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Ground penetrating radar applications in engineering, environmental management, and geology

James S. Mellett
New York University, New York, NY 10003, USA
Subsurface Consulting, Ltd., New Fairfield, CT 06812, USA

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Abstract

The ability to see through, below, and into solid materials using non-invasive techniques has important applications in a variety of fields where investigations may otherwise require intrusive or destructive methods. Probing concrete, soils, or bedrock using coring or drilling can provide detailed information about subsurface features, but is valid for only a short distance away from the test boring. Ground penetrating radar is capable of providing continuous high-resolution profiling of subsurface features, and is capable of locating objects and horizons at a variety of scales. The GPR technique is finding applications in fields as diverse as architecture, engineering, environmental management, and mineral prospecting.

1. Introduction

Ground penetrating radar (GPR) provides a number of advantages previously unavailable to individuals working in the areas of engineering, environmental management, and geology. One advantage is that the scale of features resolvable using GPR can range from a few centimeters to tens or hundreds of meters using the selection of antennas available. Another distinct advantage is the ability of GPR to provide high-resolution continuous profiling of an area, yielding much more information than conventional local sampling by test borings and excavation. Benson and La Fountain (1984) believed the use of GPR in engineering studies allows one to drill "smart holes", which would be placed to extract maximum information about underground features, rather than a conventional drilling program that might place boreholes in a predetermined pattern.

Scans made with GPR antennas are repeatable, with excellent replication of data over time. Subsurface interfaces detected by the radar reflections exhibit a contrast in electromagnetic properties and may be referred to as electrostratigraphic units (Mellett, 1990). In addition, most GPR techniques permit on-site review of the survey results for quality control of the acquired data. If a feature is not detected on one scan, or with one transducer, additional passes can be made immediately thereafter until the full capabilities of the GPR system are applied. A final advantage is the precision that can be attained in locating features or objects using GPR.

This paper will present several samples of applications showing the use of GPR in engineering, environmental management, and geology. With an array of shielded antennas, GPR has distinct advantages over other geophysical methods, particularly in urban settings. Ubiquitous structural steel and vibrations from roadway or airborne traffic make it difficult to use terrain conductivity, magnetic, or seismic methods with any degree of success. Real-time printout of results of

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a GPR survey permits immediate repositioning the antenna or additional fine tuning to obtain optimal survey results. Because it is a reflection technique, estimates of depth to a target or interface can be made with greater precision than with other methods, particularly if the dielectric constant is known. Lateral accuracy is also greater with GPR for locating spherical or cylindrical targets, because the inflection point of the reflection hyperbola indicates the top dead center of the target in question.

2. Equipment and methods

With the exception of the GPR profile shown in Fig. 7, which was made with a Pulse-Ekko IV 25 MHz unit, all of the scans shown in the accompanying illustrations were made with a SIR-3 GPR system. The SIR-3 system was equipped with a profiling recorder, and antennas having center frequencies of 80, 100, 300, 500, and 900 MHz. The profiles were made by towing the antennas by hand at a rate of about 0.5 m/s over the surface. Depth estimates indicated in the profile plots are based on a typical relative dielectric constant of between 5 and 7. The latter figures provide a range of dielectrics for a variety of unsaturated materials. If the subsurface materials are saturated or lie below the water table, depth estimate errors of up to 40% can occur. Although a variety of methods can be used to determine the average propagation velocity within the substrate, the simplest approach is to locate a target of known depth in the field (such as a utility line underground, or a conduit in a concrete slab) and make a GPR scan over the object. By comparing the known target depth to the time (depth) scale on the printout, one can directly calculate the two-way traveltime to the object and determine the propagation velocity.

3. Field survey examples

3.1. Engineering and environmental applications

The ability to see through or into solid objects instead of physically probing into them with boring tools is a major benefit in using GPR, particularly where a closely spaced series of boreholes might threaten the integrity of the structure, or produce damage to an underground tank or utility line.

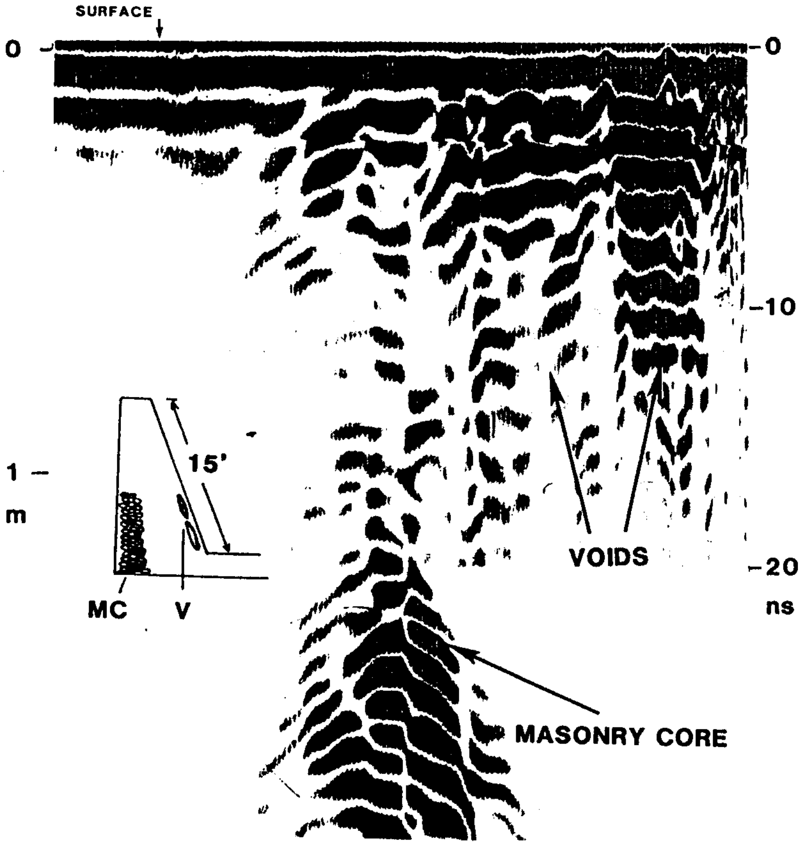
Hydroelectric canal

In 1989, an electrical storm disabled a relay that controlled a floodgate on a 400 m long hydroelectric canal. The canal subsequently overfilled with water, was undermined, and a 50 m long segment of the canal washed out. During repair and replacement of the washed out section, void spaces were detected in adjoining sections of the canal during a visual inspection of the structure. A thick grout was called for to repair the voids, but it could not be injected under high pressure for fear of disrupting the base of the canal wall, which was supported in part by a masonry core. The extent of the voids was unknown, and their distribution appeared to be highly irregular. A conventional solution would have been to core a series of holes through the concrete liner of the intact canal to map the extent of the voids, and then fill the voids with grout. The drawback of this approach was that if the voids were extensive, the entire face and floor of the canal would have been drilled with enough holes to almost guarantee subsequent leakage.

A GPR survey was run through the entire length of the canal using a 500 MHz antenna. Scans were made along parallel lines spaced 1.5 m apart on the floor of the canal for its entire length. Additional scans were made down the intact side faces of the canal at 2 m intervals within 15 m of the washout. For the rest of the canal length, scans were made down the side faces every 15 m. Fig. 1 shows a GPR profile of the side face at a location near the breach. The inset shows the interior of the canal wall. The top of the canal face is on the left of the profile. The absence of reflections indicates that the concrete and backing material are intact. Halfway down the sloping face a reflection caused by the masonry core is encountered at a depth of about 1 m. To the right in the profile, closer to the canal base, multiple echoes indicate the presence of at least two voids just below the concrete surface of the canal. Coring revealed voids that later consumed 3 m^3 of grout. Other voids were found only within 10 m zones on either side of the washout.

Underground vaults

In large eastern US cities where extensive changes in street levels and grades have been made since the colonial period, many basement areas in older buildings



. 1. GPR profile made down the sloping face of hydroelectric canal washout site in New England. Width of scan is 5 m. 500 MHz antenna,
ns range. *MC* = masonry core; *V* = voids.

ere abandoned and were bridged over and incorpo-
ted into a sidewalk or street. Occasionally, heavy
hicles driving over these vaults have caused street
ve-ins. The locations of such unmapped vaults are
known and therefore search surveys are performed
ior to construction at suspected sites. Fig. 2 shows a
PR profile over a sidewalk in New York City where
ncern was expressed about the existence of unmap-
d vaults that extended out from the buildings and
der the street. The dark multiple banding in this pro-
e indicates a void below ground showing how the
ort duration GPR pulse resonates within the rela-
ely large open chamber. If the dimensions of the
id are a multiple of the GPR wavelength, the pulse
ll be reflected many times and a "ringing" will
pear on the printout. The vault shown in Fig. 2 was
e that was already known, but served as a proof test
detection. No other echoes like this were detected
ng the street in question.

Buried utilities and rebar mapping

Where the locations and depths of distinct underground objects must be determined, GPR is the technique of choice when the host medium permits adequate penetration. It is particularly appropriate at sites where nearby metal fences and structural steel in buildings might interfere with the operation of terrain conductivity meters (EM), or magnetometers. At many industrial, commercial, and residential complexes, map layouts showing the distribution of underground utility lines (water, sewer, storm drains, electric, telephone, cable TV, etc.) are often non-existent, or inaccurate. When lines must be located for repairs or avoided when drilling or coring operations occur, the lack of accurate as-built drawings often leads to ruptured water mains or severed electric conduits, with consequent structural damage or injury to personnel. Fig. 3 shows a GPR profile made at an airport taxiway, where the location and estimated depths of

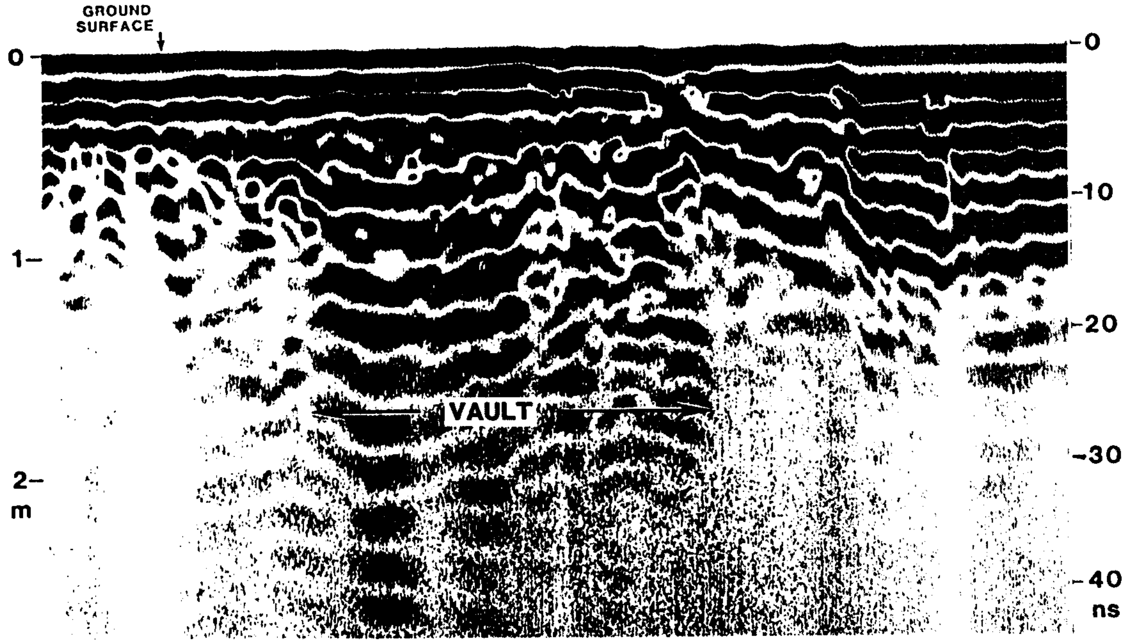


Fig. 2. GPR profile over the surface of a vault (void) below sidewalk in New York City. Width of scan is 20 m. 300 MHz antenna, 75 ns range.

electric conduits had to be determined prior to construction at the site. In addition to accurately locating multiple electric conduits at varying depths, the GPR also determined the nature of the reinforcing material within the taxiway concrete and the thickness of the slab. Steel reinforcing mesh having 15 cm spacing were mapped within the slab.

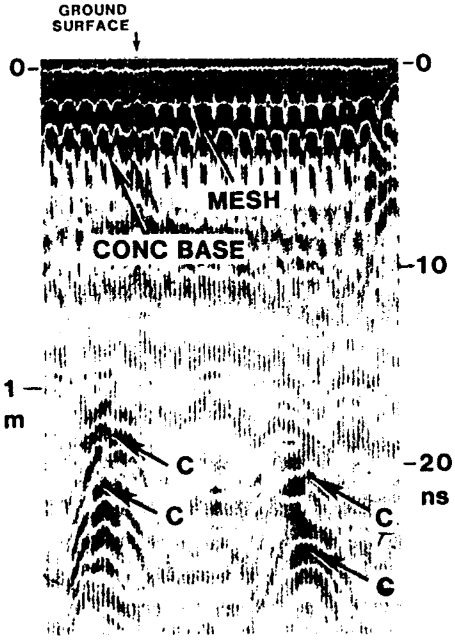


Fig. 3. GPR profile over an airport taxiway showing steel reinforcing mesh in concrete and electrical conduits at depth. Width of scan is 1.5 m. 500 MHz antenna, 50 ns range. *C* = electric conduits.

Most concrete is easily penetrated by GPR signals because the composition is similar to that of limestone rock, and many aggregates consist of quartz or other resistive rock fragments. Occasionally, aggregates may consist of highly conductive materials such as clay or slate chips, and the GPR may not penetrate more than a few centimeters into it. Also, where multiple layers of reinforcing exist, much of the GPR signal energy will be reflected or scattered, and little energy will penetrate below the reinforcing.

In many construction projects carried out at existing facilities, demolition and debris removal costs can be almost as high as construction costs for new buildings. Failure of an architect or engineer to accurately estimate the difficulty of demolition or the volume of debris to be removed may lead to serious additional and unplanned costs. Any technique that can assist in making accurate estimates of such costs is highly desirable. Fig. 4 shows a GPR profile over a concrete slab on the ground floor of a building in New York City. Although an architect initially estimated that the floor slab was only 15–20 cm thick, GPR scans indicated that two levels of reinforcing rods (rebars) existed in the floor and that the slab was at least 70 cm in thickness.

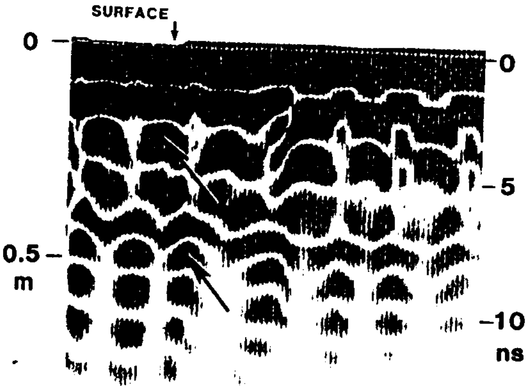


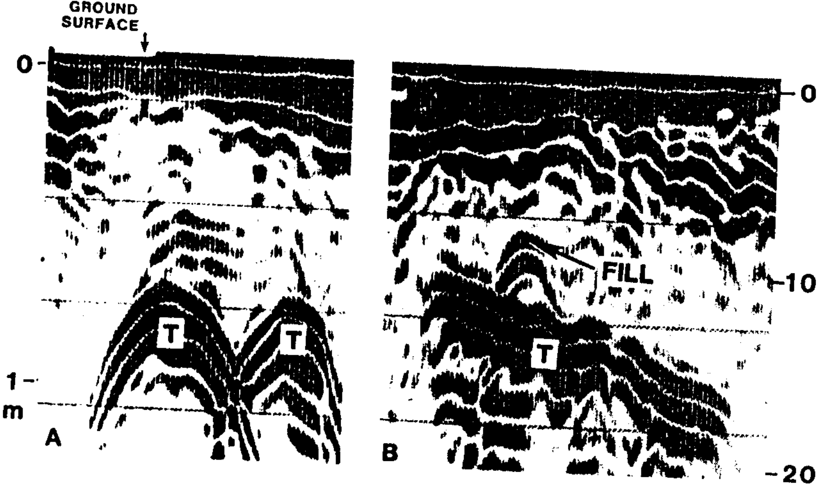
Fig. 4. GPR profile over surface of a concrete floor slab. Width of can is 2 m. 500 MHz antenna, 35 ns range. Arrows indicate two ayers of rebars.

Underground storage tanks

Underground fuel oil and gasoline storage tanks ither in use or abandoned can cause major environnental contamination if they develop leaks that allow he fuel to enter the groundwater supply. Although new stallations of underground storage tanks (UST's) equire the locations to be carefully mapped, many lder UST's have been abandoned and all surface indiations of tanks (e.g. concrete pads, vent and fill caps) ave been obliterated. Prior to removal or remediation f such a site, the tanks must be accurately located to revent accidental punctures by drilling or excavating uipment. When the tanks contain volatile fuels, such nctures may cause an explosion. Accurate knowlge of the tank location is also required when sampling the surrounding soil using test borings or when using soil gas samplers in monitoring wells. Best results are obtained if the wells and gas samplers are placed as close to the tank as possible. Without extremely precise data on the depth and orientation of the UST, it may be hazardous to attempt such sampling. Fig. 5 shows a GPR profile made at an abandoned gasoline service station in New York state. Local records of the former use of the property were destroyed in a fire at the municipal center and there was no reliable evidence of the existence of tanks. Fig. 5A shows a sample GPR profile over two tanks and Fig. 5B shows a longitudinal profile made over one of the tanks. GPR can precisely locate the center of the tank by noting the peak of the hyperbolic echo and can also determine the tank length. The width of the tank can be determined if the tank volume and length is known. The apparent downward dip of the tank profile shown in Fig. 5B is an artifact caused by the sloping ground surface.

Sinkholes and subsidence features

Areas in humid regions underlain by carbonate-, sulphate-, or chloride-bearing rocks can be subject to sinkhole formation. Even small soil sinks can have a devastating effect on roads and other structures when they reach the surface and, therefore, engineers must have some knowledge about the conditions that lie underground in sinkhole prone regions. Although sinks in Florida are well known, many eastern states in carbonate-rich regions can develop sinkholes, often as a result of human intervention in the hydrologic regime



5. (A) GPR profile over two 500 gal UST's at an abandoned service station. (B) Longitudinal profile over the left hand tank. Width of scan is about 3 m. 500 MHz antenna, 50 ns range. T = tank.

of the area (Newton, 1986; Benson and Yuhr, 1992). Sinks and cavities created in carbonates millions of years ago may be plugged today with younger deposits. Often, after frequent fluctuation of the water table caused by extensive pumping of groundwater or by heavy rains, the younger sediment may be drained downward, causing a cavity or sink to develop and migrate toward the surface. Fig. 6 shows a GPR profile made over a potential sinkhole location in Florida. The paleosurface shows the limestone bedrock. Sand and clay plug the opening in the limestone and form the overburden. At the present time the area over the cavity in the rock is stable, but alteration of the hydrologic regime might induce collapse in the future. The apparent water table appears convex upward instead of flat because the antenna was towed over a slight depression at the surface. The reflector at about 16 m depth is a multiple of the water table. Note that the depth scale in Fig. 6 is adjusted to account for the change in saturation of the substrate. Unsaturated materials above the water table have a propagation velocity of about 7 cm/ns. Below this interface, the pulse velocity drops to about 5 cm/ns, making reflections appear farther away than they really are.

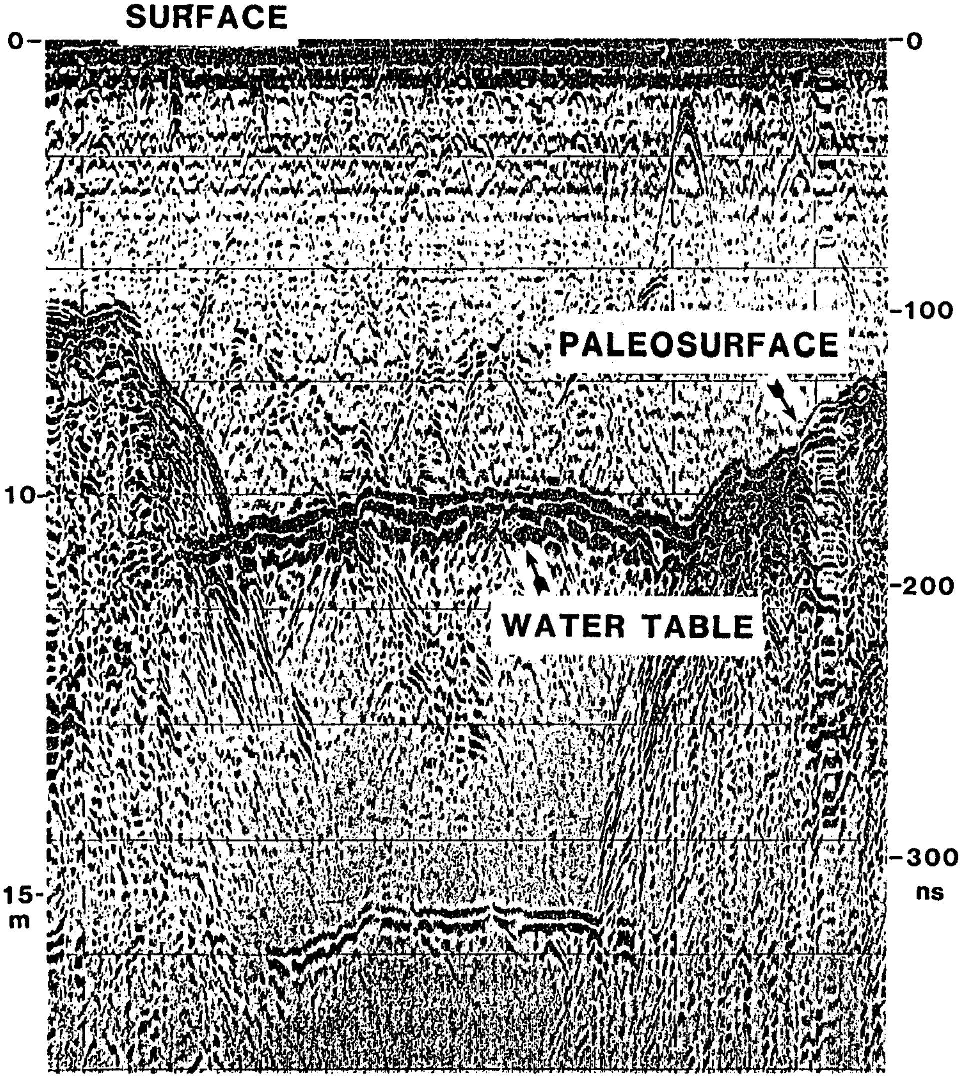


Fig. 6. GPR profile over a potential sinkhole site in Florida. Width of scan is 40 m. 80 MHz antenna, 400 ns range. (Illustration provided by R.C. Benson.)

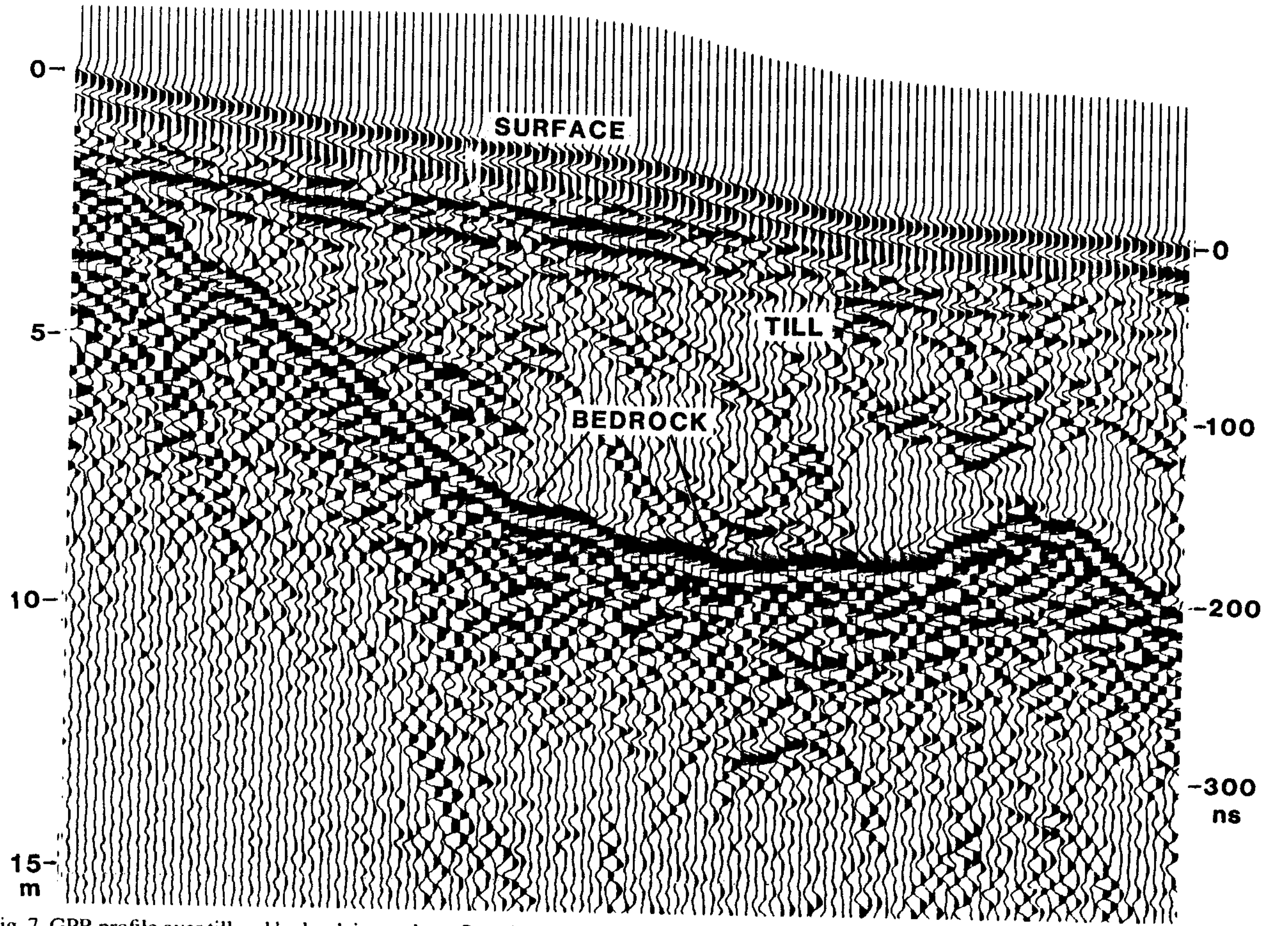


Fig. 7. GPR profile over till and bedrock in southern Ontario, Canada. Width of scan is about 150 m. 25 MHz antenna, 500 ns range. (Illustration provided by A.P. Annan.)

3.2. Geology

Bedrock–soil interfaces

Because the dielectric and conductivity contrasts between bedrock and overburden are usually sharp, GPR can often be used to detect the interface between the two. This contrast is enhanced if the local water table follows the bedrock surface. Fig. 7 shows a GPR profile in southern Ontario, using data display software that corrects for surface topography. This profile was displayed as a wiggle trace plot to show the similarity between GPR and seismic profiles. The low frequency 25 MHz antenna provides good penetrating ability even in the somewhat clay-rich soils. Because of its ability to provide a continuous high-resolution profile, GPR-determined volume estimates for mineral prospecting (e.g. peat deposits, or the sand and gravel shown in Fig. 7) can be greatly improved.

Fig. 8 shows a GPR profile over a paved parking area in a location that was alleged to contain a cache of buried drums. The depth to bedrock was found to be extremely shallow, which literally set a floor for the depth to which the drums might be buried. Areas of fractured gneissic bedrock alternated with zones of unfractured rock. Depth to bedrock shown in the profile was verified by drilling at a number of locations and was accurate to within 0.5 m. The absence of shallow radar echoes suggested that there were no buried drums present. An EM survey conducted at the site also yielded no evidence of buried metallic material.

Stratigraphic horizons detected with GPR often mirror underlying geologic structure with great accuracy. Fig. 9 shows a profile over dipping Paleozoic carbonate rocks in southeastern New York state. Although pure carbonates usually exhibit only small dielectric variations at depth, GPR pulses will respond to changes in

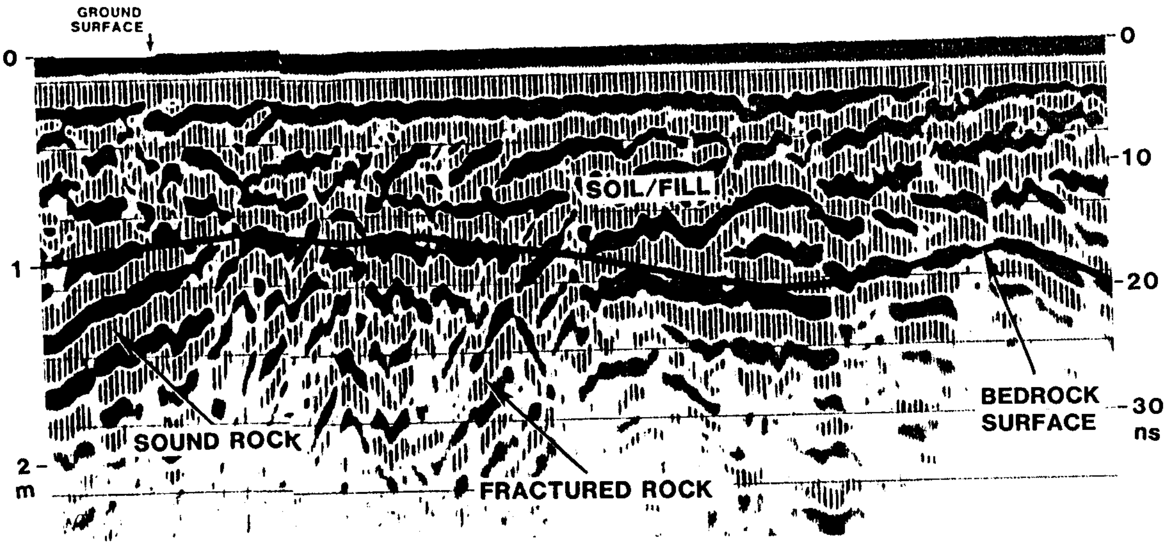


Fig. 8. GPR profile over an industrial site in New England showing depth to bedrock, and absence of suspected buried metal drums. Width of scan is 25 m. 300 MHz antenna, 75 ns range.

conductivity of contained minerals or water-filled fractures. Close inspection of outcropping strata along this profile showed the presence of abundant pyrite crystals in the rocks. The high conductivity of the pyrite-rich zones was detected by the GPR to clearly show the consistent dip of the beds below the ground. True dip in the area is about 30° to the northwest. An increased range setting or a slower traverse speed would have produced a more accurate depiction of the true dip.

Joints in gneissic bedrock

There is sometimes an element of serendipity in GPR work, because unexpected discoveries can often arise during surveys for something quite different. Fig. 10 shows a GPR profile on the surface of a shallow pond during an attempt to locate the depocenter of the water body prior to taking a core for a palynology project. While calibrating the antenna to obtain an appropriate depth setting, a very high range (700 ns) was initially

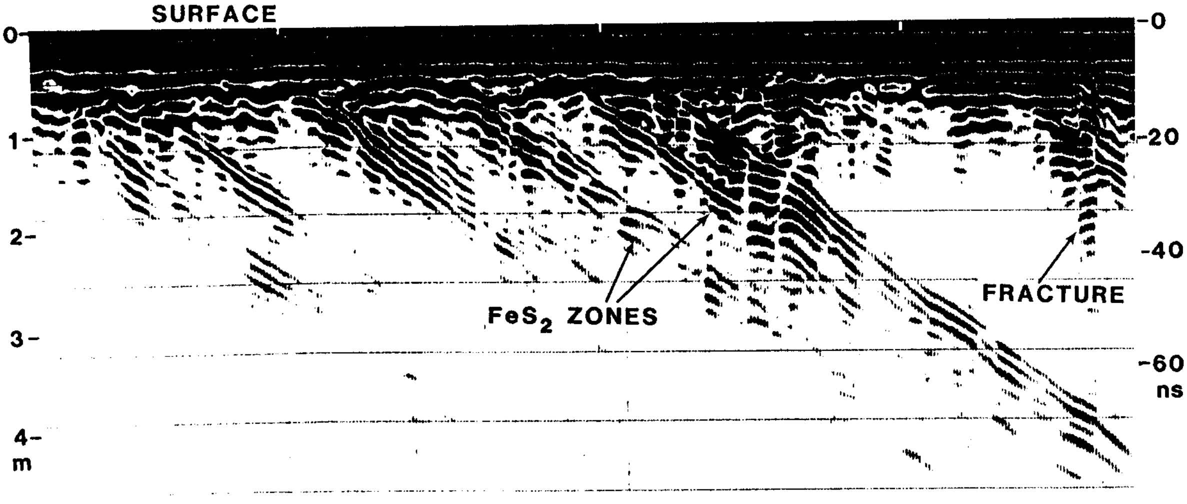


Fig. 9. GPR profile over a dipping carbonate bedrock in New York state. Width of scan is about 30 m. 100/300 MHz bistatic antennas, 100 ns range.

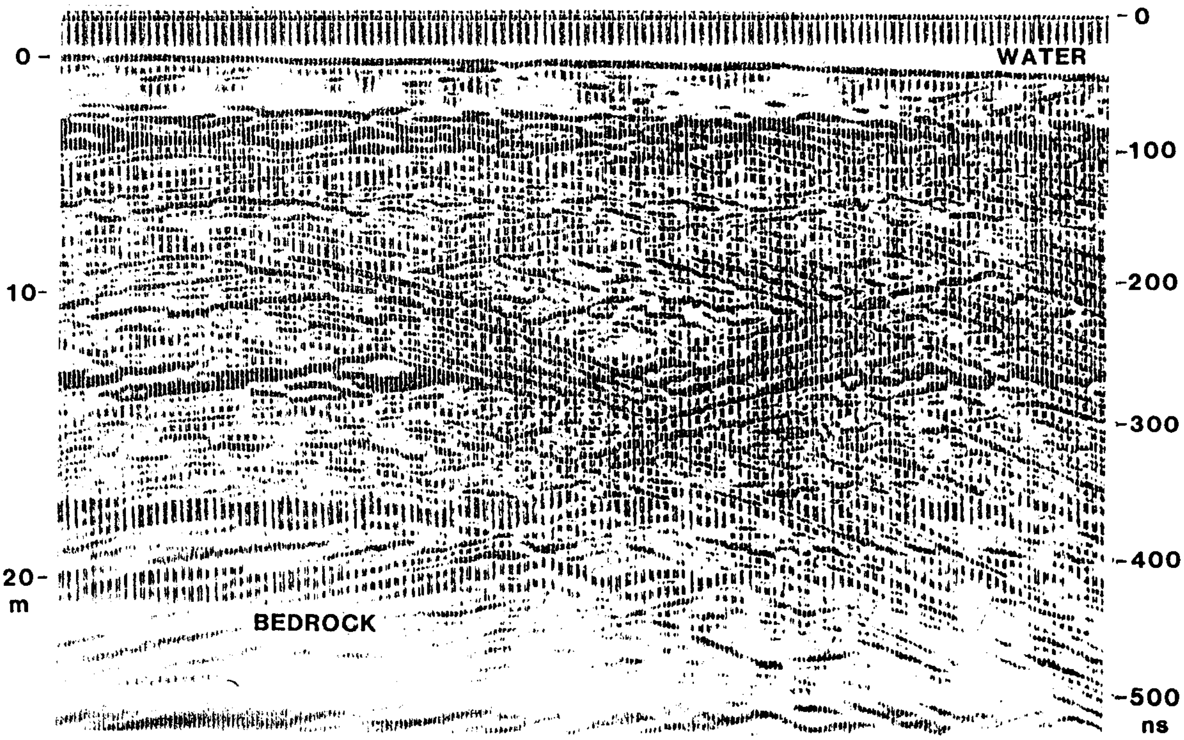


Fig. 10. GPR profile over bedrock below a shallow pond in New York state. Width of scan is about 20 m. 100 MHz antenna, 700 ns range.

set during a traverse over the pond. One surprising result was that the depth of penetration into the underlying bedrock extended to about 600 ns, corresponding to an estimated depth of about 25 m. Just on shore, penetration depth extended only to 1 m because of a clay-rich subsoil. Apparently the 0.5 m deep water column below the antenna acted as a lens, producing refractive gain (Ulriksen, 1982) and making the antenna serve more as a spotlight than a floodlight in illuminating subsurface features. This discovery suggests that a form of water lens might be placed under a transducer to heighten refractive gain in other GPR surveys.

The other obvious feature in the profile shown in Fig. 9 is the intersecting joint patterns in the gneiss, which was also clearly visible in nearby outcrops. Had the range settings and traverse speeds been different, the joints would have appeared as right angles on the printout, matching their true orientations in the field. The joints are visible in the profile because they contained water and because they may be mineralized. The ability of GPR to trace and map such potential zones of mineralization has applications in mineral prospecting.

4. Conclusions

GPR surveys can assist decision making in a number of fields in the earth sciences and engineering applications by enhancing our knowledge of subsurface features. In many of the previously cited examples, decisions had to be made about the internal characteristics of structures or below grade horizons in circumstances where "blind" drilling or excavation may have led to unanticipated or unwanted results, such as damage to the environment or risk to human life. The domain of GPR involves high-resolution mapping of the upper 2 m of the Earth's crust, a precariously thin layer but a supremely important horizon on our planet. Human civilization and all life on Earth are totally dependent on it. This thin layer is expected to provide food for the human population today and into the foreseeable future. We continuously ask this layer to store our wastes, filter our drinking water, and provide support for our civilization's infrastructure. GPR provides us with a technology to see into that layer, to learn about it, and to help to manage it.

Acknowledgements

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