

# The radio frequency dielectric properties of the stratified UG1–UG2 geological unit in the Bushveld Complex

Marc Rütshlin<sup>a,\*</sup>, Johannes H. Cloete<sup>a</sup>, Iain M. Mason<sup>b</sup>, Keith D. Palmer<sup>a</sup>

<sup>a</sup> Department of Electrical and Electronic Engineering, University of Stellenbosch, Private Bag X1, Matieland 7602, South Africa

<sup>b</sup> School of Geosciences, University of Sydney, Australia

Received 11 August 2006; accepted 22 February 2007

## Abstract

A new measurement technique enables the complex dielectric properties of the geological strata comprising the UG1–UG2 (Upper Group 1–Upper Group 2) unit of the Bushveld Complex in South Africa to be determined with unprecedented detail at radio frequencies (RF). Results of non-destructive laboratory measurements of representative diamond drill core samples from the UG1–UG2 unit are presented at 25 MHz. These data establish that the UG1 and UG2 chromitite layers are embedded in rock strata (norite, pyroxenite and anorthosite) which are translucent in the HF spectral band, whereas the chromitite layers themselves exhibit significant velocity contrast, making them good radar reflectors. The data presented here is useful for calibration of the radar system, and for predicting the range and resolution performance of borehole radars operating in both the hanging and footwalls of the economically important platiniferous UG2 reef.

© 2007 Elsevier B.V. All rights reserved.

*Keywords:* Dielectric properties; Radio frequency; Borehole radar; Platinum group metals; UG1–UG2 unit; Bushveld Complex

## 1. Introduction

The Bushveld Complex (BC) is the largest layered igneous complex in the world. Its Merensky Reef, Upper Group 2 (UG2) chromitite layer and Platreef host about 75% of the world's known platinum and 50% of its palladium reserves (Cawthorn, 1999a). Although the Merensky and UG2 systems exhibit remarkable large

scale layering, both horizons are frequently and unpredictably disrupted by potholes and other structures which may seriously obstruct mining operations (Lomborg et al., 1999). The use of borehole radars (BHR) deployed in the surrounding strata for ore body delineation is therefore of significant interest for mine planning purposes (Simmat et al., 2006).

The design of borehole geometries for optimal BHR range and resolution performance in the BC requires accurate knowledge of the dielectric properties of its various layers. These data have recently been acquired in the 1 to 25 MHz band<sup>2</sup> for the rock types encountered

\* Corresponding author.

E-mail addresses: [marc.rutschlin@gmail.com](mailto:marc.rutschlin@gmail.com) (M. Rütshlin), [jhcloete@sun.ac.za](mailto:jhcloete@sun.ac.za) (J.H. Cloete), [iainmason1@bigpond.com](mailto:iainmason1@bigpond.com) (I.M. Mason), [palmer@sun.ac.za](mailto:palmer@sun.ac.za) (K.D. Palmer).

<sup>1</sup> Present address: CST GmbH, Bad Nauheimerstr. 19, 64289 Darmstadt, Germany.

<sup>2</sup> Only data at 25 MHz will be presented to limit the length of the paper. This is a good center frequency for radars designed to operate in the UG1–UG2 system.

in the UG1–UG2 unit, using a new technique for the non-destructive evaluation of hard rock core samples (Rütschlin, 2005; Rütschlin et al., 2006) to characterise them in unprecedented detail.

Although the purpose of this paper is to present accurate data of the dielectric properties of the UG2 and its various host layers, the information can be applied to the Merensky system since it is also hosted by pyroxenite, norite and anorthosite strata (Cawthorn, 1999b).

The article is organised as follows. The Bushveld Complex is briefly described in Section 2. A discussion of the geology of the UG1–UG2 unit and description of samples obtained from the UG2 and surrounding layers are presented in Section 3. Measured results are presented in Section 4, followed by the conclusion in Section 5.

## 2. The Bushveld Complex

The Bushveld Complex is estimated to be about 2050 mega-years in age. It has the typical inverted funnel shape of layered complexes, with its rim exposed at the surface at a number of locations, and its centre deep underground. Capped by overlying Bushveld granites, amongst others, the BC itself is a composite body consisting of four sill-like intrusives which together form a series of relatively thin saucers with a total thickness of up to 8 km and a lateral extent over an area of approximately 65,000 km<sup>2</sup> in north-western South Africa (Cawthorn, 1999b).

The stratigraphy in various parts of the BC differs substantially in terms of thickness and lithological variations (Kinnaird et al., 2002). In general, however, it may be divided into four zones corresponding to the intrusives.

The basal (or lower) zone, consisting of interlayered peridotite and pyroxenite, is separated from the overlying critical zone (CZ) by a continuous chromitite

layer. The CZ consists of a succession of dunite, pyroxenite, anorthosite and chromitite layers, and is host to large deposits of chromium, platinum and palladium.

The most important of these deposits occur within the UG2 chromitite layer and the Merensky reef, which also marks the transition from the CZ to the overlying main and upper zones. The Merensky reef, discovered in 1924, was the primary source of PGMs (platinum group metals) for decades. However, since its initial exploitation in the 1970s the exploitation of the UG2 chromitite layer has increased to the point that it produced 42% of ore processed in 1999 (Johnson Matthey, 1999), and its economic importance in terms of PGM production has now come to rival that of the Merensky.

Tunnels which give miners and drillers access to the UG2 are commonly blasted in the CZ region between the UG1 and UG2 chromitite layers, also known as the UG1–UG2 unit, with the UG1 beneath the UG2. Long range HF/VHF borehole radars are typically deployed between 5 to 35 m from the UG2 reef in its footwall, but above the UG1. This is to prevent the UG1, which is also a good reflector, from attenuating radar echoes from the UG2. An accurate, quantitative understanding of radar wave propagation in the CZ region is thus of primary importance for BHR remote sensing.

## 3. Geology, sample description and measurement procedure

Exploration boreholes have revealed that the thicknesses of the layers comprising the UG1–UG2 unit are variable over the BC which, as mentioned above, covers a vast area. However, for practical BHR delineation purposes, the RF dielectric properties of the rock strata which host the UG2 chromitite layer are assumed to be spatially uniform. A specific stratigraphic column from Bleskop shaft on the BC's Western Limb near the town of Kroondal, shown in Fig. 1, serves to illustrate that

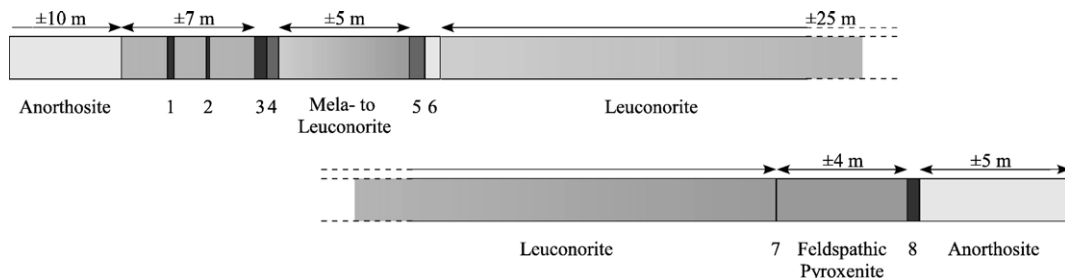


Fig. 1. The UG1–UG2 unit's stratigraphy (not to scale) at Bleskop on the Western Limb of the Bushveld Complex (Vos, 2003, personal communication). Note that the UG1 lies below the UG2. Several thin layers are numbered for clarity: 1. triplets ( $\pm 0.3$  m), 2. leader seam ( $\pm 0.2$  m), 3. main seam (UG2) ( $\pm 0.7$  m), 4. pegmatoidal feldspathic pyroxenite ( $\pm 0.6$  m), 5. pegmatoidal feldspathic pyroxenite ( $\pm 0.9$  m), 6. anorthosite ( $\pm 0.9$  m), 7. 8 mm chromitite stringer, and 8. UG1 ( $\pm 0.1$ – $1$  m).

four rock types — anorthosite, feldspathic pyroxenite, norite and pegmatoidal feldspathic pyroxenite (PFP) — make up the immediate hanging and footwalls of the UG2 chromitite layer. All were determined to be essentially non-magnetic. Hence only their relative permittivity and dielectric loss tangent determine the performance of borehole radars.

At Bleskop the UG1 chromitite layer caps an anorthosite footwall of about 5 m thickness. The UG1 consists of a main chromitite layer and a number of chromitite stringers, resulting in a unit with a variable total thickness of between 0.1 and 1 m. Above the UG1 an approximately 4 m layer of feldspathic pyroxenite is overlain by about 25 m of norite. The two layers are intermittently separated by a thin (about 8 mm thick) chromitite stringer. Above the norite layer is an approximately 1.5 m thick sequence of layers called the Bleskop Marker (BKM) because it occurs at the

Bleskop shaft. Its structure is variable and it may be completely absent in other locations. Between the BKM and the UG2 layer is another approximately 5 m thick layer of norite, capped by a thin but variable (about 60 cm thick) layer of pegmatoidal feldspathic pyroxenite which is in contact with the UG2's base. The UG2 layer itself is a chromitite layer having a relatively consistent thickness of about 70 cm (in the absence of potholes). The immediate UG2 hanging-wall is an approximately 7 m thick layer of feldspathic pyroxenite containing a number of chromitite layers of up to 20 cm thickness, including the 'leader' band (about 20 cm thick) as well as three thin layers of chromitite commonly referred to as 'the triplets'. The thickness and height of these chromitite bands above the UG2 is variable. The feldspathic pyroxenite above the UG2 is capped by about 10 m of anorthosite, followed by norite.

Table 1

Geological descriptions of samples 1–5 of the UG2 and surrounding rocks obtained from the Bushveld Complex western limb near Kroondal

Sample	Diameter [mm]	Sample description
		
UG2-1	36.10	Homogeneous sample of coarse poikilitic anorthosite taken from the hanging-wall of the UG2 above the triplets. This sample exhibited severe 'corkscrewing': its diameter varied continually, presumably due to gyration of the bit during drilling.
		
UG2-2	36.15	This sample straddles the intersection between the coarse poikilitic anorthosite and underlying medium textured feldspathic pyroxenite. The change is marked by a very narrow (2 mm) oblique chromitite stringer.
		
UG2-3	36.10	This feldspathic pyroxenite host contains the uppermost chromitite triplet (UG2 triplet 3); the 3 cm section above (to the left of) the chromitite consists of pegmatoidal feldspathic pyroxenite.
		
UG2-4	36.13	This sample's ends lie in the second and first triplets respectively, while the central region is feldspathic pyroxenite.
		
UG2-5	36.10	Fairly homogeneous feldspathic pyroxenite.

Ten sections of diamond drill core from a vertical borehole through a stratigraphy similar to Fig. 1 were selected from the UG2's hanging-wall anorthosite, pyroxenite, chromitite layers, pegmatoidal feldspathic pyroxenite base, and norite footwall. They provide a good representation of the various rock types found in the UG1–UG2 unit. Geological and photographic descriptions are given in Tables 1 and 2. The Bleskop Marker is not of general interest, however if needed its properties can be constructed from the data presented in this paper or by Rütschlin et al. (2006).

A guarded, shielded, cylindrical capacitor, fully described by Rütschlin et al. (2006), was used for the non-destructive measurement of the samples. This capacitor employs flexible electrodes which conform to the surface of the cylindrical sample, allowing the complex dielectric properties of even partially broken samples to be accurately measured (permittivity to within better than about 10%, loss tangent to within better than 0.01). The presence of air-gaps between the electrodes and the core sample can lead to inaccurate measurements, particularly of the relative permittivity. The capacitor's design allows its flexible electrodes to be pressed tightly against the sample, eliminating air-gaps completely if the sample is in good condition.

#### 4. Measured properties of the UG2 reef and its foot- and hanging-walls

The samples described in Tables 1 and 2 were measured over their entire length at 1 cm intervals. As discussed below, sample 1's condition only allowed it to be measured in a single orientation, but the other samples were all measured in four orientations (every 90° around the core). The measurements of regions of homogeneous rock were extracted to provide estimates of their bulk propagating characteristics. The measured dielectric properties at 25 MHz of the five material types found in the cores are listed in Table 3.

The properties of the chromitite layers are all similar ( $11.67 \leq \overline{\epsilon_r} \leq 12.16$ ,  $0.09 \leq \tan \delta \leq 0.11$ ) and differ as a group from all the host rocks' properties, both in terms of permittivity and loss tangent. An exception is melanorite's mean loss tangent of about 0.08, which is only slightly below that of chromitite. While chromitite has a relatively high attenuation constant of between about 0.7 and 0.9 dB/m, the other rock types (again with the exception of melanorite) provide favourable propagation conditions for BHR remote sensing. With the exception of pegmatoidal feldspathic pyroxenite, all rock types are fairly homogeneous on a local scale.

Table 2

Geological descriptions of samples 6–11 of the UG2 and surrounding rocks obtained from the Bushveld Complex western limb near Kroondal





Sample	Diameter [mm]	Sample description
UG2–6, 7	36.07	 <p>Samples 6 and 7 fit together snugly and cover the transition from the overlying feldspathic pyroxenite into the UG2 main leader, a 29 cm thick chromitite layer lying about 1.5 m above the main UG2 reef.</p>
UG2–9	36.07	 <p>This sample covers the transition from a fine feldspathic pyroxenite to the main UG2 chromitite layer. A 3 cm wide intrusion of feldspathic pyroxenite removes a 2 cm section of chromitite from the main body.</p>
UG2–10	36.10	 <p>Sample 10 starts at the very bottom edge of the UG2 chromitite layer but consists mainly of pegmatoidal feldspathic pyroxenite.</p>
UG2–11	36.10	 <p>Homogeneous sample of medium grained melanorite, which forms the immediate footwall of the UG2.</p>

Table 3  
Material properties of the individual UG2 materials at 25 MHz

Material	Sample	Permittivity		Loss tangent		Atten. [dB/m]		Velocity [m/ $\mu$ s]	
		$\bar{\epsilon}_r$	$CV_{\epsilon_r}$	$\tan \delta$	$CV_{\tan \delta}$	$\bar{\alpha}$	$CV_{\alpha}$	$\bar{v}$	$CV_v$
Anorthosite	1	7.43	3.20	0.05	9.09	0.33	10.42	109.98	1.61
Feldspathic pyroxenite	2	8.26	2.08	0.06	7.76	0.42	8.66	104.30	1.03
	3	8.31	2.06	0.05	5.01	0.33	5.44	104.00	1.03
	4	8.21	5.38	0.05	11.65	0.33	14.20	104.70	2.65
	5	8.00	3.49	0.05	12.37	0.34	13.63	105.98	1.75
	9	7.75	2.24	0.04	10.60	0.27	11.51	107.70	1.13
Chromitite	3	12.16	2.92	0.10	5.95	0.83	7.00	85.88	1.49
	6, 7	11.67	2.57	0.11	5.03	0.86	5.51	87.65	1.29
	9	11.70	4.36	0.09	4.93	0.72	6.76	87.62	2.23
PFP	10	8.28	5.89	0.06	29.69	0.38	32.21	104.29	2.76
Melanorite	11	8.19	1.23	0.08	4.27	0.52	4.67	104.68	0.62

The coefficient of variation (CV) is the percentage ratio of standard deviation to mean of a particular.

Two interesting transitions are found in samples 3 and 9. Sample 3 contains a 3 cm section of pegmatoidal feldspathic pyroxenite (PFP) between the feldspathic pyroxenite hanging wall and the third UG2 triplet. This transitional layer can be seen between the 18 and 21 cm marks in Fig. 2(a): both the permittivity and loss tangent of the PFP section are noticeably higher than for the feldspathic pyroxenite. The PFP properties correspond closely to those of the PFP in sample 10 at 25 MHz, showing that small sections of rock may at least provide an indication of expected rock properties if no other samples are available.

Sample 9's main UG2 chromitite layer is interrupted near its top edge by an intrusion of feldspathic pyroxenite. The effect on the dielectric properties is clearly visible in Fig. 2(b), which shows 5 mm resolution measurements starting from 18 cm along the core. The peak permittivity of the removed chromitite section matches that of the main body closely, as does the permittivity of the feldspathic pyroxenite that of the main hanging-wall. The loss tangent also displays the same tendencies, particularly clearly at 25 MHz.

The anorthosite properties are only an estimate since the condition of sample 1 prevented accurate measurement. Only a single orientation was measured, and the continual presence of air-gaps due to the 'corkscrewing' drill action places those results in question. Another estimate of the properties of anorthosite may be obtained from the top few centimetres of sample 2, which were measured with a resolution of 2 mm. Fig. 3 shows the measured permittivity and loss tangent of the first few centimetres of this sample at 1, 5 and 25 MHz. Anorthosite's permittivity and loss tangent are estimated from the first centimetre of these measurements as  $\epsilon_r \approx 7.95$  and  $\tan \delta \approx 0.08$  respectively, slightly higher than sample 1's properties. The air-gap present during the

measurement of sample 1 would tend to decrease the effective measured properties, but sample 1's properties do match the properties of BKM anorthosite closely

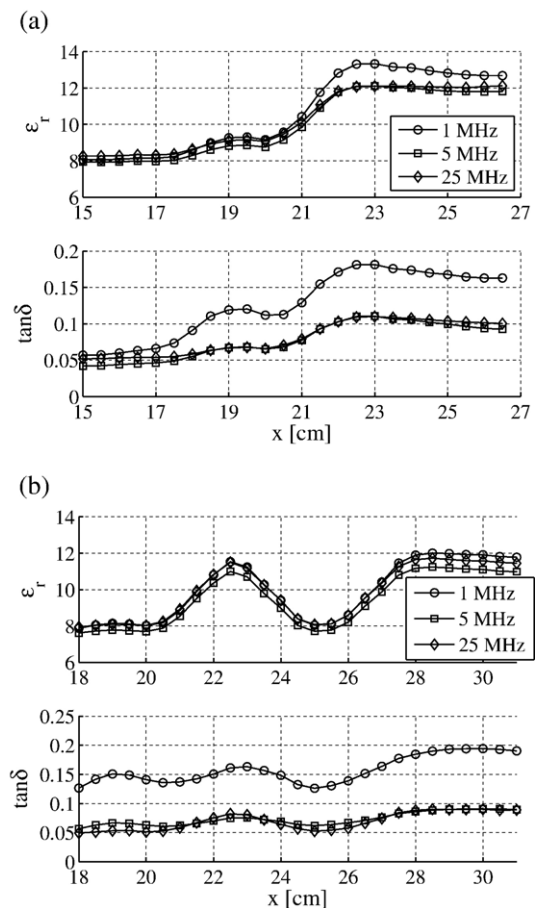


Fig. 2. Transitions between materials in samples 3 (a) and 9 (b). The results shown are the mean values of measurements of the cores in four orientations.

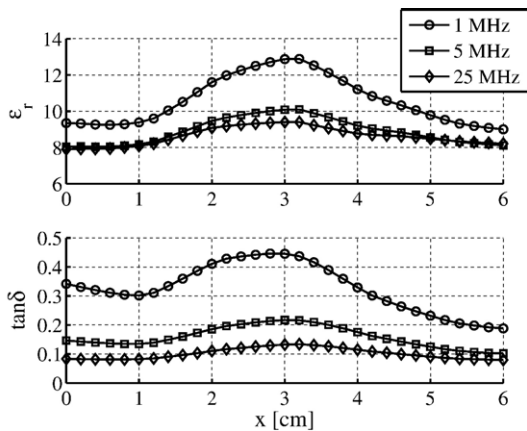


Fig. 3. The mean dielectric properties of the top 6 cm of sample 2 allow an estimation of the properties of anorthosite ( $\epsilon_r \approx 7.95$  and  $\tan \delta \approx 0.08$  at 25 MHz), and clearly show the effect of the chromitite stringer.

(Rütschlin et al., 2006). More samples would be required for a conclusive statement on the properties of anorthosite.

The measurement of the two chromitite ends of sample 4 may be used to estimate the properties of the first and second triplets. The first triplet's permittivity and loss tangent are approximately 12.5 and 0.14 respectively at 25 MHz, while the second triplet has corresponding properties of  $\epsilon_r \approx 10.7$  and  $\tan \delta \approx 0.11$ . These values fall in the same range as those observed in the larger chromitite samples (shown in Table 3).

## 5. Conclusion

The measurement of a collection of diamond drill core samples from within and around the economically important UG2 reef — representing all the major rock types — has been described.

RF attenuation by all the UG2 host rocks is found to be less than about 0.5 dB/m at 25 MHz, making for good borehole radar propagating conditions. Furthermore, propagation velocities in the host strata vary between about 105 and 110 m/ $\mu$ s, in marked contrast with the propagation velocity of about 87 m/ $\mu$ s in the chromitite layers. Significant velocity contrast<sup>3</sup> between the UG2 and its host strata is a prerequisite for radar reflectivity (Brekhovskikh, 1980, pp. 28–29).

Samples of the same rock types from the various strata have properties which were in close agreement.

<sup>3</sup> The Fresnel reflection and transmission coefficients for two half-spaces are conventionally written in terms of wave impedances  $Z$ . However similar expressions in terms of the phase velocities  $v$  follow trivially from  $Z = \eta_0 / \sqrt{\epsilon_r} = \mu_0 c / \sqrt{\epsilon_r} = \mu_0 v$  with  $v = c / \sqrt{\epsilon_r}$  the phase velocity for non-magnetic media ( $m = m_0$ ). In these expressions  $\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}$  and  $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$  are the wave impedance and velocity in vacuum.

Measurements of the same rock types from the Bleskop Marker (Rütschlin et al., 2006) also yielded similar results. There is thus a strong argument for using the measured results of localised samples to predict radar wave propagation in the bulk material, since the important host rocks are fairly homogeneous. This is supported by the propagation simulations and measured BHR data fields presented by Simmat et al. (2006).

Further support comes from comparison of the propagation velocities calculated in Table 3 with measured bulk rock velocities. These were estimated by Herselman (2003) following various cross-hole BHR experiments in the UG2 footwall at Bleskop shaft. In the first experiment the radar transmitter and receiver probes were deployed in different boreholes drilled in the rock immediately below the UG2 main chromitite reef. Three different surveys were used to estimate a peak pulse velocity of 104 m/ $\mu$ s. The laboratory prediction for the propagation velocity of the melanorite found immediately below the UG2 reef is 104.7 m/ $\mu$ s (see Table 3), which is within 1% of the bulk estimate.

In the second experiment the boreholes were drilled in the norites found between the Bleskop Marker and the UG1 reef. Herselman's estimated bulk velocity from cross-hole pulse arrivals of 110 m/ $\mu$ s also agrees within 1% with the laboratory measurements of the norites and anorthosite found in the lower section of the BKM core sample (Rütschlin et al., 2006, Table 2).

To conclude: Laboratory measurements of diamond drill core samples from the various strata of the Bushveld Complex UG1–UG2 system provide a good estimate of bulk propagation velocities, which allows accurate conversion of propagation time delays to distance. This finding is of great value in designing borehole radars intended to delineate the UG2 (and Merensky reef), and in planning, processing and interpreting BHR surveys in the Bushveld Complex.

## Acknowledgements

The authors would like to thank Rustenburg Platinum Mines Ltd. for making available core samples, and acknowledge the financial and material support of the Foundation for Research Development, Pretoria, South Africa; ARCOLab, School of Geosciences, University of Sydney; and GeoMole (Pty) Ltd.

## References

- Brekhovskikh, L.M., 1980. Waves in Layered Media, Second edition. Academic Press, New York.

- Cawthorn, R.G., 1999a. The platinum and palladium resources of the Bushveld Complex. *South African Journal of Science* 95, 481–489.
- Cawthorn, R.G., 1999b. Geological models for platinum-group metal mineralization in the Bushveld Complex. *South African Journal of Science* 95, 490–498.
- Herselman, P.L.R., 2003. Borehole radar system analysis in stratified geological systems applied to imaging of platiferous reefs in the Bushveld Igneous Complex. Ph.D. Thesis, University of Stellenbosch.
- Johnson, M., 1999. Platinum Today: Production: South Africa. <http://www.platinum.matthey.com/production/africa.php>.
- Kinnaird, J.A., Kruger, F.J., Nex, P.A.M., Cawthorn, R.G., 2002. Chromitite formation — a key to understanding processes of platinum enrichment. *Transactions of the Institute Mineralogy and Metallurgy (Section B: Applied Earth Science)* 111 (1), B23–B35.
- Lomberg, K.G., Martin, E.S., Patterson, M.A., Venter, J.E., 1999. The morphology of potholes in the UG2 chromitite layer and Merensky Reef (pothole reef facies) at Union Section, Rustenburg Platinum Mines. *South African Journal of Geology* 102, 209–220.
- Rütshlin, M., 2005. The non-destructive measurement of the radio frequency properties of hard rock borehole cores. Ph.D. Thesis, University of Stellenbosch.
- Rütshlin, M., Cloete, J.H., Palmer, K.D., 2006. A guarded cylindrical capacitor for the non-destructive measurement of hard rock core samples. *Measurement Science and Technology* 17, 1390–1398.
- Simmat, C., Herselman, P.L.R., Rütshlin, M., Mason, I.M., Cloete, J.H., 2006. Remotely sensing the thickness of the UG2 platinum reef using borehole radar. *Journal of Geophysics and Engineering* 3, 43–49.