Advances in long-range GPR systems and their applications to mineral exploration, geotechnical and static correction problems

Jan Francke[1] and Vincent Utsi[2] provide an overview of developments in GPR with the emphasis on the potential for acquiring data from deeper targets thanks to the penetration range possible deploying the latest technology.

The proliferation of ground penetrating radar (GPR) technology in the civil infrastructure sector over the last two decades has focused research efforts towards more advanced high-resolution shallow 3D-capable instruments. Conversely, geological applications, in particular resource exploration, have been limited due to a lack of development of portable long-range GPR systems caused by the absence of a sufficient market and regulatory restrictions on high-powered GPR instruments. However, new technologies are being developed which extend the penetration range of GPR as well as address the logistical restrictions imposed by conventional radar instruments.

This paper examines the principles of GPR in its application to mining exploration, the limitations imposed by current technology, and the development of deep penetration radar instruments. Examples of applications to alluvial gold and diamond exploration, lateritic weathering sequence profiling, abandoned workings detection and long-range sand dune imaging for seismic static corrections, and reservoir analogy studies are provided. New instrumentation has significantly improved the ability to rapidly collect deep GPR data in a variety of environments, thereby expanding the capabilities of the geophysicist's toolbox.

GPR principles

The foundations of GPR are based on EM theory. Maxwell's equations mathematically describe the physics of EM wave propagation as a coupled, three-dimensional polarized vector wave field. At the frequencies employed by GPR systems, the energy storage in dielectric and magnetic polarization generates wave propagation. When these waves are propagated through geological media, they travel at velocities lower than the speed of light and are scattered by variations in the electrical and magnetic properties of the subsurface.

In general, geological materials are considered to be semiconductors, or dielectrics, and can be characterized by three electromagnetic properties: electrical conductivity, electrical permittivity, and magnetic permeability.

Electrical conductivity, σ, is the measure of a material's ability to transmit a DC current, which results in energy dissipation through the conversion of electrical energy to heat. Dielectric permittivity, ε, refers to the degree to which a geological medium resists the flow of electrical charge divided by the degree to which free spaces resists the same charge. The dielectric permittivity is thus defined as the ratio of the electric displacement to the electric field strength, and is an important quantity for GPR. Most often, the term dielectric constant is used, which is the ratio of $\varepsilon/\varepsilon_o$, where ε_o is the permittivity of a vacuum. The velocity of an electromagnetic wave propagating through a medium is thus the reciprocal of the square-root of the medium's dielectric constant.

Magnetic permeability, μ, is the result of electron spin and motion in atomic orbits and also results in energy loss and storage. In most geologic environments, the effect of magnetic permeability is negligible and is often excluded from calculations.

The basis for quantitatively describing GPR signals may be found by combining the physics of EM wave propagation with the material properties of the media. GPR is most effective in regions of low electrical loss media. If $\sigma = 0$ for the ground, GPR would be able to image targets and horizons at great depths, limited only by the power of the radar transmitter and the sensitivity of the radar receiver. However, soils and rocks are not perfect insulators and their semi-conductive nature is highly variable. Clay-rich minerals and regions of saline groundwater are examples of highly conductive media through which GPR would only be effective to depths of less than a few metres, regardless of the transmitter power or the sensitivity of the receiver. Furthermore, earth materials are nearly always composites of many constituent minerals or components, each with its own electrical properties.

[1] *International Groundradar Consulting, 4389 Osler Street, Vancouver, BC, V6H 2X6 Canada.*
E-mail: jfrancke@groundradar.com
[2] *Utsi Electronics, Newton Road, Harston, Cambridge, CB22 7NZ, UK.*
E-mail: vincent.utsi@utsielectronics.co.uk

In the EM frequency range employed by low-frequency GPR (10 MHz–100 MHz), the concentration of both pore and bound water dominates the GPR response (Davis and Annan 1989). In general, bulk minerals are good insulators (0.00001–1 mS/m) and have low dielectric constants in the range of 3–15. Sands and soils have pore spaces filled with air, water, and other minerals. The water contained in the pore space of soils and sands usually contains ions from dissolved minerals, with the ionic mobility within the water being the dominant contributor to bulk electrical conductivity. It is thus generally the presence of ions in the water which causes the semi-conductor nature of soils and sands, which have bulk conductivities in the range of 1–1000 mS/m (Cassidy 2009).

Maximum GPR range

Four factors determine the maximum effective depth of penetration achievable by a given GPR system in a given environment: the number and complexity of interfaces which generate scattering (i.e. geological features), the dielectric contrasts between adjacent interfaces, the degree of signal attenuation within each horizon, and the transmitting frequency of the GPR antennas. As a wave field encounters a discontinuity in dielectric permittivities in the subsurface, a portion of the energy is returned to the surface, and the remainder continues to further depths. As the number of interfaces the wave field encounters increases, the portion of the energy which is reflected back to the surface decreases, as does the portion of energy transmitted through each successive layer. This is known as target reflection loss or scattering loss.

The electrical conductivity of the media being imaged leads to material losses, which have a large effect on the maximum effective depth of penetration. With increasing conductivity, the energy emitted by the GPR antennas is dissipated to greater degrees than in more resistive environments. Thus, in highly conductive geology such as wet clays, GPR energy is dissipated very quickly, whereas in sands, which are generally electrically resistive, GPR can be used to profile dozens of metres in depth (Noon et al., 1998).

A final type of loss is due to geometric spreading of the emitted radar energy. Although difficult to quantify in complex geologies, these losses are exponentially proportional to the depth being imaged.

The maximum depth of a GPR system may be estimated by summing these losses along with those encountered within the instrumentation. However, not all GPR configurations result in similar losses. The rate of energy dissipation in a geological medium is also dependent on the frequency of the imparted GPR signals. With lower frequency antennas, such as 12.5 MHz or 25 MHz, the wavelength is longer, resulting in less attenuation due to electrical conductivity losses and less scattering from chaotic reflections caused by small clutter. The disadvantage to lower frequency antennas is that the radar energy wavelength is increased, thereby reducing the resultant profile resolution. By lowering the antenna frequency to gain additional range, fine detail in the profile is obscured or eliminated entirely.

However, the maximum range of a GPR system may be improved without significant loss of resolution by altering various instrumentation parameters and configurations. The performance of a radar system is generally rated in terms of an instrument's dynamic range, measured in dB. One method of improving the performance of an impulse radar is by increasing the transmitter power. Transmission power is often expressed in terms of peak voltage input to the antenna terminals. The peak power is calculated as logarithmically proportional to the transmission impulse voltage, which is often 300–500 V (Jol, 1995). Thus, in order to double the penetration, an increase of 30 dB in system performance would be required, which in turn would require 32 times the peak transmission voltage. Generating many of kV in a highly portable instrument suitable for rough terrain is not practical. Some configurations are available with peak transmission voltages of up to 5 kV, although their pulse repetition frequencies (PRFs) have been lowered considerably to mitigate component saturation issues.

Increasing the PRF of a GPR presents an alternative approach to increasing penetration. To increase the signal-to-noise (SNR) of a radar system by 30 dB would require 1000 stacks. All commercial low-frequency GPR systems employ sequential sampling receivers. With a PRF of 100 kHz for most sequential sampling GPR systems and a typical waveform sampled by 256 points, 1000 stacks would require 256,000 individual pulses of the transmitter, which would require 2.5 s. For geological surveys requiring steps intervals every 0.5 m, such a delay is not feasible at each station. In practice, stacking is often limited to 32 or 64 times due to the limitations of sequential time sampling.

With sequential time sampling, single successive samples are made after each transmitted pulse. Thus, to reconstruct a single stacked radar trace of 256 points, the transmitter is activated 256 times. A trace consisting of 64 stacks would require over 16,000 repeated transmit pulses whilst the antennas are stationary.

In recent years, high-speed analogue-to-digital (ADC) chips have become available, with sampling speeds of up to 1600 million samples per second. Such technology enables the design of real-time sampling GPR systems, which permits the entire transmitted waveform to be captured simultaneously, thereby dramatically increasing the practical number of stacks possible (Johnsson and Björklund, 2005). Rather than being limited to 32 or 64 stacks, these systems can acquire 10,000 stacks, thereby providing an additional 40 dB of dynamic range.

Figure 1 *Commercial GPR system with 25 MHz antennas.*

Figure 2 *Newly developed wireless real-time sampling GPR system.*

No significant development has been made to low-frequency commercial GPR systems since 1994 due to a lack of market demand and regulatory restrictions on high-powered UWB radar technology (Annan, 2002). A significant drawback to the widespread use of existing GPR technology for geological applications has been their cumbersome antennas and control units, reliance on fibre optic cables, and their susceptibility to damage in rugged or humid conditions. Traditional low-frequency GPR instruments (Figure 1) require cut-lines through vegetated areas up to 6 m wide, vehicle batteries for power and a laptop for data viewing and storage.

Newly developed systems have overcome these limitations by orienting the antennas in an in-line configuration (Figure 2). Fragile fibre optic cables have been replaced by Bluetooth links, control units have been eliminated, and laptops have been replaced by PocketPCs or mobile phones for data acquisition and storage. In addition, these new real-time sampling systems have been designed to be waterproof and draw minimal power, allowing continuous operation for days from a single change.

Although the greater dynamic range offered by these real-time sampling GPR instruments cannot circumvent the governing EM propagation principles of radar in highly conductive media, it can offer dramatic penetration improvements over conventional systems in media where the limitation in range is the noise floor. Their rugged design has greatly increased the viability of large-scale radar surveys over previously unsuitable terrain.

Laterite and Bauxite resource definitions

A demanding application for GPR is that presented by tropical weathering environments. In both lateritic and bauxitic deposits, the need for accurate resource definition prior to mining is paramount. The primary objective of geophysical surveying in lateritic or bauxitic environments is to image the various weathering horizons in high resolution. Traditionally, this process has been speculative in nature, as the variability of layer thicknesses between even closely-spaced boreholes can be extreme.

Although laterites generally contain a high clay fraction, GPR has proven effective at imaging partially-weathered rocks and the underlying parent bedrock to depths of over 30 m (Francke and Nobes, 2000). However, recent exploration programmes have focused on deposits which require deeper imaging (Francke 2007).

Figure 3 compares a profile acquired using a standard GPR instrument at a laterite project in Southeast Asia to the same profile collected using a real-time sampling GPR. The two profiles have been processed using the same parameters to enhance the detection of a rocky saprolite layer. As both systems employed 50 MHz centre-frequency antennas, the resolution of the profiles is similar, although penetration achieved by real-time sampling GPR is significantly deeper. In addition, the commercial GPR system required 4 m wide cutlines though the jungle and over an hour to acquire, whereas the real-time sampling GPR required only a trail and less than 20 minutes over the rough terrain (Figure 4).

Using newly developed GPR systems, laterite deposits have been imaged to depths in excess of 80 m with excellent correlation to boreholes. The use of GPR in laterite and bauxite resource evaluations greatly reduces the cost of drilling with saturation coverage, allowing a fewer number of holes to be strategically placed in the most promising zones. Figure 5 shows isopach maps of depth to bedrock at a laterite project based on drilling at 100 m X 100 m alone, compared to GPR results. Although drilling is irreplaceable due to the need for grade control, GPR often achieves a more detailed definition of the bedrock topography.

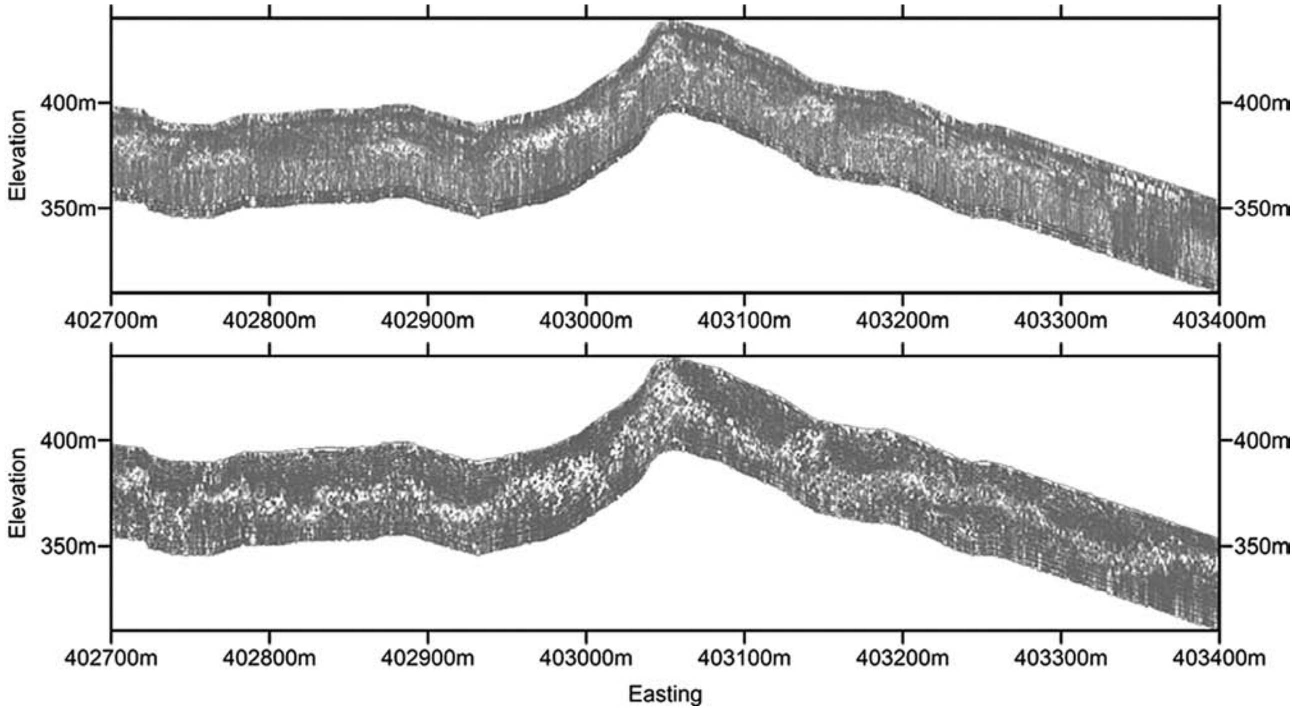

Figure 3 *Comparison of saprolite horizon as imaged by commercial GPR (top) and real-time sampling GPR (bottom).*

Figure 4 *New GPR systems are able to rapidly survey the most extreme terrain.*

Paleochannel delineation

Placer deposits occur in fluvial environments where precious metals or gemstones have been eroded or weathered from primary sources, transported and re-deposited amongst sands and gravels within active water courses or paleochannels. An understanding of the complex subsurface geology of the paleofluvial environment is critical to resource exploration, project economics, as well as mine engineering. Of primary importance is information related to bedrock topography and grain-size distribution within the fluvial facies.

Traditionally, boreholes or trenches are placed at intervals across a known or suspected paleochannel in order to map bedrock topography and fluvial lithology. However, these techniques are costly and often produce results which are unrepresentative of the true complexity of a deposit. In order to mitigate these drawbacks of traditional exploration, geophysical techniques are increasingly employed to provide a focused approach to excavations and drilling. Techniques such as refraction seismic, electrical imaging, or electromagnetic surveying suffer from either inadequate resolution or high costs, whereas GPR has been applied with some success.

Although the largest concentration of heavy minerals and gemstones are generally found along the base of the incision amongst course-grained aggregates, the overlying sediments are commonly fine-grained silts and clays. As such, traditional GPR instruments have been limited to

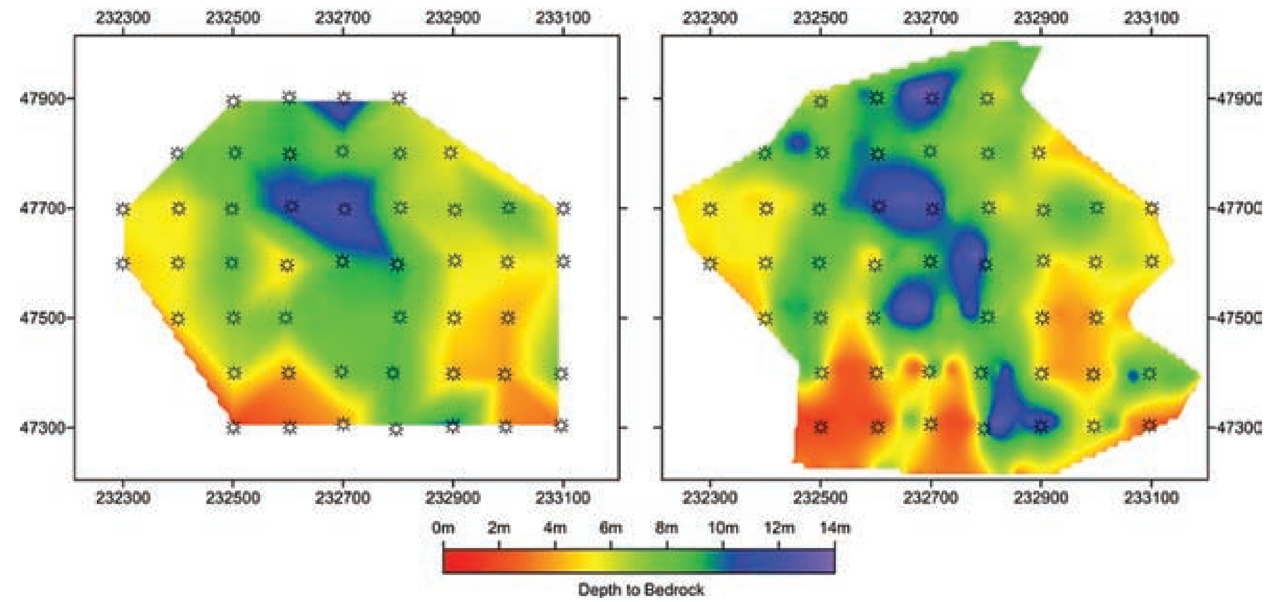

Figure 5 *Comparison of isopach map of depth to bedrock beneath a lateritic weathering environment generated by drilling along (left) and by GPR (right). Note the GPR data correlates well with the drilling depths but provides significantly more detail between holes.*

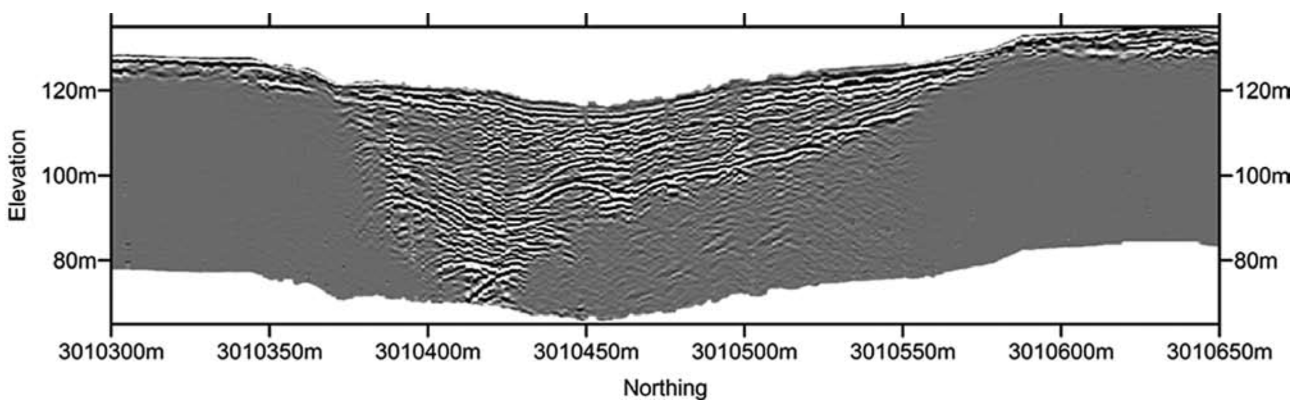

Figure 6 *Data acquired over a paleochannel using a newly developed GPR system showing penetration to 40 m.*

imaging depths of less than 10–15 m at most deposits (Francke and Yelf, 2003).

Newly developed GPR systems offer significant advantages for placer exploration. Their in-line wireless design allows large areas to be surveyed rapidly, and real-time sampling achieves deeper penetration than traditional radar instruments. Figure 6 shows a paleochannel detected by real-time sampling GPR at a diamond project in West Africa. The project site consists of clays and silts underlain by gravels, with cobbles lining the incised bedrock surface. The bedrock topography is well imaged, showing the paleothalweg to be situated at approximately position 3010425N.

Iron ore deposits

Although often relatively resistive, iron ore deposits are often problematic for traditional geophysics due to the presence of heterogeneous ground conditions with friable layers and significant lateral variations in ore thickness (Butt and Flis, 1997). Commercial GPR systems have been limited to penetrations of at most 30 m, requiring 6 m wide cutlines. Conversely, newly developed radar instruments have been able to image friable and non-friable zones, as well as the depth to bedrock to over 60 m using existing walking trails at deposits in South America (Figure 7). In addition to the increased depth range, the resolution achieved has enabled advanced image analysis tools to be applied to the datasets to identify friable ore as shown in Figure 8 (Francke, 2007a).

Abandoned tunnel detection

Open pit mines are often faced with the challenge of mapping abandoned historical underground workings ahead

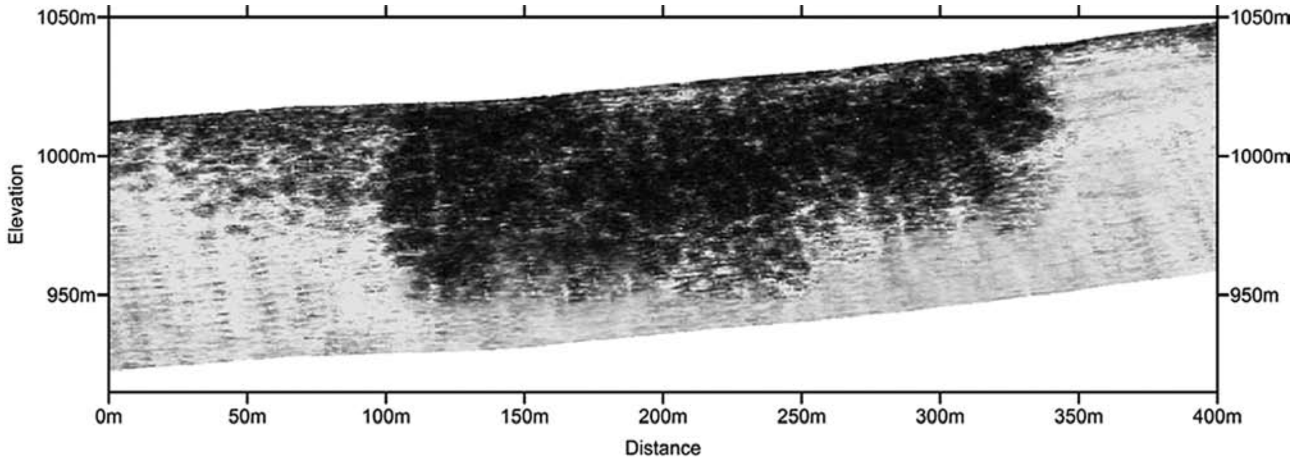

Figure 7 *Profile showing the thickness of iron ore (dark region) generated with newly developed GPR.*

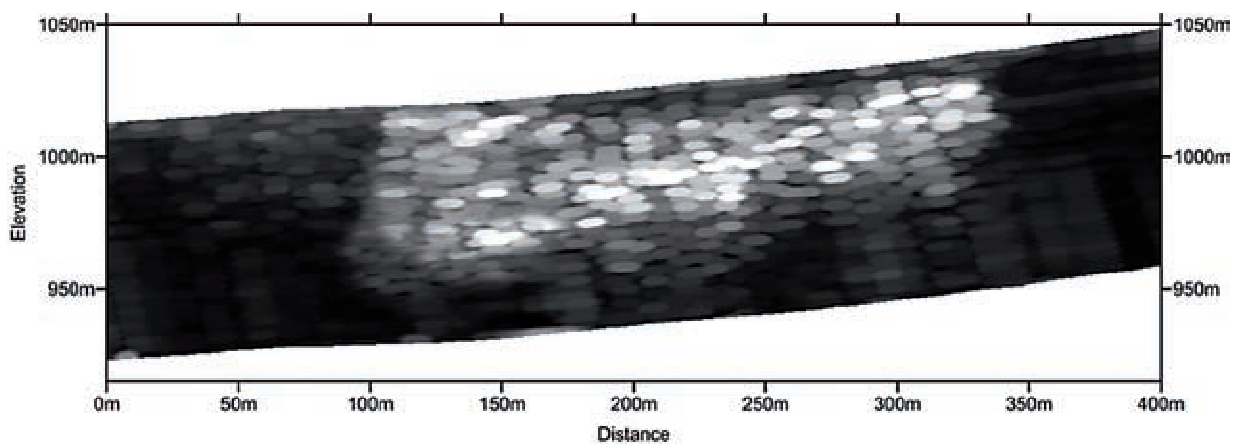

Figure 8 *The application of image textural analysis enhances the differentiation of friable and non-friable zones.*

of their operations. Microgravity, resistivity imaging, and fixed-frequency EM geophysical approaches have seen limited operational success due to the high cost of surveying and the lack of target resolution. As the ore deposits are frequently situated within resistive crystalline bedrock, GPR has been trialled at numerous pits worldwide over the last two decades with promising results (Fenner, 1995). Target detectability has generally been limited to depths less than that of the next bench and the instrumentation has required a smooth operating surface. Although the degree of success depends on the target geometry and the proximity to above-ground reflecting surfaces which often produce interference patterns superimposed on the data, new real-time GPR systems have produced deeper images of tunnels than were previously possible. Figure 9 shows a profile over a series of coal seams in East Asia which contain known voids.

Seismic static corrections and reservoir analogy models

Although GPR has long-produced exemplary results from sand dunes across the globe (Bristow et al., 2000), in practice traditional GPR technology suffers from a number of drawbacks which limit its effectiveness. GPR resolution is proportional to the frequency of the antennas and inversely proportional to the depth of penetration. Ideally, a survey will employ the highest frequency antennas which attain the required penetration. In recent years, researchers have experimented with its use to assist with constructing reservoir analogies by imaging contemporary dunes (Adetunji et al., 2008). However, GPR's range-resolution trade-off has limited penetration to less than 30 m over most dunes.

On-going research with real-time sampling GPR systems has produced significant improvements in depth range without lowering antenna frequencies. Figure 10 shows a

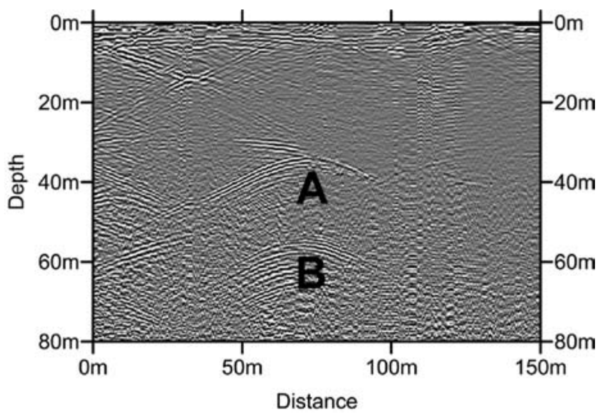

Figure 9 *Example of long-range imaging of voids in coal strata (A and B). Other layered reflections below 30 m are coal strata whereas those above 20 m are due to above-ground reflections.*

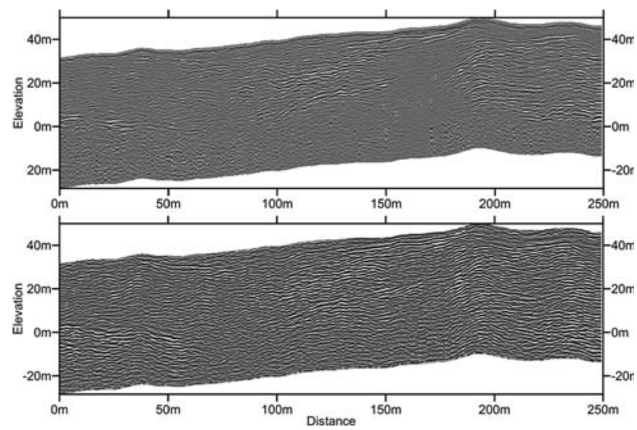

Figure 10 *Comparison of commercial GPR with 50 MHz antennas (top) to newly developed GPR (bottom) over silica-rich sand dunes.*

comparison between a GPR profile acquired using a traditional GPR system and a profile acquired with a real-time sampling system over a sand dune in Australia. In addition to the deeper range of imaging, the in-line configurations of these new GPR systems enable the rapid creation of 3D assemblages of dunes by towing the instruments at up to 30 km/hr.

Figure 11 shows a profile from North Africa, highlighting the potential of new GPR technology in constructing 3D models of internal dune structures for reservoir analogies. The goal of a current research project is to assemble a catalogue of 3D models of various dune stratigraphies using this new long-range GPR

With a compromise of resolution, the quest to image the base of high dunes for static corrections is being pursued through the use of high-power pulse-compression GPR technology. A transmitter has been designed whereby the transmit pulse is a burst of a direct sequence spread spectrum code with a chip rate the same as the carrier frequency. An FET amplifier gives a peak transmit power of 2 kW, with an average power of 70 W. The receiver is a real-time digitizing ADC with a FPGA for pulse code compression and stacking to achieve 120 dB of dynamic range (Utsi, 2007).

Figure 12 shows the results of this pulse-compression GPR from a sand dune in Southern Africa. Although the 15 MHz antennas offer insufficient resolution to image dune stratigraphy, the undulating base of the dune is imaged to over 90 m (Singh, 2007). Such technology holds potential for rapidly mapping the thickness of low velocity zones over desert dunes at low cost.

Mine waste dumps

A pulse compression GPR has been used to image depths of over 100 m through a mine waste dump in Central Asia. The waste rock matrix, consisting of 60% schists, 20% interstitial clays and up to 20% air, was up to 150 m thick. Underlying this unit was a clay-rich glacial moraine, which varied in thickness from 10–90 m (Francke and Utsi, 2008). During initial field testing above-ground reflectors were detected from as far away as 500 m. Although this level of sensitivity is critical in designing a radar system for achieving deep penetration, mine sites are rife with sources of such reflections, ranging from large moving machinery to power lines and the flat walls of the open pit benches. In order to minimize this interference, two large screen cages were built around the transmitter and receiver antennas (Figure 13).

The data were analysed using image processing techniques, including a spatial textural analysis. In most GPR profiles where the imaging of geological structure is the primary objective, horizons are often more discernable based on textural variations rather than reflection amplitude changes. Figure 14 shows the result of this processing, revealing the base of the waste rock material to depths of over 100 m. Although this type of radar is impractical for most applications, this example clearly demonstrates that given suitable ground conditions, sufficient power and the use of new GPR system designs, significant imaging depths are possible.

Conclusions

Although the vast majority of the hundreds of GPR systems sold worldwide each year are employed for civil infrastructure applications, a growing market exists for the use of GPR in the mining, geotechnical, and hydrocarbon exploration sectors. Since the commercialization of the technology, low-frequency GPR systems have relied on impulse transmitters with sequential sampling receivers, limiting their SNR-enhancing stacking to 32 or 64 times. Their often unwieldy design and reliance on fragile fibre optics and laptop computers have limited their practical applications to surveys of restricted spatial extents and depths.

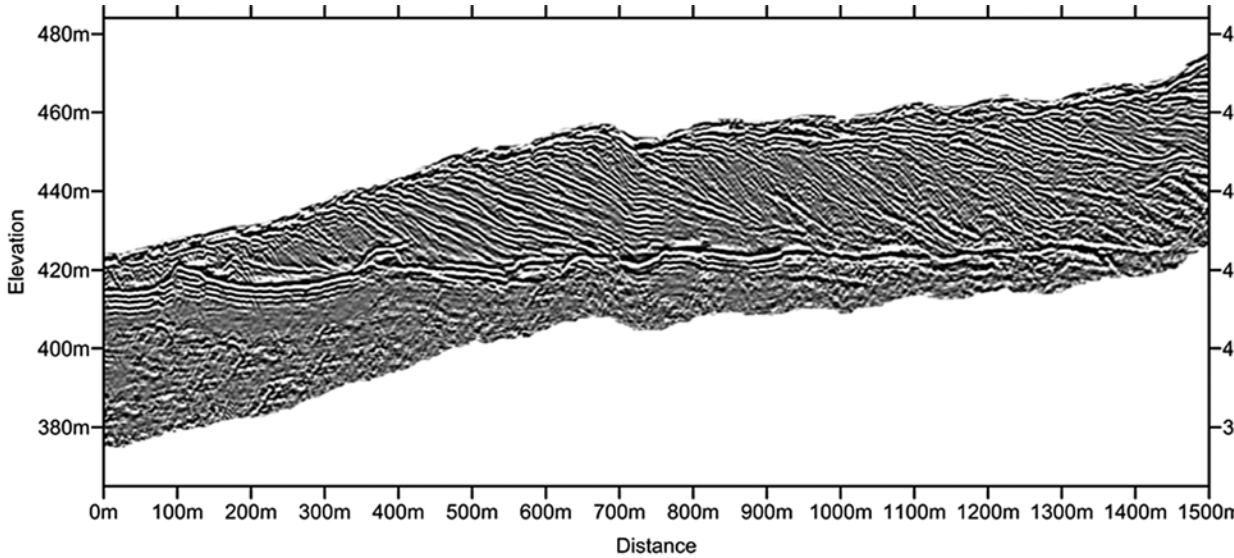

Figure 11 *Modern GPR systems may be towed over sand dunes at high speed, producing high-resolution images of dune stratigraphic.*

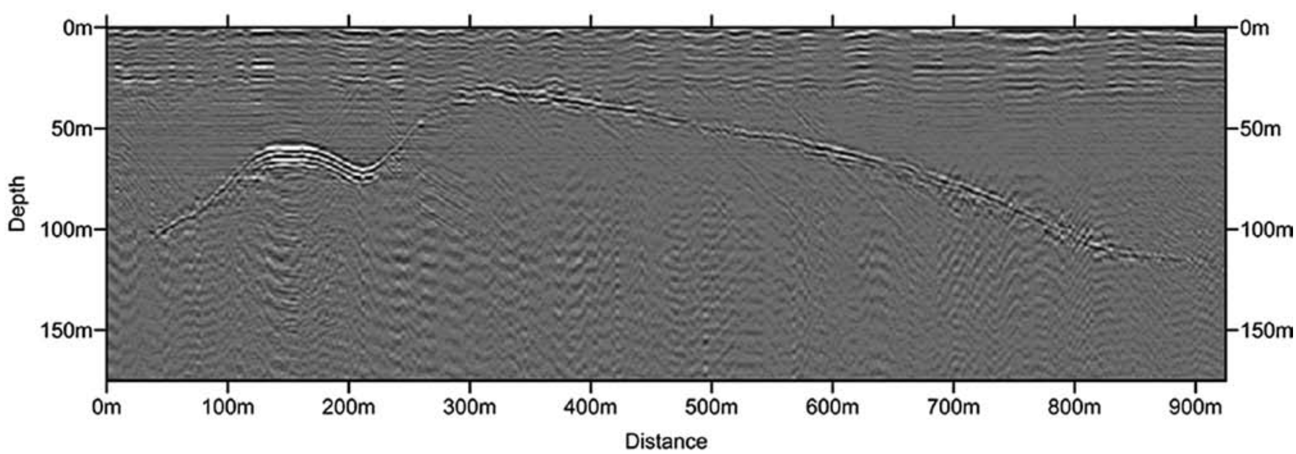

Figure 12 *Example of data acquired with pulse-compression GPR showing base of sands to depths of over 100 m.*

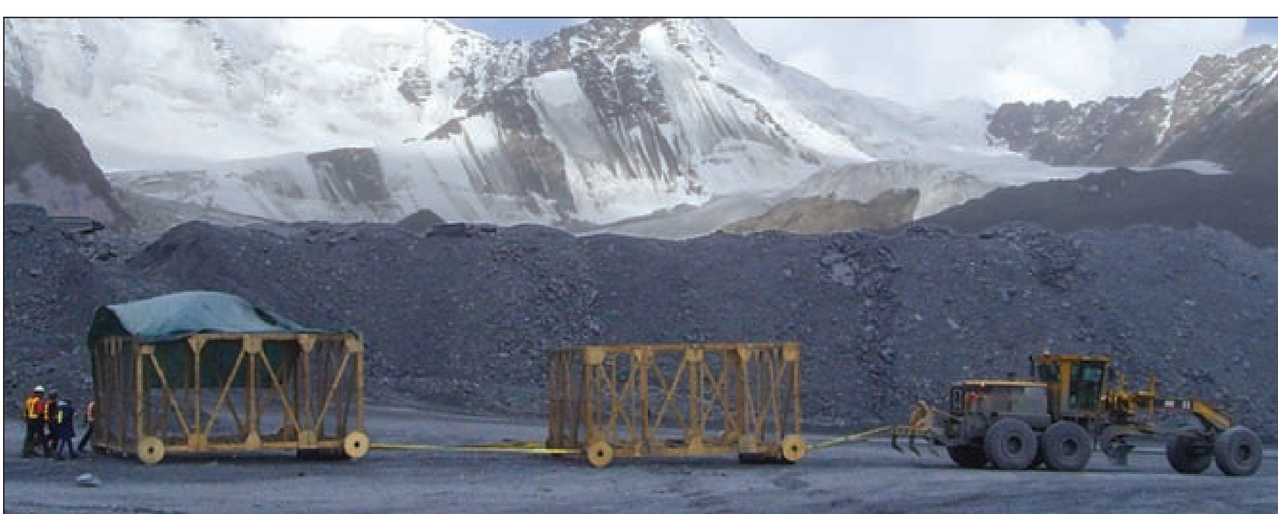

Figure 13 *What are believed to be the largest mobile shielded GPR antennas built surveying a mine waste dump.*

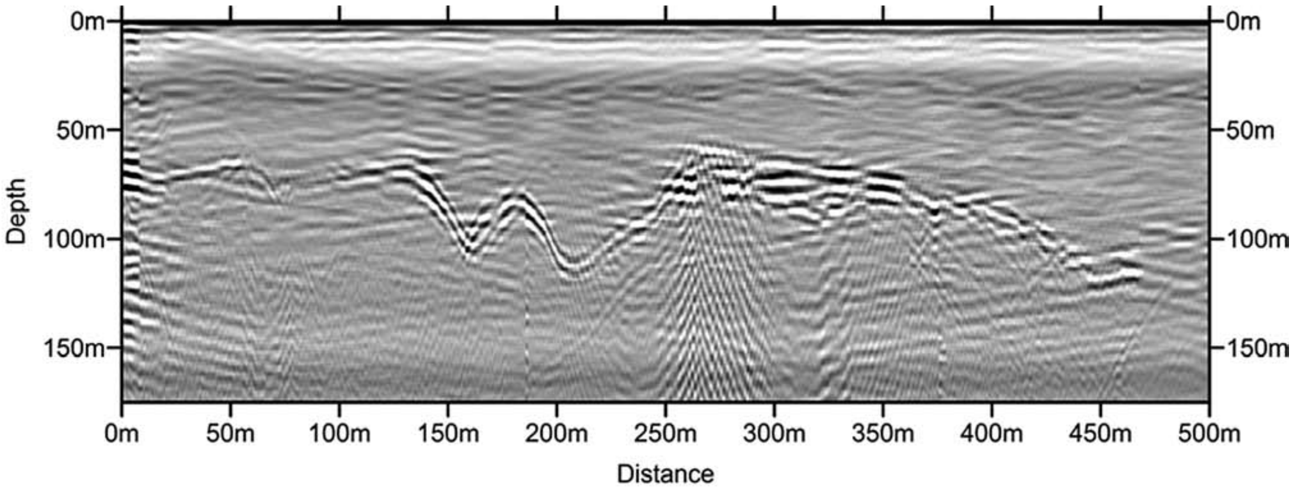

Figure 14 *Image processing revealed the base of the waste dump to depths approaching 130 m.*

Newly developed GPR systems employing real-time sampling and pulse compression technology have been shown to significantly improve the depths of penetration possible with radar in suitable geologies. Furthermore, these systems have overcome the practical limitations of traditional GPR systems by employing wireless technology, long-lasting power sources, and PocketPCs for data display and storage. These systems have the potential to dramatically increase the myriad of applications for which GPR has been found suitable.

References

Adetunji, A.Q., Al-Shuhail, A. and Korvin, G. [2008] Mapping the internal structure of sand dunes with GPR: A case history from the Jafurah sand sea of eastern Saudi Arabia. *The Leading Edge*, **27**(11), 1146-1452.

Annan, A.P. [2002] GPR - history, trends, and future developments. *Subsurface Sensing Technologies and Applications*, **3**(4), 253-270.

Bristow, C.S., Bailey, S.D. and Lancaster, N. [2000] The sedimentary structure of linear sand dunes. *Nature*, **406**, 56-59.

Butt, A.L. and Flis, M.F. [1997] The application of geophysics to iron ore mining in the Hamersley Basin, Western Australia. *Exploration Geophysics*, **28**, 195-198.

Cassidy, N.J. [2009] Electrical and magnetic properties of rocks, soils and fluids. In: Jol, H.M. (Ed) *Ground Penetrating Radar: Theory and Applications*. Elsevier Science, Amsterdam, 41-72.

Davis, J.L. and Annan, A.P. [1989] Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy. *Geophysical Prospecting*, **37**(5), 531-551.

Fenner, T. [1995] Ground penetrating radar for identification of mine tunnels and abandoned mine stopes. *SME Transactions*, **298**, 85-90.

Francke, J. [2007] Laterite resource definition cost reduction through high-resolution ground penetrating radar. In: Geociencias2007: *III Simposio Sobre Geología, Exploración y Explotación de Lateritas Niquelíferas,* Sociedad Cubana de Geología, Havana, 435–449.

Francke, J. [2007a] The application of image processing and analysis algorithms to complex GPR datasets. *Symposium on the Application of Geophysics to Engineering and Environmental Problems*, Curran Associates, Denver, 1220 -1228.

Francke, J. and Nobes, D. [2000] Preliminary evaluation of GPR for nickel laterite exploration. In: Noon, D.A., Stickley, G.F., and Longstaff, D. (Eds) *GPR 2000: Proceedings of the 8th International Conference on Ground Penetrating Radar,* Society of Photo-Optical Instrumentation Engineers, Bellingham, 7-12.

Francke, J. and Utsi, V. [2008] Ultra long-range radar imaging of a mine waste dump. *GPR 2000: 12th International Conference on Ground Penetrating Radar,* University of Birmingham, Birmingham.

Francke, J., and Yelf, R. [2003] Applications of GPR for surface mining. In: Yarovoy, A (Ed) *2nd International Workshop on Advanced Ground Penetrating Radar,* Delft University of Technology, Delft, 115-119.

Johnsson, T. and Björklund, N. [2005] Real-time sampling of ground penetrating radar and related processing. M.Sc. Thesis, Luleå University of Technology.

Jol, H.M. [1995] Ground penetrating radar antennae frequencies and transmitter powers compared for penetration depth, resolution and reflection continuity. *Geophysical Prospecting*, **43**(5), 693-709.

Noon, D.A., Stickley, G.F. and Longstaff, D. [1998] A frequency-independent characterisation of GPR penetration and resolution performance. *Journal of Applied Geophysics*, **40**(1-3), 127-137.

Singh, N.K. [2007] Ground penetrating radar (GPR) 'Mineral base profiling and orebody optimization'. *Back to Basics 6th International Heavy Minerals Conference,* Southern African Institute of Mining and Metallurgy, Johannesburg, 179-182.

Utsi, V. [2007] Design of a GPR for deep investigations. *4th International Workshop on Advanced Ground Penetrating Radar,* IEEE Computer Society Press, Washington, 222-225.