GROUND PENETRATING RADAR—COMING OF AGE AT LAST!!

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ABSTRACT

Ground penetrating radar (GPR) has been around for approaching three decades. As with all geophysical techniques, a substantial amount of time must pass before an understanding of the method and its benefits are appreciated in a broad user community. Over the last few years there has been a surge of interest in GPR with the range of applications expanding greatly.

We have a much better understanding of the geological settings in which GPR is effective. Not only do we understand the fine scale geological texture better than we ever did before, we also have attained a good understanding of the physical properties which control the penetration and reflection of radio waves.

Instrumentation developments have surged ahead. Radar systems with higher power, and high quality digital data recording capability have appeared. Furthermore, the microcomputer revolution has opened the door to enhanced digital data processing and presentation impossible just a few years ago.

The evolution of quantitative interpretation tools for GPR is just beginning. With the advent of computer graphics and 3-D visualization on affordable platforms, GPR processing is becoming widespread, inducing major changes in the state-of-the-practice.

GPR has come of age in the last decade. While the technique is still not fool proof and much is still to be learned, GPR is now a recognized weapon in the geophysical arsenal. In favourable geologic settings, GPR is unparalleled in the wealth of detailed information it can provide.

INTRODUCTION

Ground penetrating radar is one of the newer geophysical methods. By exploiting the wave propagation characteristics of electromagnetic fields, GPR provides a very high resolution sub-surface mapping method. In many respects GPR is the electromagnetic counterpart of seismic reflection.

In the exploration context, GPR has limited exploration depths, so it is not necessarily a tool for all applications. GPR is most effective in electrically resistive environments where very detailed information is desired. Applications in the mining exploration context include mapping of veins and fracture zones, delineating crown pillar thickness, mapping overburden thickness, locating old mine workings, and definition of placer potential.

GPR in its present form started to emerge from the polar ice radio echo sounding in the late 1960s. Since that time, the method has seen a constant and continuous growth both in applications, number of practitioners and in instrument sophistication. Early utilization of the method for engineering and soils applications as well as mining are given by Morey (1974), Cook (1973), Annan and Davis (1976), Coon *et al.* (1981), and Ulriksen (1982). An extensive overview of the method is given by Davis and Annan (1989). The proceedings of GPR conferences held biannually during the last decade also provide an excellent source of GPR reference material.

GPR can be deployed in a number of manners; the primary modes are either in a reflection configuration or in a transillumination mode as depicted in Figure 1. The most common approach to carrying out GPR surveys has been to work in the reflection mode at the ground surface or occasionally in boreholes. Reflection measurements can be a single source and receiver combination or more sophisticated multi-transmit/receive observation such as those used in multi-fold seismic reflection. More recently developments have lead to a growing use of the transillumination mode (Annan and Davis 1978; Owen 1980; Davis and Annan 1986; Olhoeft 1988; Olsson 1990; and Annan *et al.* 1997).

In the following, a brief overview of the physical and theoretical basis of GPR, current instrumentation performance levels, survey procedures, as well as data processing, interpretation and display are presented. It is impossible in this brief forum to provide an exhaustive review of the method. The articles referenced in this paper are specifically selected to lead readers to more in-depth studies.

In “Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration” *edited by* A.G. Gubins, 1997, p. 515–522

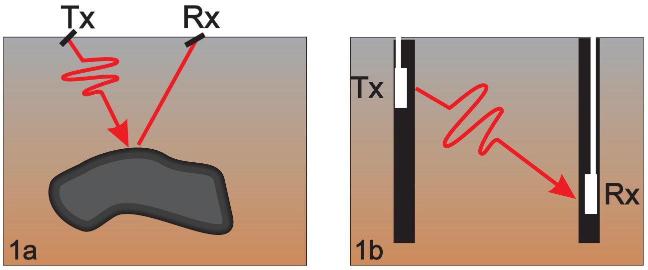


Figure 1: *GPR can be deployed in a number of ways. The two principal approaches are depicted in Figure **(a)** illustrates the reflected signal detection concept while **(b)** demonstrates the signal transmission or transmillumination concept.*

EM FUNDAMENTALS AND MATERIAL PROPERTIES

Ground penetrating radar requires a geologic regime where radio waves can propagate a sufficient distance through earth materials to be useful. GPR frequencies are predominantly in the 1 to 10 000 MHz range. In general, electrical conductivity dictates depth of exploration. In sea water, for example, radio signals will only penetrate a few millimetres whereas in highly resistive granite formations signals can be transmitted through tens and even hundreds of metres of rock and still be detected. A good overview is given by Davis and Annan (1989); some of the main points will be reviewed here to stress their importance.

Figure 2 shows the electromagnetic wave propagation properties versus frequency for typical geologic materials. When velocity and attenuation show a plateau (which occurs typically in the 1 to 1000 MHz frequency range), then GPR becomes a viable method. This plateau occurs when displacement currents dominate conduction currents in the medium. In the plateau region, velocity and attenuation become essentially frequency independent and electromagnetic pulses can be transmitted with minimal dispersion although suffering significant attenuation. This plateau is sometimes referred to as the GPR window. Since attenuation is exponential with distance, there is always a finite depth of exploration.

The frequency at which the GPR wave property plateau occurs increases as the DC electrical conductivity rises. Often the plateau disappears all together as the low frequency conductivity merges with loss effects at higher frequencies which are most often induced by the presence of water. The extreme behaviors are depicted in Figure 2d. In general, clay minerals and electrically conductive pore water limit penetration while changes in water content dominate velocity and reflectivity. The subject of electrical properties of geologic materials is extremely wide ranging. An extensive discussion of the subject is given by Olhoeft (1987). Most important for GPR users is the exploration depth. A simplified chart of exploration depth for common materials is presented in Figure 3.

Reflection GPR maps subsurface features by detecting electromagnetic waves which are reflected. By measuring at a number of positions, the location and the depth of subsurface objects can be inferred. Reflections are caused by changes in electrical character between the reflector and the surrounding host material. Even very minor changes in material composition or in water content give rise to changes in electromagnetic impedance which in turn cause radar reflections. Mineralized zones which form metallic conductors will reflect all incident signal. As a

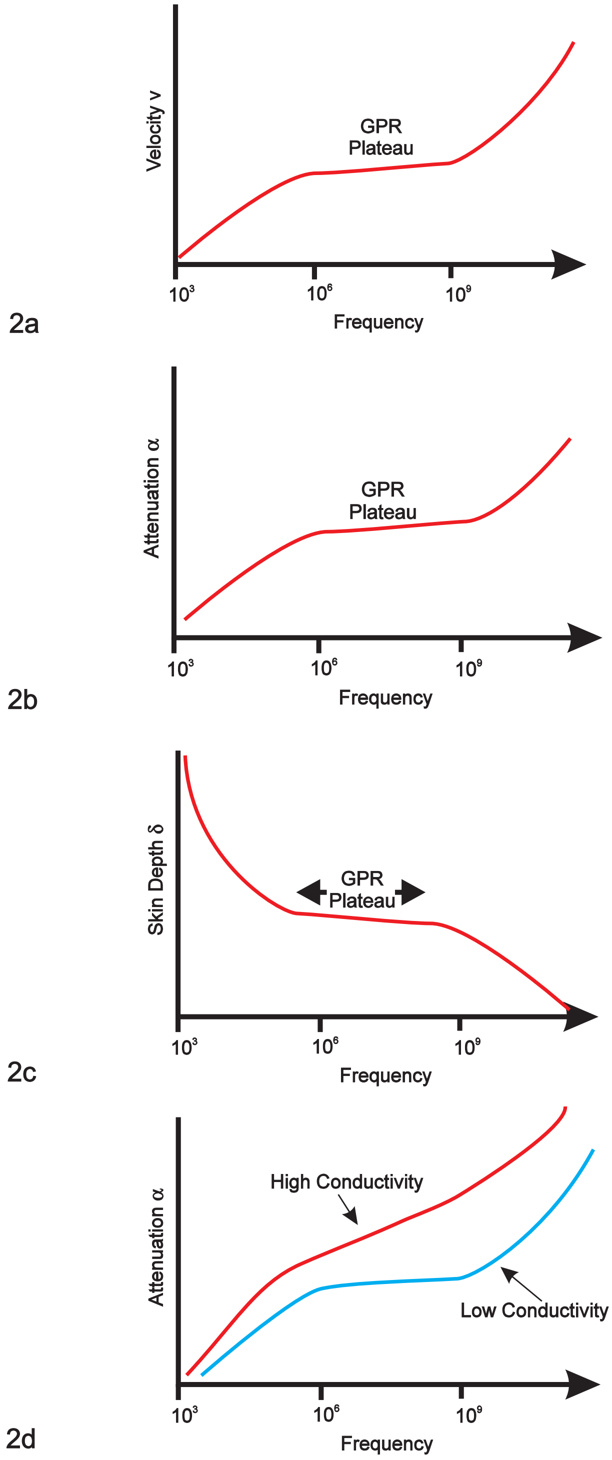


Figure 2: *GPR waves are characterized by the velocity of propagation and degree of attenuation. Velocity generally increase with frequency as depicted in **(a)**. Attenuation also increases with frequency **(b)** and its alternate form, skin depth ($\delta = 1/\alpha$) decreases with frequency **(c)**. For successful GPR measurements a plateau event exist where these properties become frequency independent. In some high loss materials, the plateau may never exist as depicted in **(c)**.*

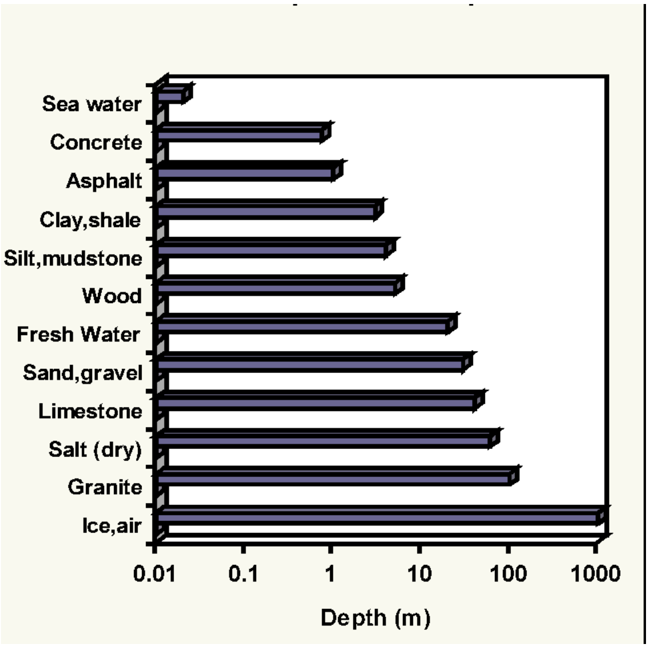


Figure 3: *Typical exploration depths achievable in common materials where GPR is a useful technique.*

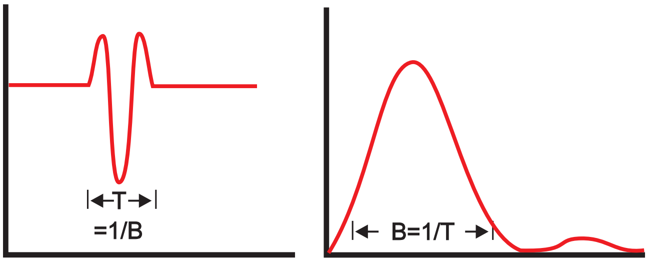


Figure 4: *GPR wavelets are generally as shown in **(a)** which is characteristic of small dipole antennas. The corresponding frequency spectrum is shown in **(b)**. Pulse duration and bandwidth are inversely related.*

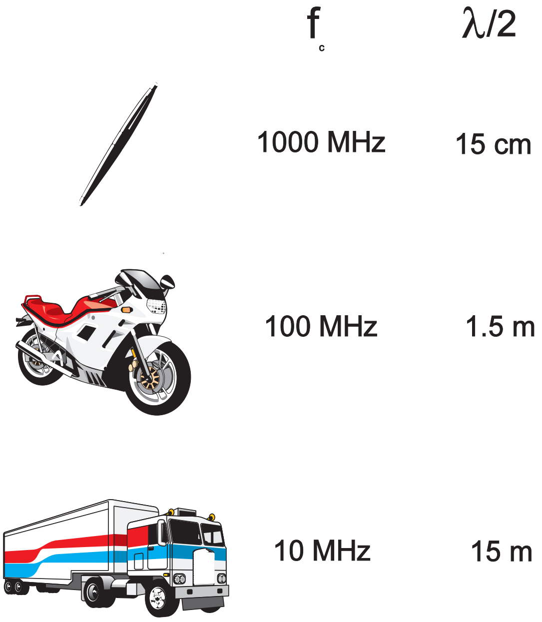


Figure 5: *The spatial scale of measurements is not always easily estimated when only the radar frequency is quoted. This graphic illustrates typical wavelength scales in terms of common everyday items.*

result, contacts between rock types, fracture zones, shear zones and mineralized areas as well as voids and cavities give rise to good detectable radar responses and are most often the targets in GPR investigations.

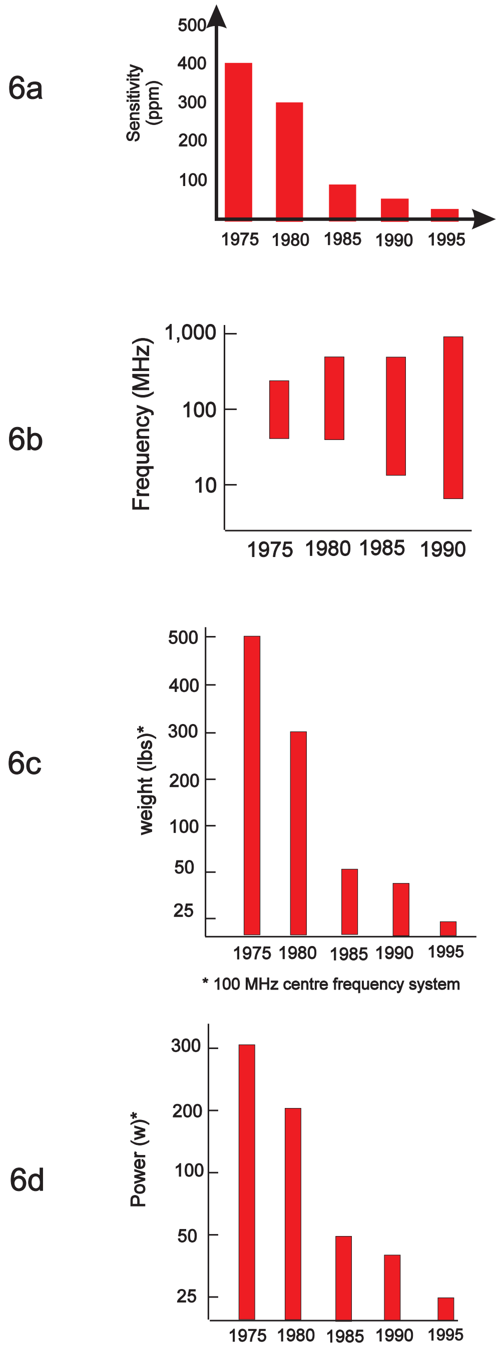
Transillumination surveys measure the transit time, amplitude and frequency content of the signals transmitted through the material. The velocity and attenuation are obviously directly indicated by the observations. Transillumination differs from reflection measurements in that the observed data represent a summation of properties over the whole path length whereas reflection methods only detect changes or gradients in properties. Transillumination measurements are much more amenable to quantitative measurement of EM wave and material electric properties.

INSTRUMENTATION

GPR instrumentation operates primarily in the 1 to 1000 MHz frequency range. Systems operating in the time domain predominate in the commercial marketplace. These systems generate pulses which typically have 2 to 3 octaves of bandwidth. Instrument design goals are normally a bandwidth to centre frequency ratio of unity making the pulse length and centre frequency inversely related as depicted in Figure 4. Spatial pulse lengths are about 10 m at frequencies of 10 MHz and decrease to about 10 cm at frequencies of 1000 MHz (see Figure 5). By changing the spectrum centre frequency, the radar pulse duration is modified giving different resolution scales of measurement. In general, one tries to keep the frequency relatively low so that the fine scale texture of geologic materials does not scatter too much energy and mask the deeper structure as discussed by Annan and Cosway (1994) and Watts and England (1976).

The rapid evolution of GPR can be attributed to instrument developments. One of the primary areas has been the evolution of high quality recording instrumentation. In the pioneering days of GPR, many of the data recorded were contaminated by system noise which made it very difficult to see “real” ground responses. Furthermore, the data were in analog form and not readily manipulated into alternate presentation formats. Great effort has gone into the development of instruments which provide high quality data plus also give data in digital form so that techniques common to petroleum seismic data can be exploited.

Several manufacturers of the GPR instrumentation exist in the commercial market place. The leading technologies encompass highly stable digital time bases, digital signal sampling and recording in light weight, battery powered portable packages. In all instances the ubiquitous personal computer (PC) is the data recording and display device. Current technology records 16 bit data; noise levels are primarily determined by external sources (i.e. radio, TV, cell phone) in the higher performance commercial products.



* 100 MHz centre frequency system

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Figure 6: *Instrumentation changes over the last 25 years have been extensive. These changes depict how various system parameters have changed.*

Figure 7: *Simple light weight one man operation survey system.*

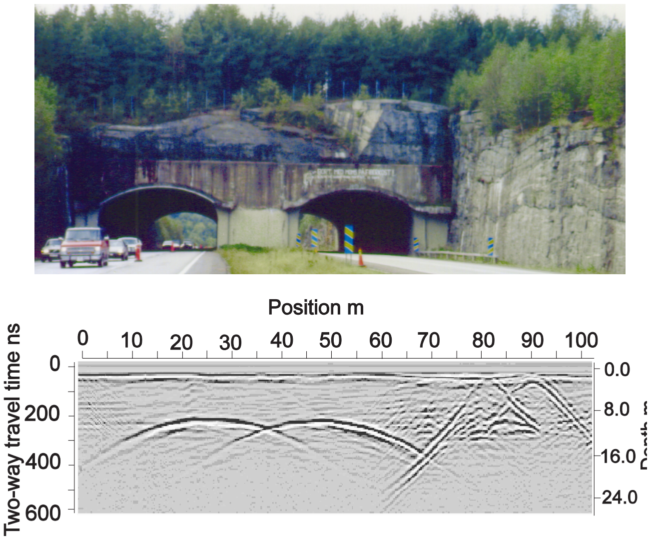

Figure 8: *An example of single fold reflection GPR data over two tunnels cut through a gneissic bedrock. The reflection data were acquired with a 50 MHz centre frequency system.*

The evolution of instrumentation is best illustrated in graphic form. Figure 6a shows how the noise floor of detection has dropped versus time over the last 25 years. Figures 6b, 6c and 6d show the change in operating frequency range, the weight and power consumption of the GPR instruments. Acquisition of data from a few MHz through to 2000 to 3000 MHz with modern lightweight battery powered digital equipment is very easy. Instruments generally have radiated power levels substantially lower than cellular phones. Power levels of commercial systems will remain low because of the need to meet government radio frequency emission regulations. Figure 7 shows a backpack mounted system ; total system weight is about 20 kg. including batteries and PC.

SURVEY METHODOLOGY

Reflection–single-fold

The most common mode of GPR data acquisition is referred to as "reflection mode–single-fold" coverage. A single transmitter and receiver are transported over the ground surface in a fixed configuration and data acquired versus position. A typical radar record is a reflection section such as shown in Figure 8 which display position horizontally and travel time vertically with the amplitude of the echoes coming back out of the ground being displayed as a gray scale amplitude plot. Note that examples presented here are intentionally formatted in a variety of manners to indicate the various display methods now used.

Conducting a survey requires considerable planning. First, one must define the operating frequency range. Second, the geometry of the measurement system such as the spacing between the antennas and the antenna orientation must be decided. Next, the spatial and temporal sampling intervals must be defined. In addition, most real surveys must cover a 3 dimensional area so line separation or (line density) must be defined as well as line orientation must be established. Many of these topics are discussed by Annan and Cosway (1992).

Common offset single fold reflection data acquisition has been the main stay of the GPR field. Speed and economics dictate that this will likely remain so. Interpretation has traditionally been carried out on such sections either in raw form or in some cases after some minor processing. More recently, with the advent of digital systems, digital data storage and computer data manipulation, more complex field surveys have been undertaken.

Multi-fold and CMP soundings surveys

In the last five years, it has become practical to acquire multi-fold data. In a multi-fold survey a multiplicity of measurements are made at different spatial separations between the transmitter and the receiver over common point (See Figure 9a). These data are processed just as in multi-fold seismic to extract velocity versus depth and also to stack the traces together to improve signal to noise (Fisher *et al.*, 1992). The benefits of these more sophisticated measurements are two-fold; improved signal-to-noise plus a measure of velocity versus depth such as shown in Figure 9b and 9c which allows the radar travel times to be converted to depth estimates.

Design and execution of multi-fold surveys are based on the fundamentals of simpler single-fold measurements. In general, most of the parameters have to be defined in the same way. As indicated, the benefit of such a survey is in the extraction of velocity versus depth which helps to transform the original data image into a true depth cross-section. An example of further refining velocity versus depth for the Fisher *et al.* (1992) data is presented by Greaves *et al.* (1994).

3-D surveys

In recent years, the advent of low cost, high powered computing capabilities has led to the emergence of 3-D GPR surveys. 3-D GPR surveys to date consist of a multiplicity of simple single-fold sections acquired on tightly spaced parallel lines. Fundamental GPR transducer characteristics mean then 3-D GPR often differs from the seismic

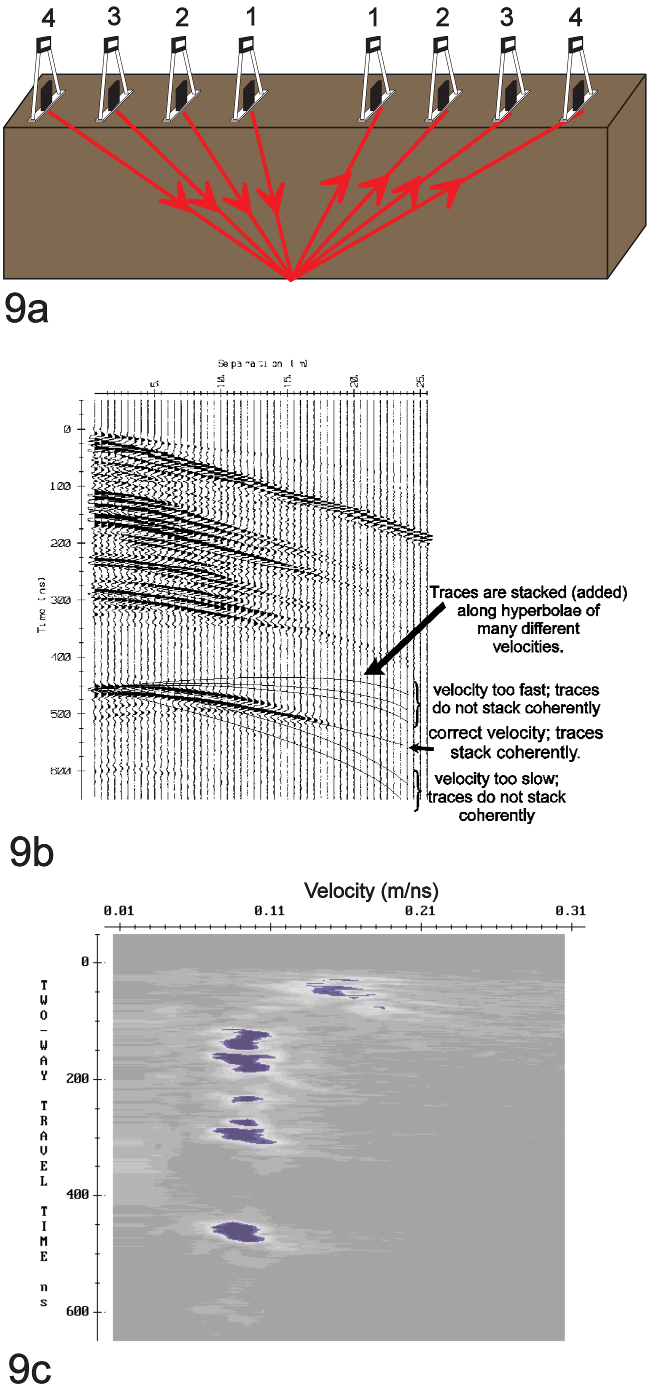

Figure 9: *Multifold data are normally acquired or sorted in CMP (common mid point) gathers as* ***(a)*** *represents in raypath form. Data have the character* ***(b)*** *consisting of hyperbolic time distance behavior. An optimum stacking velocity versus travel time can be extracted which permits coherent summation of multifold survey data as well as a velocity depth function such as shown in* ***(c)***

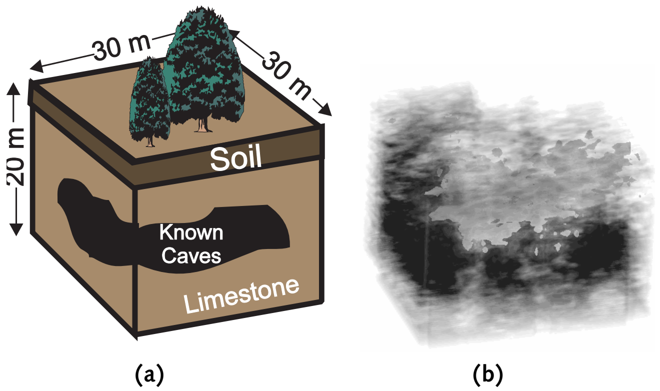

Figure 10: *Recent economic access to volume visualization has lead to volume displays. The above data are from a karst limestone area depicted in **(a)** and GPR yields the image in **(b)**. The power of such presentations are best when dynamic, computer animated colour images are employed.*

approach (Annan *et al.*, 1997). These data are then inserted into a volume visualization software package that facilitates volume rendering of the data. Such 3-D display tools are powerful aids in helping understand complex environments such as the karst limestone example shown in Figure 10.

In general, 3-D data require some pre-processing in order to make the image useful. Migration plus other temporal and spatial filtering are common. Many of the tools available from the seismic field are exploited. Excellent examples of 3-D GPR can be found in papers by Grasmueck (1996), using full seismic workstation capabilities and by Sigurdsson and Overgaard (1996), and Jol (1996) using more basic PC facilities.

Transillumination surveys

Transillumination measurements are just emerging from the research phase. These surveys examine signals transmitted through a volume and use tomographic reconstruction techniques to image the volume between measurement points.

These types of measurements have been conducted sporadically to look at rock stability between boreholes. Extensive work has been done in boreholes for nuclear waste disposal assessment. In general, the technology has been expensive and user friendly software non-existent, making the technique inaccessible to all but a few. As a result, widespread utilization of the technique has not occurred.

A related method is the Radio Imaging Method (RIM) method (Vozoff *et al.*, 1993; Rogers *et al.*, 1987; and Wedepohl 1993) which has seen some extensive testing in coal and base metal mines. RIM operates in a similar manner, but continuous wave sinusoidal transmitters are employed and received signal amplitude is the primary quantity measured.

More recently, the evolution of software on PC's with user friendly interfaces plus rapid field acquisition with low cost crosshole radar instruments are inducing this survey type to expand. An example of a derived conductivity tomogram is shown in Figure 11. Excellent examples for shallow engineering applications are given by Gilson *et al.* (1996), Redman *et al.* (1996), and Annan *et al.* (1997).

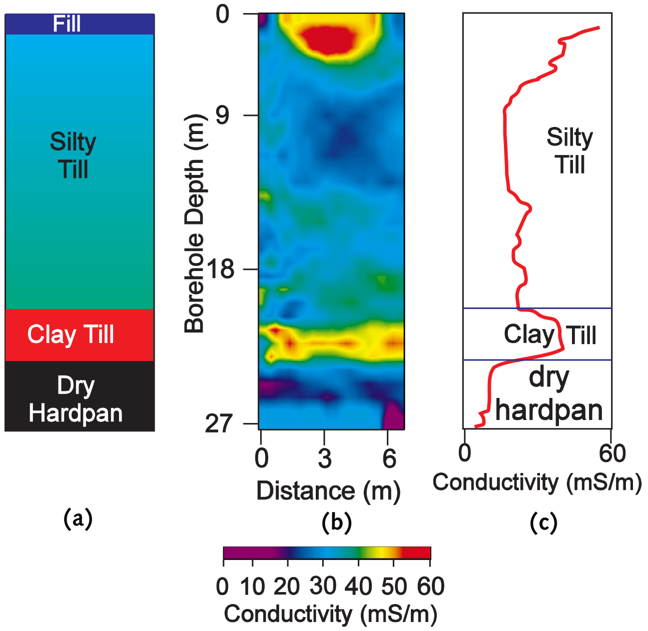

Figure 11: *Transillumination measurements now yield physical property measures on a scale not previously possible with GPR. **(b)** demonstrates a conductivity image derived from a GPR tomography survey. The core derived geology are shown in **(a)** and induction log conductivity shown in **(c)**.*

MODELLING

The ability to model GPR responses has only appeared recently. Even now practical accessible modeling is limited to scalar 2-D wave equation or ray tracing solutions with little consideration for losses. The evolution is much like that in seismic although it has been at a slower pace. Simple 1-D synthetic radargrams (Annan and Chua, 1992) were quickly followed by 2-D scalar wave equation and ray tracing solutions (Cai and McMechan 1995; Zeng *et al.* 1995; Goodman 1994) as shown in Figure 12.

As interest has grown in the modelling community and demands for more sophisticated analysis appeared, lossy 2-D (Powers and Olhoeft 1994; Casper and Kung 1996) and full blown 3-D models have appeared (Wang and Tripp 1995; Alumbaugh and Newman 1994). The full 3-D modelling codes are still the domain of researchers with access to super computers.

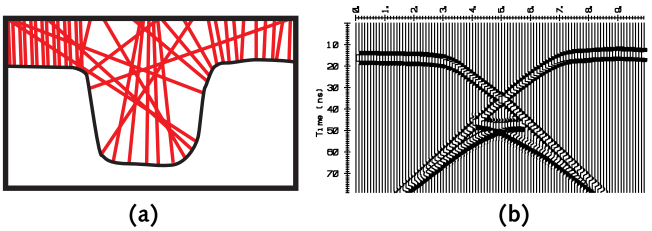

Figure 12: *Numerical simulation of GPR responses is a rapidly expanding area. Readily available software facilitates 2-D simulations such as the classic buried valley **(a)** and bow-tie response **(b)**.*

Quantitative interpretation via inversion techniques is still in the future. Faster computers and faster codes will be needed for inversion to become available to the user community. Attempts at inversions using 1-D codes have shown some success in specific layered earth environments (Sanders 1995). Even when modelling becomes faster, the need to include source-ground interactions in system transfer functions may still limit the inversion procedures.

DATA PROCESSING, PRESENTATION AND INTERPRETATION

The advent of the modern PC with extensive CPU, power graphics and vast data storage means that many of the techniques which were inaccessible only a few years ago are now quite available to the average practitioner at a very low cost. While presentation and basic processing and display tools are now readily available, there are still limits placed on quantitative interpretation as the preceding modelling discussion has indicated.

The GPR problem perspective is best understood by the data volume that can be collected. A geological mapping survey would typically yield 10 Mbytes of data volume for a day. For high speed data acquisition in open ground conditions on a vehicle then volumes can approach 200 to 500 Mbytes per day. For rapid highway travel, data volumes can reach many Gbytes per day of surveying. If one just looks at the data storage capacity of the average PC, one can see that the computing technology for handling of such volumes relatively easily and at low cost have only appeared in the last 4 or 5 years. The enhancements in GPR processing, presentation and interpretation are now exploding. Many of the basic seismic processing techniques Yilmaz (1987) are now applied to GPR (Annan 1993; and Maijala 1992). All are primarily based on scalar wave equation concepts. Interpretations are based on time of flight and relative signal amplitude. These are the same concepts that reflection seismic has employed so successfully for many years.

It is beyond the scope of this discussion to address all the possibilities. The data examples presented in Figure 8 through 11 were all created on PC's and illustrate some of the possibilities available. In most cases these presentations use software that did not exist 5 years ago. In addition, most of the processing and presentation would not have been possible except on a mini or mainframe computer.

APPLICATIONS

The applications of GPR are endless. The biggest single problem is the translation of GPR information into useful quantitative information for end users (i.e., the geologist, engineer, hydrologist, etc.). Often radar sections will be acquired in which there is so much information that the information density overwhelms the more simplified understanding of the geological conditions at a site. Much remains to be done to advance the method in the level of extracting more quantitative information about ground conditions from the radar images.

Table 1 shows some of the more common applications of GPR for mining. Examining this list shows that many of the applications lie more in the engineering and infrastructure inspection and related fields than in exploration for natural resources. For a broader view, the GPR biannual series of proceedings provide excellent reading. Some specific mining applications are addressed by Davis *et al.* (1985), Annan *et al.* (1988) and Sigurdsson (1995).

Table 1: ***Common applications of GPR for mining***

Mining Applications
Placer Exploration
Placer Mining Exploration
Overburden Thickness - Open pit
Tailings Dam Seepage
Rock Stability in Roof and Pillars
Seam Thickness In Coal & Evaporites
Fracture Mapping in Nuclear Repositories
Mineralized Vein and Altered Shear Zone Remediation
Roof Rock Thickness Evaporite/Gypsum
Crown Pillar Thickness

SUMMARY AND CONCLUSIONS

As we stated at the outset, our goal has been to show that GPR has come of age. GPR truly is a modern tool with all of the trappings needed to make it very effective in a many diverse applications. The instrumentation advances have been great. Our understanding of ground conditions where radar can be used effectively have expanded enormously. In addition, our understanding of how the radar signals interact with ground conditions and the limitations of measurements are much better developed.

Perhaps one of the biggest boons to GPR has been the enormous expansion in the computing area. The ability to handle large data volumes cost effectively, quickly and a graphic and visual form means that GPR now can be used effectively. Further rapid advances can be anticipated in this area.

People are now recognizing GPR's power and many researchers are now active in the area. This all bodes well for further expansion of the method's utilization and GPR's growth in new application areas.

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