A borehole radar system for South African gold and platinum mines

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ABSTRACT

Borehole radar is an electromagnetic tool that can be applied to assist in the delineation of orebody geometry, ideally using routinely drilled cover and exploration boreholes. Successful trials of borehole radar for delineating reef horizons on South African gold and platinum mines have led to the development of a borehole radar system specifically designed for routine application in those environments. The radar design includes novel elements, including a receiver with instantaneous sampling down the borehole, and it is implemented in probes that can operate in 48 mm boreholes, with development planned for 38 mm boreholes. The radar is known as the Aardwolf BR40.

The need for information about dislocations of 3 m to reefs determines the desirable radar resolution while available access geometry determines the range requirement. The electrical properties of typical gold and platinum rocks show that the range/resolution trade-off is feasible for the majority of economically important reef horizons. Boreholes drilled horizontally or upwards are accessed using a borehole crawler.

Trials of the radar show that it meets its performance specification. The radar is robust enough for routine work underground and is easy to use. The borehole radar is a useful addition to the toolbox of the mining geoscientist because it can give information about the reef plane along a line, rather than the single point information about the reef given by a borehole.

Introduction

Borehole radar is the application of Ground Penetrating Radar (GPR) within a borehole. GPR is a geophysical tool that creates images of the subsurface by using short pulses of radio energy. GPR and borehole radar offer the highest spatial and depth resolution of any geophysical imaging technique for resistive rock environments. The pulses are transmitted into the earth, and reflect off discontinuities in electrical properties, for example the interface between a quartzite and a shale (Annan and Davis, 1977; Daniels, 1997). There are three requirements for successful implementation of GPR or borehole radar reflection imaging:

1. The host rock must be resistive. Radio waves do not travel through conductive rock.
2. There must be a sharp interface in electrical properties between the host and the target horizon. Graded contacts do not produce a good reflector. In addition, the target horizon must have different electrical properties to the host rock.
3. The target must run parallel or sub-parallel to the survey line. With borehole radar, the borehole is the survey line. Targets that intersect the borehole at right angles will not produce a reflection.

In 1996 and 1997, borehole radar trials were conducted on a number of economically significant South African mining targets, using the Swedish Malå RAMAC system. Surveys targeting the Ventersdorp Contact Reef (VCR) were particularly successful (Vogt *et al.*, 1997). At the time, the RAMAC system did not function at the temperatures encountered in deep level gold mines but the success of the technique convinced the DEEPMINE collaborative research programme to fund further work. The GeoMole borehole radar system developed at the Centre for Mining Technology and Equipment in Sydney, Australia (Turner *et al.*, 2000) was applied at a number of surface and underground sites with success (Trickett *et al.*, 1999; 2000). Late in 2000, the CSIR decided that the local requirement warranted development of a borehole radar system specifically for South African mines. The design of that tool, the Aardwolf BR40, is described here.

Problem description

The majority of gold in South Africa occurs along the edge of the Witwatersrand Basin, which was a vast inland sea more than 2714 million years ago (Armstrong *et al.*, 1992). The gold bearing seams, known as reefs, are typically a metre thick, gently dipping and of very large lateral extent. The reefs are typically conglomerate layers hosted within a sedimentary succession consisting of quartzites, shales and conglomerates. Basin evolution ended with the outpouring of the Ventersdorp Supergroup lavas at 2714 Ma (Schweitzer and Johnson, 1997).

Some of the reefs have very strong physical property contrasts from the surrounding rocks, particularly the VCR, because of the difference in density and electrical properties between the lava and the reef footwall rock types. Other reefs are not associated with any physical property changes, for example, the Vaal Reef. Some reefs such as the Carbon Leader that do not themselves have a contrasting physical property to the surrounding rocks are closely associated with marker horizons. For example, the Carbon Leader is overlain by the Green Bar Shale (Schweitzer and Johnson, 1997).

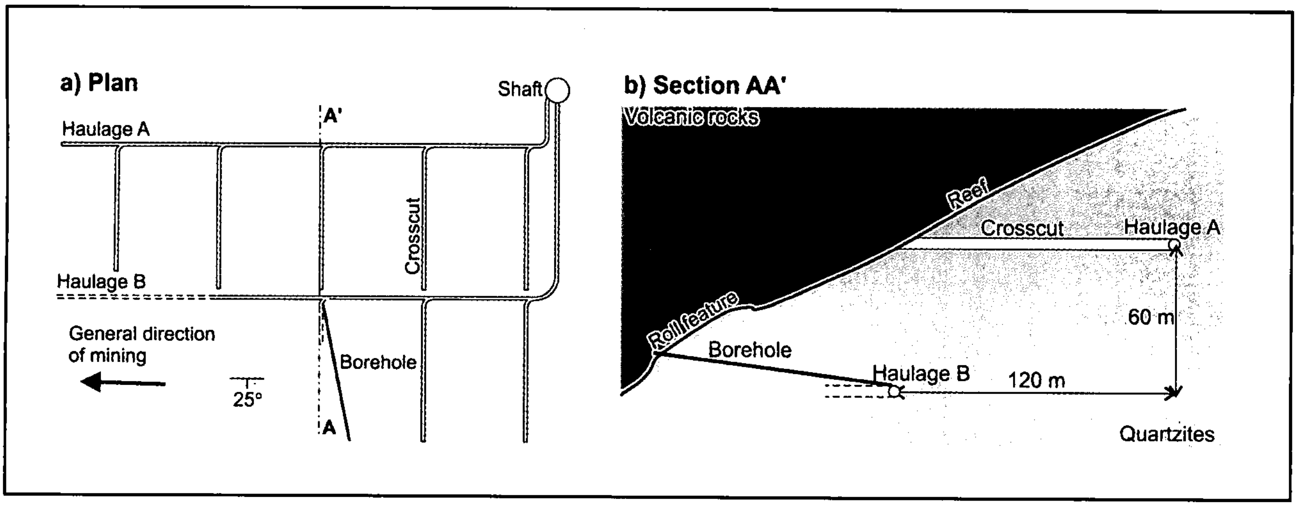

Figure 1. Typical plan and section of a tabular Witwatersrand orebody, showing a cross-cut cover drilling borehole.

By analogy, the majority of the South African platinum mining occurs on the margins of the Bushveld Complex. The platinum occurs in chromitite and pyroxenite seams hosted within a sequence of rocks such as norites and anorthosites (Sharpe, 1981). The geometry of the reefs is very similar to that of the gold reefs: thin, gently dipping seams of very large horizontal extent.

In the platinum environment the economically significant seams are good geophysical targets: the chromitite has a large density and electrical property contrast to the surrounding rock types. The disadvantage is that the succession in the platinum environment contains a large number of geophysical targets and only some are economically significant.

In both types of reef, gold and platinum, mining is typically undertaken by developing footwall or hangingwall drives or haulages parallel to strike (Figure 1). Cross-cuts are then developed perpendicular to strike, until they intersect reef. Mining then proceeds up the reef plane from level to level.

The geophysical challenge is to define the reef plane in sufficient detail that once mining commences, it can occur without encountering unexpected disruptions to the reef. Classically, geologists have mapped the reef plane from boreholes, outcrops or existing development. It is possible to achieve any desired resolution of the reef plane using different densities of boreholes, but the cost is almost always prohibitive. In situations where reef topology is the critical piece of required information, geophysics can often play an important role.

From a strategic point of view, 3D surface seismics can provide an excellent image of the reef plane and all its major features. Resolution is typically limited to 10 m – 50 m horizontally and perhaps the same vertically. This resolution is more than sufficient for identifying major fault zones, dykes and subcrops and has lead to 3D seismics becoming a routine technique, particularly on platinum mines (Düweke *et al.*, 2001).

However, once the major development has been sited, and mining begins, the required resolution increases dramatically. Typically, if mining encounters a dislocation of reef of less than 3 m, it is possible to continue without redevelopment. Dislocations of more than 3 m require redevelopment, with associated lost opportunity costs. If dislocations can be identified in advance, mine production planning can be improved and production will not be lost unexpectedly.

Borehole radar offers the most effective means of delivering a resolution of less than 3m along the reef plane. It is most economically applied from boreholes that would be drilled in any event, particularly haulage and crosscut cover boreholes. The geometry of the cross-cut cover borehole with respect to reef (Figure 1) defines the range that is required from borehole radar, typically in excess of 60 m, to image the reef in the vicinity of the collar of the borehole.

Technical requirements

The typical host rocks in the gold environment are quartzite or lava. The quartzites encountered in the Witwatersrand Basin typically have a relative permittivity of 7 at 64 MHz, and a loss tangent of between 0.04 and 0.15. The permittivity of the Westonaria lavas is about 9, with a loss tangent of about 0.04. The difference between the complex permittivity of the quartzite and that of the lava is sufficient to provide a good reflector. In the Bushveld Complex, the host rocks are anorthosite and norite, with relative permittivities of between 7 and 11, and loss tangents from 0.04 to 0.15. The target is typically associated with a chromitite, with a relative permittivity of between 12 and 15 and a loss tangent of between 0.1 and 0.3.

The reef elevation must be mapped to a resolution of better than 3 m which implies an upper bound on the radar wavelength of 6 m. From the permittivity of the host rocks in both the gold and platinum mines, the minimum required bandwidth is 16 MHz. The accuracy requirement is not as severe: the dislocation lies on the reef horizon and the absolute position of the reef horizon is well known from mining and exploration drilling.

The range requirement is set by the desire to map over the vertical distance between two levels, and is typically 60 m. The nomograms in Noon *et al.* (1998) indicate that a loop gain in excess of 140 dB is necessary, setting the required performance of the system. The loop gain is the total spreading and attenuation loss that can be tolerated by a system before the received signal falls below the minimum level of detection.

If the radar receiver has a dynamic range that can resolve the whole 140 dB of loop gain, then no further work is required. However, 140 dB corresponds to 23 bits, and is beyond current analog to digital converter (ADC) technology except at sampling rates less than about 100 kilosamples per second (kS/s). The receiver dynamic range should be large enough to cover the difference between the noise level and the largest received signal. Since the largest received signal is often substantially lower than the transmitted power, the required dynamic range can be reduced. If a loop gain of 140 dB is required, and the strongest received signal is 44 dB lower than the transmitted signal, then a dynamic range of only 96 dB is required, equivalent to 16 bits. ADCs with a dynamic range of just 16 bits are still not commodity items at sampling rates above 10 MS/s.

From Trickett *et al.* (2000), it is known that a radar with a bandwidth of about 100MHz can provide the range required. For the development of the Aardwolf radar, the target bandwidth is 90 MHz, and the minimum acceptable bandwidth is 16 MHz.

The receiver must be capable of resolving the transmitted pulse over a period of possibly several microseconds, with a time resolution dictated by the Nyquist sampling theorem: the received signal must be sampled at least twice for each Hertz of bandwidth. For a 90MHz system, a sampling rate of at least 180 MS/s is required.

The gold and platinum environments set one additional design criterion: the majority of in-mine exploration and cover drilling is currently AX (48 mm diameter) but more and more mines are moving to EX (38 mm diameter) to reduce the impact of intersecting gas filled fissures. The borehole radar must be thin enough to operate at least in AX holes, preferably in EX.

The borehole environment places additional restrictions on the design: the antennas should not be supported on cable, because cable can cause unwanted coupling between transmitter and receiver and because the high frequency radar pulses are significantly attenuated in cables. For operation in boreholes deeper than tens of metres, optical fibre communication is required between the antennas and the control unit. The probes must also be capable of functioning in boreholes filled with air or water at temperatures of up to 70° C.

Meeting the requirements

An ideal borehole radar system would sample the full transmitted pulse at full dynamic range in a single acquisition - a situation common in seismic systems. At present, such a combination of speed and dynamic range is not available in a single ADC. GPR designers approach the challenge in a variety of ways:

- The majority of commercial GPR systems (including radars from GSSI, Sensors and Software, Malå, ISS Geophysics and ERA Technology) employ a stroboscopic sampling system. A high-speed analog sampler acquires a single sample from each transmitted pulse. Each successive transmitted pulse is sampled slightly later, building up a complete trace. Once the sample has been acquired, it can be digitized at a leisurely rate, so a high resolution ADC can be used. The principal technical difficulties of stroboscopic sampling are the accurate identification of the trigger instant of each trace, and the implementation of an accurate delay between the trigger instant and the required sampling instant.

  It is not necessary to acquire the whole pulse with full dynamic range. Initially, the signal is strong, but later reflections are of considerably lower amplitude. If time varying gain is applied, the required dynamic range of the receiver can be reduced. High resolution is only necessary to separate strong reflectors from weak reflectors occurring at the same time. GPR produces situations where strong air reflectors are present late in time in the trace, at the same time as weak rock reflectors. Borehole radar does not suffer from air reflectors.
- Because borehole radar does not require high instantaneous dynamic range, an alternative approach can be followed: rather than sampling once per trace with high resolution, the whole trace can be sampled instantaneously with low resolution, and stacked to improve resolution. Instantaneous sampling is attractive to the radar designer, because it overcomes the need for the very accurate timing required in stroboscopic systems and because it enjoys good time efficiency (Wright *et al.*, 1989). The GeoMole borehole radar used by Trickett *et al.* (1999; 2000) follows this philosophy (Hargreaves, 1995). The good quality of the data acquired with the system validates the design choice for application in South African mines.

  Both stroboscopic sampling and instantaneous sampling with stacking are subject to smearing at high acquisition speeds. Stroboscopic systems acquire each point along the trace at a different position, while instantaneous sampling averages the traces from different positions. An instantaneous sampling system can acquire data more quickly than a stroboscopic system for a given system performance, but that advantage is not pursued here.
- The "third way" of time domain system implementation is a compromise between stroboscopic and instantaneous sampling: more than one sample is

acquired per pulse, thereby cutting down on the number of pulses required to sample a full trace. One system (Siever, 2000) samples at 8 MS/s, with 16 bit resolution. To acquire a trace at 200 MS/s then requires only 25 transmit pulses.

- Some designers who advocate the use of frequency domain systems (Kong and By, 1995; Noon, 1996; Langman and Inggs, 1998). Frequency domain systems can be more efficient than time domain systems (Hamran *et al.*, 1995) but commercial use is not yet widespread.

Implementation

The Aardwolf BR40 borehole radar system follows the philosophy of single shot acquisition, stacked to provide improved dynamic range. The radar has a bandwidth of 90 MHz and transmit pulse voltage of 1000V. It is 33 mm in diameter, and has two separate probes containing the transmitter and receiver. The transmitter operates with a pulse repetition frequency of 1 kHz. The received signal is acquired in a single shot, with 8 bit resolution, and is stacked within the probe. The dynamic range is increased to 16 bit by stacking 256 traces. Four traces are delivered each second to the control unit outside the borehole (Figure 2).

Instantaneous acquisition and stacking downhole is unique in a slimline borehole radar probe. Because data is transmitted digitally out of the borehole, the distance that the radar can travel down the borehole is not restricted by cable performance. In addition, the surface control unit does not require any radar specific components, so it can be an off-the-shelf solution that is robust enough for in-mine work without further adaptation.

Although the Nyquist theorem requires a sampling rate of double the bandwidth, Tektronix, the manufacturer of digital oscilloscopes, recommend that to resolve a time domain signal, a sampling rate of 2.5 × fi the bandwidth should be applied (Tektronix, Inc., 2001). Higher sampling rates are always useful, because the analog bandwidth of the radar can then be increased, if required. The Aardwolf BR40 is designed to sample at 400 MS/s.

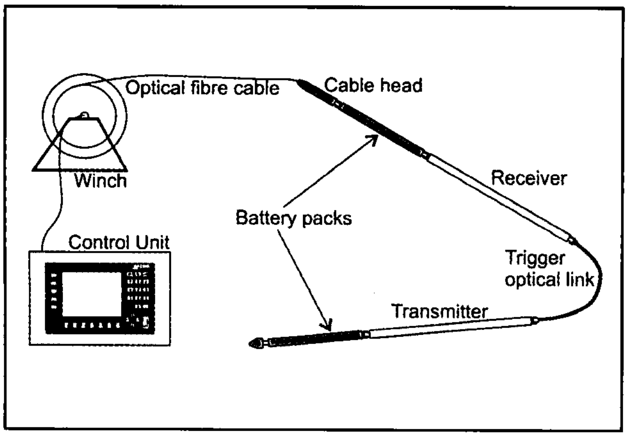

Figure 2. The borehole radar system diagram.

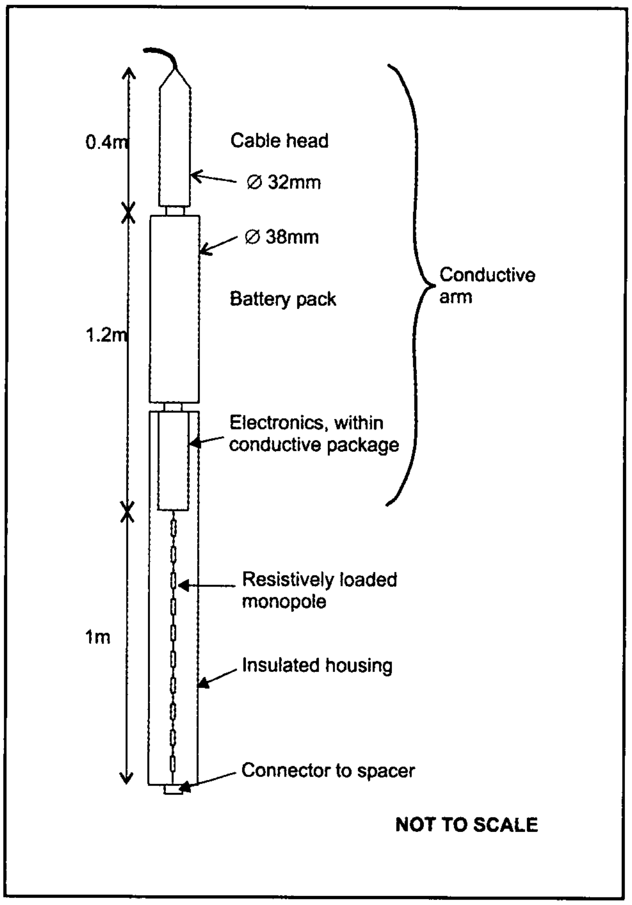

Figure 3. The receiver antenna geometry. The transmitter is identical, but does not include the cable head.

Four objectives guided the design of the radar:

Low cost: Geophysical instruments generally sell in very low volumes. Design time is the major expense for low volume developments, so as far as possible, off the shelf solutions were used to minimize design time. All the components used in the design had to be standard items, readily available in small quantities. The cost of the probes themselves also had to be kept low because of the chance that a probe might be lost in a borehole.

Slimline: Exploration boreholes are typically AX, 48 mm in diameter, or EX, 38 mm in diameter. The borehole radar must be able to travel in narrow holes with a low risk of snagging. The narrower the probes, the less likely they are to snag.

Battery powered: The borehole radar cannot be suspended on wires. If the radar is suspended on optical fibres, it has to be battery powered. Given the constraints on physical size, the power pack is a battery pack providing 12V to 14V with a capacity of 2 Ah. The battery must be capable of powering the system for a shift of about 8 hours.

Excellent robustness and ease of use: A survey instrument will not find work if the field crews find it difficult to use or unreliable.

Antennas

Both the transmit and receive antennas are dipoles made up of a conductive arm and a resistively loaded arm. The length of the conductive arm sets the centre frequency, and the resistively loaded arm broadens the bandwidth (Claassen *et al.*, 1995). The conductive arm contains the battery and the electronics. The resistively loaded arm is designed with a Wu-King taper (Wu and King, 1965), and implemented using $^{1}/_{4}$ W metal film resistors. The receiver is illustrated in Figure 3. The transmitter has similar dimensions but does not include a cable head, so its conductive arm is somewhat shorter. The spacing between the two antennas can be varied but it is typically 1.5 m or 5.5 m.

Battery packs

Maximum flexibility is achieved by the use of separate battery packs. The battery itself consists of twelve C size nickel cadmium cells and has a capacity of 2200 mAh at 12V to 14.4V. The battery pack is currently constructed within a 38 mm diameter stainless steel tube.

However, flexibility comes at a price. The bare metal tube that houses the battery pack is electrically lengthened by the surrounding water and rock, and leads to a centre frequency well below that desired. The battery pack is currently being redesigned with a dielectric housing and a smaller diameter to allow operation in 38mm boreholes.

Data acquisition

Computer microprocessors are becoming ever faster. However, memory speed is not increasing at the same rate, and is now the limiting factor on computer performance and on cost effective, fast data acquisition. It is possible to obtain fast ADCs, 200 MS/s and faster, consuming low power, but memory faster than 100MHz is not yet readily available. The Aardwolf radar system is designed around a memory queue, implemented using 100 MHz First-In First-Out (FIFO) integrated circuits. Each FIFO is driven by a low power 100 MS/s 8 bit ADC. The full sampling rate is achieved by running four ADC – memory circuits, offsetting the sample clock of each ADC by 2.5 ns (Figure 4). The transmitter triggers data acquisition at the receiver through an optical link. Each ADC then fills its attached FIFO, with up to 2048 samples.

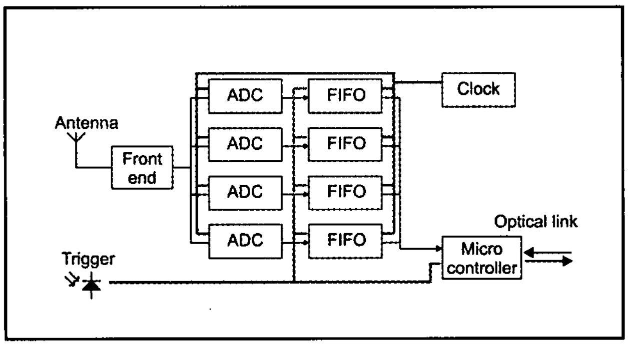

Figure 4. Receiver system diagram.

A microprocessor in the probe downloads samples from each FIFO in turn, building up a full trace. The microprocessor also stacks full traces, building up a 16 bit stacked trace that it transmits to the control computer. The data acquisition unit gains considerable flexibility by including a microprocessor. For example, it is simple to implement gain control and composite gain trace production (Siever, 2000). The presence of the microprocessor also makes it possible to add additional sensors, to further increase the value of the information provided by the tool.

Communications

The pulse repetition frequency of the transmitter is 1 kHz. The transmitter is joined to the receiver through a short length of optical fibre cable. The receiver is suspended in the borehole by a longer optical fibre cable. The receiver communicates with the control computer using a serial protocol, over two fibres in the optical cable. Outside the borehole, the optical signal is converted to a standard RS232 signal. Because the communications link is digital, it can run over distances of up to 2000 m in the optical fibre cable.

Control

A standard personal computer (PC) is used for data acquisition and control, packaged in a robust watertight enclosure. The use of PC components ensures low cost and widespread availability. Software development can be undertaken using low cost, user-friendly development tools. The data acquisition program runs under Windows, and presents a radargram to the operator as the data is acquired. The operator controls data acquisition using dedicated keys on the computer, so no mouse is required in the field. Data can be exported in SEGY format for further processing and interpretation.

Borehole access

If development occurs in the footwall, almost all boreholes available for borehole radar will be horizontal or drilled upwards. Routine application of radar depends on a reliable method of accessing holes where gravity will not feed the radar probe. The borehole crawler (Figure 5) provides a method of placing an anchor at the end of the borehole (Berger, 1997). Once the anchor is placed, the rope running through the pulley on the anchor can be used to pull a radar probe into the borehole.

Results

The Aardwolf borehole radar has been tested at a surface VCR test site, on the property of Durban Roodepoort Deep (DRD) gold mine (Figure 6). The test borehole intersects the Elsburg quartzites comprising the footwall, the VCR, and Westonaria Formation hangingwall.

The result of the test shows that the Aardwolf BR40 is capable of imaging the VCR (Figure 7).

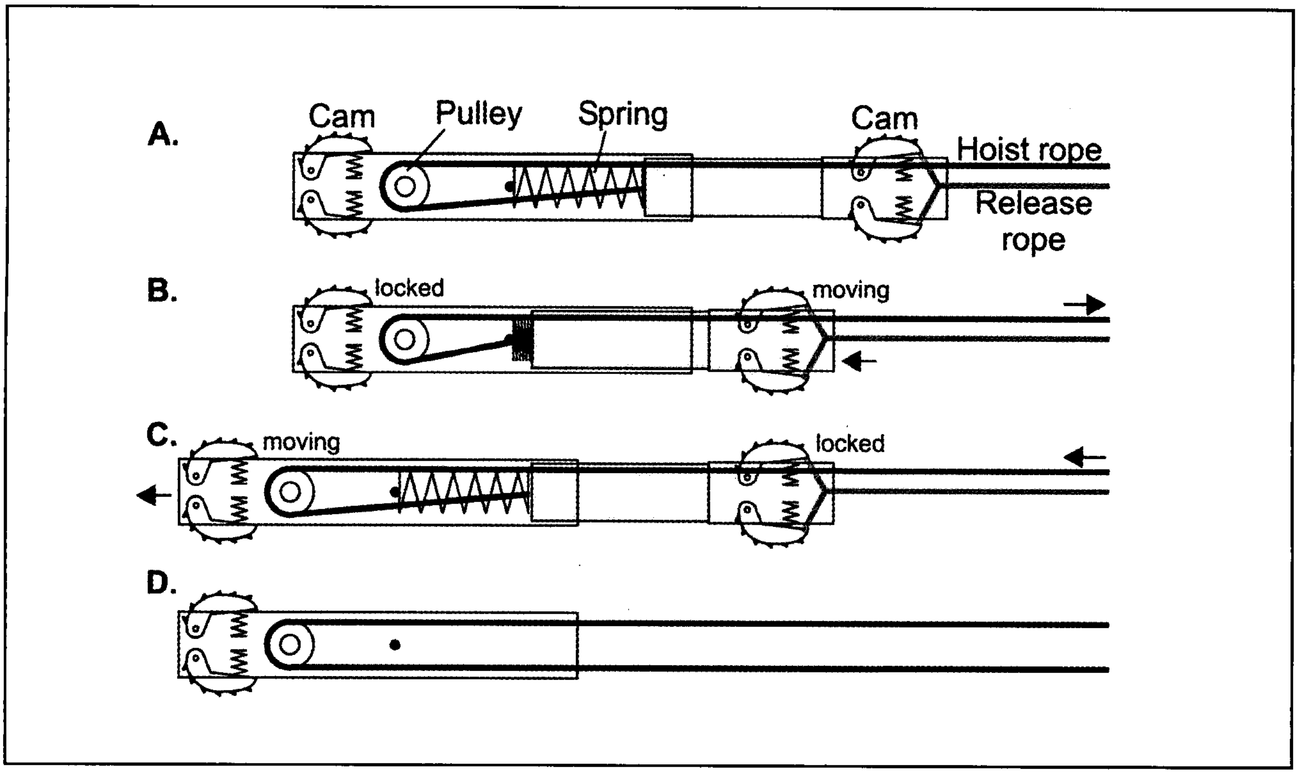

Figure 5. The borehole crawler. (**A**). As the hoist rope is pulled, cams on the upper section lock in position, and the lower section is pulled toward the upper section (**B**). When the hoist rope is released, cams in the lower section lock in position, and the spring forces the upper section up the hole (**C**). By alternatively pulling and releasing the hoist rope, the crawler inches its way up the borehole. When it reaches the top of the borehole, the release rope is pulled, releasing the cams in the lower section, and pulling the other end of the hoist rope out of the borehole. The anchor with its pulley remains (**D**).

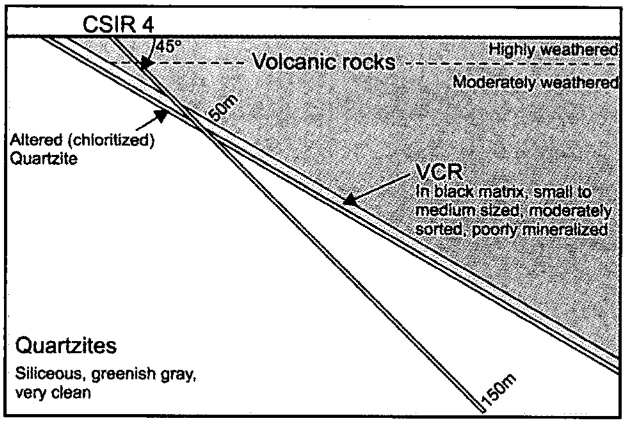

Figure 6. A section through the CSIR geophysical surface test site at Durban Roodepoort Deep gold mine. Borehole CSIR 4, which was used to conduct the borehole radar survey (Figure 7), is detailed.

For comparison, a result is presented from the Malå RAMAC system operated in the same borehole some years earlier. The comparison shows that the Aardwolf has a somewhat higher resolution, due to its higher bandwidth. It also shows that the range achieved by the Aardwolf is of the same order as that of the RAMAC radar. The intent is not to compare the performance of the two systems, because the comparison ignores differences in survey speed, acquisition parameters and processing, but it does illustrate that the Aardwolf provides the expected level of performance.

If a borehole crosses the plane of a reflector, the borehole radar response is characterized by an inverted V, as the probe comes closer to the reflector, then moves through it and away again. The images in Figure 7 do not show the left hand arm of the inverted V for the VCR reflector because the lava above the reflector is more conductive than the quartzite below. When the probe is in the lava, above 50 m down the borehole, no strong reflector is measured from the VCR interface.

Analysis of the trial result indicates that the radar achieved a bandwidth of 40 MHz, exceeding the required minimum bandwidth of 16 MHz, but short of the desired bandwidth of 90 MHz. The low bandwidth is a consequence of using battery packs that are not insulated from the surrounding rock because the rock electrically lengthens the antenna arm, lowering its bandwidth. Bare metal antennas are also influenced by the medium immediately surrounding the borehole, and perform differently in water filled boreholes to air filled boreholes. The borehole at DRD was water filled to within 15 m of the surface.

The lower bandwidth of the separate battery pack configuration is a two-edged sword: the resolution is not as high as it could be, but the range is significantly higher than expected. The bandwidth will be increased through a different antenna design, but the lower bandwidth model will be retained for long range imaging applications.

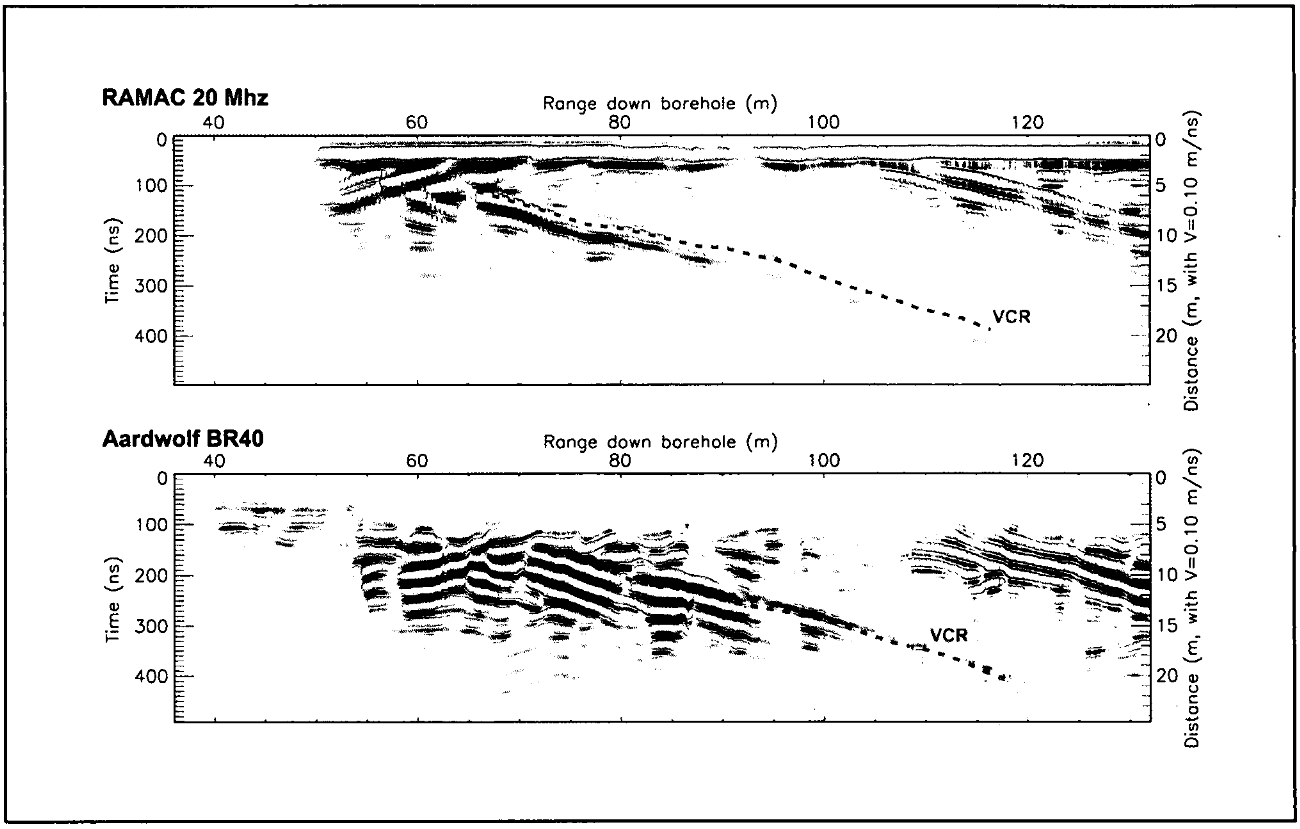

Figure 7. A comparison of results from the Malå RAMAC borehole radar with 20MHz antenna and from Aardwolf BR40 obtained from surveying borehole CSIR 4, illustrated in Figure 6.

If the 20MHz bandwidth of the RAMAC system is sufficient, why is the specification of the Aardwolf 90 MHz? Practical experience has shown that the actual range of operation desired is usually less than what can be achieved using the lower bandwidth so the excess range is traded off for higher resolution. The majority of users have requested higher resolution, rather than increased range.

One difficulty in interpreting the image presented in Figure 7 is determining the direction of the various reflectors. The VCR is assumed to lie above or below the borehole based on a-priori knowledge of the geology of the test site. Other reflectors cannot be so easily interpreted. Directional antennas would greatly assist in the interpretation of borehole radar data, but the small diameter of the boreholes and the relatively low frequency of the system combine to make the design of efficient directional antennas difficult. If the value of directional data is great enough, it may be implemented in more costly, larger diameter boreholes, but the cost benefit trade-off has not yet been defined.

If directional information is not available, interpretation techniques can be improved by incorporating all available information about the survey area, including data from geological mapping, borehole logging, surface seismics and borehole radar data from other nearby boreholes (Drummond, 2001). An ideal interpretation environment will facilitate the manipulation of potential reflectors in three dimensions, thereby making the directional ambiguity explicit.

Conclusion

A borehole radar system has been designed specifically for the South African underground gold and platinum mining environments. The combination of downhole data acquisition and slim probes that can be used in boreholes up to 1000 m long has been achieved using standard, widely available electronics components. Windows-based data acquisition provides a fast, graphical review of data quality.

The tool can provide a cost effective solution to typical problems in gold and platinum mines. It delivers a line of information about reef elevation, where a borehole can only deliver a single point, with a resolution better than 3 m.

Engineering is underway to reduce the diameter of the probe so that it can be routinely applied in 38 mm diameter boreholes. The major area of research that still needs to be undertaken is into visualizing the radar data within a full 3D environment, in order to resolve its inherent directional ambiguity.

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References

Annan, A. P. and Davis, J. L. (1977). Radar range analysis for geological materials. *Report of Activities, Paper 77-1B. Geological Survey of Canada*, 117-124.

Armstrong, R. A., Compston, W., Retief, E. A., Williams, I. S. and Welke, H. J. (1992). Zircon ion microprobe studies bearing on the age and evolution of the Witwatersrand triad. *Precambrian Research*, **53**, 243-266.

Berger, A. (1997). An access system for emplacing geophysical and surveying probes in vertical or inclined boreholes within mines. *Technical Report 97-0094, Council for Scientific and Industrial Research, South Africa*, 23pp.

Claassen, D. M., Bansal, R., Mason, I. M. and Hargreaves, J. (1995). Resistively loaded antennas for narrow borehole radar. *Proceedings of the 1995 International Geoscience and Remote Sensing Symposium, Institute of Electrical and Electronics Engineers*, **3**, 1711–1713

Daniels, D. (1997). *Surface-penetrating radar. Institute of Electrical Engineers, London, United Kingdom.* 300pp.

Drummond, M. L., Lightfoot, N., Donovan, S. J., Grodner, M.W., Schweitzer, J. K. and Sellers, E. J. (2001). The evolution of an integrated data-visualization environment for mining with the VTK open-source library. *In:* Xie, Wang and Jiang (Editors), Computer Applications in the Minerals Industries, *A. A. Balkema, Rotterdam, the Netherlands*, 373-377.

Düweke, W., Trickett, J. C., Tootal, K. and Slabbert, M. (2001). Three dimensional reflection seismics as a tool to optimise mine design, planning and development in the Bushveld Igneous Complex. *Extended Abstracts, 7th Technical Meeting, South African Geophysical Association.* (unpaginated).

Hamran, S.-E., Gjessing, D. T., Helmstad, J. and Aarholt, E. (1995). Ground penetrating synthetic pulse radar: Dynamic range and modes of operation. *Journal of Applied Geophysics*, **33**, 7-14.

Hargreaves, J. (1995). A Multichannel Borehole Radar for Three Dimensional Imaging. *Unpublished PhD thesis, University of Oxford, United Kingdom*, 159pp.

Kong, F. and By, T. L. (1995). Performance of a GPR system which uses step frequency signals. *Journal of Applied Geophysics*, **33**, 7-14.

Langman, A. and Inggs, M. R. (1998). New technology UWB stepped CW radar. *Proceedings of the Progress in Electromagnetic Research Symposium workshop on Advances in Radar Methods.*

Noon, D. A. (1996). Stepped-Frequency Radar Design and Signal Processing Enhances Ground Penetrating Radar Performance. *Unpublsihed PhD thesis, The University of Queensland, Australia*, 180pp.

Noon, D. A., Stickley, G. F. and Longstaff, D. (1998). A frequency-independent characterisation of GPR penetration and resolution performance. *Journal of Applied Geophysics*, **40, 127**-137.

Schweitzer, J. K. and Johnson, R. A. (1997). Geotechnical classification of deep and ultra-deep Witwatersrand mining areas, South Africa. *Mineralium Deposita*, **32**, 335–348.

Sharpe, M. R. (1981). The chronology of magma influxes to the eastern compartment, Bushveld Complex, as exemplified by its marginal border groups. *Journal of the Geological Society, London*, **81**, 373-378.

Siever, K. (2000). Three dimensional borehole radar measurements – a standard logging method? Eighth International Conference on Ground Penetrating Radar, *International Society for Optical Engineering*, **4084**, 676-681.

Tektronix, Inc. (2001). XYZs of oscilloscopes. *Technical Report 03W-8605-2, Tektronix, Inc., Beaverton, Oregon, United States of America*, 64pp.

Trickett, J., Mason, I. M. and Stevenson, F. (1999). Borehole radar at an underground Ventersdorp reef site. *Extended Abstracts, 6th Technical Meeting. South African Geophysical Association*, (unpaginated).

Trickett, J. C., Stevenson, F., Vogt, D., Mason, I. M., Hargreaves, J., Eybers, H., Fyn, R. and Meyering, M. (2000). The application of Borehole Radar to South Africa's ultra-deep gold mining environment. Eighth International Conference on Ground Penetrating Radar, *International Society for Optical Engineering*, **4084**, 676-681.

Turner, G., Mason, I., Hargreaves, J. and Wellington, A. (2000). Borehole radar surveying for orebody delineation. Eighth International Conference on Ground Penetrating Radar, *International Society for Optical Engineering*, **4084**, 282-287.

Vogt, D. R., Trickett, J. C. and Wedepohl, E. C. (1997). Borehole radar at a surface Ventersdorp Contact Reef site. Extended Abstracts, 5th Technical Meeting, *South African Geophysical Association, Swakopmund*, (unpaginated).

Wright, D. L., Bradley, J. A. and Hodge, S. M. (1989). Use of a new high-speed digital data acquisition system in airborne ice sounding. *Institute of Electrical and Electronics Engineers, Transactions on Geoscience and Remote Sensing*, **27**, 561-567.

Wu, T. T. and King, R. W. P. (1965). The cylindrical antenna with nonreflective resistive loading. *Institute of Electrical and Electronics Engineers*, Transactions on Antennas and Propagation, AP- 13:369-373. *Correction in Institute of Electrical and Electronics Engineers, Transactions on Antennas and Propagation*, **AP-13**, 998.

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