POWER AND WATER AUTHORITY
WATER RESOURCES DIVISION

USE OF GROUND PENETRATING RADAR
FOR GROUNDWATER INVESTIGATIONS
IN THE NORTHERN TERRITORY

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SUMMARY

An assessment of the use of ground penetrating radar (GPR) for groundwater investigations was undertaken by the Water Resources Division during July and August, 1994. GPR surveys were undertaken at eight sites in the Northern Territory, which represented a variety of geological environments.

Ground penetrating radar proved to be very effective for mapping shallow stratigraphy in environments with low electrical conductivities (<10 mS/m). At East Alligator River Ranger Station, depths of investigation of up to 30 m were observed in highly resistive sandstone. For highly conductive ground, such as the black soil plains at Keep River and Howard East, depths of investigation were severely limited due to attenuation of the radar signal.

GPR proved to be very effective for locating sinkholes and caves in the Tindal Limestone near Katherine and locating fracture zones in the Kombolgie Sandstone at East Alligator River. The method also showed potential for mapping the bedrock surface beneath alluvial sediments, although the depth of investigation was limited when clays were present.

Reflections from large trees proved to be a major problem encountered during the surveys. These reflections created interference patterns which often dominated the signal and made interpretation difficult. Reflections from powerlines and vehicles caused similar interference patterns.

Further use of ground penetrating radar is warranted in environments where electrical conductivity is low. Future improvements in GPR technology will likely expand the range of suitable applications.
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1. INTRODUCTION

During July and August 1994, Ground Penetrating Radar (GPR) equipment was hired by the Water Resources Division, Power and Water Authority to evaluate the suitability of this technique for groundwater investigations in the Northern Territory. The technique has been successfully applied elsewhere for groundwater investigations, mapping of soils, location of hazardous wastes, geotechnical investigations, and archaeological studies.

Eight sites, representing a variety of geological environments, were chosen for the evaluation of ground penetrating radar. These are: Lake Woods (lacustrine sediments); Oenpelli water supply (paleochannel detection); East Alligator Ranger Station (fracture detection); Mount Bundey Training Area (fracture detection); Katherine (sinkhole detection in Tindal Limestone); Turkish Bath Cave (detection of underground voids); Keep River Plains (stratigraphy and conductivity); and Howard East Borefield (stratigraphy).

Since GPR is a relatively new technology, not previously used by the Water Resources Division, this project provided an opportunity to become familiar with the operation and interpretation of the technique. This report documents the results of the surveys and makes recommendations on the future use of Ground Penetrating Radar.
2. GROUND PENETRATING RADAR PRINCIPLES

2.1 The Ground Penetrating Radar Technique.
Ground penetrating radar (GPR) is a relatively new geophysical technique. A pulse of high frequency (10 to 1000MHz) electromagnetic energy is transmitted into the ground. The signal is then reflected from within the ground towards a receiver, as shown in Figure 1. The GPR method shares many similarities with the seismic reflection method. The output is a wiggle trace plot (radar section or radargram), identical to a reflection seismic section. Real-time processing allows the radar section to be viewed in the field during data acquisition. Most processing and interpretation methods for GPR have been adapted from those used in the seismic industry. A comprehensive outline of the GPR method is given by Scaife and Annan (1991).

2.2 Electrical Properties Affecting Radar Propagation.
The velocity of a radar wave is given by the expression:

\[ v = \frac{c}{\sqrt{K}} \]

Where \( v \) is the velocity of the radar wave, \( c \) is the speed of light (0.3m/ns) and \( K \) is the dielectric constant of the medium. The dielectric constant ranges from 1 in air to 80 in water. Most minerals have low dielectric constants (<4), but the presence of clay and water in rocks and sediments results in great variations of the dielectric constant. As with the seismic method, reflections are produced at an interface where there is a velocity contrast. Radar velocity usually decreases with depth (due to increasing water content), whereas seismic velocity increases with depth. As a result, subsurface refractions of the radar signal are deflected downwards and do not reach the surface. Therefore, there is not a radar equivalent of the seismic refraction method. Radar refractions will occur for a reflected signal impinging on the soil-air interface at the critical angle. The signal then travels as an air-wave (0.3m/ns) to the receiver. The transmitter and receiver should be located close together to avoid recording these refractions.

High electrical conductivity in the ground results in strong attenuation of the radar signal, limiting the effective depth of investigation. Therefore, GPR is not well suited to saline or clay-rich environments. The attenuation of the signal also increases with increasing dielectric constant or frequency. The attenuation, \( a \), in dB/m can be approximated by (Davis and Annan, 1989):
where $f$ is the radar frequency in Hz, $\sigma$ is the DC conductivity, $K'$ is the real component of the dielectric constant, $K''$ is the imaginary part of the dielectric constant and $\varepsilon_0$ is the free space permittivity. The dielectric constant, conductivity and attenuation for common geologic materials are listed in Table 1.

2.3 Depth of Investigation
At late two-way travel times, the amplitude of the signal is low due to spherical divergence and attenuation as described above. Stacking increases the signal-to-noise ratio, however when the signal can no longer be resolved from the background noise, the effective depth of investigation has been reached. Attenuation of the signal increases with frequency, so low radar frequencies are used where maximum depth of investigation is desirable. At higher frequencies the effective depth of penetration is much less, but the shorter wavelength allows greater resolution of the layering. Attenuation of the signal also increases with electrical conductivity limiting the depth of investigation in conductive terrain.

2.4 Reflection Profiling
Most GPR surveys are undertaken to map the subsurface stratigraphy. Reflection profiling is conducted by fixing the transmitter - receiver separation and moving the GPR over the ground so that a section showing two-way travel time versus antennae position is obtained.

The depth to reflectors can be calculated using an estimate of the radar velocity. This velocity can be obtained from a CMP sounding, but more often a typical velocity for the type of geologic material is used. Due to high velocity of the radar waves, the time window for each trace is usually less than 1ms, and several hundred traces can be stacked in less than a second. This allows the survey to be run continuously at a walking pace.

2.5 Common Mid Point (CMP) soundings
To determine the velocity of the radar signal in the ground, a common mid-point (CMP) sounding is often performed. The separation between the antennae is progressively increased so that a plot of two-way travel time versus antennae offset is produced. Velocity analysis, a technique developed for seismic CMP interpretation, is then used to estimate the velocity of the reflectors. The velocity of the air and ground waves can also be determined from the CMP.
2.6 GPR Equipment.

The system used in this study was a PulseEKKO IV GPR manufactured by Sensors and Software and hired from GeoInstruments in Sydney. Hire costs are $2500 per week for the 200/100 Mhz GPR and $3000 per week for the 100/25 Mhz (high power) GPR. The system, shown in Figure 2, consists of a transmitter and receiver connected to a console by fibre-optic cables. The GPR was supplied with 25 and 100MHz antennae, but 12.5, 50, and 200MHz antennae are also available. The console is controlled by a notebook computer via an RS-232 interface. The system is supplied with software for editing, plotting, converting data formats, synthetic radargrams, Common Mid Point (CMP) interpretation, and depth/range calculations.

For reflection profiling, the transmitter and receiver were spaced 0.91m apart on a PVC sled towed 15m behind a quad bike (Figure 3). Tests proved that the air-wave reflection from the quad bike was not detectable at a distance of 15m. The computer and GPR console were mounted on the quad bike. A tire rotation counter was used to measure the distance traversed. With this configuration, data could be acquired at a rate of up to 2km/hr, with station spacing of less than 1m.

2.7 Gains and Filters.

The software provides four different types of gain:

AGC (Automatic Gain Control)
- gain is inversely proportional to signal strength
- does not preserve relative amplitudes

SEC (Spreading and Exponential Compensation)
- exponential function to compensate for spherical spreading and attenuation
- same for all traces so relative amplitudes preserved

Constant Gain
- constant multiplier for each data value

User Defined Gain
- linear gain function designed by user.

Three types of filters are available (Sensors and Software, 1993):
a) Trace-to-trace (spatial low pass filtering) averaging,

b) Down the trace (temporal) averaging and

c) trace-to-trace differencing (spatial high pass filtering).

2.8 System Noise.
System noise, most often originating from the transmitter, was observed at late arrival times when the reflected signal was low in amplitude. This can be recognised as low frequency coherent noise slightly higher in amplitude than background random noise, as illustrated in Figure 4. Use of an Automatic Gain Control (AGC) function to display the data should be avoided so as not to amplify this noise. The Spreading and Exponential Compensation (SEC) gain function is more appropriate for displaying radar data since it is constant for all traces.

2.9 Interference from Vehicles, Fences, and Power Lines.
Metallic objects above the ground surface such as vehicles, buildings, fences and power lines return strong air wave reflections that may dominate the signal and mask subsurface reflections. In Figure 5, data were acquired while moving a Toyota Troop Carrier and a quad bike away from the radar system. For the Troop Carrier, strong reflections can be identified at up to a distance of 75m. This vehicle would be unsuitable for towing the GPR, unless only shallow depth of investigation is required or if a very long tow rope used. The quad bike, being much smaller did not produce detectable reflections. Buildings, fences, and power lines produce responses similar to a large vehicle. The interference is easily identified as a hyperbola with limbs sloping at 0.15m/ns on the radar section. This slope results from the radar signal returning through air at the speed of light (0.30 m/ns). This interference is also characterised by narrower wavelets due to the higher frequency content of air waves.

2.10 Reflections from Trees.
Reflections from trees were observed in many surveys. The reflections are strongest from tall trees with a large leaf area. The response is easily recognised as it forms a hyperbola similar to that of power lines, but of weaker signal strength, as shown in Figure 6. The effect is greatest in areas of high conductivity where the antenna pattern emits more energy upwards (Turner, 1992). Modifications to the antenna design such as shielding or phased arrays could be used to reduce this problem, although this was not attempted on this project. Annan et al. (1988) placed radio-frequency absorbing material around the antennas to reduce spurious signals for radar profiling in an underground mine.
2.11 Underground Cables and Pipelines.

Underground services such as cables and pipelines can be detected by GPR. These are seen as large amplitude signals which attenuate rapidly laterally when compared to surface objects, such as fences, due to the absorption of the signal in the ground. The radar section obtained over an underground high voltage cable is shown in Figure 7.
3. PREVIOUS APPLICATIONS OF GROUND PENETRATING RADAR

There are many examples of GPR applications in the literature. A selection of previous studies that are relevant to groundwater applications in the Northern Territory is described below. Other examples are given in Davis and Annan (1989) and Scaife and Davis (1991).

3.1 Saline intrusion: Norway.
Soldal et al. (1994) carried out GPR surveys to map the boundary between fresh and saline groundwater in two fjord delta aquifers in western Norway. The depth of penetration of the GPR is limited by the depth to saline water, as shown by the radar section in Figure 8a. The penetration depths obtained from a grid of GPR lines was used to plot the contour map shown in Figure 8b. The interpretation was then used to optimise the location of abstraction wells.

3.2 Water table mapping: The Netherlands.
GPR surveys were used by van Overmeeren (1994) to locate a deep water table in dipping sandy sediments. The 25MHz radar section, shown in Figure 9, clearly identifies the water table at 30m elevation as a strong reflection. To the south, where the surface elevation is higher, this reflection is not continuous due to the investigation depth limit being reached. The greatest depth at which the water table could be detected was 42m, based on a velocity of 0.145m/ns.

3.3 Locating karstic zones: Switzerland.
Robert and de Bosset (1994) investigated the use of GPR to locate sinkholes on a building site. A typical response obtained over a karstic zone is shown in Figure 10. Sinkholes can be identified by a series of truncated hyperbolic reflections which can be observed only when the GPR is nearly directly above. Subsequent drilling confirmed 88% of the sinkholes located by GPR. The method was therefore very effective in locating the sinkholes.

3.4 Mapping alluvial and lacustrine sediments: Connecticut.
Beres and Haeni (1991) used GPR to study stratified sediments at several sites in Connecticut. These included a borefield, a gravel pit, a river and a lake. Penetration depths (at 80MHz) ranged from 7m in fine-grained lacustrine sediments to 21m in coarse sand and gravel. A radar section produced across Mansfield Hollow Lake is shown in Figure 11. To profile beneath the lake, the GPR was mounted in two canoes. The interpreted lithologies were verified by drilling.
3.5 Mapping fractures in plutonic rocks: Manitoba, Canada.
GPR was used by Stevens et al. (1995) to map fractures in granitic and gneissic rock as part of a study to find a suitable location to store nuclear waste. A radar section acquired at a frequency of 25MHz over a granite outcrop is shown in Figure 12. The fracture zone can clearly be seen at a depth of 40 to 50m depth. The GPR proved to be an effective method for mapping the continuity of fractures for hydrological studies.

3.6 Discussion.
The studies reviewed above illustrate the wide range of applications to which GPR is being applied. In the Northern Territory, investigating saline intrusion in coastal areas, monitoring seasonal changes in the water table, locating sinkholes in the Katherine area, mapping alluvium thickness, investigating lacustrine sediments at Lake Woods and locating fractures for water supplies are applications to which these studies are relevant. As GPR becomes more widely used and the technology improves, there will no doubt be many more groundwater applications developed.
4. RESULTS OF GPR SURVEYS IN THE NORTHERN TERRITORY

GPR surveys were carried out at a several sites in the Northern Territory. Due to the large amount of data acquired, only a portion of the data is presented below.

4.1 Lake Woods, Elliott.
Des Yin Foo of the Power and Water Authority, and Karl-Heinz Wyrmoll of the University of Western Australia are undertaking a study of the paleohydrology of Lake Woods (PAWA/WRD Project RMD 5529). Geomorphological evidence suggests that Lake Woods was much larger in areal extent during the past 500,000 years. The variations in lake extent have produced a complex series of lake sediments, dune structures and prior shorelines. Recharge to the deep aquifers occurred during these lake extensions. These events were separated by long dry periods in which very little recharge occurred. As part of this study, six lines of GPR data were acquired near Lake Woods, located as shown in Figure 13, with the purpose of investigating the shallow stratigraphy in the Lake Woods area.

4.1.1 Lake Woods Line 1.
Line 1 traversed westwards up slope from a previous lake bed. The radar section acquired at 100MHz is shown in Figure 14. The main feature is a reflection that deepens from 2 to 3.5m (0.12m/ns velocity) when moving uphill from station 80m to 140m. This is interpreted to be an earlier lake bed. After 50ns the signal contains reverberations, system noise and reflections from trees. Therefore, the maximum depth of investigation is limited to about 3.5m due to conductive clays. Using the 25MHz antenna, as shown in Figure 15, results in lower resolution of the layering although the maximum depth of investigation is increased to 10m.

4.1.2 Lake Woods Line 2.
Line 2 was acquired to map the extent of a calcrete layer deposited on a prior lake shore. The 25MHz radar section acquired is shown in Figure 16. The calcrete layer, at a depth of about 5m, exhibits a strong reflection that disappears, 40m to the north, indicating the extent of the layer. Moving uphill to the north, the thickness of sediment above the calcrete layer increases. The maximum depth of investigation is approximately 10m, due to conductive clays.

4.1.3 Lake Woods Line 3.
The 25MHz radar section for line 3, shown in Figure 17, traversed a large dune to the west of Lake Woods. The GPR located an erosional surface at 8m depth near bore RN29271. The stratigraphy for the
bore is 7.5m of sand overlying 16m of sandy clay. The strong reflection (with multiple reflections) from this clay layer, and high absorption of the signal penetrating the clay, limits the depth of investigation to the sand-clay interface. Moving downhill to the south, this interface becomes shallower as does the investigation depth.

4.1.4 Lake Woods Line 4.
Line 4 was acquired at bore RN29270 where 7.75m of lime-sand and clay overlies 10m of lime and quartz sand. Very little change in structure is evident in the 25MHz radar section shown in Figure 18. The reflection at 120ns corresponds to the clay/sand interface beyond which only system noise is present, indicating a maximum depth of investigation in the order of 10m. A CMP acquired for line 4, shown in Figure 19, clearly illustrates the shallow penetration and the domination of the signal with system noise at late arrival times. The CMP also clearly identifies the ground-wave, air-wave, reflected subsurface waves and refracted waves.

4.1.5 Lake Woods Line 5.
Line 5 was acquired to map the subsurface while traversing from the shallow Proterozoic sandstone of the Ashburton Range, onto the lake deposits of Lake Woods. In the 25MHz radar section shown, in Figure 20, the western boundary of the Proterozoic rock is marked by the sudden disappearance of the strong 100ns reflection at the 165m station. Maximum depth of investigation is less than 10m due to high electrical conductivity.

4.1.6 Lake Woods Line 6.
Line 6 was acquired near Bore RN29272. A portion of the 25MHz radar section, shown in Figure 21, is strongly affected by interference from fences at the 70m station. A 20ns rise near the 120m station may indicate a sand bar at approximately 10m depth. After 300ns the signal is dominated by coherent noise originating from the laptop computer which was close to the receiver during this survey. The maximum depth of investigation is about 15m.

4.1.7 Discussion.
The GPR results obtained at Lake Woods did demonstrate the ability of the method to map subsurface stratigraphy. The main limitation for GPR was the shallow penetration depth due to the high electrical conductivities of clay-rich sediments. An electromagnetic survey would be useful in identifying areas of high electrical conductivity. Higher frequency (100 and 200MHz) GPR surveys may be useful in resolving the finer structures in the top 2 metres of lake deposits.
4.2 Oenpelli Water Supply.
A GPR survey was undertaken to assist in determining additional bore locations for the Oenpelli community water supply. The Kombolgie sandstone is a poor aquifer, so the primary objective was to locate paleochannels filled with alluvium that might contain a water supply. Determining the lithology from drill cuttings is difficult because the alluvium has derived from the underlying weathered and fresh Kombolgie Sandstone. This makes it difficult to determine the placement of screens in production bores. Seismic refraction surveys had been carried out to the west of the present study area to determine the thicknesses of alluvium and weathered Kombolgie Sandstone (Furness, 1984). The GPR survey was proposed as an efficient method of obtaining alluvium thickness. Reflections would be expected from the top of the weathered sandstone and the top of the fresh sandstone since the porosity difference at each interface creates a dielectric contrast. The locations of the GPR lines, GPR located paleochannels, and bores are shown in Figure 22. Several bores had been drilled previously in the study area, with an additional 32 bores drilled after the GPR survey.

4.2.1 Oenpelli Line 1.
A portion of the 100MHz radar section for line 1 is shown in Figure 23. Surficial sediments are indicated by the horizontal layering, while bedrock is seen as an irregular surface. Reflections from below the bedrock surface are not detected due to signal attenuation. Maximum depth of investigation is about 7m.

4.2.2 Oenpelli Line 2.
Line 2 was acquired on the alluvium below the waterfall. The 100MHz radar section, shown in Figure 24, indicates a sequence of horizontal layered sediments to a depth of about 5m, underlain by weathered and fresh sandstone.

4.2.3 Oenpelli Line 3.
Line 3 was acquired on the track to the waterfall. A portion of the 100MHz radar section for line 3 is shown in Figure 25. The westwards dipping reflection is interpreted to be the bedrock surface. The depth of investigation is limited to 5m due to high electrical conductivity.

4.2.4 Oenpelli Line 4.
Part of the 25MHz radar section for line 4 is shown in Figure 26a. The corresponding 100MHz radar section for Line 4 is shown in Figure 26b. The bedrock surface can be distinguished from the overlying alluvium. Previous drilling encountered sandstone at 5.9m in Bore RN23251 (550N) and 11.1m in production bore RN23253 (910N). Both of these bores agree with the interpreted depth to bedrock. The aquifer at RN23253 is coarse sand at 9.1 to 11.1m depth. This sand onlaps the bedrock surface at 810N.
limiting exploitation of the aquifer to the south-east of the production bore. The interpreted 8m deep paleochannel at 650N was tested by drilling bore RN29557. Sandstone was encountered at 6m depth beneath sand and clay alluvium. The difference between the actual and interpreted depth is likely due to the uncertainty in the radar velocity of the alluvium. This paleochannel proved to be too shallow to provide a source of water. The production bore extracts water from depths greater than 9m.

4.2.5 Oenpelli Line 5.
Part of the 25MHz radar section for line 5 is shown in Figure 27. A slight deepening of the bedrock surface to 10m (using a velocity of 0.12m/ns) can be seen at the 110m station. At bore RN29279, weathered Kombolgie Sandstone was encountered at 6m depth, confirming the interpretation. Maximum depth of investigation is about 12m.

4.2.6 Oenpelli Line 6.
The 25MHz radar section for line 6, shown in Figure 28, is very similar to line 5. The alluvium can be seen to on-lap the weathered bedrock surface. The lowest reflection is due to fresh bedrock. Bedrock (Dolerite) was encountered at 10m depth in bore RN29298 and at 11m depth in bore RN29299, correlating well with the depth to fresh bedrock estimated on the radar section.

4.2.7 Oenpelli Line 8.
Part of the 25MHz radar section for line 8 (line 7 was not acquired) is shown in Figure 29. The main feature is the gently-folded shallow bedrock to the north-east, and the two narrow features interpreted as erosional channels in the bedrock. They are not prospective aquifers since they are too narrow, too shallow and the strong multiple reflections suggest that they may be clay-filled. A 100MHz survey would provide more detail on the nature of these channels. Also evident is the interference from trees and the limited depth of investigation of about 10m.

4.2.8 Oenpelli Line 9.
A portion of the 25MHz radar section for line 9 is shown in Figure 30. The feature at station 100m is due to a buried water pipeline. There is also interference from power lines and trees along this line. Depth to bedrock is interpreted to be less than 5m with the depth of investigation limited to about 10m.

4.2.9 Discussion
Of the twelve paleochannels interpreted from the GPR survey, only five were tested by drilling. Three of the most prospective paleochannels were not tested. Most of the other bores drilled after the GPR survey were located using air-photo interpretation, but this proved to have a poor success rate with only
4 production bores and 4 monitoring bores resulting from the total of 32 bores drilled (Wallis, 1994). Drilling of all the GPR targets would have been desirable in order to properly evaluate the success of the method. The advantage of acquiring a radar section at 25 and 100MHz was clearly illustrated on line 4, and future surveys should make use of more than one frequency. In addition, closely spaced parallel GPR surveys should be utilised to define the true width, direction and extent of the paleochannels. The shallow depth of investigation in conductive terrain and interference from trees also limited the success of the GPR survey at Oenpelli.

4.3 East Alligator Ranger Station, Kakadu National Park.

A pole-dipole resistivity survey was carried out by the Water Resources Division in 1993 at East Alligator River Ranger Station (Karp, 1994). The production bores (RN23449 and RN23450) are located in fractured Kombolgie Sandstone. The aim of the resistivity survey was to site an additional production bore on the same fracture system. The bore (RN29010) intersected narrow fractures at 50 to 60m depth and returned an air lift of 1.5 l/s. The production bores have much higher yields since they intersect wider fractures at shallower depth (25m). It was hoped that bore RN29010 would intersect fractures at a similar depth, resulting in a higher yield. The resistivity survey was not successful at locating a high yield bore because it could not accurately locate the position and depth of fractures.

The Kombolgie Sandstone has low primary porosity and is highly resistive. Near-surface apparent resistivities are often greater than 10,000 ohm-m, resulting in low attenuation and large depths of investigation for a radar signal. A GPR survey was conducted on line 2, near bore RN29010 and on line R1, near the production bores, to evaluate the potential of locating fractures and faults in a resistive environment. These location of these lines and the previous resistivity survey are shown in Figure 31.

4.3.1 East Alligator Line 2.

The 25MHz radar section past bore RN29010 (1 l/s), and the corresponding pole-dipole resistivity profile is shown in Figure 32. Due to the low electrical conductivity, a depth of investigation of up to 30m was observed for the GPR survey. The red clay layer encountered at 21.3m depth in the bore can be seen as an eastwards dipping reflector. It is likely that high conductivity of this clay layer is the cause of the resistivity low on which the bore was originally sited. Discontinuities of reflectors east of the bore are interpreted as faults, which would be better prospects for a water supply.

4.3.2 East Alligator Line R1.

The 25MHz GPR survey acquired along the road past the production bores (RN23449 and RN23450), shown in Figure 33, indicates faulting near the bores. Higher electrical conductivity along this line...
reduces the depth of investigation to less than 20m.

4.3.3 Discussion
Due to the low electrical conductivity, the survey was successful in defining the stratigraphy to a depth of over 30m. However, a survey at a higher frequency (100Hz) and closer spacing, would have better defined thin layering and structures within the alluvium and sandstone. By providing detail of the subsurface structure, GPR can locate faults and fracture zones.

4.4 Southern Road Site, Mount Bundey Training Area.
A GPR survey (Figure 34) was acquired on Mount Bundey Training Area with the aim of siting a road construction bore. Previous bores in the area are located in fracture zones within shale, and it was hoped that the GPR would detect a fracture zone. The 25 MHz radar section, shown in Figure 35, indicates conductive ground as the signal consists of noise or reflections from trees beyond 150ns. There is some indication that depth to bedrock may vary 0 to 5m. A 100MHz GPR survey may have been useful in defining the bedrock surface. At Bore RN29440, 36m of weathered red shale was found to overlay 32m of grey shale. The bore returned an airlift of only 0.3 l/s. GPR was therefore not an appropriate technique for locating fractures in this shale due to the poor signal penetration.

4.5 Sink Hole Detection, Katherine.
An extensive GPR survey (27 line km) was carried out at a construction site near Katherine to locate shallow sinkholes. GPR has been used successfully elsewhere for cavity detection (Turner et al., 1993, Robert and de Bosset, 1994). Previous methods used to detect sinkholes in the Katherine area included microgravity and resistivity surveys, but these are slow and costly methods (Cresswell, 1988).

A typical GPR sinkhole response obtained during the survey is shown in Figure 36. Note that the sinkhole can be detected only when the GPR is nearly directly above it. The response attenuates laterally due to absorption of the radar signal in the ground. In contrast, the response from surface features such as trees and power lines does not attenuate rapidly since the signal travels through the air.

A station interval of less than 1m and a line spacing of 5m was used to detect sinkholes in the survey area. When the locations are plotted on a map, it is evident that the sinkholes are situated along northwest trending linear fractures, as shown in Figure 37.

A detailed section across a sinkhole, shown in Figure 38, was acquired using a station interval of 0.25m.
to illustrate the benefit of using closely spaced data points. Subsequent excavation indicated these
sinkholes to be at a depth of 2 to 3m. Two-dimensional radar modelling, which has recently been
developed (Cai and McMechan, 1995), would be useful in determining the size and type of fill (whether
empty, water or soil filled) of a sinkhole. Previous excavations are easily distinguished from sinkholes
as they are relatively shallow and the fill used after excavation is visible on the radar section.

Figure 39 is a 25MHz radar section acquired across the sinkholes. The depth of investigation is increased
to 20m, but the individual sinkholes cannot be identified due to the lower resolution at the longer
wavelength. Assuming the wavelength of radar signal in limestone is 4m at 25MHz and 1m at 100MHz,
this would indicate that the diameters of the sinkholes are between 0.5 and 2m if 1/2 wavelength is used
as the resolution limit (Beres and Haeni, 1991). The undulating reflections across the sinkhole zone in
the 25MHz radar section may be indicative of karst.

4.6 Turkish Bath Cave, Katherine.
A GPR survey was undertaken at Turkish Bath Cave, Cutta Cutta Nature Reserve, 25 km south of
Katherine to evaluate the ability to detect large voids. A plan of the Turkish Bath Cave is shown in
Figure 40.

The 100MHz radar section for line B, shown in Figure 41, detected the upper and lower chambers of the
cave. The 100MHz radar section for line D, shown in Figure 42, detected 3 underground voids that
correlate with the position and depth with the mapped passages in the cave. An extensive grided survey
would be useful in mapping out the cave system.

4.7 Keep River Plains.
A 25MHz GPR survey consisting of three lines, located in Figure 43, was conducted on the Keep River
Plains near the border of the Northern Territory and Western Australia. This area is under consideration
for an expansion of the Ord River irrigation system. The Water Resources Division is undertaking a
study to determine the subsurface hydrology and hydrogeology of the Keep River Plains (Humphreys
et al., 1995). An airborne Transient Electromagnetic (TEM) survey has been completed over the area,
as well as drilling to determine the distribution of salt storage in the Keep River Plains. The purpose of
the GPR survey was to evaluate the method in highly conductive surface conditions and to compare the
results with conventional EM methods.

Due to the high electrical conductivities near the surface (> 50mS/m), the depth of investigation for the
GPR was limited to less than 7m at 25MHz. Very little structural variation could be identified on the GPR section for line 5, a portion of which is shown in Figure 44. At bore RN25201 (3000m station) the lithology is 3m of black soil, underlain by 3m of sandy clay and 17m of sand and gravel. To the east at station 1700m, the lithology at bore RN29665 is 1.7m of black soil, underlain by 5.2m of red clay and silt and 10.8m of sand and gravel. The discontinuous reflection on the radar section corresponds to the base of the black soil. The amplitude of this reflection is dependent on the clay content of the underlying layer. In areas of low clay content, the reflection is weak or absent due to the low dielectric contrast with the overlying black soil. Lower clay content also results in a higher radar velocity and lower attenuation through the layer, resulting in an earlier arrival time and stronger amplitude for the reflection from the top of the underlying sand and gravel.

The corresponding EM-31 apparent conductivity profile does not correlate well with the radar section, likely because the electromagnetic response is influenced more by groundwater salinity than the conductivity of the unsaturated zone. The EM-31 has an investigation depth of 6m, which is below the depth of the GPR investigation. Bulk electrical conductivity, soil electrical conductivity, and total gamma logs for bore RN29665 are shown in Figure 45. The water table is at a depth of approximately 10m, which is below the depth of investigation of the GPR in this conductive environment. For the purposes of the Keep River study, the EM survey was found to be much more suitable for mapping paleochannels and saline groundwater.

4.8 Howard East Borefield, Howard Springs.

During investigations at the Howard East Borefield in the 1980s, extensive seismic and resistivity surveys were conducted by the Water Resources Division. The seismic survey was conducted with a geophone spacing of 28m and a shotpoint interval of 336m. The pole-dipole survey had a current electrode - potential electrode spacing of 200m. These surveys were designed to profile to depths of over 100m, and are not comparable to the shallow information provided by the GPR. Howard East was chosen as a calibration site for future GPR surveys due to the availability of bore data and the close proximity to Darwin.

A 25MHz GPR survey was conducted on line 1 of Benham's Lagoon Grid as located in Figure 46. For the majority of the survey, the depth of investigation is less than 7m due to high electrical conductivity, although 20m depth was achieved at two localities. A portion of the radar section is shown in Figure 47. The lithologies of bores RN21765 and RN21398 conform to the interpretation of a 20m deep paleochannel infilled by sand and clay. A 100MHz GPR survey at this location would better define the shallow stratigraphy.
5. CONCLUSIONS

Overall, the results obtained with ground penetrating radar (GPR) were encouraging. The Lake Woods GPR survey successfully identified the stratigraphy in the top 10m. The Oenpelli Water Supply survey demonstrated the ability of GPR to map the bedrock surface, although the drilling program did not test all of the paleochannels that were identified. For the survey at East Alligator, depths of investigation of up to 30m were observed, and the location of faults and fractures could be determined. The detection of sinkholes and caves near Katherine was highly successful, due to low electrical conductivities and the high dielectric contrasts between the sinkholes and limestone. The surveys at Keep River, Mount Bundey Training Area and Howard East were of limited success, with depths of investigation of less than 5m due to high electrical conductivity.

By mounting the GPR on a sled, data could be obtained at a rate of up to 2km/hr. Another advantage is that the radar section is created as the data is acquired, allowing the data to be interpreted in the field. The data is automatically stored on a computer, simplifying the task of processing and plotting. In many cases, GPR may be the preferred alternative to a shallow seismic survey, due to lower acquisition and processing costs.

The major disadvantage with GPR is that the depth of investigation is limited in conductive ground. In addition, the interference from trees can confuse the interpretation, although modifications to the antennae could suppress these air-wave reflections.

For future groundwater projects, GPR should only be considered where the depth of investigation is less than 30m and electrical conductivities are low to moderate (<10mS/m). This could be determined by first carrying out an EM survey. GPR surveys should be conducted at low and high frequencies (i.e. 25 and 100MHz) so that both depth penetration and resolution of the layering are achieved.

Further evaluation of GPR is warranted for karst investigations, fracture detection in highly resistive sandstone and mapping alluvial thickness. Geotechnical projects, such as road construction, could also benefit from a radar survey.
6. ACKNOWLEDGMENTS

The data presented in this report was gathered with the assistance of Justin Anning, Gary Humphreys, Paul Schober and Chris Walton of the Water Resources Division, Power and Water Authority.
7. REFERENCES


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site? Exploration Geophysics. v24, 819-832


Subiaco, Western Australia.
### TABLE 1. Typical Dielectric Constant, Electrical Conductivity, Velocity and Attenuation Observed in Common Geologic Materials at 100MHz (from Davis and Annan, 1989).

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>$\varepsilon$ (m$^3$/m$^2$)</th>
<th>$\sigma$ (mS/m)</th>
<th>$v$ (m/ns$^{-1}$)</th>
<th>$\alpha$ (dB/m)</th>
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<td>Air</td>
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<td>0</td>
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<td>0.5</td>
<td>0.033</td>
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<tr>
<td>Sea Water</td>
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<td>0.011</td>
<td>$10^{-3}$</td>
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<td>0.01</td>
</tr>
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<td>Saturated Sand</td>
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<td>0.03-0.3</td>
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<td>0.12</td>
<td>0.4-1</td>
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Figure 1. Field operation of Ground Penetrating Radar (a) and resulting radar section (b). From Davis and Annan, 1989.
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Explored, surveyed and tagged July 1974 by Graeme Pattison, Helen Wallis and Dick Legge, to Oud 2. Drawn by Graeme Pattison, scale 1:200

$\&$: denotes unexplained rock markings

K30 Turkish Bath Cave
Katherine, N.T.

UTM 225734 E +/- 100m
8386305 N +/- 100m

Figure 40. Plan of Turkish Bath Cave, Cutta Cutta Nature Reserve, showing location of GPR lines. From Cresswell, 1988.
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