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Ground penetrating radar (GPR) 'Mineral base profiling and orebody optimization'

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The calculation of resource volumes for large mineral sands deposits is the process of systematically compiling all known data in order to define the volume of ore contained and its intrinsic economic value. Traditionally, this process has been highly speculative in nature, as the variability of the layer thickness, even between closely spaced, boreholes can be highly variable. The issue of horizon continuity is of critical importance in mine modelling and resource definition. Accurate volume estimates are difficult to derive from drilling data alone, as the borehole spacing of an economically viable drilling programme is often greater than the spatial frequency of the variations in profile thickness. The limitations associated with this inferential approach to resource estimation can be mitigated through the use of newly developed ground penetrating radar (GPR) methods, thereby maximizing orebody optimization by reducing contamination and orebody loss.

The use of GPR in the mining industry has historically been limited to shallow, high-resolution applications, such as the location of voids in limestone or the mapping of paleochannels for alluvial gold and diamonds (Francke and Yelf, 2003). These limitations have not been technology based, but rather market based, as the vast majority of GPR systems were originally designed for civil engineering applications. A new generation of GPR technology, designed specifically for maximum penetration in sand environments, is now being developed.

This technology has been trialled extensively at the Richards Bay Minerals heavy mineral sand deposit in South Africa with optimistic results. The clay base of the mineral sands has been imaged to some 120 metres. Further equipment refinements are expected to yield even deeper profiling and higher resolution. The resolution offered by this technology is unique, allowing individual depositional sequences to be imaged and modelled in three dimensions.

This paper will discuss the advances in GPR technology relevant to the mineral sands industry, as well as methods to optimize and integrate GPR data into existing mine models. Also addressed will be approaches to three-dimensional modelling of high-resolution GPR data and subsequent volume estimations.

Introduction

The Richards Bay Mineral (RBM) sands deposit is located along the southeast coast of South Africa, approximately 160 km from Durban. The deposit consists of a series of parallel dunes along the coast of the Indian Ocean. Although the placer sands, which comprise the orebody, contain numerous identifiable stratifications, of primary concern for resource evaluation studies is the base of the deposit, which consists of a formation of coarse calcarenite or aeolinite formed in a paleo-beach environment. This formation, which is not dredgeable due to its high slime and clay sand fractions, is generally situated at the present day sea level. However, significant variations occur in the topography of this basal formation, complicating resource evaluations. Although critical for grade determination, the historical approach of drilling is often unrepresentative of the true deposit geometries at any economical or practical drill spacing.

Ground penetrating radar

The concept of applying radio waves to image the subsurface in high resolution dates from the 1920s with the use of radio echo sounders to profile ice thickness in the polar regions. Although the instrumentation has advanced dramatically in the intervening years, all impulse GPR systems use a short burst of electromagnetic energy, which is radiated from a transmitter at frequencies ranging from 10 MHz to over 1 GHz, depending on the transmitting antenna. The energy is propagated through the ground and reflects off geological interfaces, returning to the surface to be detected by a receiving antenna. As the emitted energy travels through the subsurface at rates approaching the speed of light, the transmission, reflection and detection process requires only nanoseconds. Signal-enhancing stacking may be performed at each station in a fraction of a second. The instruments are then moved along the survey profile and the process is repeated. A two-dimensional 'slice' of the subsurface may thus be acquired, showing lateral and vertical variations in geological interfaces. Although a detailed discussion of the physics of electromagnetic wave propagation is beyond the scope of this paper, reflections are generally caused by variations in the dielectric constant of the subsurface media, which, in turn, are primarily a function of the electrical conductivity of the soil/rock matrix and, to a lesser extent, the degree of water saturation. The concepts involved are similar to those used in reflection seismics, with the exception that electromagnetic energy is used in GPR rather than acoustic energy. In practice, the two methods are often complementary since traditional radar systems generally do not penetrate to depths greater than 70 m, and seismic reflection exploration is very difficult at depths of less than 25 m due, in part, to the effects of surface waves.

The penetration range of GPR is governed primarily by the electrical conductivity of the ground, the transmitting frequency, and the transmitted power. Lower frequencies allow the deepest penetration but poor resolution and higher frequencies produce detailed images with limited penetration. Optimal penetration is achieved in electrically resistive soils such as sands and gravels, whereas saturated clays generally limit penetration to decimeters.

Research conducted in recent years with commercially available GPR systems has suggested that the electrical characteristics of mineral sand deposits may be ideal environments to achieve maximum penetration. Initial experimentation has shown that depths of up to 60 m are achievable with traditional GPR systems, albeit significant limitation of impractical equipment sizes.

The main objective for most geophysical applications in mineral sand deposits is to image the base of the sand body, which generally defines the lower limit of mining. In the Richards Bay Minerals (RBM) mining area, the base of the mineable Sibayi Formation dunes sand is primarily a thick clay horizon comprising Kosi Bay Formation weathered aeolian sands underlain by the Port Durnford Formation estuarine sediments of middle to late Pleistocene age (Maud and Botha, 2000). In most environments, sands overlying a clay layer would pose an ideal environment for GPR. This has been demonstrated through the GPR profiling complex dune forms in the Maputaland coastal plain area to the north (Botha *et al.*, 2003). However, at RBM, the sediment conductivity close to the marine environment and depth requirements of the deposits have proved to be well beyond the practical limitations of traditional GPR systems.

Resource evaluations of heavy mineral deposits include parameters that consider the thickness, grade and chemistry variations in the sand body. In tabular deposits such as heavy mineral orebodies, reliable resource estimation depends on reliable thickness estimates. This is particularly the case when the thickness of the deposit is more spatially variable than the grade.

The ability of GPR rapidly to determine both the base of the profile and well as interstitial depositional morphology is of significant value to exploration and resource geologists as it addresses issues related to complex geological conditions as well as variations in profile thickness. In particular, the latter restricts even tightly spaced infill drilling campaigns from converging on a stable volume estimate.

Sonic drilling

From the initial discovery of the economic minerals within the RBM lease area, the traditional means of reverse circulation (RC) drilling has been the preferred method to analyse geologically the orebody—from lithological characteristics to grade determination. Though this method has guided mining for many years, in 2002 RBM had a goal of achieving a representative undisturbed sample that will aid in mitigation of orebody grade uncertainty, thereby eliminating the currently used upgrade factor. An added spin-off would be understanding the orebody geology from first principles. After careful investigation it was determined that the use of sonic drilling could provide RBM with the tool to reach this goal.

The sonic system utilizes high-frequency resonance that creates a frictionless environment immediately around the drill string, and the resonant energy displaces sands and gravel, shears clay, and fractures boulders. The sonic drilling advanced quickly and obtained high quality continuous core samples subject to precise control from the drilling technician. The system has provided more precise grade information on the orebody in comparison to the existing reverse circulation drilling samples. In addition, the sonic drilling system was able to penetrate through the mineral base and identify the higher grade zone associated with this basal horizon. The existing reverse circulation geological system often failed to identify correctly the mineral base, resulting in lost opportunity in terms of orebody. Sonic drilling provided the representative samples, which indicated the RC drilling has underestimated grade. This is crucial information because it explains the variations in actual grades vs. predicted grades that the mineral sand industry has lived with for many years.

Though the use of sonic drilling has in many ways revolutionized the way that RBM interprets its orebody in terms of both geology and grade determination, the variability of the orebody requires drilling, of both reverse circulation and sonic drilling at various grid spacing to ensure the integrity and reliability of the database for confident orebody resource and reserve calculations.

The detection of the mining base reliably by GPR, will allow for a possible increase in the current drill-hole spacing, permitting large cost savings. For example, if the drilling grid could be opened up from 50 metres to 200 metres, the number of drill holes required would be decreased by a factor of 16. The use of GPR to both map interstitial morphological units and to detect the base, can be used in conjunction with sonic drilling to derive a comprehensive database representative of the orebody with an economically viable technique. GPR is in no way a replacement technique to drilling but rather a complementary technique to drive down costs and rapidly to acquire pertinent data.

Preliminary studies with GPR at Richards Bay

Over the past two years, RBM has experimented with the use of GPR to provide information on profile thickness, thereby allowing the strategic placement of a fewer number of boreholes. The studies employed various commercially available GPR systems and produced data of varying suitability.

At the Zulti South deposit, where the profile thickness is known to be approximately 30 m as indicated by sonic drilling, GPR was able to image the base of the orebody in significant detail. The system used employed an impulse GPR system and 25 MHz antennas, towed behind a bulldozer and tracked by GPS (Figure 1).

The data produced, once corrected for topography generated by aerial photogrammetry, clearly showed the base of the sands, as well as significant detail of the various depositional sequences within the deposit (Figure 2). The surveys were limited to regions known to be less than 30 m thick as initial testing indicated this to be the practical limitation of the GPR configuration. As previously stated, lowering the transmitting frequency provides a deeper

Figure 1—Towed 25 MHz GPR system surveying at RBM

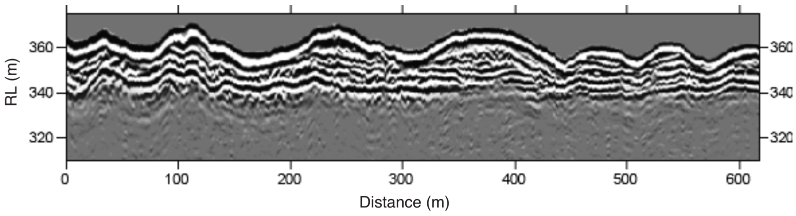

Figure 2—Sample 25 MHz GPR data corrected for topography showing base of sands and interstitial dune morphology

penetration range, at the cost of larger equipment. Initial experimentation with 12 MHz antennas proved to be impractical for the undulating dune environments found at the Richards Bay Mineral deposits. Nevertheless, data were recorded to depths approaching 60 m with these antennas. Various other systems and configurations were studied, including a newly developed towed antenna concept. In each case, the practical depth limitation appeared to be approximately 30 m.

Custom ultra-deep GPR system

Based on the encouraging data produced by the numerous GPR trials conducted by RBM, and the potential of GPR to reduce significantly exploration costs at heavy mineral deposits, it was determined that a custom GPR system be developed to meet the various requirements of the RBM mining environment, being; (1) increased penetration depths (~200m), (2) high resolution for morphological differentiation, and (3) robust design to be used practically in undulating dune environments.

The application required technology that, although theoretically possible, had not yet been built nor field tested. When one considers a GPR system for deep geological profiling, the most restrictive limitation is the high attenuation of the transmitted signal as it traverses the ground. This attenuation is proportional to depth and inversely proportional to frequency. The resultant low signal to noise ratio has traditionally been addressed using the concept of stacking. Stacking involves the repetitive firing of the transmitter at the same spot on the ground, thereby enhancing real reflections from geological interfaces and subduing background noise, which due to its random nature, cancels itself out.

A potential solution is to lower the frequency of the GPR antennas. RBM experimented with various antenna frequencies in an attempt to gain additional depth of penetration. However, the depth of penetration required for RBM's results in a frequency low enough, and thus antenna length long enough, to be impractical for use on dunes.

The approach to equipment design for a custom ultra-deep GPR system was to increase dramatically transmitter power. When considering the power of a GPR system, it is important to consider only the average power and not the peak power. The commercially available systems trialled by RBM have average transmitter powers on the range of 1 W. Using a spread spectrum technique and correlation pulse compression receiver, the custom ultra-deep GPR system has been accurately measured to output an average power of approximately 70 W.

In order to achieve resource modelling objectives, RBM required a GPR solution, which could reach up to 200 m in depth with a range resolution of ± 3 m. Assuming a radar energy velocity in RBM sands of 0.1 m/ns, this translates in a listening time for radar returns of 4000 ns. A range resolution of ± 3 m then translates to 60 ns. It was determined that 15 MHz antennas would offer the best compromise between depth of penetration and range resolution. A 15 MHz antenna corresponds to a period of 60 ns. In order to increase the average power, the pulse length was increased to eight cycles, as compared to a single impulse of commercially available systems. The drawback of this approach is that the transmitted signal completely obliterates the first 30 m of data in environments such as that found at RBM. After the initial eight cycles, the receiver initiates listening to the returned signals from the ground. The initial 30 m of profiling can be covered using commercially available GPR technology during a concurrent survey to provide complete profile imaging.

Figure 3—Prototype custom ultra-deep GPR system being trialled on RBM sands

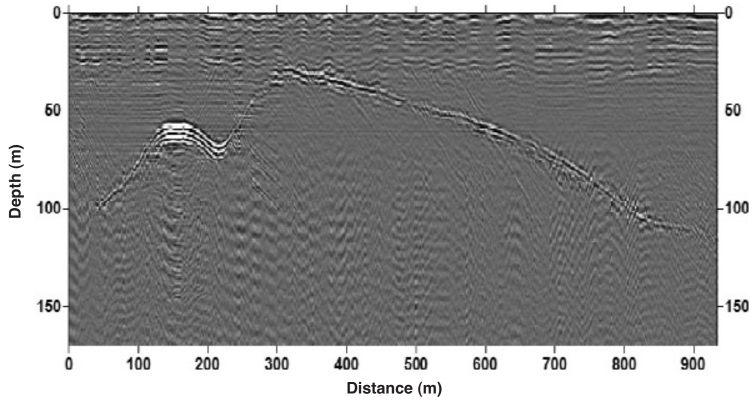

Figure 4—Data acquired using ultra-deep GPR at RBM

A novel approach to antenna design was also used, with a narrow transmission and received beam and thus more power in the downwards direction; the antennas consist of two element parallel arrays of resistively loaded dipoles. The receiving antennas are towed 15 m behind the transmitting antennas to reduce interference between the antennas. Figure 3 shows the custom GPR system.

The data acquired at RBM using the custom ultra-deep GPR system were of excellent quality, with the buried topography in the clayey sedimentary unit at the base of the mineralized sands clearly imaged to depths of over 120 m (Figure 4). Due to the power of the transmitters and the frequency of the antennas employed, the profile resolution was insufficient clearly to image the interstitial dune morphology. However, a fourfold increase in depth of penetration represents a revolution in near-surface geophysics for heavy mineral deposits. A final production version of the ultra-deep GPR is expected to be able to reach over 200 m through mineral sands deposits.

From the various trials conducted within the minerals sands environment at RBM, it is evident that manipulating the key parameters effecting GPR (power and frequency) both the desired depth of penetration and quality of resolution can be attained. Noting the variability of the RBM orebody, with respect to morphology and varying basal depths, it is apparent that a series of tests are to be conducted across the orebody to develop a GPR system that is robust enough to reach basal depths of ~200 m, and still yield resolution reflecting morphological changes.

Conclusion

If a robust GPR system can confidently image the erratic mining base across the RBM orebody, it will allow for an increase in the drill-hole spacing of both the sonic and reverse circulation drilling, thereby driving down the cost curve and build a comprehensive geological database that is both representative and valid.

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