\*, and P. du Pisani\*

## Synopsis

A brief summary of the propagation characteristics of rock provides the necessary understanding to design effective radar surveys. Measurements of the electrical properties of the major Bushveld platinum-bearing horizons and their host rocks show that radar is an excellent tool for both short- and longer-range mapping. Experimental work confirms the performance predictions.

High frequency, 500 MHz ground-penetrating radar (GPR) is a first-rate tool for mapping features in the hangingwall of the orebody, locally known as a 'reef', for the purposes of determining hangingwall stability. The triplet chromitites above the UG2 have been clearly mapped, as has the Leader Seam above the UG2.

Borehole radar at lower frequencies has been used over longer ranges to map reef elevation. Potholes in the UG2 are clearly distinguished in range and elevation to within metre accuracy. The nature of the slump in the various footwall horizons is also apparent.

In future, as GPR is routinely applied, it is likely to become used for other purposes. Borehole radar is being developed to operate at higher frequencies, which will allow it to be deployed from boreholes that are within 5 m of the target horizon.

Keywords: GPR, borehole radar, Bushveld Complex, UG2, Merensky, pothole, triplet

## Introduction

The platinum-bearing layers of the Bushveld Complex exhibit remarkable lateral continuity on a regional scale<sup>1,2</sup>. However, as one zooms in to mine scale, the picture often changes dramatically. Geological features such as potholes, replacement bodies and faults frequently disrupt the lateral continuity of the Merensky Reef and UG2 chromitite layer<sup>3,4</sup>. The occurrence of these features results in the loss of mineable ground and compromises mine planning and safety.

There is also considerable regional and local variation in the middling between important lithological units. On a regional scale, there is a series of chromitite bands in the hangingwall of the UG2. On the eastern portion of the western limb, they are known as the triplets and are just metres above the reef. Where they are close to the reef, they may pose a hazard, depending on the middling.

They may also present a problem when they unexpectedly occur higher than anticipated, as roofbolt support is then rendered ineffective.

On a local scale, the chromitite layers may vary from 1 m to 3 m above the reef over a distance of 1 000 m, and may vary by more than 50% over distances as short as one mining panel, typically 30 m. Low angle thrust faults and dome structures are other unpredictable hangingwall features that can compromise safety if they are not correctly identified.

For mine planning, it is also important to identify sudden changes in the reef plane ahead of mining. Van Schoor<sup>5</sup> has applied electrical resistance tomography to map the positions of reef disruptions in plan over relatively large areas. However, the mapping does not have sufficient resolution to determine the exact position of the edge of a pothole and it also cannot determine the vertical extent of the feature.

To date, reef elevation and disruptions have been estimated using exploration drilling, and geological mapping from existing mined areas. Large potholes, greater than 15 m in diameter and with a slump depth of greater than 15 m, important for regional planning, can be identified from surface 3D seismics. In shallower areas, anomalies revealed in magnetic surveys conducted on surface correlate well with disruptions of the reef plane underground. In terms of determining the vertical structure of the reef hangingwall, holes are drilled into the hangingwall and logged once mining is underway.

Radar techniques provide a faster method of determining the geometry of the reef and associated horizons either ahead of or after mining.

\* CSIR Mining Technology, Auckland Park, South Africa.

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## An introduction to radar and its application in-mine

Ground-penetrating radar, or GPR, has matured as a geophysical technique over the last twenty years. As an indication, the standard text by Daniels<sup>6</sup> written in 1996 has more than doubled in length in its second edition released in 2004<sup>7</sup>. It now contains over a hundred case studies from many fields including archaeology, mining, road and railway condition monitoring, geotechnical engineering, ice studies, military uses, tunnelling, utility detection and others. The maturity has developed due to the good understanding that now exists about the physical basis for the technique and the ready availability of high quality instrumentation.

In a typical radar system, a single radar pulse is transmitted into the earth from a transmit antenna, reflects off interfaces in the earth, is detected by a receive antenna and recorded (Figure 1). The signal from a single transmitter position is called a trace (Figure 2), and shows the received signal as a function of time. GPR data is usually collected by capturing a trace, then moving the antennas along a line to the next position before capturing the next trace. A collection of traces along a line is known as a profile.

GPR data is typically displayed in a manner similar to seismic data: traces are presented vertically, next to each other, at positions corresponding to the positions where they were acquired. Normally, signal strength on each trace is represented using colour or shades of grey. In Figure 3, the vertical axis represents time and the horizontal axis indicates the position of the antennas along the radar line. Reflections within the subsurface are clearly visible as white or black, against the background grey.

## Propagation

The propagation of radar waves in the subsurface is

controlled by two physical properties of the rock: its conductivity and its permittivity, or dielectric constant. These physical properties are in turn controlled by the minerals within the rock and by its water content. In general, permittivity controls the velocity of the radar wave and conductivity controls its depth of penetration.

For rocks that are suitable for GPR, the velocity of propagation of the radar wave is:

$$v = \frac{c}{\sqrt{\epsilon_r}} \quad [1]$$

where  $c$  is the speed of light ( $\approx 3 \times 10^8$  m/s) and  $\epsilon_r$  is the relative permittivity of the rock. For most rocks suitable for GPR,  $\epsilon_r$  lies between 4 and 16, and is typically close to 9. Equation [1] gives a rule of thumb for radar velocity: it is typically 10 cm/ns. In radargrams, the time associated with a target is the time for the signal to travel to the target and back, or the two-way travel time. Since the apparent distance is double the actual distance, the apparent velocity is half the actual velocity. When analysing radargrams, the rule of thumb for velocity is 5 cm/ns. In other words, if a target appears at 100 ns, it is 5 m from the radar antenna. If a more accurate estimate of velocity is required, it can be determined experimentally in a number of ways<sup>7</sup>. As a result of Equation [1], the wavelength of the radar signal can be estimated for a given frequency:

$$\lambda = \frac{c}{f\sqrt{\epsilon_r}} \quad [2]$$

where  $f$  is the frequency. As a rule of thumb (accurate for  $\epsilon_r = 9$ ) the wavelength in metres is one hundred divided by the frequency in MHz. The wavelength is important because it determines the resolution. A conservative definition of

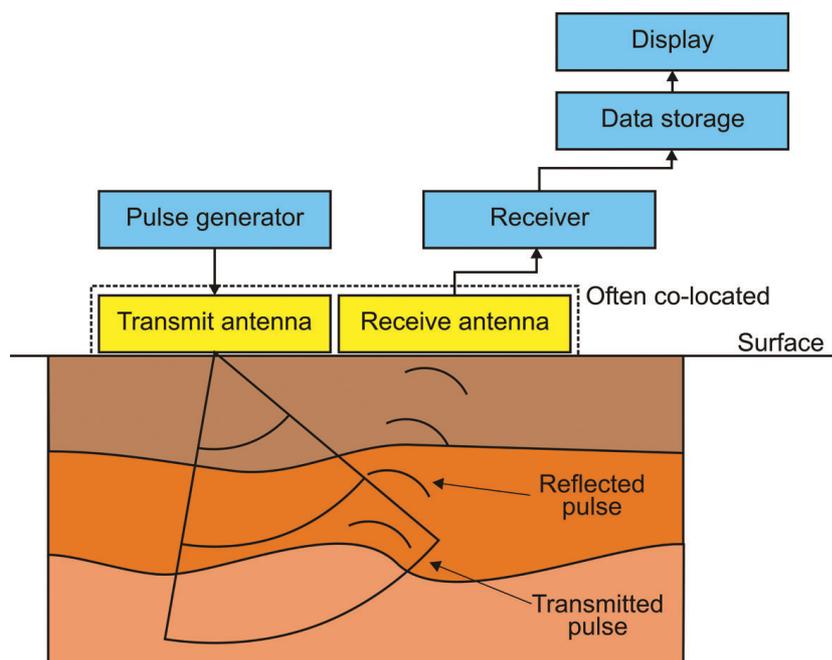


Figure 1—Schematic of a ground-penetrating radar system

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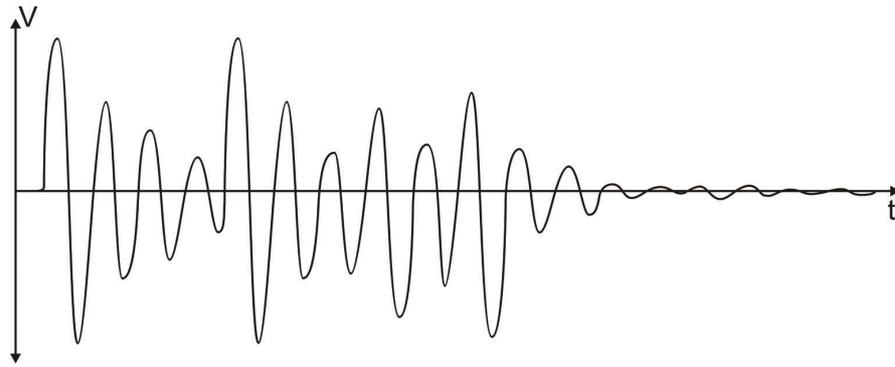


Figure 2—A typical radar trace

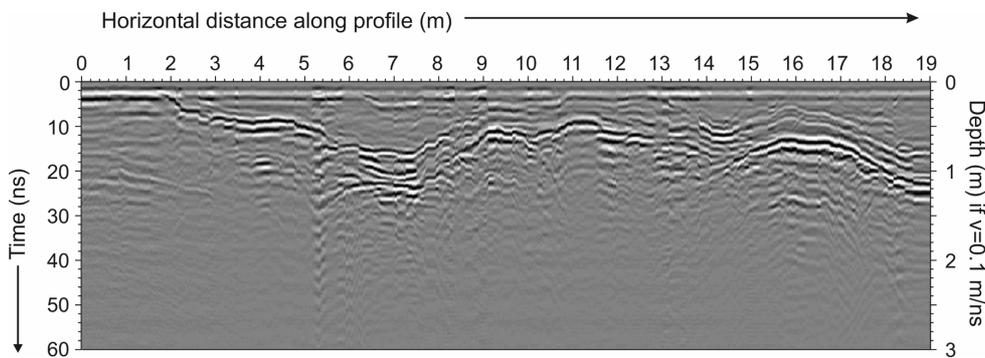


Figure 3—A typical radargram. Brightness in the image indicates the strength of the reflector

resolution is one half of the dominant wavelength. For example, if the relative permittivity is 8, a 500 MHz system will have a dominant wavelength of 0.21 m, and therefore a resolution of 0.1 m. In other words, it cannot discriminate two targets that are closer than 0.1 m apart as being separate targets.

The permittivity also determines how much signal is reflected at the boundary between two media:

$$\Gamma = \frac{\sqrt{\epsilon_2} - \sqrt{\epsilon_1}}{\sqrt{\epsilon_2} + \sqrt{\epsilon_1}} \quad [3]$$

where  $\epsilon_1$  is the permittivity of medium 1 and  $\epsilon_2$  is the permittivity of medium 2. The permittivity can be replaced by the refractive index to produce the same equation for optical materials. Equation [3] shows that if the permittivity of medium 2 is infinite, which can occur for good conductors, all the transmitted signal will be reflected. In optical terms, this occurs at a mirror surface. Equation [3] also shows that there is no reflection between two media with the same permittivity. In geological settings this occurs where two layers have the same mineralogy, but different grain sizes: such a boundary cannot be detected using radar.

The conductivity of the rock determines the depth to which radar signals can propagate and still be received successfully. Unfortunately, conductivity is frequency dependent, so the frequency of operation needs to be known to determine the attenuation, or rate of decay of the signal. This represents a challenge, as the frequency is usually the

required variable. It is more useful to work with the loss tangent,

$$\tan \delta = \frac{\sigma}{\omega \epsilon_r \epsilon_0} \quad [4]$$

Here, the conductivity,  $\sigma$ , and permittivity,  $\epsilon$ , are measured at a particular frequency,  $f$ , which is converted to angular frequency,  $\omega$ , where  $\omega = 2\pi f$ . As before,  $\epsilon_r$  is the relative permittivity, while  $\epsilon_0 = 8.854 \times 10^{-12}$  is the permittivity of free space.

There is substantial experimental evidence to show that the loss tangent is constant over wide frequency ranges for many rock types<sup>8,9</sup>. Where the constant loss tangent assumption breaks down, it usually leads to slight underestimation of radar range. If a constant loss tangent is assumed, it is possible to express radar performance as<sup>10</sup>:

$$LE \approx \frac{e^{-4\alpha R_{\max}} \lambda^2}{4\pi^3 R_{\max}^4} \quad [5]$$

where  $LE$  is the equivalent loop gain, to be discussed in more detail,  $\alpha$  is the loss of the host medium, and  $R$  is the range in metres. Equation [5] cannot be solved for  $R_{\max}$  analytically. Equation [5] uses  $\alpha$  to express the loss, but it can be transformed to an expression in terms of the loss tangent, which is applicable across different frequencies.

The easiest technique to estimate radar performance is to use the nomogram in Figure 4. The spreading and attenuation loss on the  $y$ -axis is a parameter of the radar

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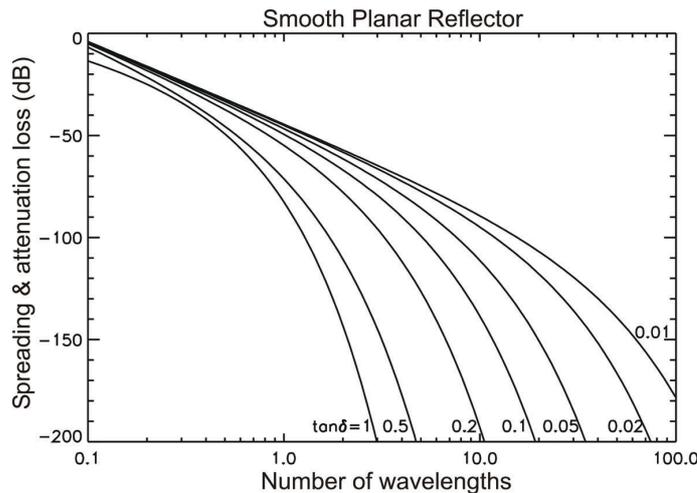


Figure 4—A nomogram of radar system performance when used to map a smooth planar reflector (after<sup>10</sup>)

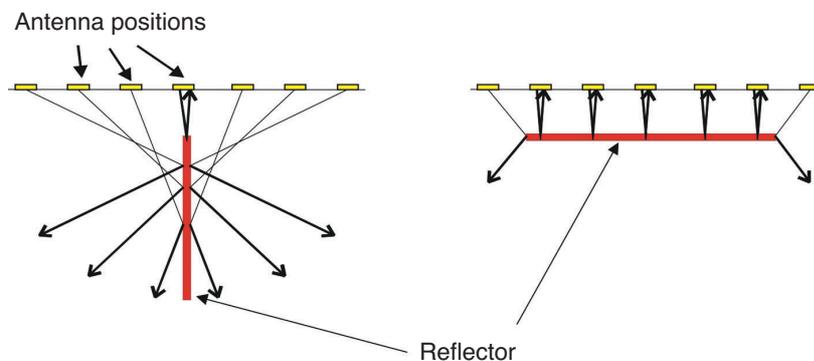


Figure 5—Radar response of a perpendicular feature

system, equivalent to the loop gain in Equation [5]. For typical commercial systems it is in the region of 120 dB. The range is expressed in wavelengths on the  $x$ -axis, and there are a number of curves corresponding to rocks with different loss tangents. To use the nomogram, choose a curve that represents the loss tangent of the expected host rock and determine its intersection with the equivalent loop gain of your system. The  $x$ -axis value of that intersection gives the range in wavelengths. For example, a system with a performance of 120 dB used in a rock with a loss tangent of 0.05 gives a range of about 12 wavelengths.

The nomogram gives a good estimate of what performance may be expected, but it has a number of shortcomings:

- ▶ The nomogram in Figure 4 assumes that the target is a smooth planar reflector, where smooth is relative to wavelength. If the target is a point, or a rough plane, different nomograms can be used<sup>10</sup>
- ▶ Strictly speaking, the reflectivity of the target horizon has to be subtracted from the equivalent loop gain before estimating the range<sup>11</sup>. In practice, the reflectivity of good targets causes a relatively small drop in loop gain. For poor targets, the usefulness of the technique should be determined experimentally

- ▶ The nomogram depends on a measured loss tangent. Rock physical properties show high spatial variability and are often different *in situ* and in the laboratory. At best, the nomogram gives an approximation of expected radar performance.

The nomogram predicts performance in wavelengths, confirming the general geophysical phenomenon of range-resolution trade-off. As the resolution increases, the range must decrease. It is now possible to determine which frequency to use to image a particular target: a 500 MHz system in rock with a permittivity of 9 has a wavelength of 0.2 m. For the previous example of a penetration of 12 wavelengths, it can detect targets to a distance of 2.4 m, with a resolution of 0.1 m. Alternatively, a 100 MHz system in the same rock can detect targets to 12 m, with a resolution of 0.5 m. Note that it is not possible to simultaneously detect targets at 12 m with a resolution of 0.1 m, unless the system or the rock type change. The choice of operating frequency depends on the electrical properties of the host rock, and the expected depth to the target.

The nomogram also shows that for loss tangents greater than about 0.2, radar range will be negligible compared to resolution. In fact, for loss tangents much greater than 1, the approximations used here cease to hold, and wave propagation becomes impossible.

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## Requirements for successful GPR

The physics of radar imposes three absolute constraints for successful use of GPR. There is an additional condition that leads to better quality interpretations, but it is not absolutely necessary for success:

- The host rock between the antenna and the target must have very low conductivity, or high resistivity. This leads to a low loss tangent and reasonable range.
- The target must have a sharp contrast in permittivity with the host rock. Gradational changes lead to gradational reflections that cannot be detected.
- The target should lie parallel or sub-parallel to the line of access. Radar is unable to delineate targets that lie perpendicular to the line of access, although it might be able to detect them. In Figure 5, the radar receives reflections as it profiles directly above the dyke, but it never receives reflections from the side of the dyke, so it is not possible to map the dyke with any detail. By contrast, in the same situation a sill will be accurately mapped all along its length.
- Although not required, the final constraint on GPR is the need for ground truth. Typical GPR profiles contain many reflectors, and it is sometimes difficult to pick a particular reflector as the desired geological target without ground truth from boreholes or other mapping. Once a reflector is identified, it can be mapped over long distances.

## Electrical properties of Bushveld rocks

The electrical properties of a number of samples of typical Bushveld rock types have been measured in a laboratory at radar frequencies<sup>12</sup>. Electrical properties are highly variable, so the results presented here should be taken as guidelines only. In Figure 6, histograms are presented for a statistically significant number of samples of norite, anorthosite and pyroxenite. There are only six chromitite samples in the CSIR database, so their properties are not graphed. The average

permittivity of the six chromitite samples is 17, and their average loss tangent is 0.085.

The most important electrical properties are those of the host. The host has to be sufficiently resistive to determine the position of the target. The typical hosts are norite, anorthosite and pyroxenite. Norite and anorthosite have relatively low loss tangents, less than 0.1, while pyroxenite is still typically less than 0.12. Since permittivity values for anorthosite and norite are very similar, there will be no reflections from boundaries between the two rock types. There is a significant difference between pyroxenite and anorthosite or norite, which makes the boundary between pyroxenite and other rock types an excellent reflective target. Chromitite has a high permittivity compared to all the other rock types, so it will always be a strong reflector.

## Applications for radar

The electrical properties of Bushveld rocks are favourable for radar use: the hosts are resistive, and there is a good permittivity contrast between the host and typical target horizons. The nomogram of Figure 4 shows that radar can be applied for high resolution, short-range imaging, or for lower resolution at longer ranges.

An investigation conducted within the PlatMine research programme<sup>13</sup> determined that the major requirement for GPR within platinum mines is to investigate the structure of the reef hangingwall, particularly to determine the distance from the excavation to the most dominant parting planes. The application is ideal for GPR: the resolution required can be achieved using a 500 MHz antenna, which is of convenient dimensions for in-mine use.

There is also a requirement for determining the reef topography ahead of mining. This is difficult because the geometry of profiling does not run parallel or sub-parallel to the target (Figure 7). Although the line of access is parallel to the feature, the feature is not perpendicular to the radar wave, so reflections do not return to the GPR antenna. For

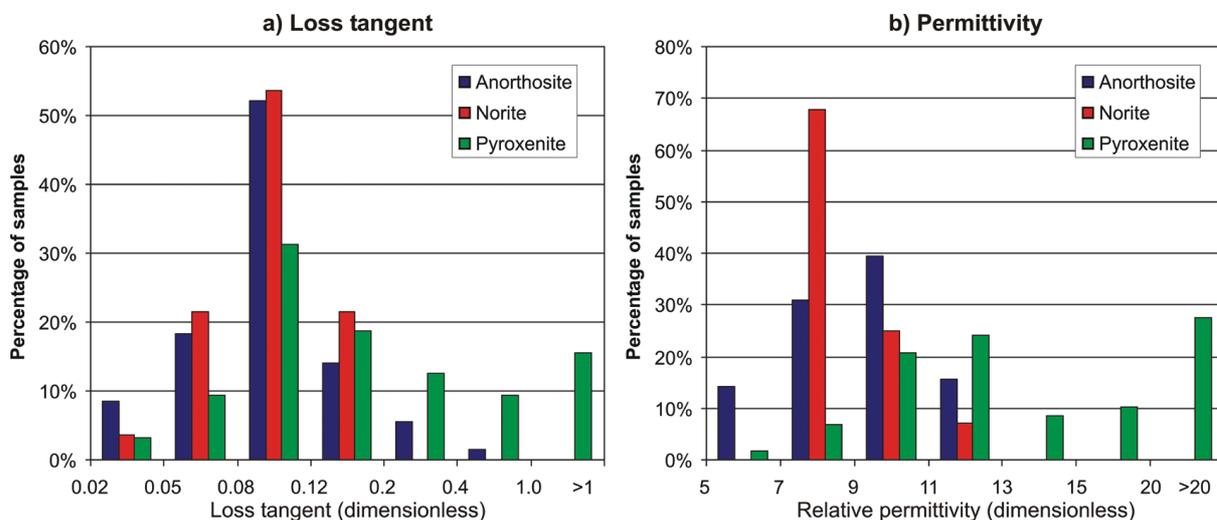


Figure 6—The electrical properties of a selection of Bushveld rocks

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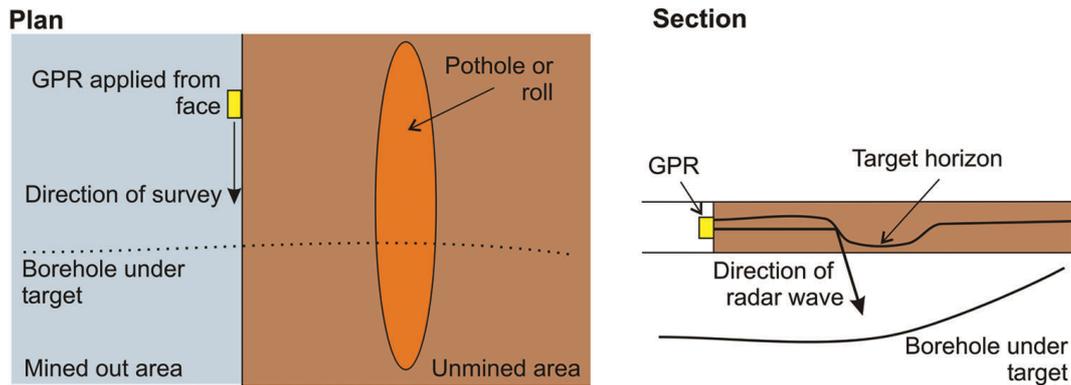


Figure 7—The geometry for mapping reef topography using GPR

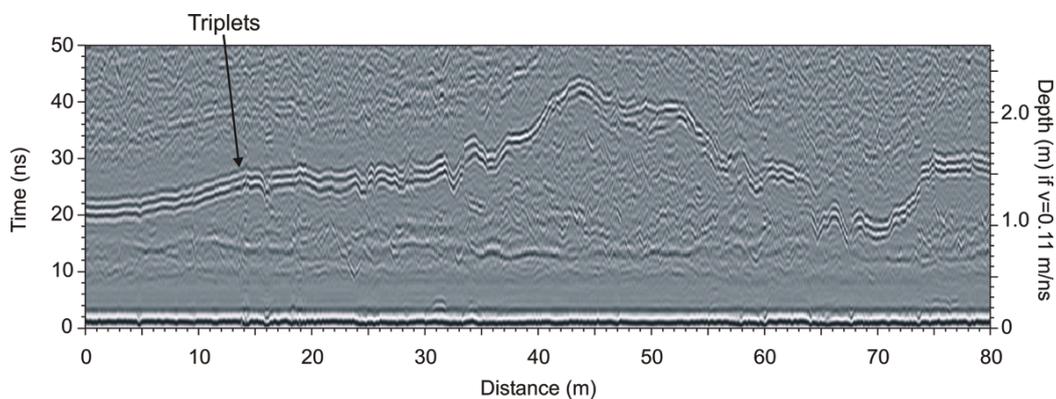


Figure 8—Mapping the triplet chromitite over large horizontal distances at Bleskop Shaft, Rustenburg Section

this application, the geometry can be made favourable by placing the GPR antenna in a borehole, shown below the reef in Figure 7. The technique then becomes borehole radar, and the antenna is now profiling sub-parallel to the roll feature to be mapped. Placing the radar in the borehole has two significant advantages:

- ▶ The borehole can be used to position the radar near the target over large distances. Although the radar range may be only 20 m in a particular area, the borehole might be used to allow 200 m of profile along the reef to be mapped
- ▶ In order to achieve longer range, larger antennas are required. In the case of GPR, these antennas must be located within the excavation, which is not practical. In the case of borehole radar, once the antenna is within the borehole any length is practical.

Borehole radar at lower frequencies (<100 MHz) does have one drawback: the antenna is not directional in azimuth. In general, other a-priori information is required regarding the environment to remove the directional ambiguity. Here, interactive fast forward modelling is used to place the reflectors correctly in 3D space<sup>14</sup>.

## Case studies

Two GPR case studies and two borehole radar case studies are presented. The two GPR applications deal with the problem of chromitite layers in the hangingwall of the UG2.

When the chromitite layer is vestigial, it is known as a stringer. It becomes a leader when it has adequate thickness. In some areas a series of three leaders occur in a cluster, locally known as triplets. In general, if the radar can detect the presence of a stringer, there is sufficient chromitite present to form a potential parting plane in the hangingwall.

### GPR at Bleskop Shaft, Rustenburg Platinum Mine

GPR was used to track the position of the triplet chromitite layers in the hangingwall of the UG2 at Bleskop Shaft, RPM Rustenburg Section over a horizontal distance of approximately 80 metres. A Rock Noggin 500 MHz system from Sensors and Software was used to acquire the data.

A typical output radargram with interpretation is shown in Figure 8. The profile was acquired along the length of a raise line. The triplets manifest as a clear package of reflectors at an average distance of between 1 m and 2 m into the hangingwall. It is not possible to determine whether the topography seen on the triplets is real, or an artefact caused by topography of the hangingwall. However, at any point along the hangingwall, it is possible to give an accurate distance to the triplets. For example, at 50 m along the profile, they are located 2.4 metres from the surface of the hangingwall. The support requirements for the area can now be determined. This result illustrates how GPR can be routinely applied by rock engineers for determining the middling distance or beam thickness.

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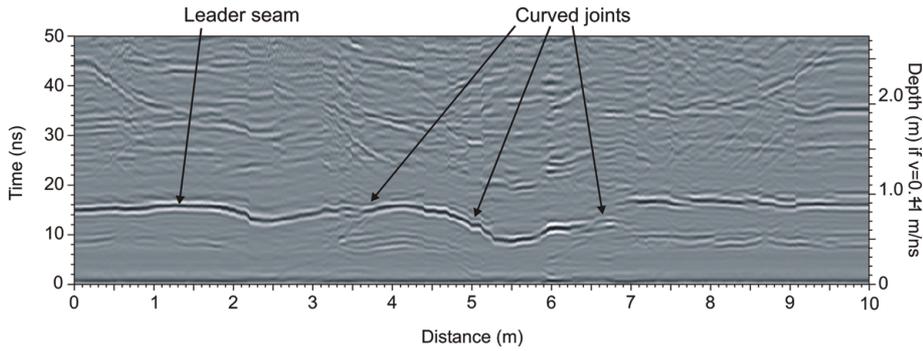


Figure 9—Mapping the Leader Seam and known curved joints at Waterval Mine, Rustenburg Section

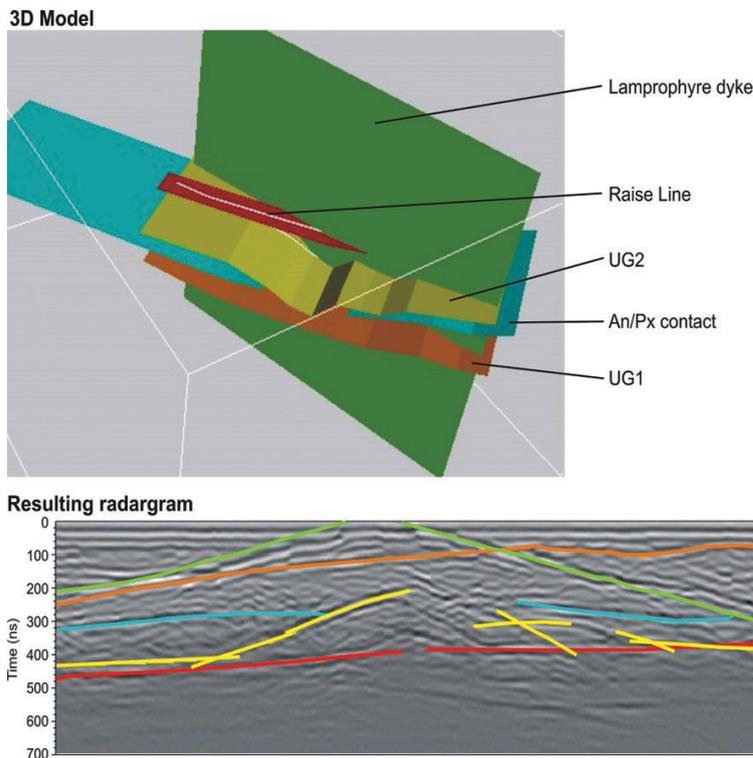


Figure 10—Resultant forward model and borehole radargram for a borehole radar survey of a simple pothole at Impala

### GPR at Waterval Shaft, Rustenburg Platinum Mine

The second case study shown is from Waterval Shaft at RPM Rustenburg Section, where the aim was to determine whether GPR could map the position of the Leader Seam above the UG2 seam and if GPR could detect curved joints. A Rock Noggin 500 MHz system from Sensors and Software was used to acquire the data. A profile was conducted directly over a known curved joint occurrence. Of particular interest to the mine was whether or not these joints extended beyond the Leader Seam into the hangingwall, as this affects roof stability. The resulting radargram is shown in Figure 9. Several curved joints can be identified as indicated. The GPR output does not indicate that these features 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 middling to the Leader Seam on Waterval Mine. Curved joints and their vertical extent can also be mapped.

Historically, there has been some resistance to the routine application of GPR in platinum mines, due mainly to the difficult logistics of applying GPR systems, as well as concerns regarding the application of GPR near roofbolts. Modern, commercially available GPR systems require only two persons to operate, or even one person with specific equipment. The systems are light and rugged, and can display profiles underground to immediately determine critical parameters, such as the distance to hangingwall parting planes. We have also shown that roofbolts do not affect the quality of data that is acquired.

### Borehole radar at Impala Platinum Mine

Borehole radar is used to map reef topography over longer ranges than GPR, so lower frequencies are employed.

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Borehole radar provides only reef elevation along a single line on reef, corresponding to the single borehole, so it cannot be applied indiscriminately to determine reef elevation for an entire 200 m × 200 m mining block. A lower resolution technique that gives plan information about the reef plane, such as 3D seismics applied from surface, or electrical resistance tomography applied in-seam can be used to determine which areas on the reef plane are likely to contain discontinuities that require further definition using radar.

A pothole had been intersected in a raise. A borehole was drilled semi-parallel to the raise to determine if it was possible to resolve the pothole using borehole radar. The borehole is in the footwall of the UG1, approximately 25 m below the UG2 target. A CSIR Aardwolf 40 MHz borehole radar was used to acquire data in the borehole. The radargram that was acquired (Figure 10) is relatively complex. In order to resolve the various reflectors, the interactive fast forward modelling program, Fresco<sup>14</sup>, was used with the result illustrated in Figure 10.

A lamprophyre dyke crosses the borehole halfway along the profile. It is known from other evidence to be approximately vertical, so it was placed as vertical in the 3D model. It was then manipulated in the model until its strike produced a reflector that matched the measured reflector. The rest of the reflectors were given the regional dip and strike, then manipulated to match the detail present on the radargram. The raise itself is clearly visible on the radargram. Three stratigraphic horizons are visible in the radargram. Immediately above the borehole, the UG1 is visible, and it has not been disturbed by the pothole in the UG2. Between the UG1 and the UG2 there is an anorthosite/pyroxenite contact that shows some disturbance. The UG2 pothole is

clearly visible. Its extent below the raise and the exact position where the pothole starts are also immediately evident in the data. Note that in the model, all targets are presented as planes, but in fact, the only information gathered about the target is the illumination line. For example, the raise certainly does not have the horizontal width illustrated in the model. Wide planes are used in the model purely to aid visualization.

The case study shows that pothole edges and their topography on the UG2 can be determined with metre scale accuracy from boreholes 20 m or more away from the target.

## Borehole radar at Modikwa Platinum Mine

At Modikwa Platinum Mine, a borehole was drilled below the reef horizon, to determine if the reef was disturbed by faulting. A CSIR Aardwolf 40 MHz radar was used to acquire the data. The radargram in Figure 11 clearly shows the layered stratigraphy, and there is no evidence of major faulting. However, even in this relatively low resolution data, there is evidence for curved joints or low angle thrust faults similar to those depicted with much higher resolution in the GPR image in Figure 9. Borehole radar can clearly map reef elevation, but the results in Figure 11 indicate that it may be possible to map other important discontinuities, not usually associated with such marked electrical property contrasts.

## Conclusions and recommendations

The electrical properties of the host rocks to the Merensky and the UG2 reefs indicate that radar is a viable technique within Bushveld platinum mines. The case studies presented here confirm the theoretical performance prediction.

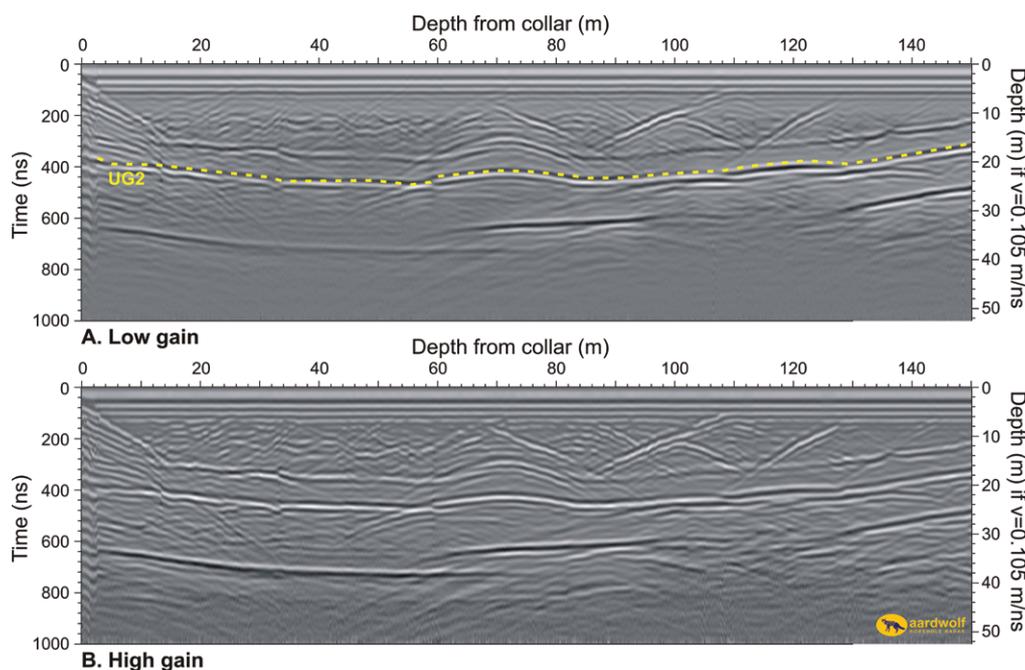


Figure 11—Radargram of the UG2 from its footwall at Modikwa Platinum Mine

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Although the presented case studies all deal with the UG2, the Merensky Reef is also an excellent radar reflector.

The GPR studies show that GPR is an effective tool for determining the distance to some of the important parting planes in the hangingwall of the UG2. There are also strong indications that it can detect the presence of low angle thrust faults and calcite dome structures, giving substantial information on which to base decisions about support methodologies.

Modern GPR systems are lightweight and easy to use, and provide results immediately. We have demonstrated their effectiveness for the specific application of parting plane detection. As the equipment becomes more routinely used underground, other applications may become commonplace, including determining rock mass rating, fracture mapping and finding lost boreholes.

It may be possible to determine whether a stope will encounter a pothole within a few metres using GPR to look into the face (Figure 7). Although the target geometry is not favourable, because the target does not present a direct reflector to the radar, the ground disturbance due to the pothole may still be detectable. This application should be investigated.

Borehole radar has been applied to map the topography of the reef along a line. The depth and extent of potholes along the line can be determined with metre accuracy. A novel modelling and visualization technique assists in interpretation and in removing directional ambiguities from the data. Although borehole radar is not ideal as a reconnaissance tool, because of the cost of drilling required to survey a large area, it is an accurate technique for mapping the position of features identified using lower resolution techniques including electrical resistance tomography, surface seismics or geological mapping. There is an indication that borehole radar may also be applicable for mapping curved joints, which suggests the possibility of imaging dome structures.

Borehole radar has been applied in boreholes as much as 30 m from the target horizon. The Aardwolf BR40 cannot operate closer than 5 m from the target, because the target becomes obscured within the direct arrival from transmitter to receiver. There are many situations where boreholes are routinely drilled within 5 m of the target horizon. For these situations, a higher frequency radar will offer significant advantages. A higher resolution radar will also provide better information on secondary targets such as curved joints. In addition, if it is possible to achieve directionality within the 48 mm diameter boreholes available on Bushveld platinum mines, a directive antenna would remove ambiguity from the measured data.

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### References

1. CAWTHORN, R.G. Platinum in South Africa. *South African Journal of Science*, vol. 95, 1999. pp. 481–489
2. THE SOUTH AFRICAN COMMITTEE FOR STRATIGRAPHY (SACS) 1980; *Stratigraphy of South Africa, Handbook 8, Part 1: Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia and the Republics of Bophuthatswana, Transkei and Venda*. Compiled Kent, L.E., Department of Mineral and Energy Affairs, Geological Survey, Pretoria, 1980, 690 pp.
3. CARR, H.W., GROVES, D.I., and CAWTHORN, R.G. Controls on the distribution of Merensky Reef potholes at the Western Platinum Mine, Bushveld Complex, South Africa: implications for disruptions of the layering and pothole formation in the Complex. *South African Journal of Geology*, vol. 97, no. 4 1994. pp. 431–441.
4. SCOON, R.N. and MITCHELL, A.A. Discordant iron-rich ultramafic pegmatites in the Bushveld Complex and their relationship to iron-rich intercumulus and residual liquids. *Journal of Petrology*, vol. 35, 1994. pp. 881–917.
5. VAN SCHOOR, M. The application of in-mine electrical resistance tomography (ERT) for mapping potholes and other disruptive features ahead of mining, *SAIMM: This volume*. 2005.
6. DANIELS, D.J. *Surface penetrating radar*, IEE. 1996.
7. DANIELS, D.J. *Surface penetrating radar*, 2nd edition, IEE. 2004.
8. TURNER, G. and SIGGINS, A.F. Constant Q attenuation of subsurface radar pulses. *Geophysics*, vol. 59, 1994. pp. 1192–1200.
9. VOGT, D. The modelling and design of Radio Tomography antennas, DPhil thesis, unpublished, University of York. 2000.
10. NOON, D.A., STICKLEY, G. F., and LONGSTAFF, D. A frequency independent characterisation of GPR penetration and resolution performance. *Journal of Applied Geophysics*, vol. 40, 1998. pp. 127–137.
11. PLUMB, R.G., NOON, D.A., LONGSTAFF, D., and STICKLEY, G.F. A waveform-range performance diagram for ground-penetrating radar. *Journal of Applied Geophysics*, vol. 40, 1998. pp. 117–126.
12. DU PISANI, P. and VOGT, D. The radar frequency electrical properties of a selection of Bushveld and Witwatersrand Basin rocks. *Eighth SAGA Biennial Technical Meeting and Exhibition*. 2003.
13. PLATMINE, [Web document]: accessed 6 December 2004, Available at <<http://platmine.csir.co.za>>. 2003.
14. DU PISANI, P. and VOGT, D. Borehole radar delineation of the Ventersdorp Contact Reef in three dimensions, *Exploration Geophysics*, vol. 35, 2004. pp. 278–282. ◆

# New sources of supply could eliminate tantalum price fluctuations\*

## New report analyses tantalum supply and demand worldwide

Over the past few decades, the tantalum market has been characterized by long periods of stability punctuated by sharp price increases, according to a new report from market analyst Roskill. These price fluctuations were largely created by strong global demand and fears, usually unfounded, of impending raw materials' shortages.

*The Economics of Tantalum* (9th Edition, 2005) explains that stability was reinforced in the market in 1991, when Cabot and Stark, the world's largest tantalum processors, entered into long-term, fixed-price supply contracts with Australia's Sons of Gwalia (SoG), the leading mine producer. Those arrangements helped to keep prices in the open market fairly constant, at about US\$30/lb, even when global demand for tantalum entered into a period of strong growth during the second half of the 1990s, in response to rapid expansion of the demand for consumer electronics, and mobile telephones in particular.

## Growth of mobile phone demand

Between 1998 and 2000, global sales of mobile phones rose from 168 M units to 413 M units. Booming sales resulted in supplies of electronic components, including tantalum capacitors, becoming tight, and prices increased. Demand for tantalum raw materials also increased, rising to levels that could not be met by traditional suppliers. Spot tantalum prices rose to US\$40–50/lb by mid 2000 and by December had reached US\$240/lb.

## Capacitor manufacturers enter long-term supply contracts

In early 2001, a number of capacitor manufacturers, made nervous by spiralling tantalum prices and the threat of raw material shortages, entered into long-term, fixed price contracts with processors. They also intensified efforts to find cheaper and more readily available substitutes for tantalum, and with significant success. The long-term contracts, however, soon proved to have been a disastrous move.

Instead of continuing to grow, the mobile telephone market turned downward in 2001, as did other end-use markets, such as the aerospace industry. Tantalum prices started to fall sharply. By the end of the year prices were back to pre-boom levels, and in early 2005 prices remain at

below US\$40/lb. Capacitor manufacturers were particularly hard-hit by the downturn, and were left with large over-valued tantalum inventories and an obligation to keep purchasing material at prices much higher than those available in the open market.

## End-use markets

In 2005, the principal end-use markets for tantalum—mobile telephones and other electronic equipment, aerospace and automobile manufacturing—have returned to a long-term growth trend. That will not, however, fully translate into additional demand for tantalum. In the capacitor segment, smaller case sizes are reducing unit consumption of component materials, and tantalum is also losing market share to other materials, such as ceramics, aluminium and niobium, in applications where it previously had little competition. Increasing rates of recycling will also result in secondary materials accounting for a larger part of total supply.

## New deposits

There are numerous deposits of tantalum that could be brought into production given the right market conditions, with some large projects already in advanced stages of development. Examples are Abu Dabbab in Egypt, Ghurayyah in Saudi Arabia, and the Big Whopper and Fir/Verity projects in Canada.

The commercialization of new deposits could be the key to securing the future of much of the tantalum industry. Consumers have become cautious of tantalum because of uncertainty over raw materials' availability and pricing. The supply base is currently rather narrow, with only a few large producers. It would only take a disruption in output from one major mine to throw the market into disarray once more and lead to redoubled efforts among consumers, capacitor manufacturers in particular, to eliminate tantalum from their products.

*The Economics of Tantalum* (9th edition, 2005) is available at £2100/US\$4200/EUR3675 from Roskill Information Services Ltd, 27a Leopold Road, London SW19 7BB, England.

Tel: +44 20 8944 0066.

Fax: +44 20 8947 9568.

E-mail: info@roskill.co.uk ◆