Quantitative ground penetrating radar for rock mass characterization

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Introduction

The applicability of ground penetrating radar (GPR) in numerous qualitative applications has been demonstrated over the past five years in the South African mining industry. These applications include the delineation of faults and dykes, fracture mapping, delineation of shear zones, mapping of depth of weathering, and the delineation of contact between different rock types. The qualitative nature of the data collected using existing commercial GPR systems, often relying on expert interpretation, has however mitigated against the full-scale routine application of GPR in the mining industry. The recent development of the RockRadar system by ISS International has, to a large extent, overcome these problems. The result is that quantitative rock-mass studies can now be performed with the RockRadar system.

Ground penetrating radar (GPR) produces a two-dimensional pseudo-cross-section of the subsurface that is similar in nature to a reflection seismic-section. GPR operates on the principle of the reflection of electromagnetic waves to delineate subsurface structure. A transmitting antenna launches an electromagnetic impulse into the subsurface. The wave spreads out as it travels through the subsurface, until it reaches an object with different dielectric properties from the surrounding ground. Upon reaching the object, part of the energy is reflected back to the surface, while part of the energy continues to travel onward. A single trace records the reflected amplitudes as a function of time (depth). An increase in amplitude corresponds to a dielectric interface at a certain travel-time away from the transmit-receive antennas. In practice, measurements are made by towing the antennas across the ground. Data can be collected at fixed station spacing (usually < 1.0 m) or continuously as the antenna is dragged across the surface. The successive traces are plotted next to each other, so developing a pseudo-cross-section of the subsurface.

Theoretical background

Unlike a conventional radar system, which emits continuous waves, where the energy is confined about a particular frequency, impulse radar emits pulses containing a broad band of frequencies. This energy can also not be focused as accurately as that from a narrow band system. The broadband nature of the radiation has advantages: the higher frequencies give better resolution, while the lower frequencies have superior penetration capabilities. Depending on the antenna used, the centre of the frequency band ('centre frequency') may range between 10's of MHz and several GHz. The bandwidth can extend up to 100% of the centre frequency. Peak radiated power may be as high as several thousand Watts—nevertheless the very low duty cycle (time ratio of power-on to power-off) is so low that no significant health risk exists for personnel in close proximity to the system. The energy is radiated from an antenna into the subsurface, and energy is then reflected from interfaces where the **dielectric constant** changes. For simplicity, consider a two layer subsurface system, having dielectric constants ε_1 and ε_2. The reflection coefficient R_{12} of the interface (i.e. the amount of energy reflected back from the interface) is given by:

$$R_{12} = \left(\frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \right)^2 .$$

In general, the pulse propagates at a velocity v given by

$$v = \frac{c}{\sqrt{\varepsilon}}$$

where $c = 3 \times 10^8$ m/s is the speed of light in free space, and ε is the dielectric constant of the medium, typically varying between 5 and 25 for most geological environments. The depth of an object d can be calculated from the two-way travel-time t of a pulse according to:

$$d = \frac{ct}{2\sqrt{\varepsilon}} .$$

The resistivity of the ground determines the range of penetration: the higher the resistivity, the greater the penetration. Resistivity values greater than 10's of Ω.m are usually required for successful GPR work.

Ground penetrating radar systems

An impulse radar system comprises the following components:

- High-powered pulser
- Transmit antenna
- Receive antenna
- RF amplifier
- Sampler (with associated timing electronics)

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- A-D converter
- Associated digital electronics
- Control unit.

The transmit and receive **antennas** are generally some form of dipole, usually heavily loaded to prevent ringing in the vicinity of the ground. Some form of shielding (usually a grounded backplane) is often utilized to reduce the amount of above-ground signal. Alternative antenna designs are also available (including modified YAGI-type antennas and horn antennas) from different suppliers. The main requirement of the **pulser** is to produce an extremely short sharp pulse, up to 900 V with a rise-time of 1 nsec (0.001 μ sec). Alternative pulser designs produce low-power monocycle pulses, but the commercial use of these is limited to horn-antennas (1 GHz and 2.5 GHz). The **sampler** converts the received radio-frequency (RF) signal (in the frequency range 10 MHZ to 2.5 GHz) to an audio-frequency (AF) signal (50 kHz). Radio-frequency signals, by their very nature, are extremely sensitive to interference. Because of this, the RF–AF conversion should be done as close to the receive antenna as possible. The **analog-to-digital converter** (A-D) converts the analog signal into digital information. Again, this should be done as close to the receive antenna as possible, before signal degradation can take place. The associated digital electronics permit general control of the data-acquisition process. The **control unit** provides the user-interface with the system, as well as allowing some data pre-processing, as well as data storage. It is usually necessary to apply a suite of post-processing tools to the data after acquisition. This is usually done in the office after data is acquired. Most of the **post-processing** algorithms are standard digital filtering algorithms.

Performance and limitations

The three measures of performance of ground penetrating radar are:

- Maximum depth of penetration
- The ability to delineate a subsurface interface
- The resolving power, i.e. the minimum size of a buried object.

The resolution, detection and penetration capabilities of a GPR system for a given object depend on the electrical properties (dielectric constant and resistivity) of the subsurface, the centre frequency of the antenna, the power output of the antenna, and the dynamic range of the system. Dry resistive rocks and soils yield the highest penetrations. Moist clayey soils (low resistivity) yield the lowest penetrations. In general, GPR works worst in a subsurface which contains a combination of clay, water and salts. Nevertheless, fairly good penetrations can be obtained in dry clay. Lower frequency antennas usually yield greater penetrations for most soil and rock types. Higher centre frequency antennas provide better resolution, but with worse penetration ranges.

In field survey conditions, a number of other factors affect the ability of GPR to accurately delineate subsurface conditions. These include, but are not limited, to the following.

- Survey access: Often it is not geometrically possible to access a specific target from the best position. For example, if a cavity under a structure cannot be directly imaged below the structure, it may be necessary to place the receive and transmit antennas on opposite sides of the structure.
- Man-made interference: All antennas are susceptible to receiving reflections from above-ground (steel equipment etc.). These reflections appear within the data, and may be misinterpreted as originating from below-ground.
- Depth calibration: Although a Common Depth Point (see for example Steeples and Miller[1]) measurement provides reasonably accurate depth calibration in many situations, a drill-hole is still the best method of calibration.
- Cross-correlation with other techniques: As an example, when utilizing GPR to determine depth to bedrock, the results will often be cross-correlated with those obtained by trenching with a mechanical excavator. The definition of 'bedrock' for an excavator may be very different to that for radar (depending on weathering etc.) and may even be different from excavator to excavator (depending on the size of the excavator).

Recent advances

The qualitative nature of the data collected using existing commercial GPR systems, often relying on expert interpretation, has however mitigated against the full-scale routine application of GPR in the mining industry. The main reasons for this include the following: (i) data acquired with first generation digital GPR systems is often severely contaminated with incoherent and coherent noise, some of which cannot be reliably filtered from the data, and indeed cannot be distinguished from real data, (ii) repeatability of results could not be guaranteed due to complex instrumentation setup requirements, and (iii) the success or failure of the technique in an environment could not be predicted (without secondary measurements) prior to application.

The development of the RockRadar system by ISS International has, to a large extent, overcome these problems. Sources of incoherent and coherent system noise have been largely eliminated through advanced electromagnetic isolation of subsystems, and highly simplified operating requirements ensure repeatable system setup. An example of data collected with the RockRadar system at Vaal Reefs is shown in Figure 1, together with the interpretation in Figure 2. The RockRadar system has the following features:

- High true dynamic range
- Intelligent antennas allowing preprocessing of data
- All fibre-optic cabling between antennas and the control unit
- Ethernet communications between the antennas and the control unit
- A 32-bit multitasking operating system on the control unit allows data acquisition, processing and printing simultaneously
- Antenna centre frequencies between 50 and 300 MHZ
- Automatic data processing for shallow survey interpretation
- Sophisticated data and image processing capabilities for data interpretation in difficult survey environments.

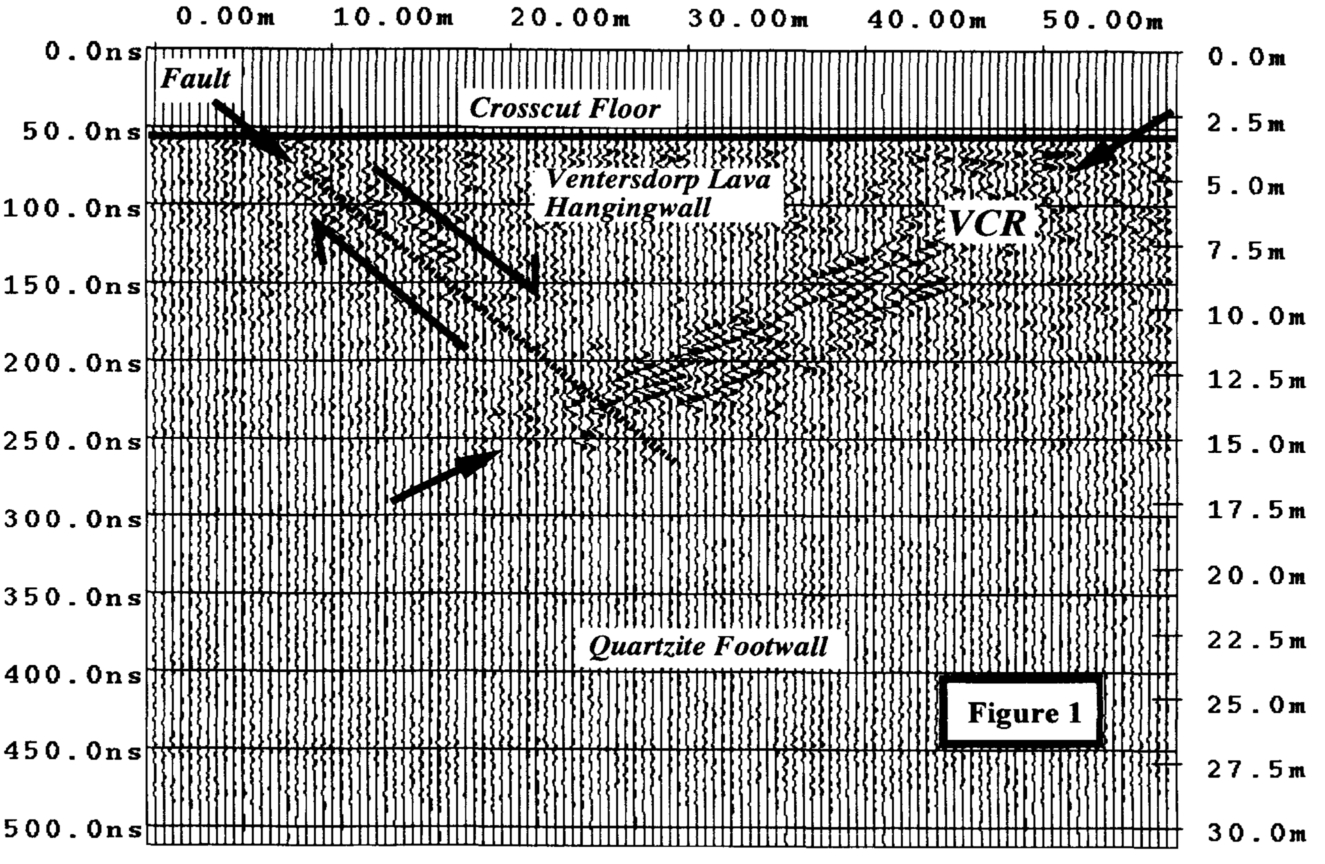

Figure 1—An example of data collected with the RockRadar system at Vaal Reefs

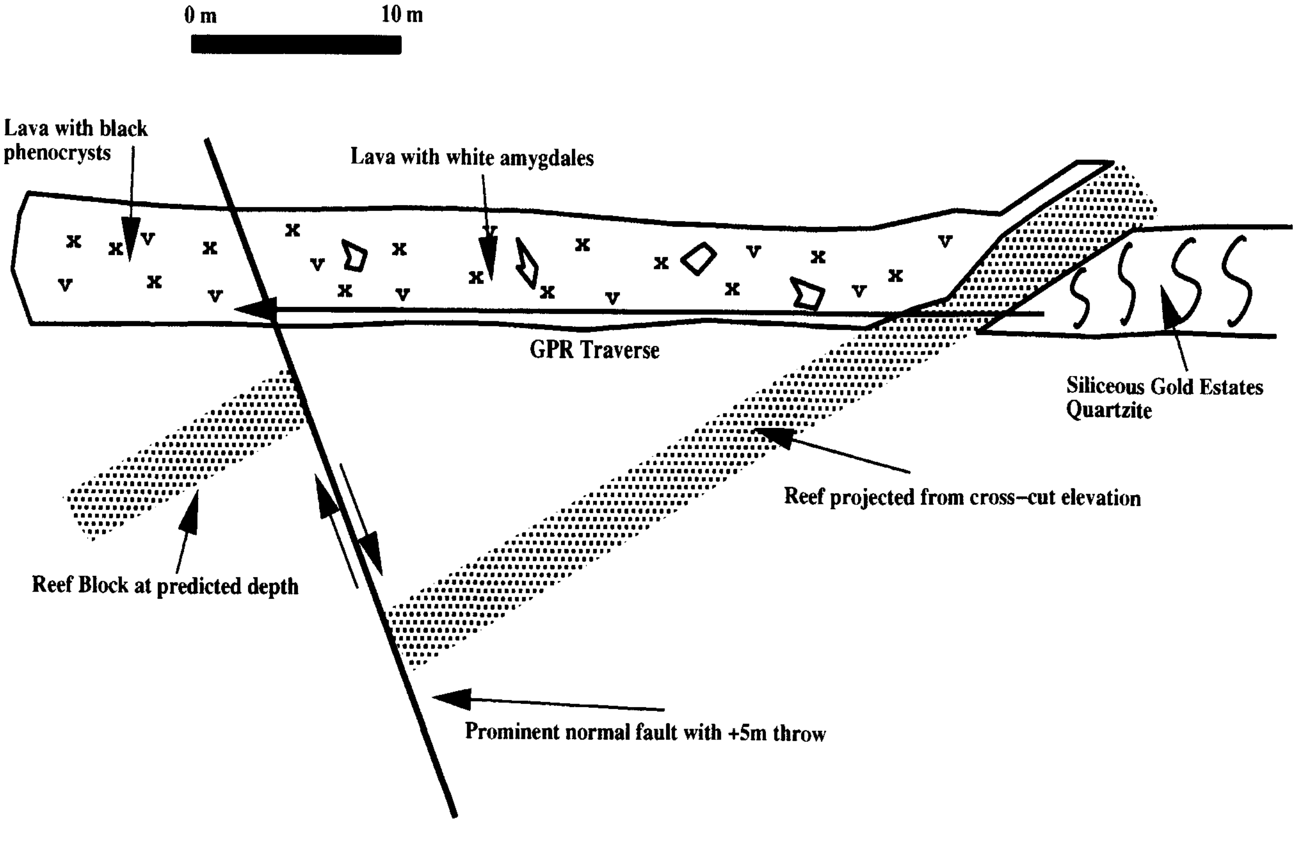

Figure 2—Interpretation of data collected with the RockRadar system at Vaal Reefs

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Current and future developments

The recent advances discussed above ensure highly improved data quality to the extent that system performance is highly predictable in any environment, based on simple operational guidelines. The result is that quantitative rock-mass studies can be performed with the RockRadar system. Studies aimed at extending the quantitative application of GPR in subsurface characterization have, or are being, initiated. These include the following.

(i) Quantitative determination of the dielectric properties of the subsurface, including permittivity, conductivity and dispersion relations, and correlation with physical characteristics of the rock-mass. This allows the following to be achieved, for example:

- The depth to a fault-zone can be accurately determined directly from GPR measurements.
- The fracture zone surrounding an excavation can be dielectrically characterized, and the dielectric properties correlated with physical (mining) properties.
- Correlation between mineralization and dielectric properties.

(ii) Fully flexible data acquisition geometries, including fixed-offset, common mid-point, tomographic and large-offset setups are now supported. Examples of new applications arising from this include the following:

- The ground beneath a structure can be imaged by placing the transmit and receive antennas on either side of the structure.
- Tomographic 'time-of-flight' investigations of pillars can be performed.
- In cases where standard reflection studies are not successful (in conductive environments, for example), transmission studies can assist in dielectric characterization of the subsurface. Recent work on a clay-core dam-wall conducted by ISS International illustrates this point: The conductivity of the dam-wall was too high for standard reflection studies to be of much use, and so an acquisition geometry was used whereby the transmitter was placed on top of the wall and the receiver at the foot of the wall. Time-of-flight measurements through the dam wall (from top to bottom) allowed the complete dielectric characterization of the wall, including determination of the clay-core geometry.

(iii) In certain situations, GPR refraction (the analog of seismic refraction, see for example Lankston[2]) can now be performed. An example of this is the following:

- Determination of the thickness of a horizontal mineralized ore-body, underlain by barren sedimentary layers.

Conclusion

In conclusion, with the advent of the RockRadar system, quantitative ground penetrating radar studies of the subsurface can now be done. The technique of GPR has thus matured to a similar level to that of seismic reflection and refraction evaluations. ◆

References

1. Steeples, D.W., and Miller, R.D. 'Seismic reflection methods applied to engineering, environmental and ground water problems', *Geotechnical and Environmental Geophysics (Investigations in Geophysics no. 5),* Society of Exploration Geophysicists, USA, 1990. pp. 1–30.
2. Lankston, R.W. 'High-resolution refraction seismic data acquisition and interpretation', *Geotechnical and Environmental Geophysics (Investigations in Geophysics no. 5),* Society of Exploration Geophysicists, USA, 1990. pp. 45–74.

New appointment at Mintek*

Mr C.J. (Hans) van Vuuren has been appointed Senior Director: Metals Technology at Mintek.

Mr Van Vuuren, who has spent most of his professional life in various technical and managerial positions at Iscor, is also Professor Extraordinary: Material Science and Metallurgical Engineering at the University of Pretoria. ◆

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Lecturer Award

Professor Michael J. Nicol of the University of the Witwatersrand has been awarded the 1998 Extraction and Processing Distinguished Lecturer Award from The Minerals, Metals and Materials Society (TMS) of the United States. This award recognises an outstanding scientific leader in the field of extraction and processing metallurgy by inviting him/her to present a comprehensive lecture at the Society's Annual Meeting. ◆