Journal of Applied Geophysics 81 (2012) 29–37

Contents lists available at SciVerse ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

A review of selected ground penetrating radar applications to mineral resource evaluations

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ARTICLE INFO

Article history:
Received 17 October 2010
Accepted 9 September 2011
Available online 26 September 2011

Keywords:
Laterite
Bauxite
Iron ore
Kimberlite
Paleochannel
Mineral sand

ABSTRACT

Since the commercialisation of ground penetrating radar (GPR) in the 1970s, the technology has been relegated to niche applications in the mining industry. Advances in radar technology, such as flexible collinear antennas and the integration of live differential GPS positioning, have spurred GPR's acceptance in recent years as a standard exploration method for a number of deposit types. Provided herein is an overview of commercialised GPR applications for surface mineral resource evaluations, covering examples of alluvial channels, nickel and bauxitic laterites, iron ore deposits, mineral sands, coal and kimberlites.

1. Introduction

Three decades since the commercialisation of ground penetrating radar (GPR), the vast majority of radar instruments are now applied for civil infrastructure applications. Current instrument research is primarily focussed on technological advancements for this lucrative market, such as multi-channel arrays, rotating multi-polarised antennas and novel antennas designs. However, some of the first terrestrial uses for radar were for mineral exploration (Pittman et al., 1984), a niche application which in recent years has seen significant growth as the technique has gained acceptance in the mining industry.

In addition to the legislative restrictions on the low-frequency ultra-wide band GPR systems required for mining applications, the complexity of these geological environments and the geological expertise required to interpret often subtle textural variations in radar data often relegate the application to experienced users. Compared to the hundreds of published works on civil infrastructure and UXO applications each year, only a handful of papers have been written on surface mining applications for GPR (Davis and Annan, 1988; Davis et al., 1985; Francke and Yelf, 2003).

The surface mine resource applications for GPR addressed herein are not intended to be comprehensive, but address the most suitable environments which have been found for surface-based GPR. Not discussed herein are the myriad underground mining applications for GPR, such as measuring the thickness of hanging walls, nor the use of borehole radar for the mapping of fracture and ore zones, platinum reef potholes, pegmatites, *etc*.

2. GPR instrumentation

Mineral exploration applications of GPR often require the deepest penetration possible, whilst maintaining a sufficient degree of profile resolution to discern the strata of interest from the overburden and the underburden or bedrock. Penetration may be gained by lowering the antenna frequency and/or increasing the transmitted power. In most environments where radar has been shown to be a viable exploration tool, the high permittivity associated with a shallow water table or a high bound-water content in the clay mineralogy causes shorter wavelengths and high attenuation rates, thereby limiting gains in depth made with low-frequency antennas. High-voltage transmitters offer some increases in penetration, although most are limited in their pulse repetition frequency (PRF) to avoid circuit overloading (Langman and Inggs, 2001). Decreasing the PRF of a radar system somewhat offsets the benefits of an increased transmission power, mainly because radar traces cannot be recorded as rapidly, thereby reducing the increased signal-to-noise benefits of stacking.

Whilst novel electrically large antennas such as magnetic (Bellett and Leat, 2003) and Vivaldi designs have been discussed in literature, the lowest frequency commercially available shielded, broadside-oriented radar antennas are centred at 100 MHz. However, most mineral exploration applications require antenna centre frequencies in the range of 20–50 MHz. Such antennas are up to 8 m in width and therefore require extensive line clearing through vegetated areas (Arcone et al., 1998). Recent developments of collinear antenna configurations offer rapid

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0926-9851/$ – see front matter
doi:10.1016/j.jappgeo.2011.09.020

areal coverage with minimal line clearing, although their sub-optimal radiation patterns may result in data cluttered with above-ground reflections from trees, terrain or other spurious targets (Sun and Young, 1995). The integration of real-time GPS positioning for radar surveys using such towed antennas has dramatically increased the feasibility of large surveys.

Collinear, or in-line antenna systems, employ resistively loaded dipoles housed within a thin flexible hose as antennas. Receiver and transmitter electronics are contained within pods situated along the hose, whilst the radar control unit and recording computer are contained in a backpack. Recent systems weigh less than 5 kg and use wireless technology for communication between the receiver and recording computer (Fig. 1).

3. Mineral exploration and resource evaluations using GPR

Resource exploration and evaluation surveys involving GPR are generally conducted on large scales, often involving hundreds of hectares and dozens of line kilometres over difficult terrain in remote locations. Exploration projects in particular are often situated in densely vegetated areas through which cut lines must be established. Geologically, many sites consist of a conductive surficial weathering layer, beneath which the facies of interest may be located. In tropical regions, soils with high dielectric permittivities are often encountered due to a shallow water table and high rainfall.

In each case, factors such as high attenuation rates and scattering from partially weathered layers often restrict radar penetration. Conversely, sites are often located far from cultural noise sources and are of such large scale that profile resolution is not a priority in comparison to the ability to distinguish gross features, enabling the use of low-frequency antennas.

The objective of most GPR surveys for these applications is to provide horizon continuity between existing or planned boreholes. To ensure correlation between the interpreted GPR depths and drilling information, accurate radar velocities must be applied. Due to the profile length and depth scales involved, and the variability of various lithologies at each site, techniques such as common mid-point (CMP) surveys often only provide representative velocities for the shallowest horizon, and only at a specific location. Single radar profiles often span ridges and valleys, traversing sub-surface media with variable water contents, and thus dielectric permittivities. Dielectric permittivity meters with surface or short probe lengths are highly accurate at determining conductivities and permittivities at very shallow depths, which are often not representative of an entire profile due to variations in water saturation between the drier surficial soil and the vadose zone.

Over most profiles, reflection hyperbolae caused by partially weathered rocks, voids or other distinct anomalies may be used to calculate velocity distributions. In addition, any available co-located drilling information can be correlated to GPR depths to confirm the radar velocities calculated from the hyperbolic reflections. In each of the case examples which follow, radar velocities were calculated from a combination of borehole data and hyperbolic reflections.

4. Case examples

4.1. Aggregate and limestone quarrying

Sand and gravel deposits are numerous and consist of high-bulk and low-unit-value resources generally exploited near-urban areas. As transportation costs account for up to 60% of the delivered price, mine development is often sought in regions where land use competition is significant, frequently creating controversy over new projects (Poulin et al., 1994). In order to maximise the yield of a proposed aggregate mine whilst minimising its impact in near-urban locations, comprehensive resource evaluations are critical.

Whereas historically, test pitting was employed for cursory estimations, the restrictions imposed by modern mining legislation require more rigorous evaluations using boreholes. Drilling alone is inherently inferential and is often supplemented by electrical resistivity surveys which offer a low-resolution indication of lithologies and depth to bedrock. By definition, ideal aggregate resources are characterised by coarse gravels and have a low percentage of fines in their matrix. In the absence of saline groundwater or high levels of contaminants, these sites are often electrically resistive and are thus well suited to GPR.

Beyond its utility for general bedrock mapping and resource volume estimation, GPR can be employed to quantify the occurrence of uneconomic boulders and dykes, as well as groundwater tables. In aggregate mines, groundwater is commonly detectable in coarser-grained media where capillarity does not create a large gradational fringe at the base of the vadose zone. The groundwater table often defines the base of an economically extractable resource.

In the absence of conductive clays, the relative grain-size distribution of sands and gravels may be discernible. Interpretability of radar profiles from aggregate deposits may be enhanced through post-processing using image analysis. By mapping each radar sample point on each trace to a corresponding 8-bit grey scale pixel, image-processing software may be employed to consistently highlight the subtle variations in radar reflection textures which often differentiate gravels from sands. Spatial and fractal variance algorithms are often useful in converting gross textural variations to grey scale brightness differences (Francke, 2007a).

The example in Fig. 2 shows a topographically corrected radar profile acquired with 50 MHz collinear antennas at 50-cm trace intervals over a sand and gravel deposit. The processing included the removal of low-frequency "wow" effects, AGC gaining, migration and a

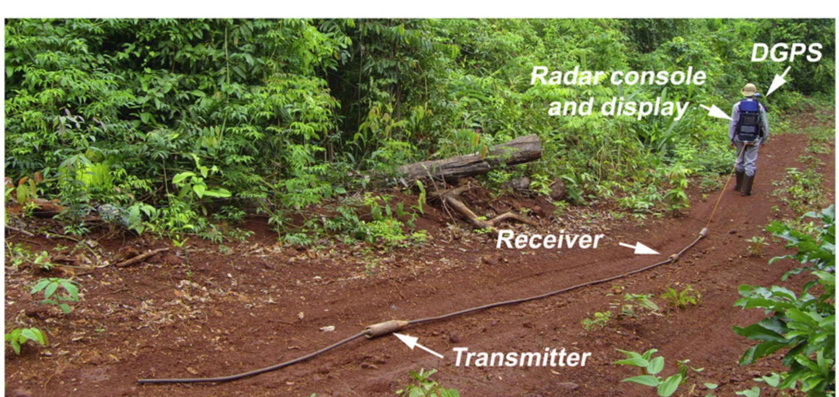

Fig. 1. 40 MHz towed GPR system with collinear antennas housed in flexible hose. The backpack contains a radar control unit and a DGPS receiver as well as the radar display.