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Measurement of electrical properties of Bushveld Complex rocks for assessment of radar performance

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ABSTRACT

A vector impedance meter was used to measure the complex impedance of samples from Bushveld complex (BC) Mines for frequencies between 1 MHz and 64 MHz. The samples were obtained from Rustenburg and Boschfontein Platinum Mines. The obtained impedance magnitude and phase angle data were imported into the Winpro computer program, resistivity and relative dielectric constant values were then computed for each frequency setting. The frequency range within which the measurements were done is very low for GPR, but ideal for borehole radar (BHR).

From the recently done electrical property studies, there is sufficient dielectric contrast between chromitite and Merensky reef, and host rocks such as norites and anorthosite, which was predicted to lead to good radar reflection signals. The hosts have high resistivity values, implying low radar signal attenuation or a longer radar range.

Key words: Ground penetrating radar, reflection, attenuation, impedance

INTRODUCTION

Ground penetrating radar (GPR) is a geophysical technique similar to seismic reflection, except that it is based on propagation and reflection of electromagnetic (EM) waves rather than elastic waves. GPR range is extended by implementing it in the form of borehole radar. Targets are successfully imaged if the borehole is drilled in resistive host formation, sufficiently close to and parallel to the target.

Successful detection of subsurface targets using radar depends on electrical conductivity, dielectric constant and magnetic permeability. However it is generally assumed that most geological materials are non-magnetic, and therefore their magnetic permeability is usually ignored. Sharp changes in relative dielectric constant between rock formations result in radar signal reflection.

A knowledge of electrical rock properties, together with the radar system performance is necessary for predicting the performance of radar in a given geological environment. In BC platinum mines, dielectric contrasts exists between platinum reef (usually UG2 and Merensky) and resistive host rocks such as norites and anorthosites. Electrical property measurement results presented in this paper confirm the effectiveness of radar imaging in the BC Mines.

BASIC RADAR THEORY

The velocity of propagation for radar waves is controlled by the permittivity or dielectric constant (ε). Normally the permittivity of a material is measured relative to that of a vacuum, and expressed as relative permittivity (ε_r). For rocks that are suitable for borehole radar application, the radar propagation velocity is given by the equation below (Vogt et al., 2005):

$$v = \frac{c}{\sqrt{\varepsilon_r}} \tag{1}$$

Where c ($\approx 3 \times 10^8$ m/sec) is the speed of light. The wavelength of a radar wave is given by:

$$\lambda = \frac{c}{f\sqrt{\varepsilon_r}} \tag{2}$$

Where f is frequency. The wavelength is important because it determines resolution. Resolution is the minimum separation between two interfaces where the interfaces can still be seen as separate events on a radar image (radargram). A rule of thumb is that resolution is half the dominant wavelength. The decay of the amplitude of radio waves is called attenuation, and depends on conductivity, permittivity, permeability and frequency. In sub-surface materials, the attenuation of the GPR wave, α, in dB/m is given by:

$$\alpha = \omega\sqrt{\varepsilon\mu\frac{\left\{\sqrt{1+\left(\sigma/\omega\varepsilon\right)^{2}}\right\}-1}{2}} \qquad (3)$$

where μ is the magnetic permeability of the rock, $1.25\mathrm{x}10^{-7}$ H/m, σ is conductivity (reciprocal of resistivity), and ω is angular frequency, $\omega=2\pi f$.
The unit of attenuation is $\mathrm{Np.m}^{-1}$. If $10\log_{10}(\alpha)$ is taken, the attenuation can then be expressed in dB/m. Generally, permittivity and conductivity vary as a function of frequency. Attenuation can also be expressed by means of a parameter called loss tangent (tan δ). For materials that allow radar signal to propagate with less attenuation, the loss tangent is much less than 1. The loss tangent is given by:

$$\tan\delta = \frac{\sigma}{\omega\varepsilon} \qquad (4)$$

The amplitude of the signal reflected radar signal at geological interfaces is expressed by the reflection coefficient Γ (equation 5):

$$\Gamma = \frac{\sqrt{\varepsilon_1}-\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1}+\sqrt{\varepsilon_2}} \qquad (5)$$

The effectiveness of radar is limited by its maximum probing range or probing distance (PD) in the medium of interest. This is determined both by the radar system parameters and the absorption loss in the probed media. Besides media properties (conductivity), penetration depth depends on the dominant (central) frequency of the antennas used to transmit and receive the EM waves or pulses. If the loss tangent is assumed to be constant, a frequency independent radar performance can be predicted (Du Pisani and Vogt, 2003). A nomogram appropriate for a particular radar reflector, knowledge of the radar system performance (in decibels per meter) and the loss tangent value are then needed to determine the range.

METHOD

The method used to measure electrical properties of Bushveld Complex rocks consisted of a Hewlett-Packard type 4815A vector impendence meter, and a sample holder or capacitive jig (Figure 1). The jig consisted of two smooth brass disks each 2 mm thick and 25 mm in diameter, with a short flexible wire soldered onto the outer flat surface of each disk. The samples were cut into thin slices using a diamond saw. A digital calliper was used to measure their thicknesses. Each sample was then placed between the inner surfaces of the metal disks in the capacitative jig, and held in place by means of non-conductive clamps. The jig was connected to the vector impedance meter and tuned to each frequency of interest (between 1 MHz to 64 MHz). Readings of the magnitude and phase of the impendence of the jig were read off the meter in units of ohms and degrees respectively, for each desired frequency value. The magnitude and phase values were then imported into a computer program for direct calculation of resistivity (ρ) and dielectric constant (ε) (Frankenhauser et al, 1995)

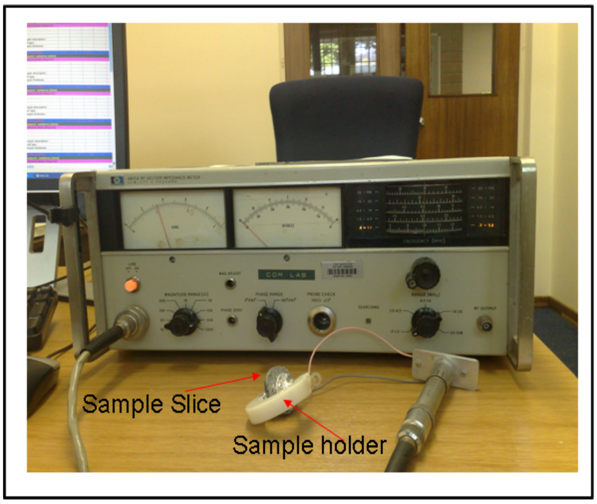

Figure 1. Vector impedance meter setup used to measure rock electrical properties in the laboratory

RESULTS

The results of electrical property measurements of samples from Rustenburg Platinum Mine (Turffontein and Brakspruit Shafts) are presented in Figure 1 and Table 1. The results generally show that there is sufficient dielectric contrast between the footwall and the hangingwall norites, and chromitite Reef, which results in a good radar reflection. The low resistivity and high dielectric constant of the Merensky makes it a good target. The low resistivity may be due to conductive sulphides however the resistivity of the host rock (norite) is sometimes low, implying possibility of signal loss and slight reduction of radar range.

The Pioneer Marker, Brakspruit Marker and Footwall Marker have fairly low resistivities and a dielectric constant contrast to the footwall and hangingwall norites, making them potential radar targets. The loss tangent values for norites and anorthosite rocks are less that 0.1, which is conducive for good radar signal penetration.

The Merensky reef is a pyroxenite; its associated upper and lower chromitite bands also give a good radar signal. Norite and anorthosite rocks are good hosts due to their high resistivity and low dielectric constants compared to the Merensky and chomitite bands. The loss tangent values of host rocks are quite low, implying less attenuation of the radar signal, before and after reflecting at the target-host interface.

The results for Boschfontein samples are shown in Figure 3 and Tables 2 to 4. Since the borehole radar used by the CSIR has a central frequency of 40 MHz, we will discuss only the measurements done at 64 MHz. There is a significant contrast in dielectric constant values, between host rocks (norite, pyroxenite and anorthosite) and UG1 and UG2 chromitite reefs (Figure 3 and Table 2). The resistivity values of host rocks are quite higher (between 100 – 400 Ohm-metres in Figure 3) compared to that of chromitites, which implies good radar signal penetration. The UG1 and UG2 reefs are good radar target due to their high dielectric constant and low resistivity value.

CONCLUSIONS

Previous and recently completed electrical property studies have confirmed that the radar method is very much applicable in the Bushveld Complex. There is good dielectric contrast between the footwall and hangingwall norite rocks, and chromitite reef, which results in a good radar reflection. The low loss tangent of norite and anorthosite rocks makes them support radar wave propagation with less attenuation.

The electrical property analysis have also shown that the Pioneer Marker, Brakspruit Marker and Footwall Marker found at Turffontein and Brakspruit Shafts (Rustenburg Platinum Mine) are also good radar targets due to their low electrical resistivity, and high dielectric constant in comparison to norite rocks. The Merensky reef was predicted to be a good radar target, because of the chromitites below and above it, and it also has a good dielectric contrast to norite host rocks

Results from Boschfontein also reveal a good electrical property contrast between host rocks and the UG1 and UG2 reefs. The geological setting is therefore conducive for borehole radar imaging of the reefs. It is important to note that a successful radar survey also depends on other factors, particularly the profiling geometry (Vogt et al., 2005)

The recent studies have provide d very useful electrical rock property information, but generalising the interpretation of results may lead to inconsistencies as the samples studied were quite few; a fair statistical representative number needs to be analysed.

ACKNOWLEDGMENTS

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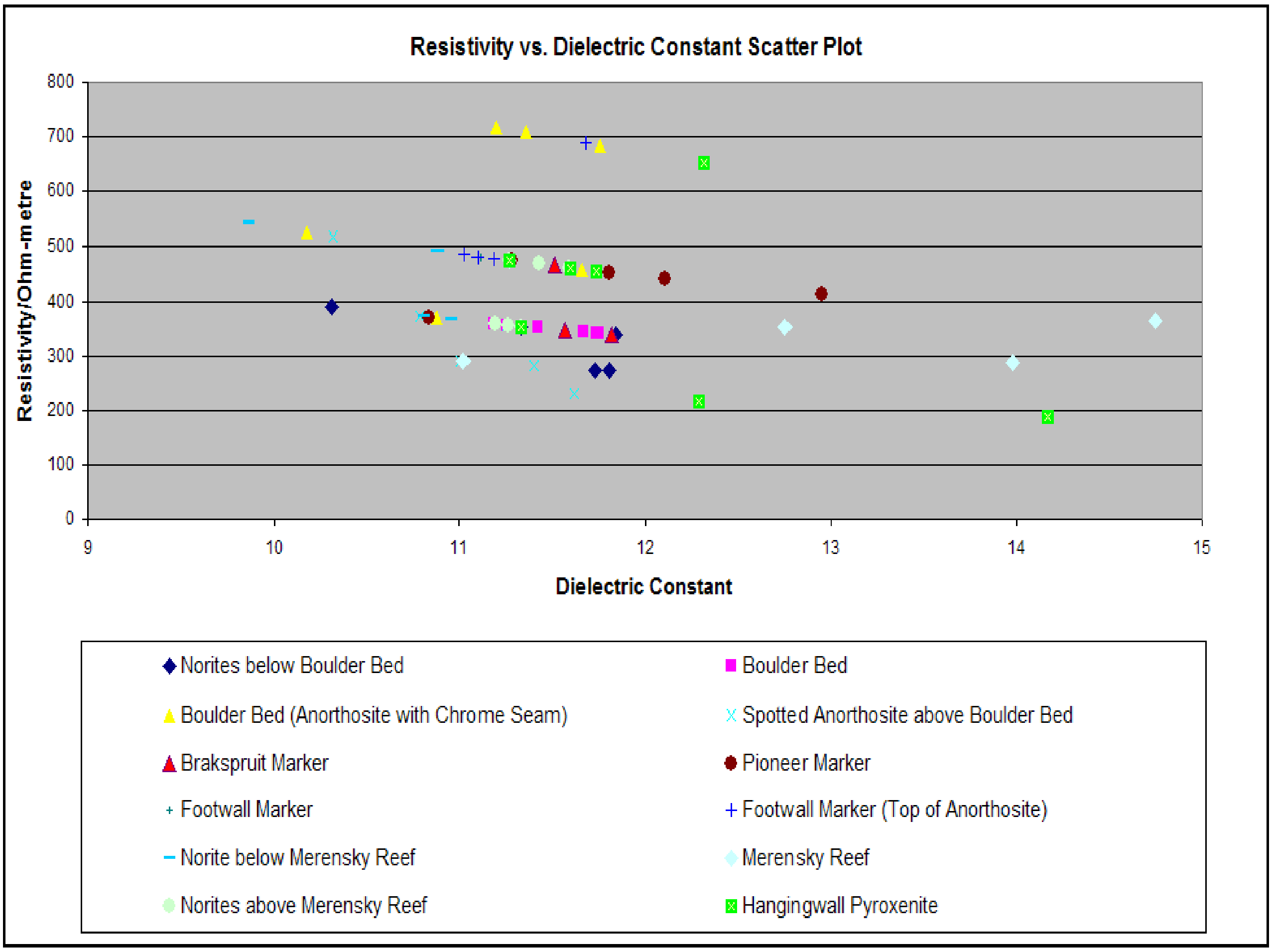

Figure 1 Resistivity vs. Dielectric Constant Scatter Plot for Samples from Turffontein and Brakspruit Shaft (Sibeko, 2007)

Sample Number	Average dielectric constant
Norites below Boulder Bed	0.012
Boulder Bed	0.011
Boulder Bed (Anorthosite with Chrome Seam)	0.007
Spotted Anorthosite above Boulder Bed	0.013
Brakspruit Marker	0.010
Pioneer Marker	0.009
Footwall Marker	0.008
Norite below Merensky Reef	0.010
Merensky Reef	0.010
Norites above Merensky Reef	0.010
Hangingwall Pyroxenite	0.010

Table 1 Loss tangent values for from Turffontein and Brakspruit Shaft (Sibeko, 2007)

Rock Name	Strat-code	Dielectric constant values for measurements taken between 1- 64 MHz frequency range						
		1 MHz	**2 MHz**	**4.4 MHz**	**8 MHz**	**16 MHz**	**32 MHz**	**64 MHz**
Pyroxenite	UG2 HW	9.87-12.2	8.26-10.74	8.18- 10.26	8.13 - 9.76	7.89 - 9.56	8.99- 10.74	12.1-16.69
Chromitite	UG2	9.92 -11.77	9.59-11.92	10.7- 10.19	9.24 -10.88	9.92-10.92	10.39-12.6	18.37-26.1
Pegmatoidal	UG2 FT	9.34 - 9.73	8.92-9.73	8.13 – 19.63	7.32 -9.73	7.1- 10.22	10.39-18.1	7.93 -10.59
Norite	UG2	9.78 -10.19	8.94 -9.7	8.09 -9.57	8.06 -9.15	7.1 - 9.17	8.95-10.17	12.78 -15.01
Anorthosite	UG 2	9.46 -12.66	9.28 -11	9.02 -10	9.1 -10.55	8.76 -10.55	9.84 -11.3	14.74 -18.53
Pyroxenite	UG 1 HW	8.91 - 10.8	7.58 -9.1	7.38 -8.87	7.34 -8.82	7.34 - 9.11	7.89-10.31	10.5 - 4.45
Chromitite	UG 1	10.25 -14.51	11.02 -14.1	11.12 - 13. 6	11.02 -12.75	9.92 -12.87	11.54-14.5	17.88 -31.2
Anorthosite	Below UG 1	12.52 -13.52	11.17 -12.63	11.02 -12.4	10.79 -12.18	11.17 -12.18	12.91-13.2	12.56 -19.78
Norite	UG1	9.78 -10.19	8.94 -9.7	8.09 -9.57	8.06 -9.15	7.1 9.17	8.95 -10.17	12.78 -15.01

Table 2 Typical Average Ranges for the Dielectric Constant values for Boschfontein Samples

Rock Name	Strat-code	Resistivity (Ωm) values for measurements taken between 1- 64 MHz frequency range						
		1 MHz	**2 MHz**	**4.4 MHz**	**8 MHz**	**16 MHz**	**32 MHz**	**64 MHz**
Pyroxenite	UG2 HW	20814.44-7581.64	15552.7-4745.77	7138.95-2831.96	5025-1874	2718-1097	854.49-426.31	221.19-95.43
Chromitite	UG2	24953.7-10862.37	16194.44-7146.2	7476.24-5099.25	6484-2932	3607-1954	964.54-87.56	206.31-87.56
Pegmatoidal	UG2 FT	110268.-50092.41	71381.55-27321.2	25476.8-12142.75	13758-7589	4529-3149	1049.92-735.57	386.5-177.27
Norite	UG2	17479.8-14686.46	11469.1-8815.74	13544.42-4879.83	7075-2806	3639-1753	670.98-525.55	204.92-112.7
Anorthosite	UG 2	27169.73-9413.9	10649.87-7770.48	4915.32-3716.32	3532-2027	1834-1013	652.37-431.56	181.32-107.84
Pyroxenite	UG 1 HW	23071.42-16608	16956.5-14120.99	13232.22-6589.8	5007-2709	2680-1900	927.95-518.3	254.61-212.71
Chromitite	UG 1	50233.42-8817.69	25437.35-4534.81	11471.75-2445.49	6359-1433	3242-836	698.71-276.14	224.58-33.87
Anorthosite	Below UG 1	48912-19007.34	25308-13578.59	11680.57-6286.38	6570-3520	3520-2712	973.63-413.98	255.67-162.32
Norite	UG1	17479.8-14686.46	11469.1-8815.74	13544.42-4879.83	7075-2806	3639-1753	670.98-525.55	204.92-112.7

Table 3 Typical Average Ranges for the Resistivity of Boschfontein Samples

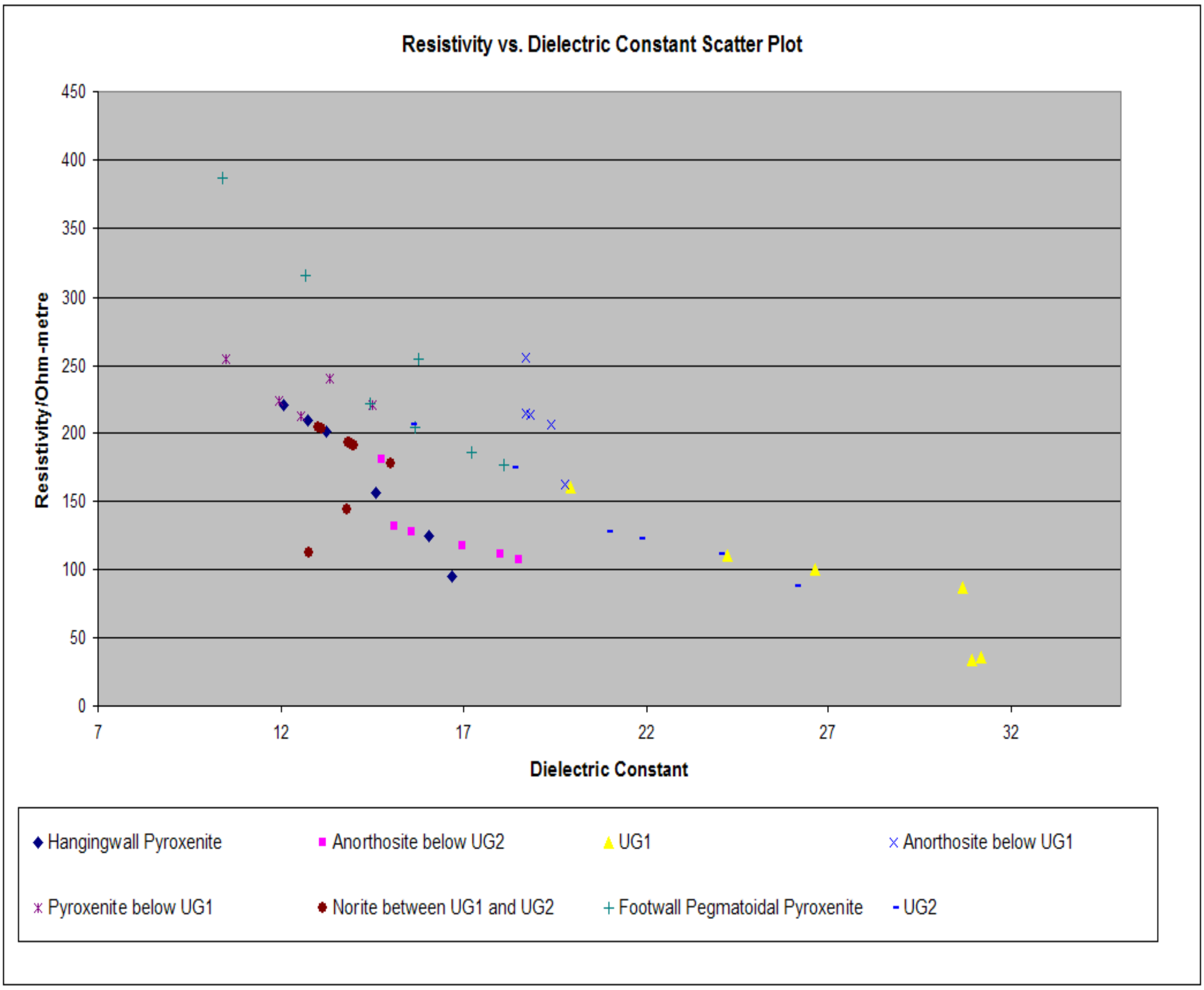

Figure 3 Resistivity vs. Dielectric Constant Scatter Plot for Samples from Boschfontein Platinum Mine

Sample Number	Average dielectric constant
Hangingwall Pyroxenite	0.020
Anorthosite below UG2	0.021
UG1	0.024
Anorthosite below UG1	0.011
Pyroxenite above UG1	0.016
Norite between UG1 and UG2	0.020
Footwall Pegmatoidal Pyroxenite	0.013
UG2	0.016

Table 4 Loss tangent values for Samples from Boschfontein