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Ground Penetrating Radar in the Detection of Subsurface Cavities Related to Sinkhole Activity in Florida

Marianne Sweeney
University of Central Florida

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GROUND PENETRATING RADAR
IN THE DETECTION OF SUBSURFACE CAVITIES
RELATED TO SINKHOLE ACTIVITY
IN FLORIDA

BY

MARIANNE SWEENEY
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RESEARCH REPORT

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ABSTRACT

The Florida peninsula is underlain by limestone undergoing a continuous solution process resulting in subsurface cavity formation. Increased land development has led to costly structural damage and water supply contamination due to surface subsidence and collapse in areas overlying such cavities. Conventional drilling methods cannot guarantee detection of isolated cavities. A geophysical technique known as ground penetrating radar (GPR) is a non-destructive method in geotechnical investigation capable of surveying large areas quickly and efficiently. GPR works as an echo sounder with a continuous similar graphic display. Cavities are identified by hyperbolic patterns caused by reflections from variations in electrical properties of anomalies as compared to the surrounding material. Due to irregular variations and inconsistencies in the properties of naturally deposited soils and rocks, interpretation of the result from a radar survey is difficult to pre-determine without an actual field investigation.

The intent of this study is to determine those circumstances under which GPR can be of use in subsurface cavity detection investigations. The results indicate that subsurface conditions in north and central Florida are generally favorable and that this method can be extremely useful in determining trends in subsurface erosion.

ACKNOWLEDGEMENTS

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In addition, the writer is thankful for the STAR research grant which made this research possible.

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NOMENCLATURE

Symbol	Description
A	attenuation (decibels/meter)
c	speed of light ($\cong$ 1 ft/nsec)
D	depth (feet)
E_r	angle of reflection
E_0	angle of incidence
ε	dielectric constant
ε_0	dielectric constant of free space = 88.50×10^{-2} farads/meter
f	frequency (MHz)
r	reflection coefficient
σ	conductivity (mhos/meter)
t	two way travel time (nsec)
V	propagation velocity (feet/nsec)
w	angular frequency = $2\pi f$

CHAPTER I

INTRODUCTION

An aerial view of Florida shows a landscape dotted with lakes formed by sinkholes over thousands of years. This karst topography is typical of areas underlain by soluble limestone. Chemical erosion of the limerock results in subsurface cavities which eventually collapse or become filled by ravelling of overlying material. The result of localized areas of subsidence over these cavities are the karst features known as sinkholes.

Problems associated with subsurface cavities and sinkholes such as foundation failures and losses of buildings and equipment, damage to utilities and roadways, failures of dams and containment ponds, groundwater contamination, and general subsidence (Army, 1970) cause thousands of dollars in damage every year. This damage can be avoided by detection of subsurface cavities prior to construction. Information on the location and extent of the cavity involved is necessary so that the cavity can be filled or the structure moved away from the site.

Close interval drilling or total excavation are conventional methods of cavity location. Closely spaced boreholes often fail to reveal buried cavities encountered during construction, and both methods are expensive and time consuming.

Several geophysical methods have been used in subsurface exploration. Gravity, seismic, electrical resistivity, magnetic, and electromagnetic techniques have all been tested with some degree of success. However, none of these methods can be applied successfully to all subsurface conditions.

The technique of transmitting electromagnetic waves into the earth and monitoring the reflected signal referred to as ground penetrating radar (GPR) is becoming an increasingly accepted method of geophysical investigation. A continuous record of subsurface strata is obtained by pulling a radar antenna over the ground surface. Electromagnetic impulses are continuously transmitted into the ground from the antenna and their reflections received by the same antenna. The reflected signals are processed by the control unit and graphically recorded on a strip chart. The hyperbolic reflection signal characteristics of subsurface cavities make their detection relatively simple under ideal conditions.

Operating principles of GPR are similar to those of aircraft and marine surveillance radars, with the major difference being the low frequencies required to achieve practical depth penetration ranges and wide signal bandwidths necessary for useful resolution of subsurface features. An antenna towed along the ground surface radiates low frequency electromagnetic (EM) pulses into the earth. Changes in electrical properties of subsurface materials cause the transmitted pulse to reflect back and be received by the same antenna which is used to transmit the signals. Changes can be due to differences in soil composition, density, or moisture content. Cavities filled with air, water, or soil cause a reflection of the radar signal because of the variation of electrical properties. A continuous record of interface reflections versus pulse travel time is generated by a strip chart recorder, similar to the display of an echo sounder. If the velocity of the pulse through the material is known, travel time can be converted to distance, and depths to various subsurface interfaces can be determined.

The success of a radar scan is limited by the penetration depth which can vary from just a few feet to a hundred feet or more. Penetration capabilities are dependent on the frequency of the antenna and the electrical conductivity of the earth materials involved. An 80 MHz antenna is used to achieve greatest penetration, while a 300 MHz antenna provides better resolution of shallow features.

Electrical properties of earth materials are dependent on water content, temperature, pressure, and impurities. Since the natural conditions of soils and rocks vary greatly, it is difficult to estimate the penetration depth of the radar signal before a survey is actually conducted. In some areas substantial penetration allows detection of subsurface strata, but in other areas maximum penetration is limited to a few feet from the surface. Typical penetration ranges from about 50 meters in resistive materials such as sands, gravels, bedrock, and fresh water, decreasing to about one meter in conductive materials such as fine-grained clays and seawater (NWWA, 1984).

Under a STAR grant to Florida Sinkhole Research Institute (FSRI), a study was conducted to determine local conditions in which ground penetrating radar can provide useful information about subsurface features, as well as those conditions where penetration is insufficient for cavity detection. Numerous field investigations were conducted throughout central and north Florida under a diverse range of conditions with varying results using the Surface Interface System (SIR) manufactured by Geophysical Survey Systems, Inc., (GSSI), Hudson, New Hampshire.

During the period of research study, the original System 4 was upgraded to the more sophisticated System 8 model, modified to provide better results. Research progress was delayed for months during the transition. Depth calibration for each model is different. Charts which had been required to calculate depth with the older model are no longer needed; however, some of the included profiles are from the old system and so the range calibration charts are included in Appendix A for reference.

On the basis of experience gained from this study, areas of dry sand overburden or shallow limestone allowed the best signal penetration, whereas the presence of a hard thick clayey layer effectively limited penetration. High moisture content was found to have an adverse effect on penetration depth due to the high conductivity of water. The case of very loose saturated sand is among the worst conditions for the propagation of radar signals.

CHAPTER II

GEOLOGIC CONSIDERATIONS

Sinkholes are a characteristic feature of karst processes in Florida. Their occurrence is related to fractures and faults as well as the lithology of the highly porous limestone underlying the state and the thickness and lithology of the overburden sediments (FSRI, 1984). Groundwater flowing through pores and along fracture lines chemically erodes the carbonate rock by solution, leaving large voids in the remaining rock framework. Continued erosion enlarges these voids until roof collapse or the ravelling of unconsolidated overburden into such voids results in sinkholes.

Sinkholes are usually circular depressions of various depths and diameters. Most are 5 to 20 feet across although a few over 100 feet in diameter have been recorded. Several recent occurrences have resulted in extensive damage. The 300 foot diameter Winter Park sinkhole of May 1981 swallowed a house, a public swimming pool and six cars; and the Keystone Heights sink near Gainesville on December 23, 1985, consumed a house within its diameter of 70 feet.

The Florida peninsula was formed over tens of millions of years time by the deposition of the shells and skeletons of marine organisms under shallow sea conditions. Typical stratigraphy in north and central Florida where sinkholes are most damaging consists of four principle geologic formations. The uppermost layer consists of unconsolidated deposits of sand and clay in varying thickness from a few inches to 40 feet. Below this layer is the Hawthorne Formation, a semi-permeable to highly impermeable layer of clay, sandy clay, dolomite, phosphate, and limestone. It is generally characterized as a clay. This layer is relatively thin or nonexistent in some areas of Florida. Pure, porous limestone of the Ocala Group is below the Hawthorne, with the Avon Park limestone formation over basement rock.

Uplift created fractures in the limestone and created "highs" where the limestone is near the ground surface. Extensive erosion due to fluctuating sea levels has resulted in a reduction of the land mass and downward movement of the ground surface.

The Solution Process

Limestone is a carbonate rock composed largely of the mineral calcite. Most carbonate rock is formed in shallow seas by the deposition of the shells and skeletons of dead organisms. A small percentage is formed by the precipitation of calcium carbonate in solution due to evaporation (Stokes, 1978).

Freshly deposited carbonate formations exhibit high void ratios due to pores between grains and fragments. These pore spaces are referred to as primary porosity. Faults and joints due to tectonic movements and flexures are known as secondary porosity. The first signs of solution in limestone appear along these faults and joints which facilitate water flow.

Natural water contains carbonic acid which reacts with calcite to form calcium bicarbonate, a soluble substance that is carried away in solution. Calcium bicarbonate is about 30 times more soluble in water than calcium carbonate; therefore, the carbonation reaction causes increasingly more rapid dissolution of the limestone (Stokes, 1978).

Acidic water percolates through joints and faults, dissolving some of the rock and enlarging the cracks. Dissolved material is removed by underground water and is either redeposited or discharged into streams. As times passes, the voids grow larger and larger until eventually they may form large passageways.

When ion saturation of the water is reached, solution of the carbonate rock stops. Therefore, increased water flow contributes to solution by allowing replacement of ion saturated water (Sowers, 1975).

Solution activity is most rapid where downward percolating water continuously rinses the rock strata, leading to the formation of vertical tunnels or "chimneys." Below the water table, groundwater moves along bedding planes and joints offering the least resistance. Solution action through pores and open spaces results in interconnection to form a continuous system of voids.

Cavity networks expand with time, with major developments occurring along fractures, joints, and bedding planes where water movement is freer and much faster. Solution and removal of limestone is more rapid along these features than in interfracture areas. Lines of sinkhole and spring locations and groundwater flow patterns all appear to be related to fracture trends.

The primary effect of solution is to enlarge the pores and increase overall porosity. This enhances water circulation and increases stress within the remaining rock framework, directly reducing the strength of the rock and inducing stress corrosion (Sowers, 1975). The abundance of springs, caverns, and underground channels are the result of these karst processes attesting to the efficiency of chemical weathering known as solution.

Sinkholes

Large voids in the limestone are the result of concentrated groundwater flow occurring where the rock is more porous or has a higher solubility. Increased solution can be caused by chemical changes in the water, increased filtration after rainfall, increased surface loading, or increased effective weight of the soil overburden due to lowering of the water table so that the bridge of cavity can no longer support the overburden weight.

Sinkholes are usually formed in one of two manners: a) roof collapse of a cavity in limestone, or b) ravelling collapse due to cavity development in unconsolidated overburden.

Collapse of the roof of a bedrock cavern produces a steep-sided, rock-walled hole, possibly widening into interconnected cave passages at depth. If the underlying cave system is water filled, a cenote is the result (FSRI, 1984).

The majority of damaging sinkholes occurring in Florida are subsidence or ravelling sinks. These occur in regions where unconsolidated overburden covers the dissolved cavities in the limestone. A piping type collapse occurs as water washes overlying sediments into the solution cavity below. As the void expands to a point near the ground surface, overlying deposits collapse, resulting in a sinkhole. Ravelling failures are the most widespread and probably the most dangerous of all subsidence phenomena that are associated with limestone, developing suddenly and without notice (Sowers, 1975).

Various circumstances trigger sinkhole collapse but the usual cause is increased filtration through the clay layer. Sinkhole collapse can be induced by changes in the relationship between the water table and the potentiometric surface, such as that caused by heavy pumping for freeze protection or increased localized surface infiltration as below sewage ponds. A high percentage of sinkholes in Florida occur either during the dry season when well draw-down leads to increased groundwater infiltration through the clay layer, or during the summer torrential rainy season when buildup of water in the surficial aquifer increases pressure on the confining layer, causing increased leakage (Ruth, 1985). This heavy infiltration enhances the ravelling process.

Electrical Properties of Soils and Rocks

Propagation velocity of the radar signal depends on the dielectric constant of the earth material. The maximum penetration depth of the radar signal is inversely dependent on the conductivity of the earth material. Sand and gravel have relatively low conductivities and allow excellent radar penetration. Limestone has a low conductivity, allowing penetration depths to over a hundred feet. Areas in which the limestone is at or just below the surface are ideal locations for GPR surveys. Locations where limestone is covered by a sandy overburden generally get good results also. A layer of highly conductive material such as clay reflects most of the incident energy and absorbs the rest; therefore, no information is available below such a layer. The thicker the clay, the less distinct the anomalies.

Water has a strong influence on the electrical properties of rocks and soil. An increase in moisture content greatly increases both conductivity and the dielectric constant. The magnitude of the effect depends on the amount of dissolved solids in the water and on the composition and porosity of the earth material. It is possible to detect the water table in coarse material where the change in moisture content changes radar reflection quickly; however, no clear reflection can be obtained in fine-grained materials where the capillary zone is broad and varying (Ulricksen, 1982).

Within the scope of this research study, the penetration depths are the greatest in low conductive materials such as dry rock and sand, and the least in highly conductive materials such as saturated clay and saturated loose sand.

CHAPTER III

LITERATURE REVIEW

Initial experiments in the propagation of electromagnetic (EM) waves known as radar waves were conducted in the early 1900's. Rapid technological advances pertaining to airborne applications were made during World War II. Much of this technology is also applicable to transmission of EM signals through solids for purposes of detecting any object capable of scattering EM waves. During experiments in the early 1950's, it was recognized that the EM wave speed varies drastically from one solid material to another.

Over half of all subsurface radar profiling research was conducted in the 1970's, peaking in 1974 with theoretical papers and feasibility studies. Articles published in the early eighties deal mainly with practical applications. Certain details of objects can be recognized by their characteristic scattering and absorption coefficients (Ballard, 1983). Since its development in recent years, various systems of GPR have been applied to many types of subsurface investigations. Many articles concern measurements in coal seams (Ulricksen, 1982). Extensive research has also been conducted relating to salt mine explorations, soil profiling, and pavement and bridge evaluations. Continued research in investigations of subsurface cavities is currently being conducted. Data interpretation skills and equipment modifications are continually improving results.

GPR systems differ in a few basic aspects. The transmitted signal can be pulsed on and off periodically, or an impulse of nanoseconds duration can be repeated. An impulse radar transmits energy over a wide frequency band in contrast to pulsed radar signals of one-half or more cycles operating at a single frequency.

Antennas can be used on the ground surface or placed in boreholes. Methods are essentially the same with the exception that the transmit and receive antennas may be in the same borehole or in different boreholes.

The U.S. Army Waterways Experiment Station (WES) conducted several tests of different radar systems in the late 1970's (Ballard, 1983):

a) The Texas A&M radar system was a frequency modulated-continuous wave (FM-CW) system. The equipment is essentially a modified airborne range altimeter ordinarily used to measure altitude of aircraft. The FM-CW radar sweeps through a range of frequencies continuously emitting signals. The transmitter is operating at another frequency when reflected signals are received. The system was unable to detect cavities as shallow as ten feet or culverts more than three feet deep in moist loess material of high conductivity and dielectric constants of 15 to 20.

b) The Technos radar system is a pulsed system manufactured by Geophysical Survey Systems, Inc. Single or dual antennas can be used to transmit and receive. A pulse of approximately three nanoseconds is radiated into the earth by a broad-band antenna. Although unable to detect much at a test site, cavities were detected at depths to 25 feet at the Medford Cave site in North Florida using an antenna with center frequency of 80 MHz.

c) Southwest Research Institute designed and built their own radar system which emits nanosecond duration EM pulses (100 MHz) from the transmitter. The system can be used from the ground surface or in a borehole configuration for crosshole testing. Air filled cavities as small as two feet by five feet were detected at the Medford Cave site.

d) The Lawrence Livermore National Laboratory (LLNL) radar equipment uses a frequency scan to determine the highest discrete frequency suited for probing the area between boreholes. The transmitter is carefully controlled to provide a constant power output. Minimas or nulls in the signal indicate anomalies. The LLNL system can be used to determine relative dielectric constants of the materials being tested.

Suhler (1981) developed a borehole probe to locate coal mining shafts in Wyoming. Using a 100 MHz antenna, a mine shaft was located 50 feet horizontally from the borehole. Owen (1981) used a hole-to-hole method to verify shallow limestone solution cavities at Medford Cave near Ocala, Florida.

The GSSI Sir System has been used in Alaska to detect cavities in permafrost, and at Medford Cave, Florida to detect cavities in limestone. It has also been used to locate buried pipes and tunnels in limestone (Army, 1970). It was found that in general, the lower the conductivity, the deeper the penetration, and that the strength of the reflected signal is stronger when the dielectric constant ratio is high. Frequency of the EM signal determined penetration depth and resolution of data.

Ulricksen (1982) conducted extensive research on the capabilities of the GSSI impulse radar system in his thesis work at Lund University of Technology, Sweden. Using bistatic radar profiling - separate transmit and receive antennas - echos from greater depths were enhanced at the cost of near surface echos. His work included measurements in soil, bedrock, and freshwater, location of pipes and cables, detection of salt damages in concrete roads, and determinations of moisture distribution.

A conference was sponsored by the U.S. Environmental Protection Agency and the National Water Well Association on Surface and Borehole Geophysical Methods in Groundwater Investigations in February, 1985. This conference discussed the use of radar in providing models of moisture content vs. depth; detecting and determining the extent of residual buried waste mass; and mapping subsurface features including water table, variations in soil strata, and depth to bedrock over 25 km of survey lines.

The penetration range of most existing ground probing radars is from about 50 meters in resistive materials such as sands, gravels, bedrock, and fresh water, decreasing to about one meter in conductive materials such as fine grained clays and seawater (NWWA, 1984). The dielectric constant of water in its liquid state are about 20 times greater than the dielectric constant of dry geologic materials, and so radar signal velocity is primarily sensitive to changes in water content. In materials with relatively uniform water content, GPR is sensitive to changes in soil and rock type. The water table could be identified by the triple reflection pattern as shown in Figure 1. In addition, GPR can detect either water or air filled fractures in geologic materials.

Kuhns (1982) conducted an investigation of GSSI's SIR System 4 using cavity models buried at known depths at a test site on the University of Central Florida campus. The experimental test site was set up to determine the type of reflection expected from an ideal cavity of known dimensions. Cavity models were shallowly buried in sand with the water table at four feet. Strong reflecting signals were received from the roofs of the air filled models and the floor of the water filled model. Due to the shallow depths of these models, frequencies of 300 and 900 MHz were used to detect them. Profiles from a buried pipe and box showing near surface cavities under ideal conditions are shown in Figure 2.

Kuhns also conducted surveys in Lake Claire on the UCF campus. Excellent profiles of the lake bottom were provided by the GPR equipment.

Kuo (1984) has used the GPR system to study underground sewage pipe leakage. The Iron Bridge pipeline in East Orange County is a seven foot diameter pipe located at a depth of 20 to 25 feet. The radar detected the pipe and leaking joints were identified by signal loss due to contamination of the surrounding soil. Kuo has also used the radar system to evaluate concrete pavement by locating rebars, voids, and other features.

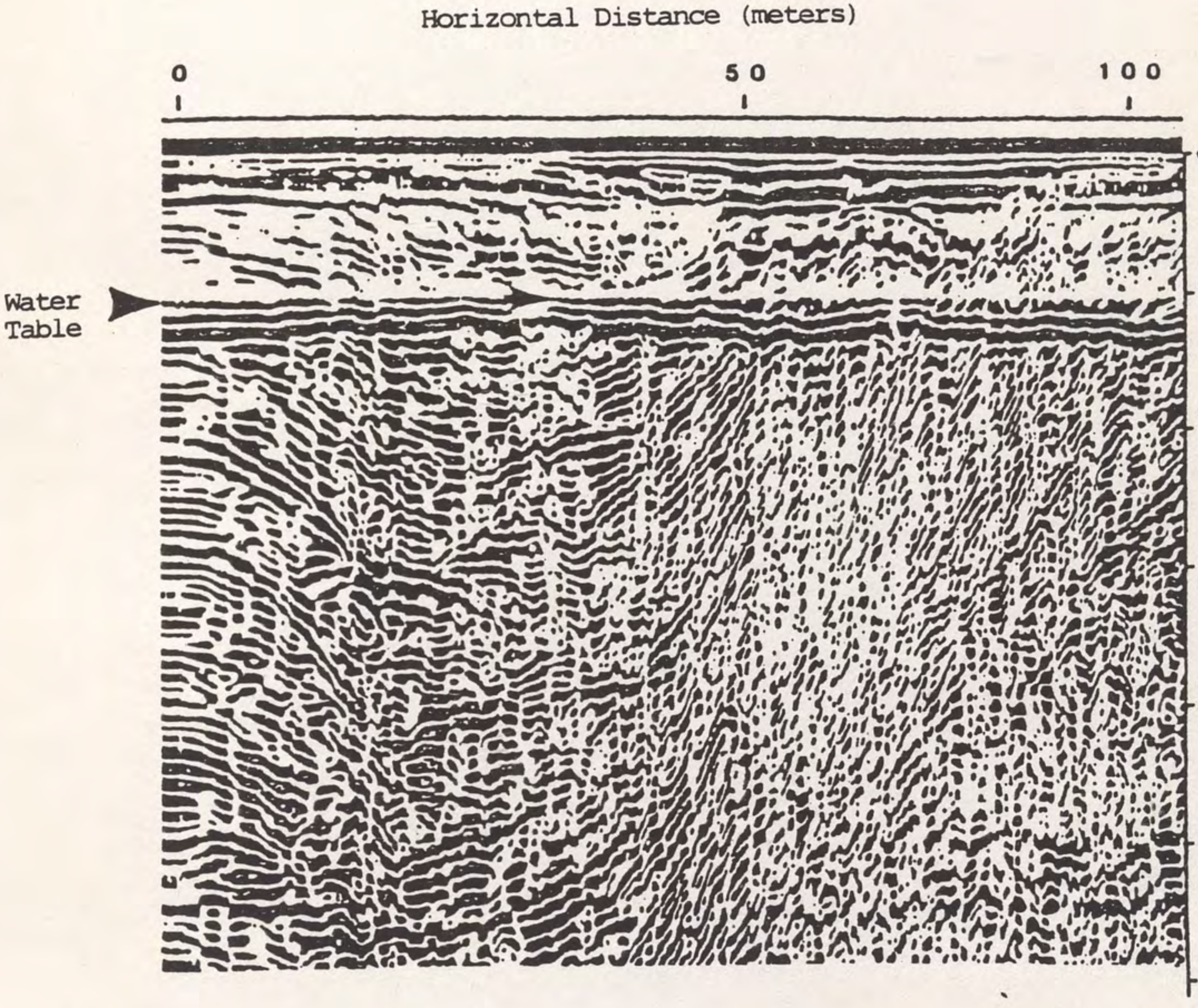


Figure 1. Radar Profile Showing Water Table (NWWA, 1984).

SIR System equipment has been used worldwide to acquire graphic profiles of subsurface features such as soil strata, depth to bedrock, subsurface voids, mine tunnels and shafts, pavement thicknesses, coal seams, pipes, cables, gas and water leaks, river and lakebottoms, steel reinforcing bars, toxic waste deposits, and the contour of contaminated groundwater (GSSI, 1982).

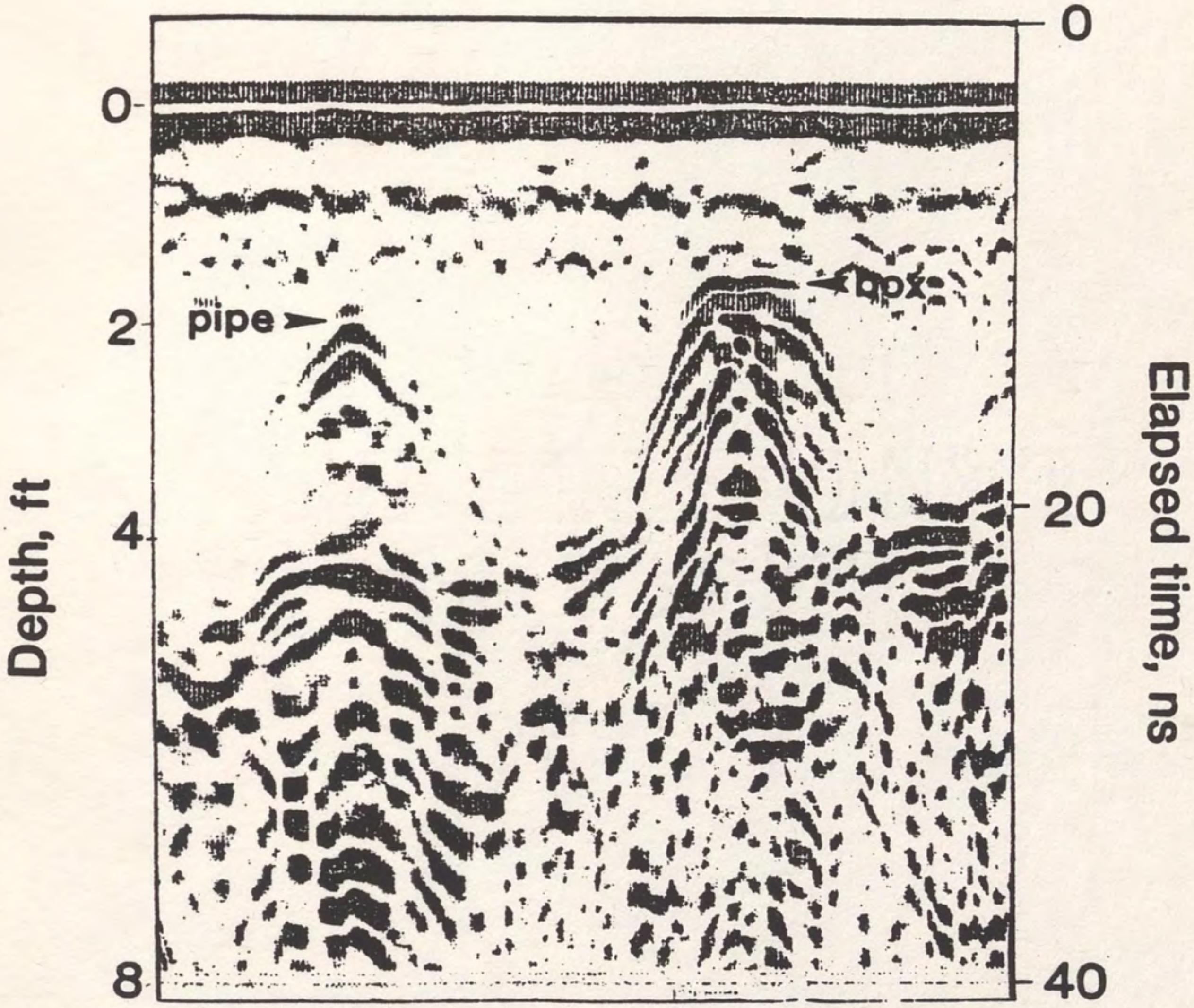


Figure 2. Radar Profile of Cavity Models at UCF Test Site. (400 XlL, System 8, 300 MHz Antenna)

CHAPTER IV

THEORY AND OPERATION OF GROUND PENETRATING RADAR

Operating principles of ground penetrating radar are based on fundamentals of electromagnetic wave theory. EM waves travel through materials at speeds proportional to the electrical characteristics of the material. Changes in the material cause changes in wave speed and partial reflection of its energy. Impulses are beamed into the earth as the antenna is towed along the ground surface, and a continuous stream of reflected signals is fed into the graphic recorder, producing a two-dimensional profile of subsurface interface.

The principles and equations governing the propagation of radar waves are well documented. If the velocity of propagation through the strata is known, travel times of the reflected pulses can be converted to depths to various interfaces. The velocity of the radar signal and depth of penetration are functions of electrical properties of the materials which can vary considerably under natural conditions.

Determination of the maximum penetration depth at a site is difficult before the actual radar survey due to the many variables which influence radar signal penetration. The electrical properties of the soil, rock, and water vary greatly from site to site. Under actual field conditions, the earth material being probed is often nonhomogeneous and the signal strength is quickly reduced due to the reflections of the signal from several layered interfaces. The size and shape of the target also affects the detection ability of the radar system.

Equipment Description and Function

The radar system used in this study is the Subsurface Interface Radar (SIR) System manufactured by Geophysical Survey Systems, Inc. (GSSI). The equipment is pictured in Figure 3 and consists of a control unit, a graphic recorder, a tape recorder, and transmit/receive antennas.

The antennas can be pulled along the ground by hand over small areas or towed behind a vehicle over long distances. It is connected to the control unit by a 200 foot cable. Power for the system is provided by a 12 volt DC battery.

During the transmit cycle, a fast acting switch creates a time-limited signal which is sent directly to the antenna. The transmitted pulse travels through the subsurface until it reaches a soil interface. Depending on the electrical characteristic at the interface, a portion of the transmitted pulse is reflected back to the surface and received by the antenna as shown in Figure 4.

The strength of the reflected wave is indicated by the intensity of the received signal. The reflected field strength between materials 1 and 2 is described by the reflection coefficient r:

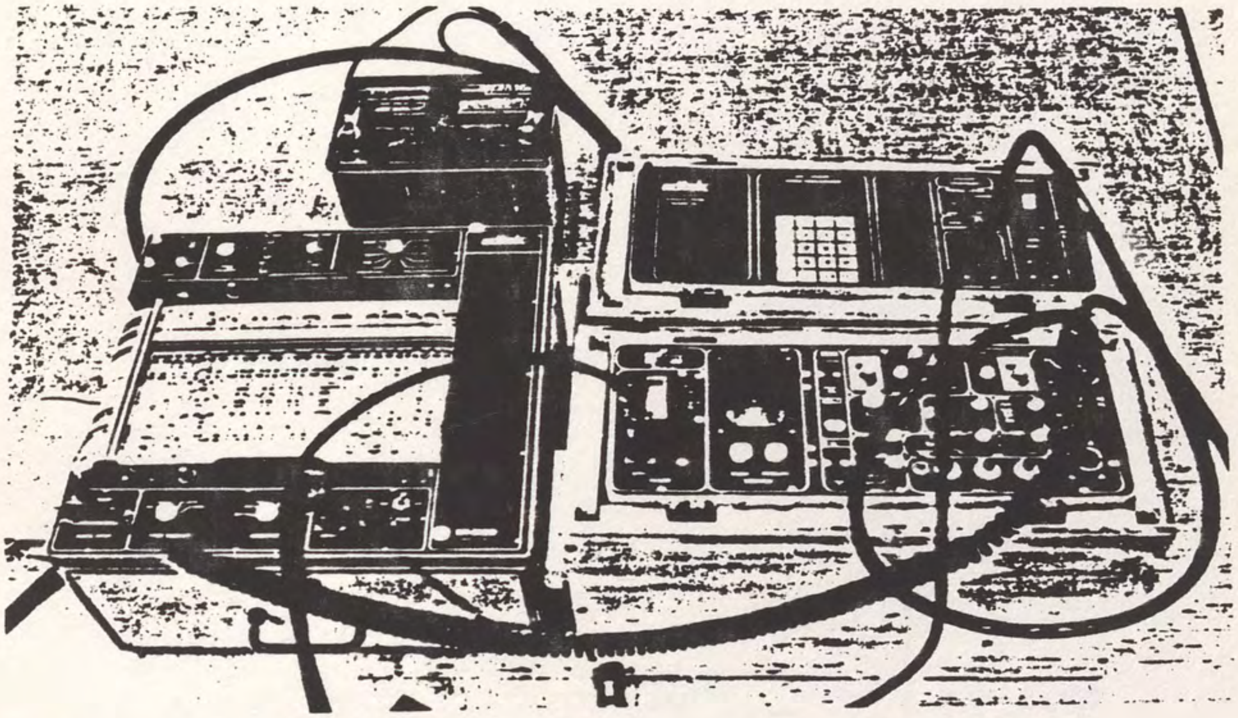
$$r = \frac{E_r}{E_0} = \frac{1 - (\varepsilon_2/\varepsilon_1)^{\frac{1}{2}}}{1 + (\varepsilon_2/\varepsilon_1)^{\frac{1}{2}}} \qquad (1)$$

where ε_1, ε_2 = dielectric constants for materials 1 and 2, respectively

E_r = angle of reflection

E_0 = angle of incidence

(Clockwise from top) 12V Battery, Tape Recorder, Control Unit, Graphic Recorder.



80 MHz (left) and 300 MHz Antenna.

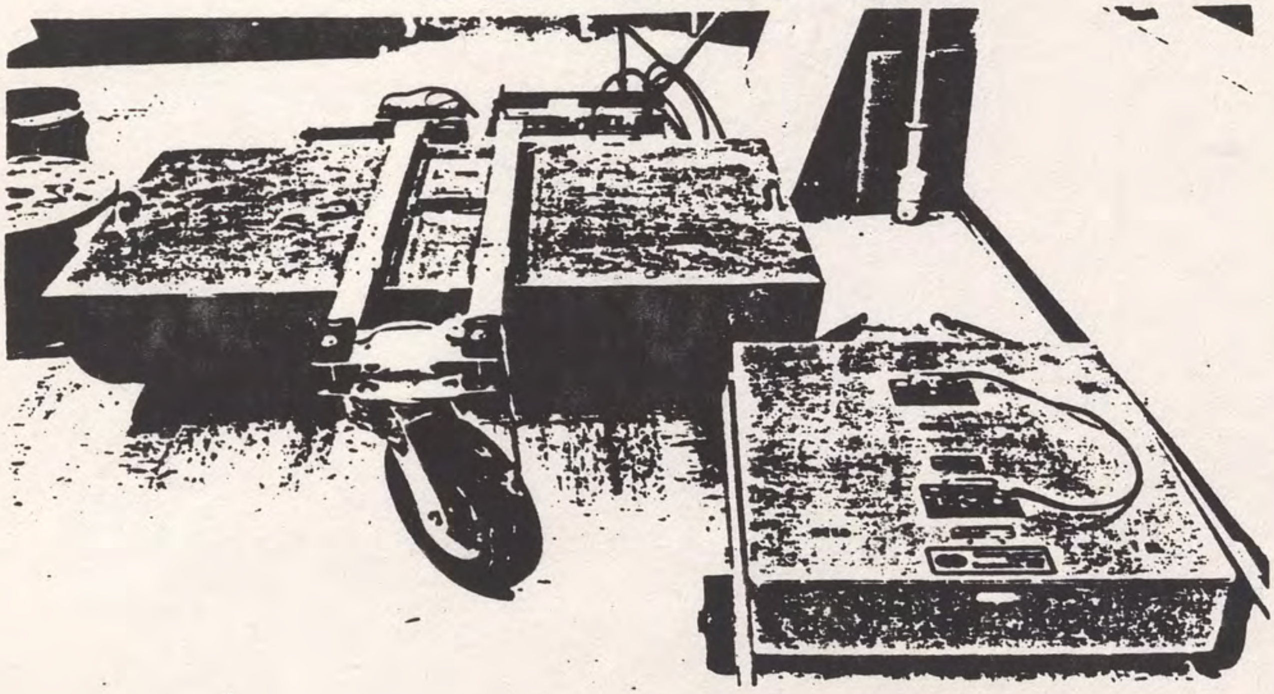


Figure 3. Photograph of GPR Equipment.

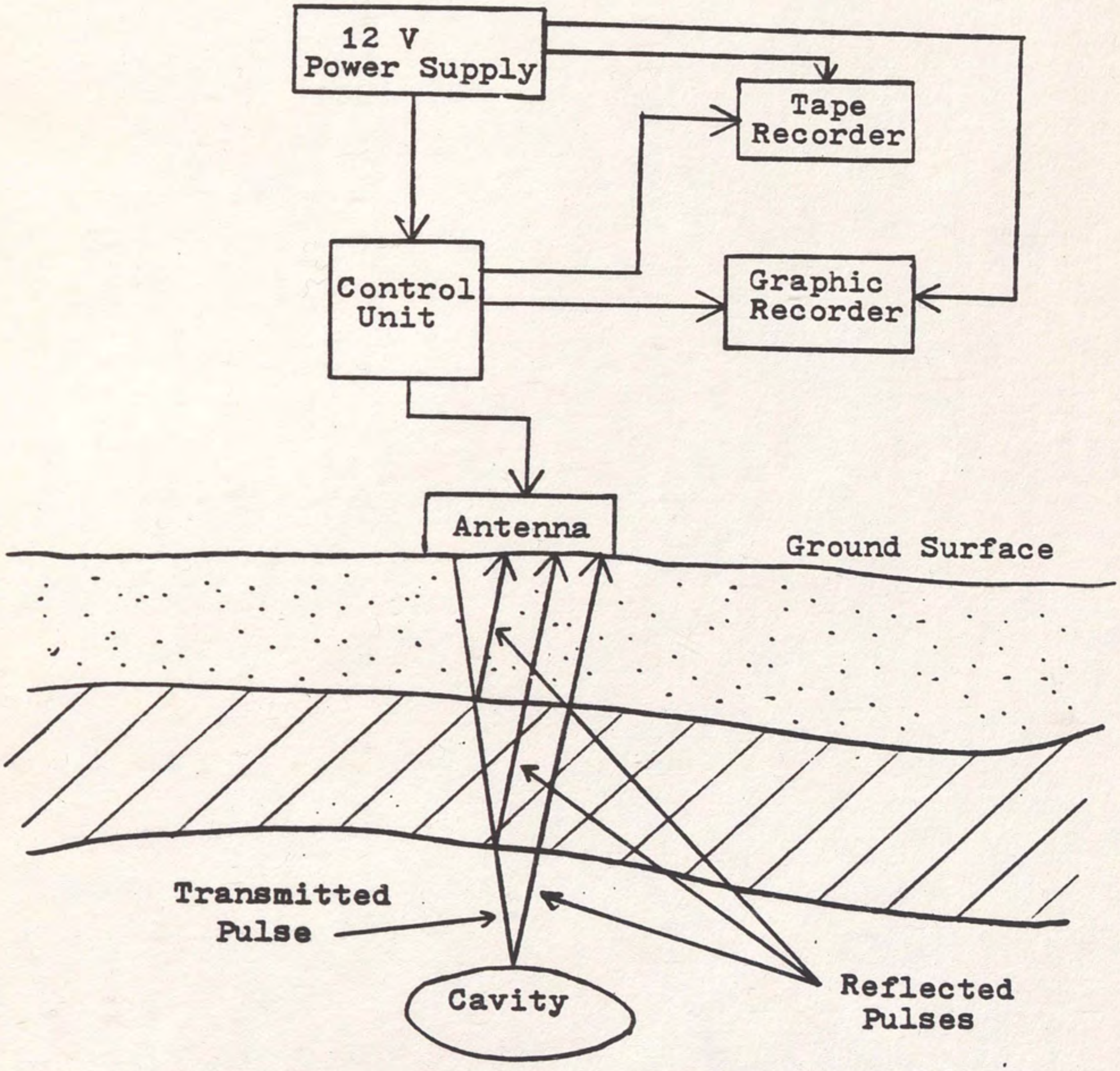


Figure 4. Functional Diagram of GPR Equipment.

If the dielectric constant of material 2 varies greatly from that of material 1, r ≅ 1 and most of the incident energy will be reflected and a strong signal will be recorded. If material 2 has a dielectric constant about the same as that of material 1, r ≅ 0 and most of the incident energy will be transmitted through the interface which will appear only faintly on the profile.

The received signals are amplified using a time-domain sampling technique to construct a waveform of similar shape to that of the actual received signal, but with a much longer time base. A trace of the processed waveform is displayed by an oscilloscope on the control unit. Subsurface features appear as dark lines and depth is determined by delay time.

The operator controls the maximum delay time and adjusts the gain for optimum display of reflected signals. The most crucial part of a radar survey is adjusting the system to obtain optimum data. Prior knowledge of targets and their depth is necessary as is some trial and error work at the site before commencing production work.

After processing at the control unit, the waveform is sent to the graphic recorder for a hardcopy display by stylus scanning intensity modulated lines across electrosensitive paper. The graphic recorder produces an image by printing strong signals as black and signals of intermediate strengths in shades of gray. As the antenna is pulled across the ground surface, the chart paper moves under the recorder stylus and sequential pulses are printed to form a continuous record.

A digital magnetic tape recorder is available for storing information for future processing and playback. The reusable cartridge is preformatted with permanent block addresses and permits easy, accurate, random access to data records. The tape allows the user to play back tapes directly to the graphic recorder or through the control unit if further signal processing is desired.

Interpretation of Data

An example of a reflected radar signal and the resulting graphic record is shown in Figure 5. The vertical scale is elapsed time. The horizontal distance scale depends on the paper feed rate of the graphic recorder and the speed at which the antenna is pulled across the ground; therefore it must be confirmed by markers at surveyed distances. The strength of the received signals is shown by the amplitude of the waveform in the signal pattern and by the intensity of the dark bands on the graphic record. Varying shades of gray are directly related to the amplitude of the returning signal.

As seen in Figure 5, the received signal consists of three basic components. The first band at the top of the profile is a feed through of the transmitted pulse, which serves as a time reference. The horizontal band immediately following the transmitted pulse is the reflection from the ground surface. The interface reflection appears at a time equal to the pulse travel time from the surface to the interface and back to the antenna.

The triple band characteristic of the reflection pattern is caused by oscillations in the reflection of the pulse. The effect of this

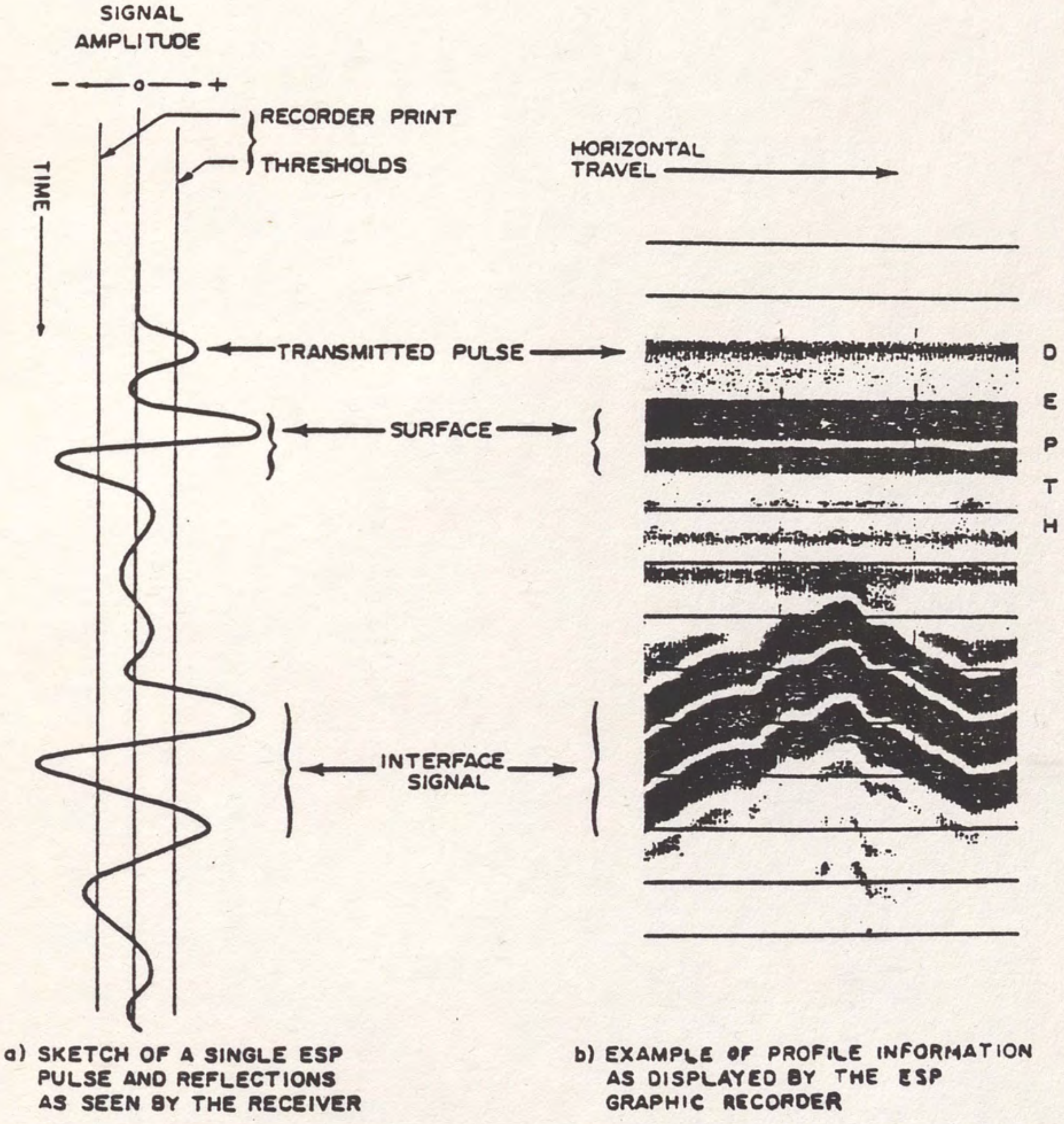


Figure 5. Example of GPR Signal and Record (GSSI, 1982).

oscillation is to reduce the ability of the system to discriminate between closely spaced interfaces. If a second interface close to the first interface generates a pulse reflection, that reflection will superimpose itself onto the oscillations of the pulse reflections from the first interface. If the superimposing waveforms are in phase, interference will be constructive and if they are out of phase, the oscillations will tend to cancel each other out. The lower interface will not be completely obscurred because portions of its own oscillations will appear, but the actual depth of the lower interface will be difficult to determine.

For instance, if a thin clay layer is surrounded on top and bottom by sand, the depth to the clay layer can easily be determined but superposition of the waveforms from top and bottom interfaces will make the thickness of the clay layer difficult to estimate. Complexity of the records becomes apparent in some areas.

The radar antenna radiates signals into the ground in a beam which is roughly conical in shape. The included angle from front to back is approximately 90 degrees and the side beam angle is about 60 degrees. Only subsurface features which are normal to some portion of the radiated signals are reflected back to the antenna.

In the case of a horizontal layer, the antenna sees only the portion directly beneath it. For curved interfaces such as round pipes, a portion of the curved surface is always normal to the conical radiation beam as the antenna approaches and passes at right angles. For this reason, reflections from curved interfaces have a hyperbolic shape. As shown in Figure 6, when the antenna is at a 45 degree angle

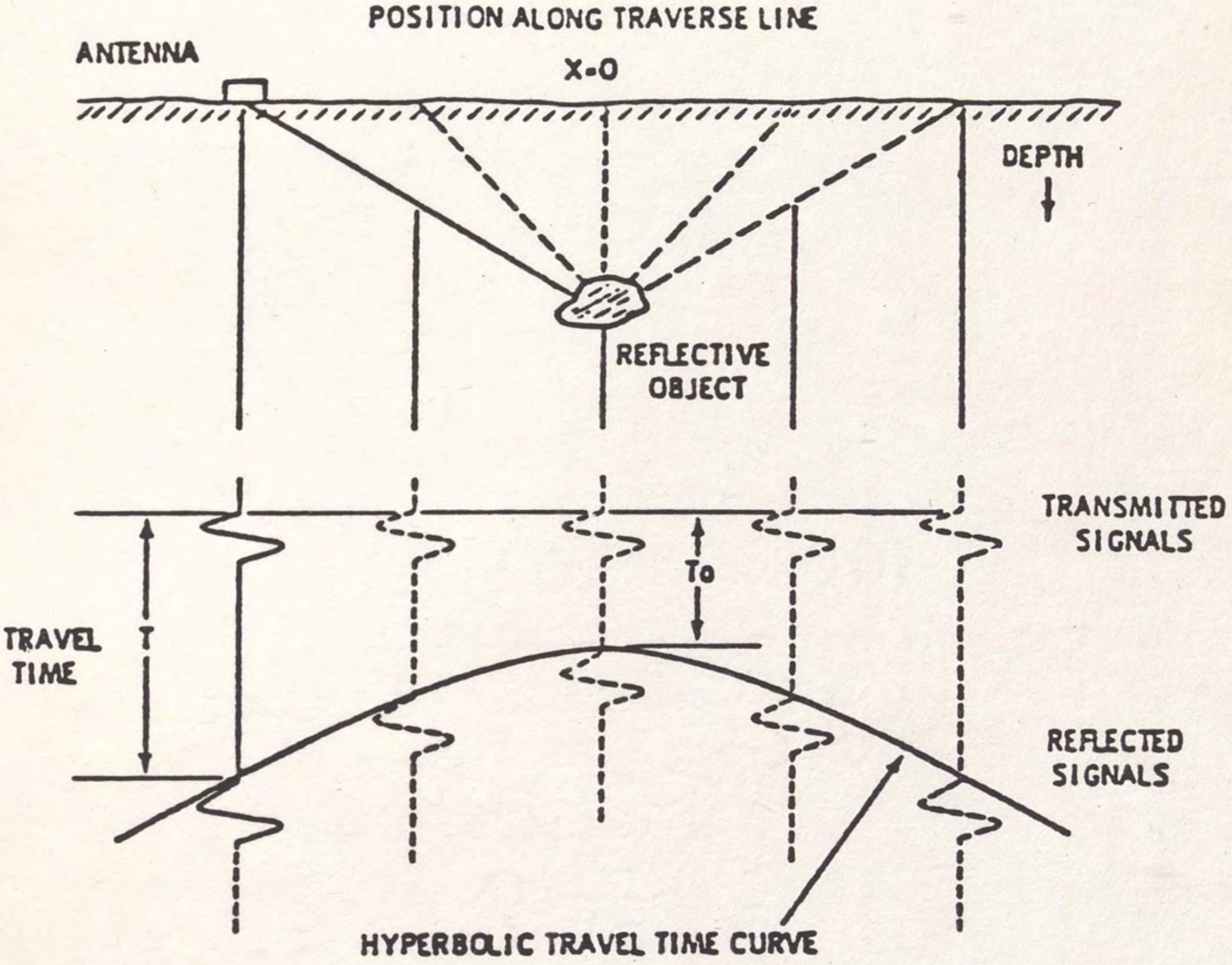


Figure 6. Development of Hyperbolic Reflection Pattern.

to the cavity, the first reflections are received. As the antenna approaches the cavity, the distance normal to the cavity becomes shorter until the cavity is directly under the antenna. This is the apex of the hyperbolic reflection curve and the true depth of the cavity. The reflection from the bottom of a circular pipe cavity has the same hyperbolic shape.

Depth Calibration

In order to transform the two way travel times into depth, the velocity of propagation must be known. If the earth material is homogeneous and the dielectric constant is known, the pulse velocity can be calculated according to the equation

$$v = \frac{c}{\sqrt{\varepsilon_r}} \qquad (2)$$

where: v = average propagation velocity of the signal (nsec/feet)

c = velocity of light (≅ 1 foot/nsec)

ε_r = relative dielectric constant of the material

By estimating the dielectric constant of the material being surveyed, the depth to various interfaces can be approximated by the relationship

$$D = \frac{ct}{2\sqrt{\varepsilon_r}} \qquad (3)$$

or

$$D = \frac{vt}{2} \qquad (4)$$

where: D = depth in feet

t = two way travel time in nanoseconds

Dielectric constants for typical earth materials encountered during this study are given in Table 1. These values are at extreme conditions (dry and saturated), and are based on typical natural conditions of temperature and pressure and the operating frequency range of the radar signal. Dielectric constants at various moisture content are under investigation by Tannous (1985) in a model study. Often, the subsurface is non-homogeneous and approximations must be made. Depth verification is necessary by physical methods.

The most accurate method of determining the velocity of the signal through a material is to scan over a target of known depth such as a pipe or soil layer. By measuring the two way travel time from the reflected profile, one can calculate the velocity from Equation 5:

$$v = \frac{2D}{t} \tag{5}$$

Once the velocity of propagation is known, the dielectric constant can be determined by the equation:

$$\varepsilon_r = \left(\frac{c}{v}\right)^2 \tag{6}$$

The pulse velocity obtained by this method is the average velocity for the material between the surface and the target, assuming uniformity throughout. It is valid if the area being surveyed has subsurface conditions similar to the target site. However, this average velocity might not be valid at depths greater than the target depth due to changes in the consistency or water content. Sample borings are useful in order to reasonably estimate the depth scale of the radar data.

TABLE 1

CONDUCTIVITIES AND DIELECTRIC CONSTANTS OF VARIOUS EARTH MATERIALS

MATERIAL	CONDUCTIVITY (mho/meter)	DIELECTRIC CONSTANT
Air	0	1
Fresh water	10^{-4} to $3x10^{-2}$	81
Sea water	4	81
Sand, dry	10^{-7} to 10^{-3}	4 to 6
Sand, saturated (fresh water)	10^{-4} to 10^{-2}	30
Silt, saturated (fresh water)	10^{-3} to 10^{-2}	10
Clay, saturated (fresh water)	10^{-1} to 1	8 to 12
Dry, sandy, flat coastal land	$2x10^{-3}$	10
Rich agricultural land, low hills	10^{-2}	15
Pastoral land, medium hills and forestration	$5x10^{-3}$	13
Marshy, forested flat land	$8x10^{-3}$	12
Limestone (dry)	10^{-9}	7
Average soil	10^{-4} to 10^{-2}	12

Data from GSSI, 1982.

Penetration Depth

The effectiveness of a GPR survey is limited in many cases by the penetration depth of the radar signal. The maximum penetration depth of the signal is dependent on the conductivity of the propagating material which is primarily governed by water content and the amount of salts in solution. Conductivity is also a function of temperature and density as well as the frequency of the EM waves being propagated. Conductivity is related to the attenuation by the relationship:

$$A = 12.863 \times 10^{-8} f(\varepsilon)^{\frac{1}{2}} \left[\left(1 + \frac{\sigma^2}{W^2\varepsilon^2}\right)^{\frac{1}{2}} - 1\right]^{\frac{1}{2}} \text{ (db/m)} \qquad (7)$$

where: f = antenna frequency (Hz)

$W = 2\pi f$ (radians/second)

$\varepsilon = \varepsilon_o \varepsilon_r = 8.85 \times 10^{-12} \varepsilon_r$

σ = conductivity (mhos/meter)

Based on the above equation, the depth of penetration of the radar pulse is governed primarily by the conductivity of the propagating material. An increase in conductivity will cause a significant increase in signal attenuation. Most soils have a low conductivity, but the presence of moisture has a large effect on this property. Earth materials with a high water content and therefore a high conductivity will attenuate the radar signal more rapidly than dry earth materials.

As seen from Equation 7, an increase in signal frequency will also increase signal attenuation. For this reason, low frequency antennas are used to achieve greatest penetration depths. Higher frequencies give greater resolution; however, many ground materials are highly absorbant of high frequencies EM energy and so a compromise must be made between resolution and penetration. Frequencies between 15 and 500 MHz are generally employed.

CHAPTER V

SITES SURVEYED AND DATA INTERPRETATION

Field investigations throughout Northern and Central Florida were conducted under varying geologic conditions to determine typical conditions under which GPR will be useful in locating subsurface anomalies. Locations of these investigations are shown in Figure 7.

Methods of investigation depended on the site involved. The areal extent, topography and vegetation, local sinkhole history, degree of certainty of the evaluation, and effects of sinkhole occurrence were considered. At some sites the radar antenna was pulled randomly over known cavities. At sites of recent sinkhole collapses the antenna was pulled around the sink to see if the incident was isolated or related to a fault system. In areas of potential groundwater contamination a grid pattern was set up to cover the area uniformly.

Available information such as aerial photographs, topographic or geologic maps, and local well logs can aid in data interpretation.

Ten sites were investigated with varying results. Sample profiles showing significant characteristics have been interpreted in this study.

SITE 1: Oak Run, FL

Oak Run is a 5000 unit housing development under construction near Ocala. Development plans call for on-site wastewater treatment

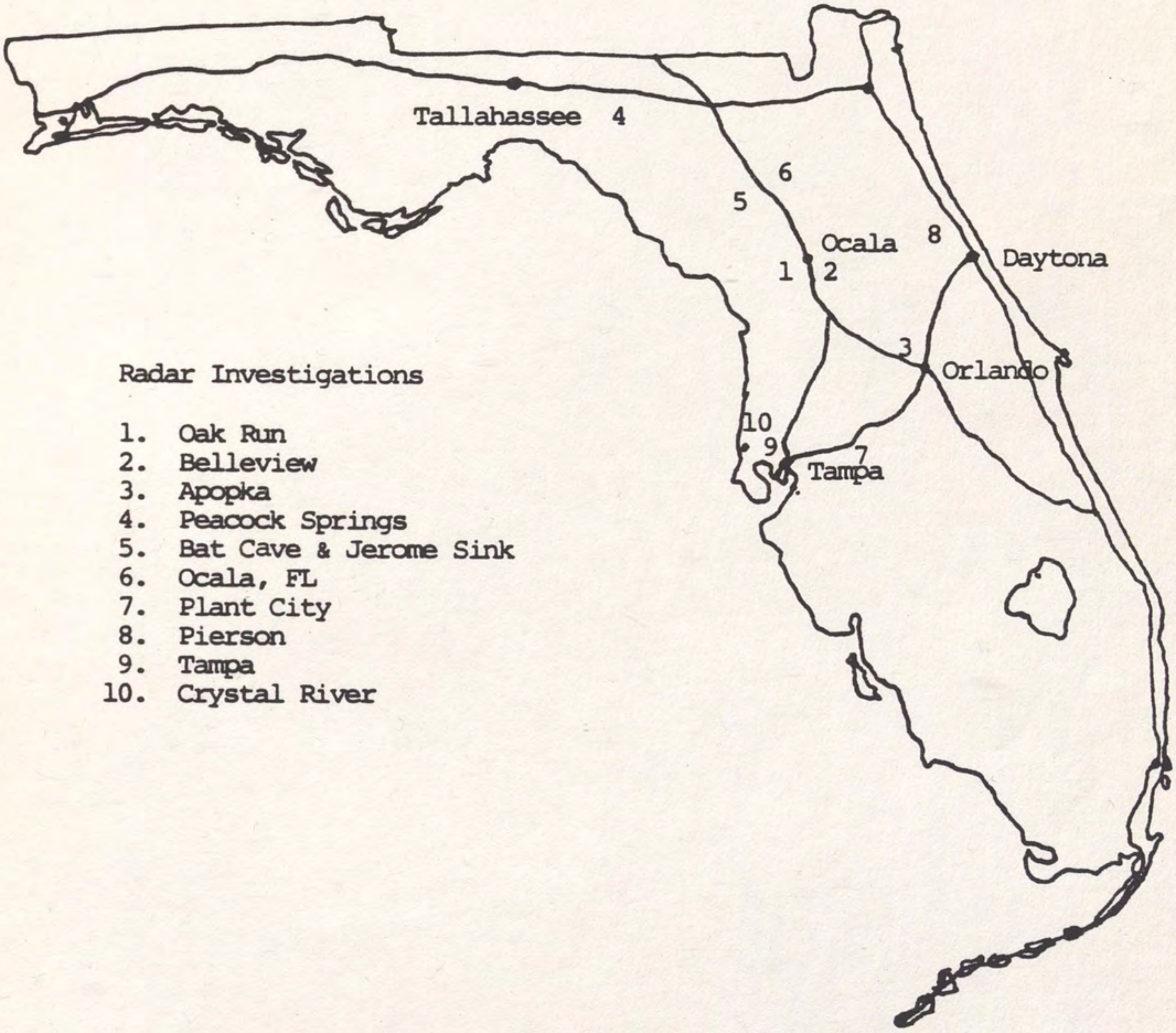


Figure 7. Map of Radar Survey Locations.

and a large area has been set aside for retention/percolation ponds. These ponds are planned under the assumption that the wastewater will be limited from infiltrating the limestone by a semi-impermeable clay layer. In areas of thin clay, an increase in percolation due to the ponds could cause sinkholes, allowing wastewater to flow directly into the limestone aquifer without filtering. This could result in contamination of the aquifer, which is the source of potable water for the development.

Documentation of discontinuities in the clay confining layer over a 500 foot by 1800 foot area was required by Florida Department of Environmental Regulation (FDER). A 50 foot, N-S x E-W grid system was surveyed over the area.

Previous boring reports showed no suspicious areas. A thick clayey layer was present over much of the site with limestone at shallow depths. The area was relatively flat but covered by weeds and small trees, limiting access to a four wheel drive jeep towing the antenna. Some excavation, clearing, and burning of debris had been conducted in the area, and surface runoff had eroded a gully through the northwest quadrant.

Initial profiles showed significant penetration capabilities. Using the 80 MHz antenna, penetration in excess of 80 feet was estimated in some areas of limestone. Figure 8 is a profile from the western edge of the site showing a solid limestone structure about 30 feet below the surface. Limestone peaks are emphasized by overlying clay which has filtered into cracks and low areas.

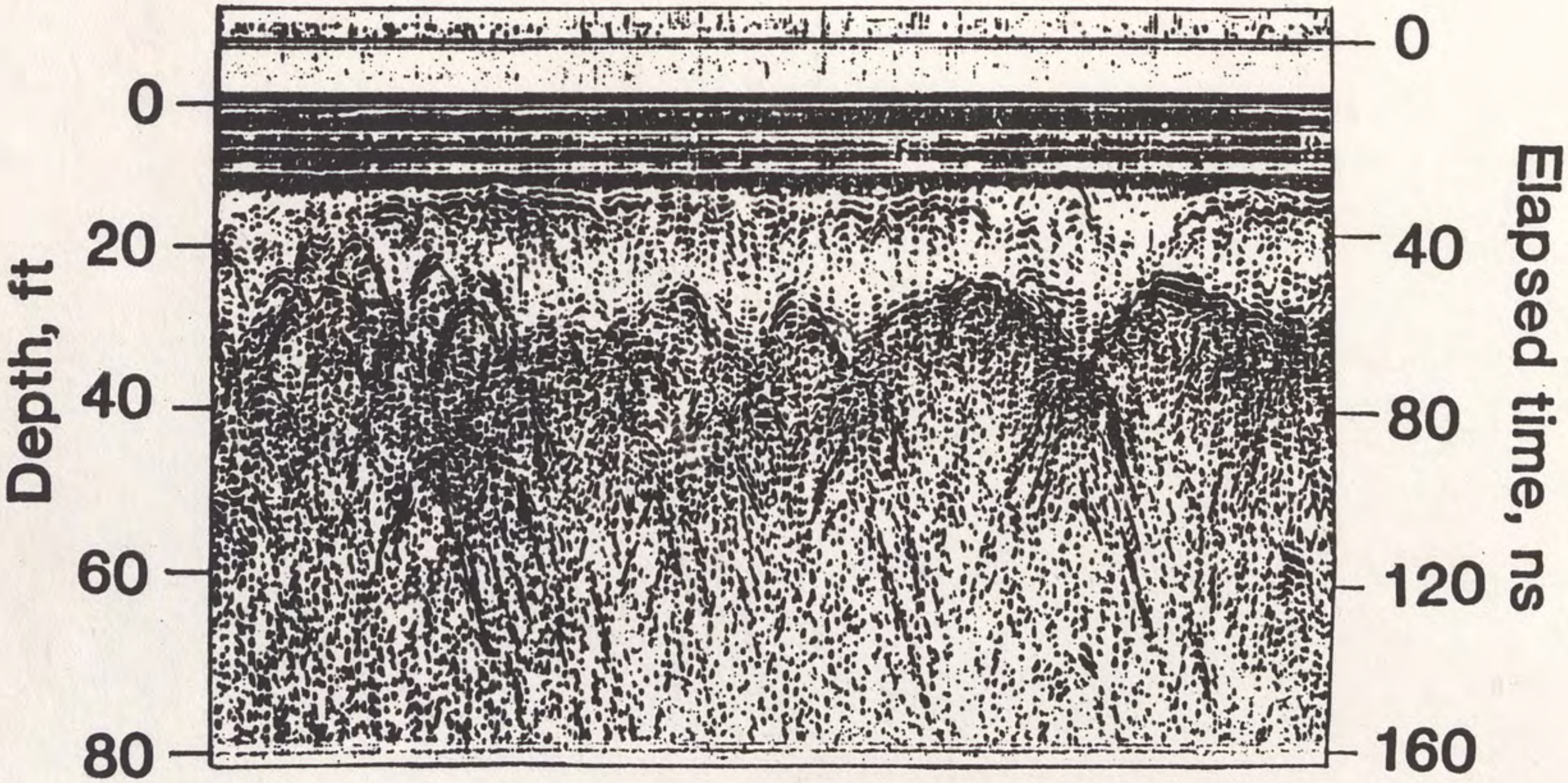


Figure 8. Radar Profile Showing Shallow Limestone at Oak Run Site.
(800 X4L, System 8, 80 MHz Antenna)

Figure 9 is a profile along the southern boundary of the site, showing a silt or clay layer overlying limestone. This clayey layer is too thick to be penetrated by the radar signals; however, a subsidence of the clay layer and several indications of cavities at about 40 feet can be identified. Loss of signal along several hundred feet was apparently due to surface runoff contaminated by burn piles increasing the conductivity of the soil. This is typical of contaminated soils.

Strong hyperbolic reflections about 200 feet to the right of this contaminated area indicated the presence of a cavity. Figure 10 is a radar profile of the cavity which was located by pulling the antenna right over the suspicious area and marking every ten feet. A drilling truck used to identify the cavity is shown in Figure 11. Loss of drilling mud occurred at a depth of 43 feet. Eleven cubic yards of concrete mix were used to grout the void.

Figure 12 shows another cavity located approximately 200 feet SW of the first cavity, verified by loss of drilling mud at 38 feet. This cavity was smaller than the first, requiring only a few yards of grout.

Confirmation of these cavities by drilling allows verification of the profile depth and provides an average value for the dielectric constant.

SITE 2: Belleview, FL

A similar percolation pond project just east of Ocala near Belleview on 600 acres of pasture and watermelon fields was also investigated.

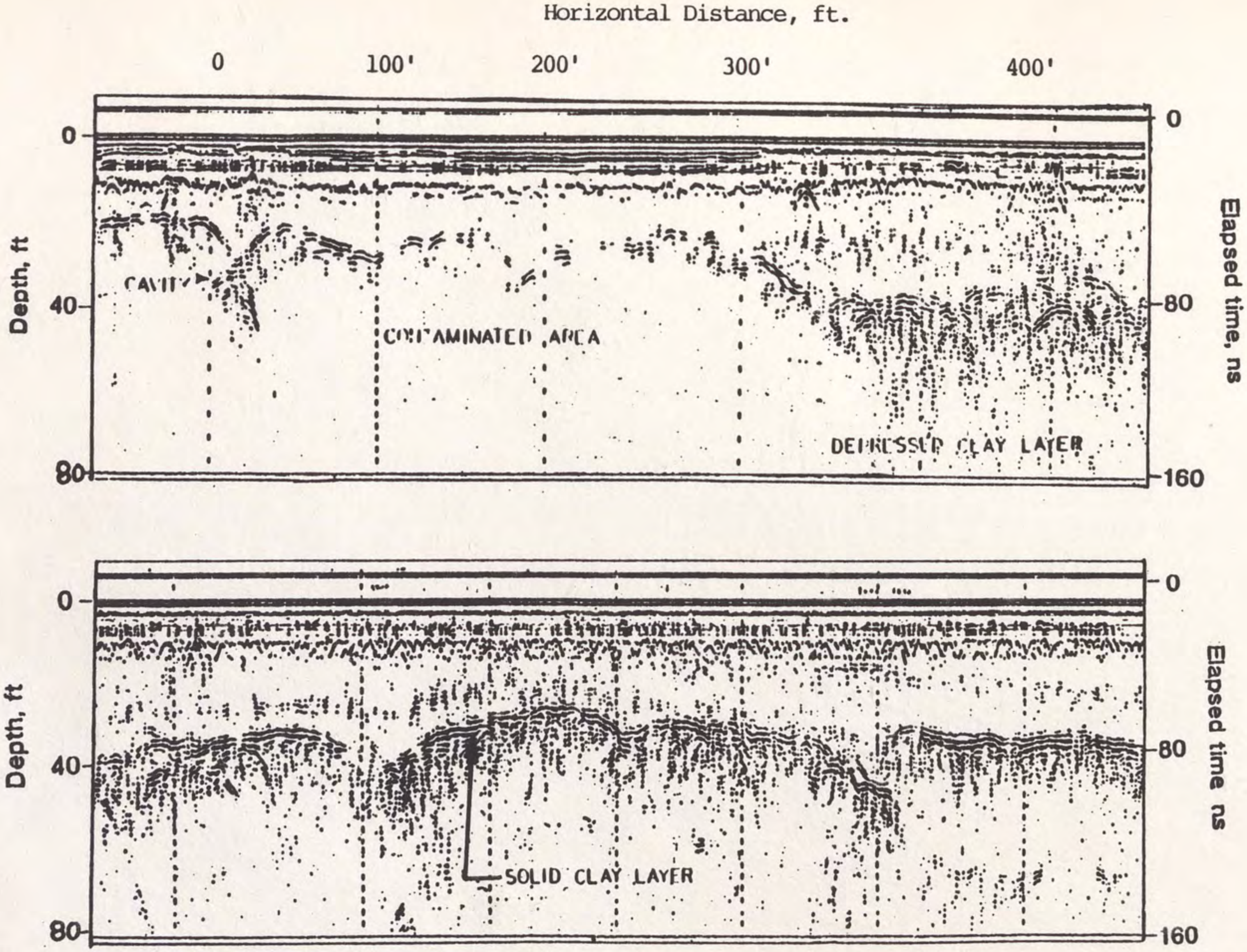


Figure 9. Radar Profile From Oak Run Showing Clay Layer, Discontinuities, and Contaminated Site (800 X4L, System 8, 80 MHz Antenna).

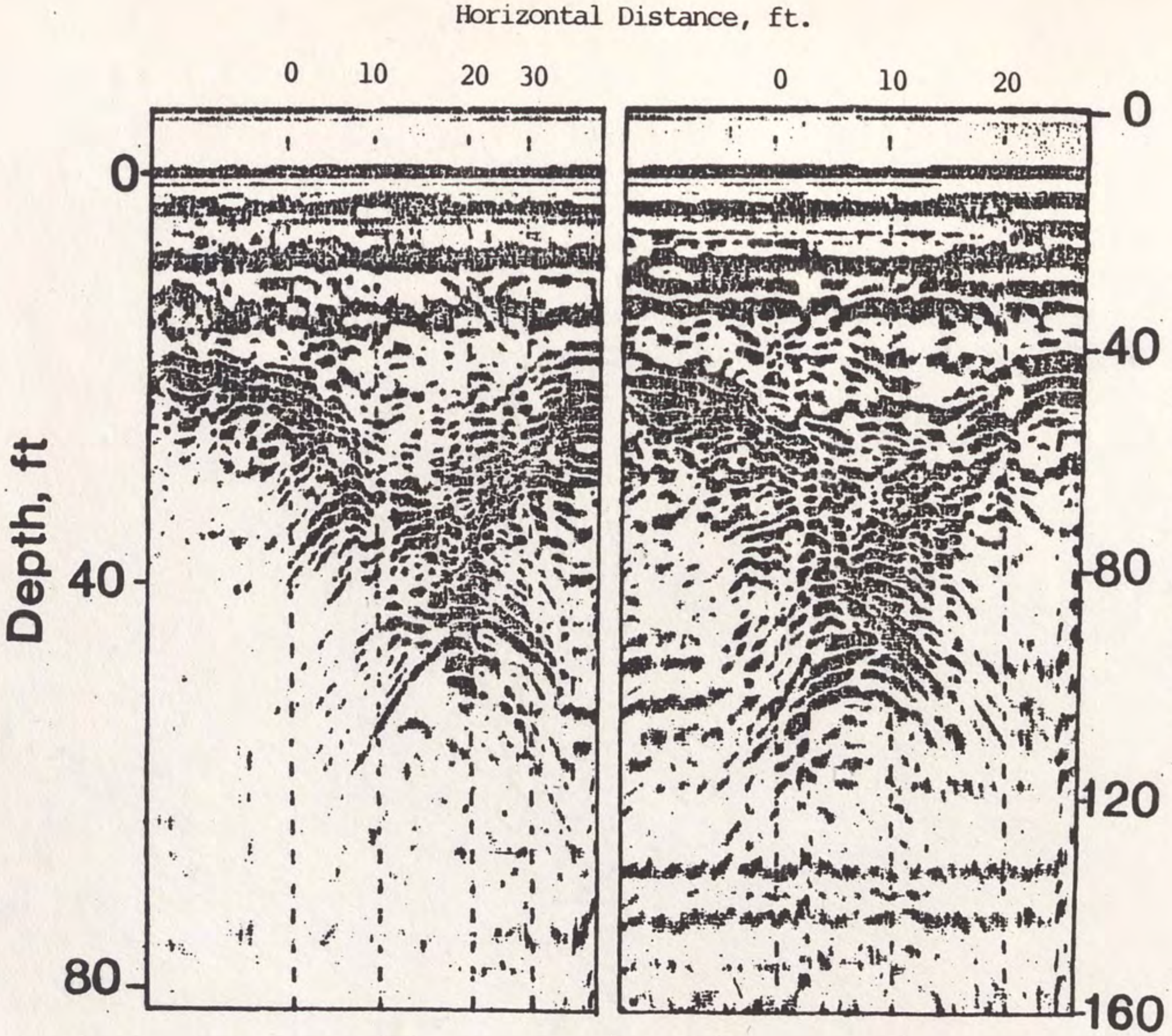


Figure 10. Radar Profile of Large Cavity at Oak Run.
(800 XL4, System 8, 80 MHz Antenna)

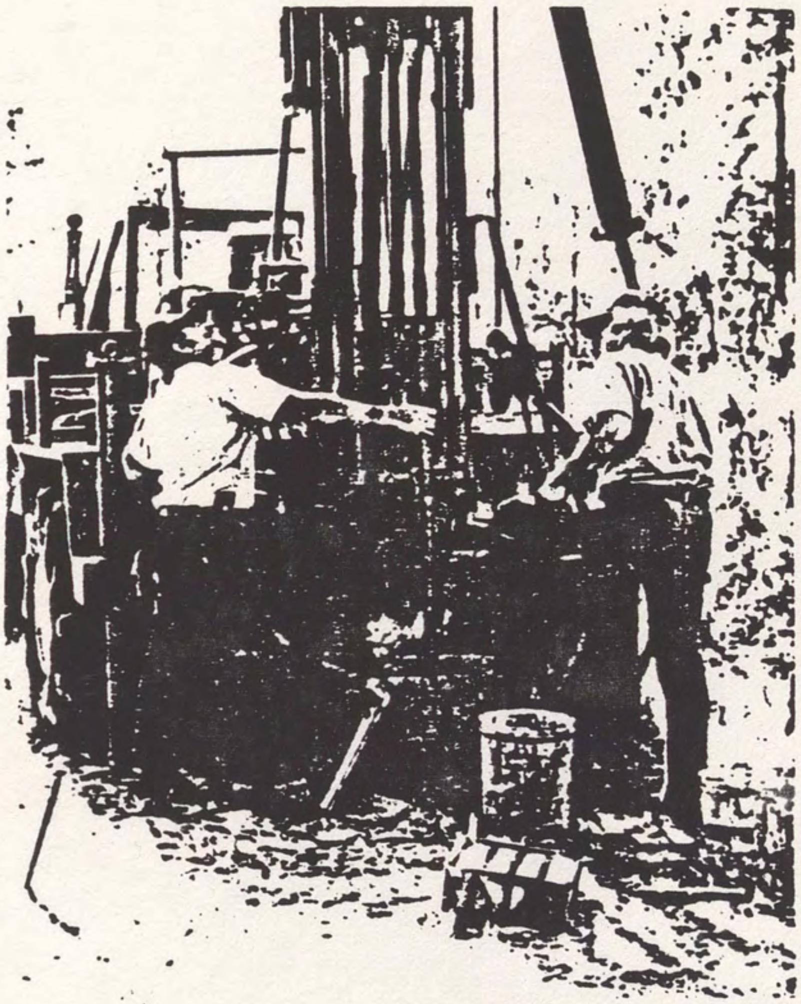


Figure 11. Drilling Truck at Oak Run.

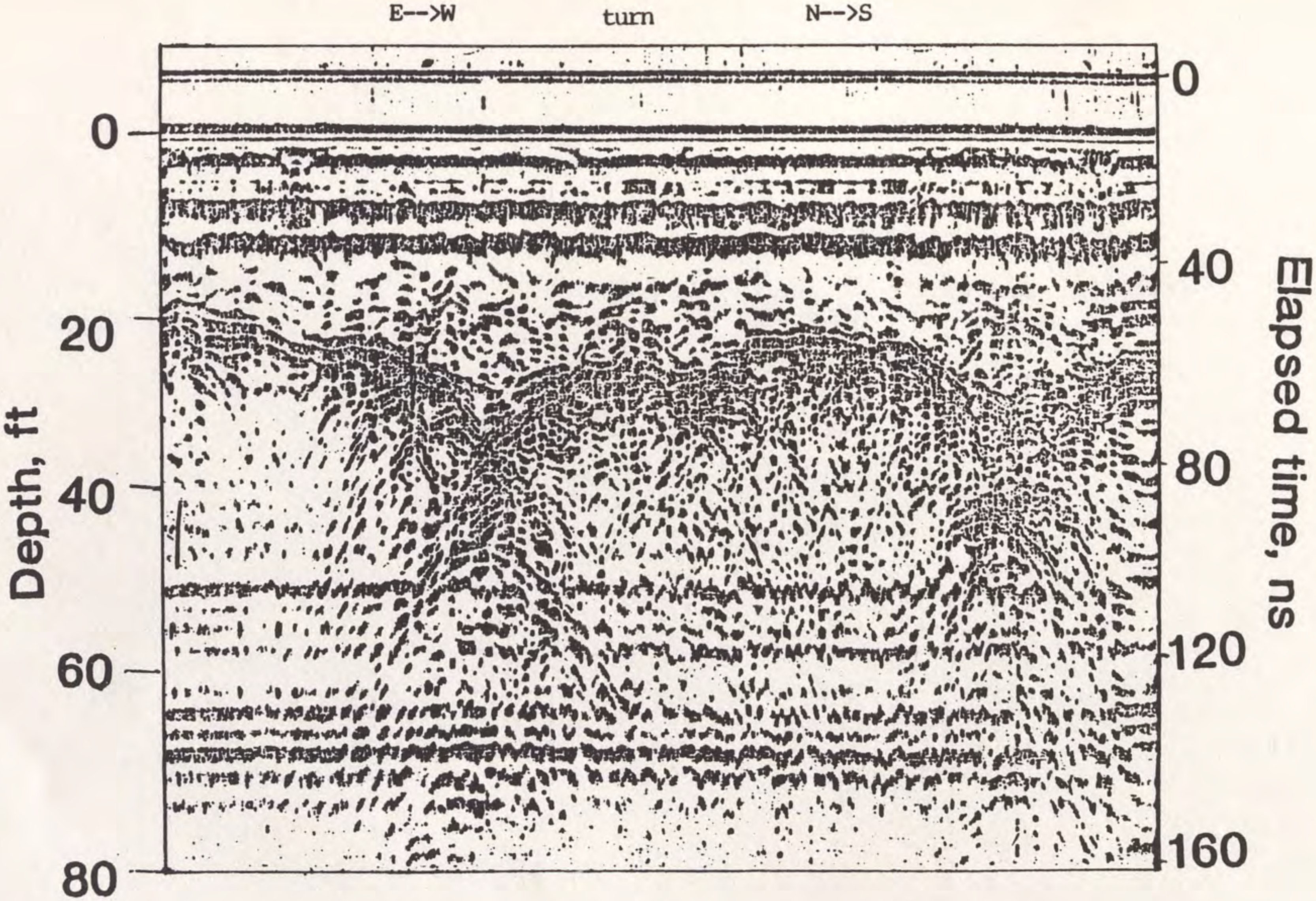


Figure 12. Radar Profile of Second Cavity at Oak Run At A Depth of 38 Feet. (800 X4L, System 8, 80 MHz Antenna)

Wastewater retention/percolation ponds were to receive 6 inches of wastewater daily. The purpose of the investigation was to determine areas of near-surface limestone and locate any areas of subsidence of the clay layer. Results of the survey showed substantial penetration with actual depth depending on the natural dielectric constant of the soil. Boring logs showed a clean loose sand over a thick clay layer. Deep borings in some areas reached the limestone layer at 40 feet.

A radar survey was done over a localized surface depression on the far east side of the site. The radar profile of Figure 13 shows a distinct depressing of the silty clay layer at the site. Apparently clayey soils subsided into a cavity in the underlying limestone at a depth of over 40 feet.

Several other areas of subsidence in the silty clay layer were also detected at this site as shown in Figure 14. These occurrences could not always be predicted from surface elevations.

SITE 3: Apopka, FL

Apopka Blue Sink is one entrance to a cave system in Orange County with another entrance at Rock Springs. This limestone cave system has been approximately mapped by local cave divers as shown in Figure 15. Radar surveys in this site were initially attempted to determine the locations of caves from the ground surface.

The site is located over the Ocala Uplift, a NNW-SSE trending anticlinal ridge. Thus the limestone is shallower here than in many areas.

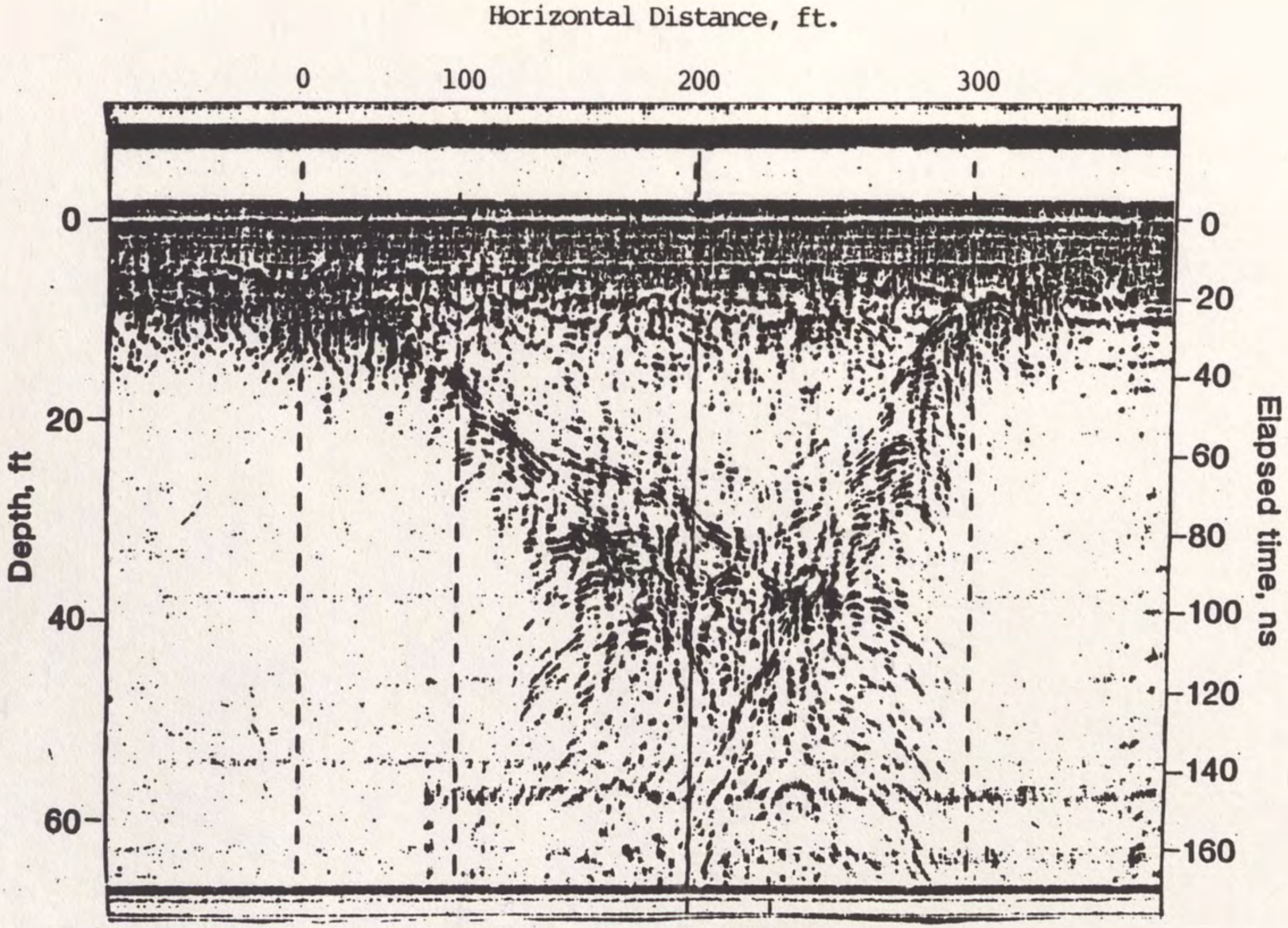


Figure 13. Radar Profile Over Surface Depression at Belleview. (900 X4L, System 4, 80 MHz Antenna)

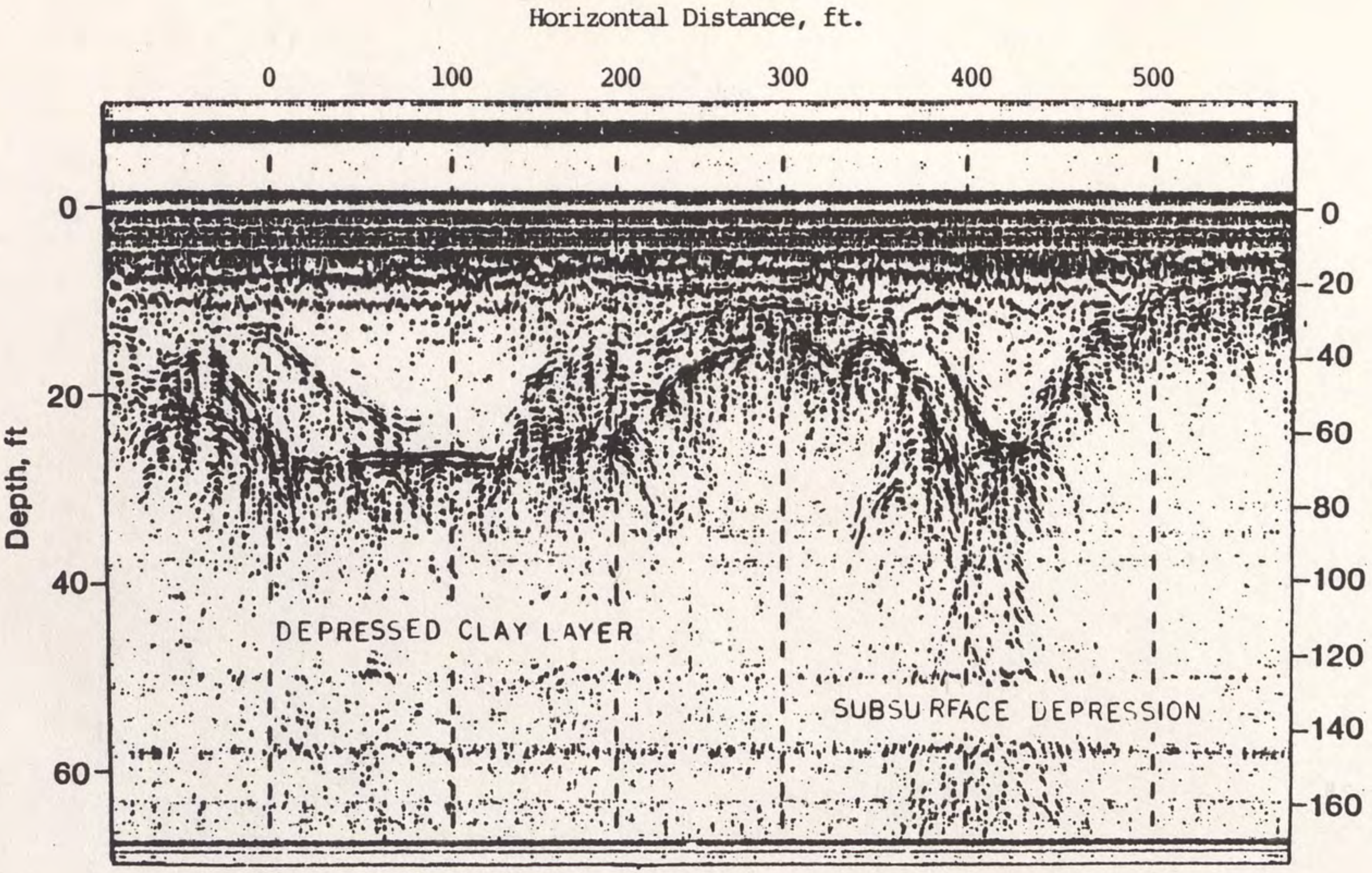


Figure 14. Radar Profile at Belleview Showing Depressed Clay Layer and Subsurface Depression (900 X4L, System 4, 80 MHz Antenna)

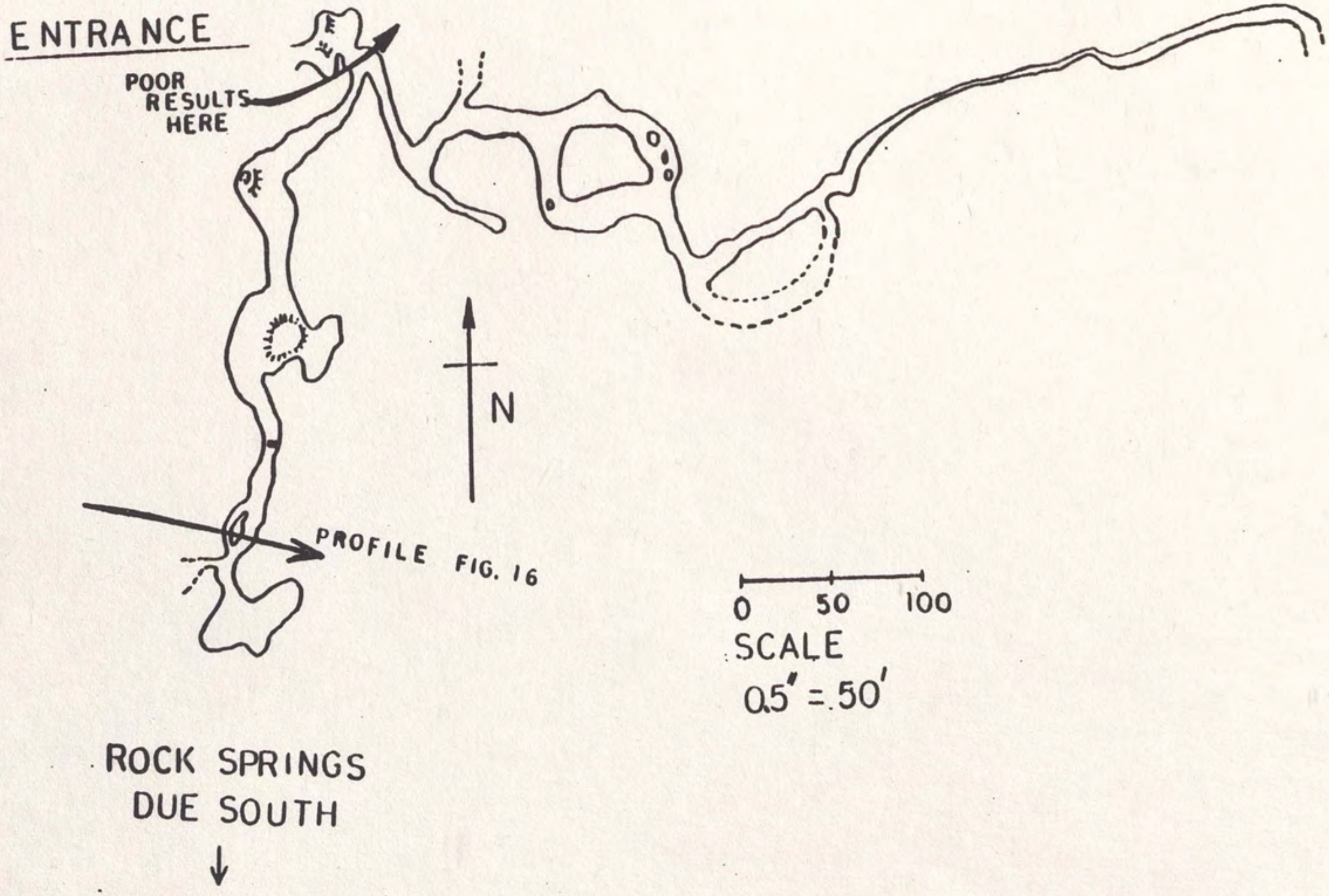


Figure 15. Map of Apopka Blue Sink Cave System.

The water table is relatively low, making this area an ideal location for a radar survey. Maximum penetration reached approximately to 65 feet. Resulting profiles near the cave entrance were poor because of overlying thick clay which attenuated most of the impulse energy. However, Figure 16 shows a profile of shallow side-by-side caves under an area along the south side of the existing sinkhole. The location matches the diver's map well.

Surveys over the entire pasture showed that some areas exhibit a definite subsiding which indicates a ravelling of overburden soils into subsurface voids. The profile in Figure 17 shows a distinct large cavity with depressed subsurface. The ground surface shows no sign of depression.

A large surface subsided area overgrown with weeds was also investigated. The resulting profile presented in Figure 18 shows a picture similar to that of Figure 17. This area collapsed about six months later, verifying prediction of potential collapse.

At the south of the existing sinkhole in this pasture, evidence of a small collapsed sinkhole had recently occurred. The antenna was pulled around the perifery of the sinkhole. The resulting profile is shown in Figure 19. The profile is similar to those of Figures 17 and 18 except a longer and darker soil column is seated on the top of a good sized cavity. This is because the ravelling soil was bridged and consolidated above the cavity, preventing further collapsing.

Rock Springs is a state-owned park about two miles south of Apopka Blue Sink featuring a fresh water spring, which is surface discharge

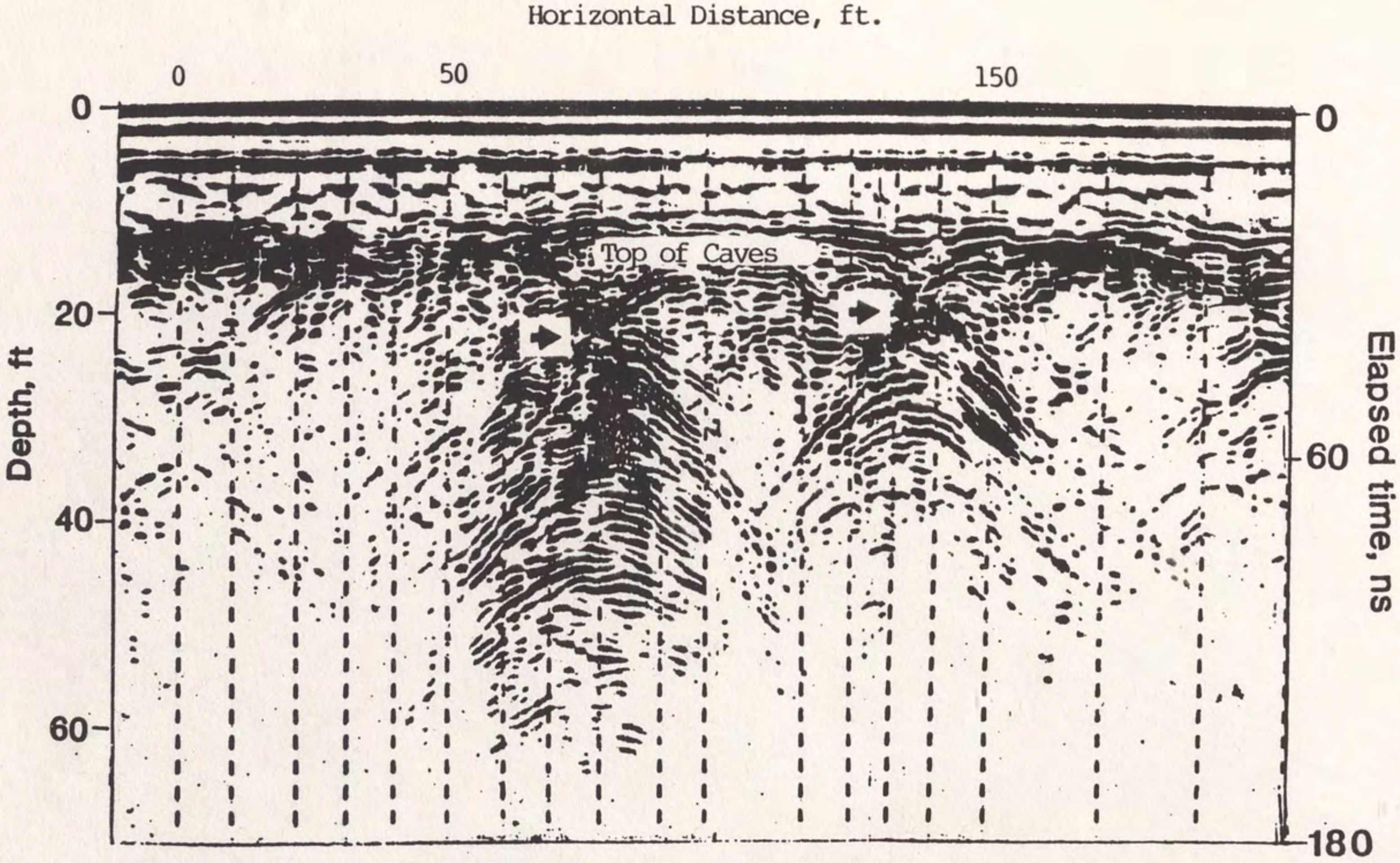


Figure 16. Radar Profile of Side-by-Side Caves at Apopka Blue Sink. (900 X4L, System 8, 80 MHz Antenna)

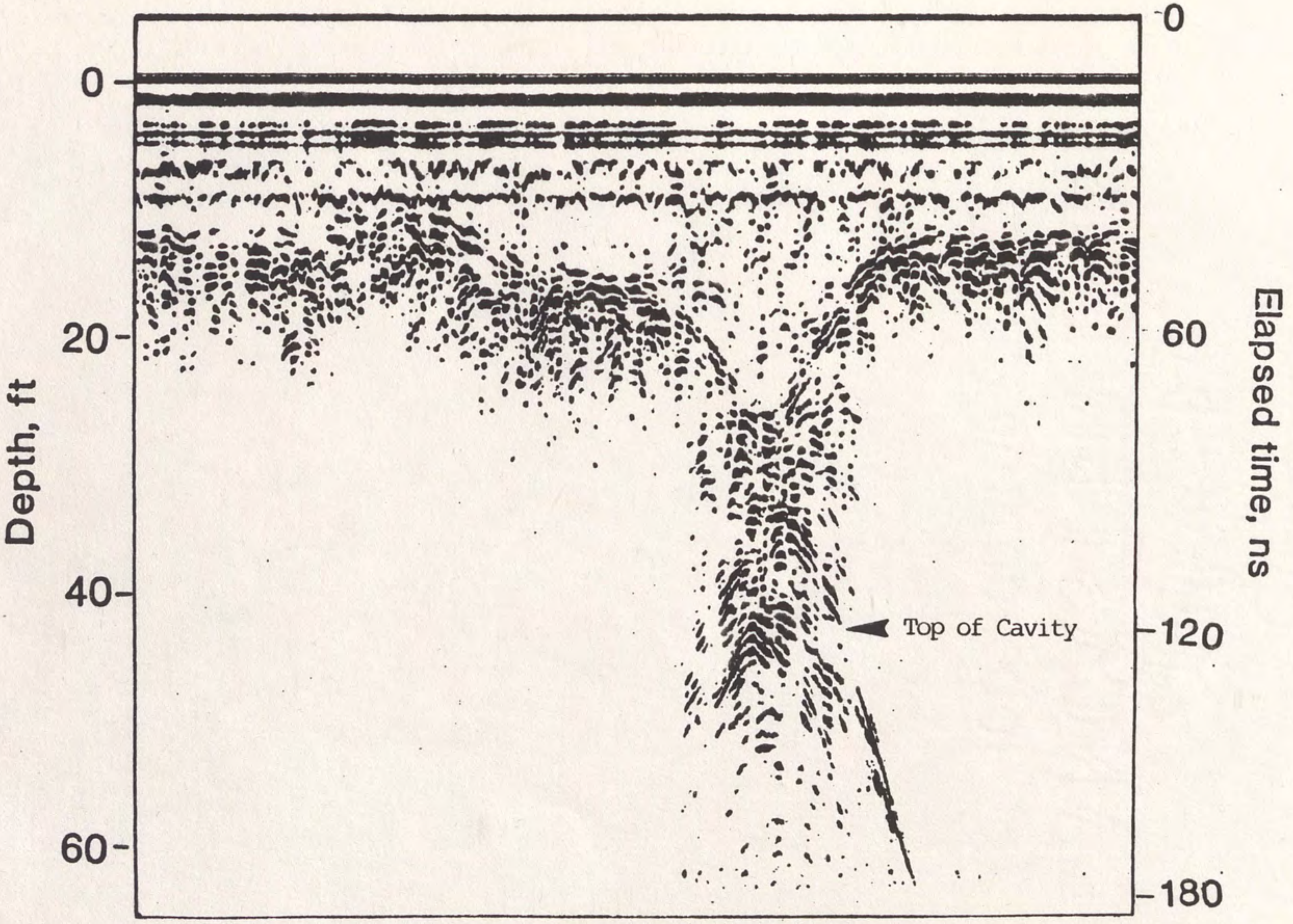


Figure 17. Radar Profile at Apopka Blue Sink Showing Cavity and Depressed Clay Layer Below Flat Ground Surface (900 X4L, System 8, 80 MHz Antenna)

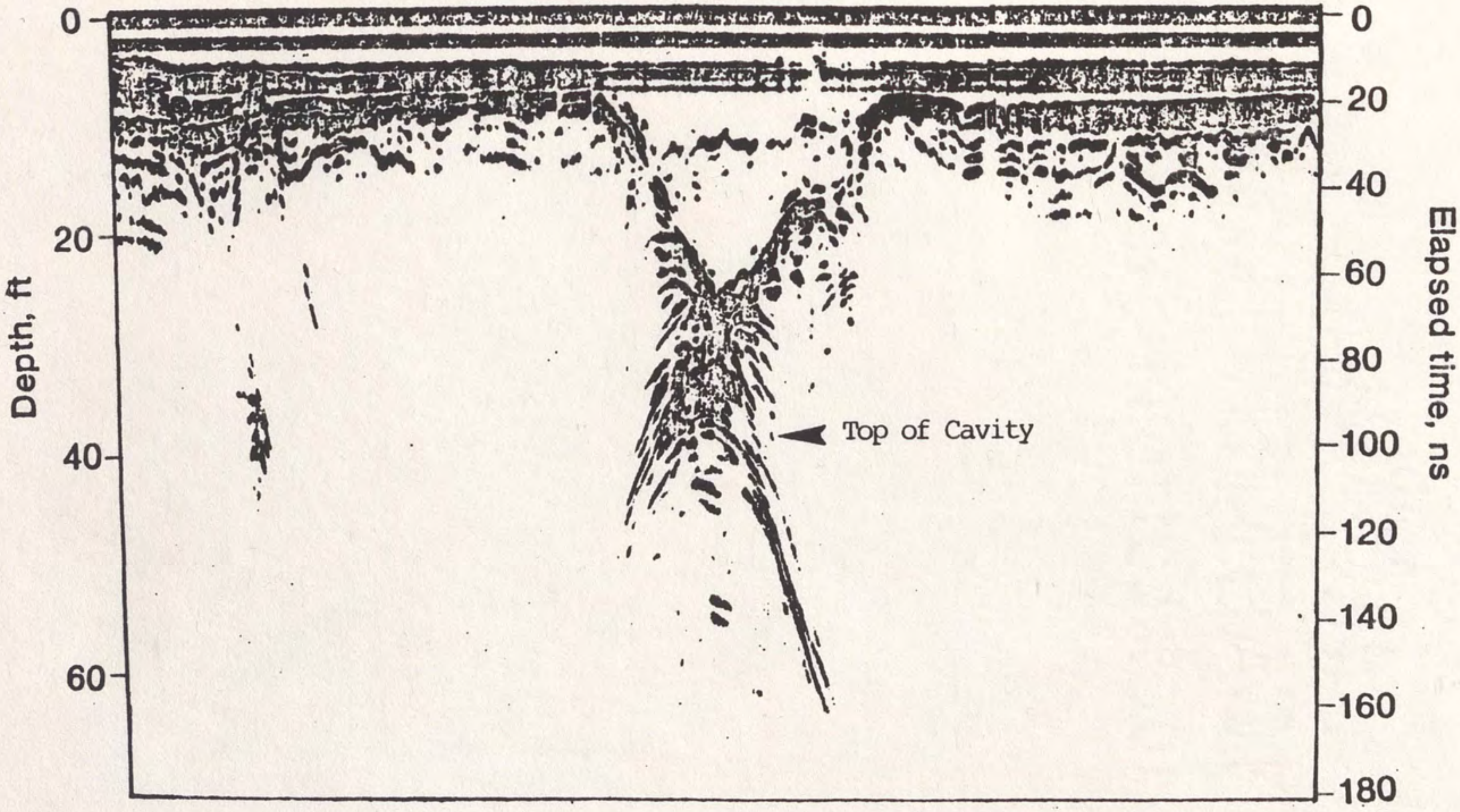


Figure 18. Radar Profile Showing Depressed Clay Layer Below Ground Surface Depression (900 X4L, System 8, 80 MHz Antenna)

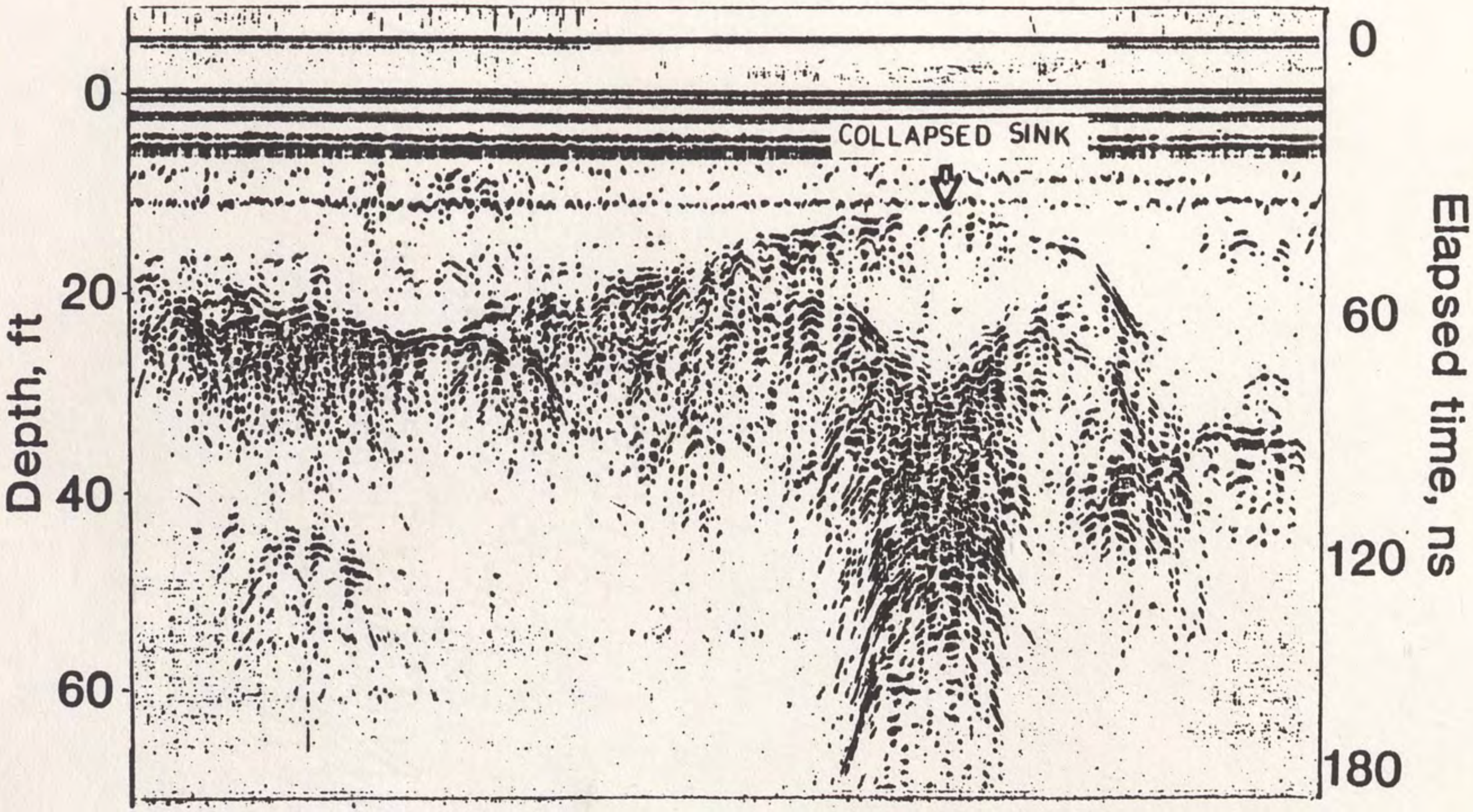


Figure 19. Radar Profile Showing Consolidation and Bridging Over Recently Collapsed Cavity (900 X4L, System 8, 80 MHz Antenna).

from the aquifer. This cave entrance is connected to Apopka Blue Sink, although this connection is not mapped. The radar was pulled over the surface at the mouth of the cave to verify the cavity signature. Figure 20 shows strong signal returns from the limestone interface which is apparent at a depth of 13 feet.

SITE 4: Peacock Springs

Peacock Springs is a submerged cave system near Live Oak in North Florida. Several caverns were detected by ground penetrating radar surveys at locations shown on the cave map of Figure 21, yet several sites gave disappointing results. Auger borings at this site indicated that in the general area, a thick clay layer was overlying the limestone formation. The water table was about 25 feet. A relatively high dielectric constant of 13 for average soil was used to calculate radar penetration depth.

Figure 22 shows a radar profile obtained from a site where a dry dome exists under Peacock Road at a depth of about 14 feet below the asphalt paved road. In the profile of Figure 23 just north of Peacock Springs, the hyperbolic cavity signal corresponding to the mapped cave is very flat due to the slow speed of antenna travel. Figure 24 shows a profile taken just east of Pothole Sink. The highly conductive clayey soil was attributed to limitation of the impulse signal.

SITE 5: Bat Cave-Jerome Sink, Newberry, FL

Bat Cave is a partly dry cave system located in Newberry, Florida, just west of Gainesville on the Ocala Uplift. Limestone has surface

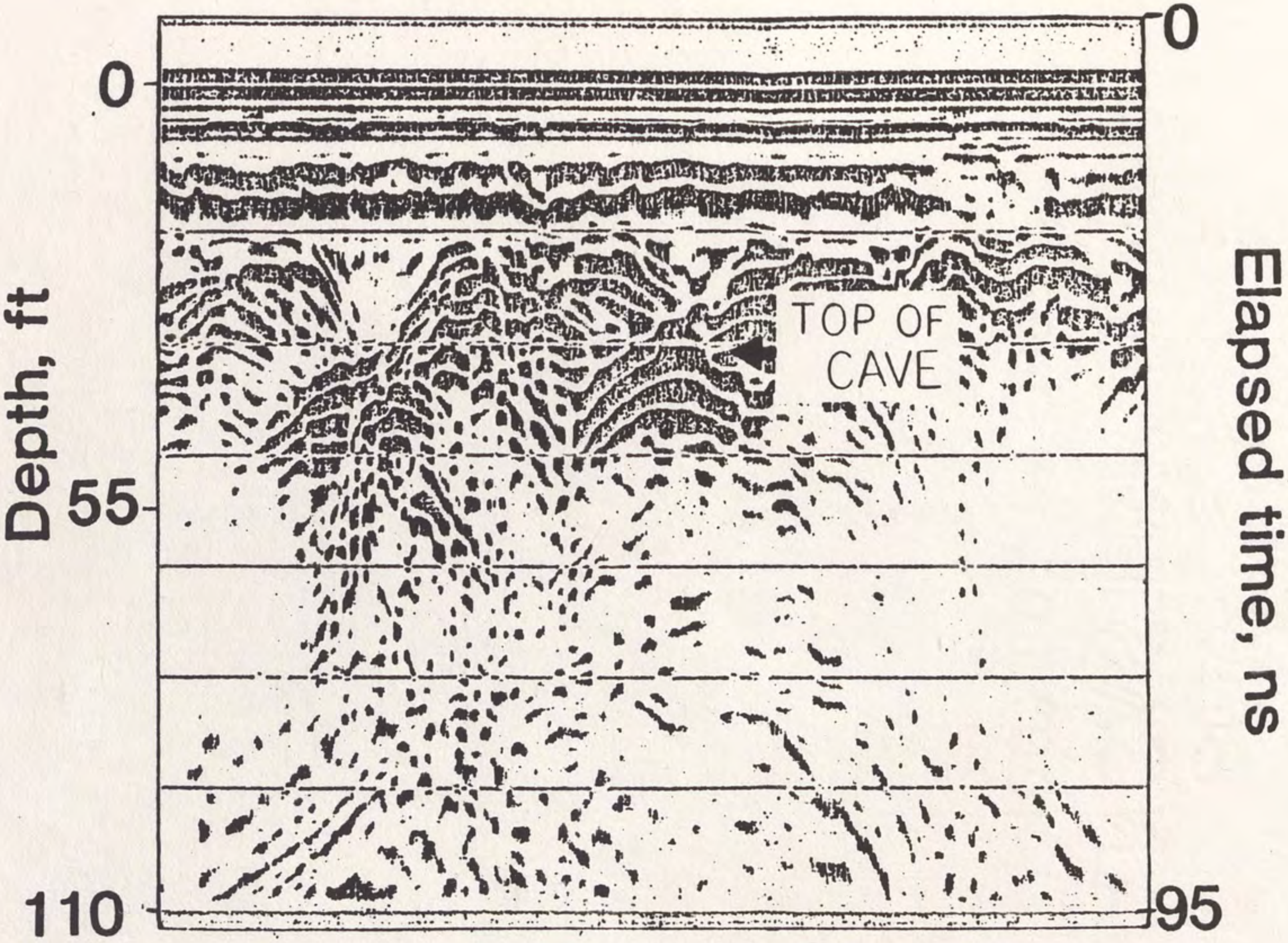


Figure 20. Radar Profile at Mouth of Rock Springs Cave (950 X2L, System 8, 80 MHz Antenna).

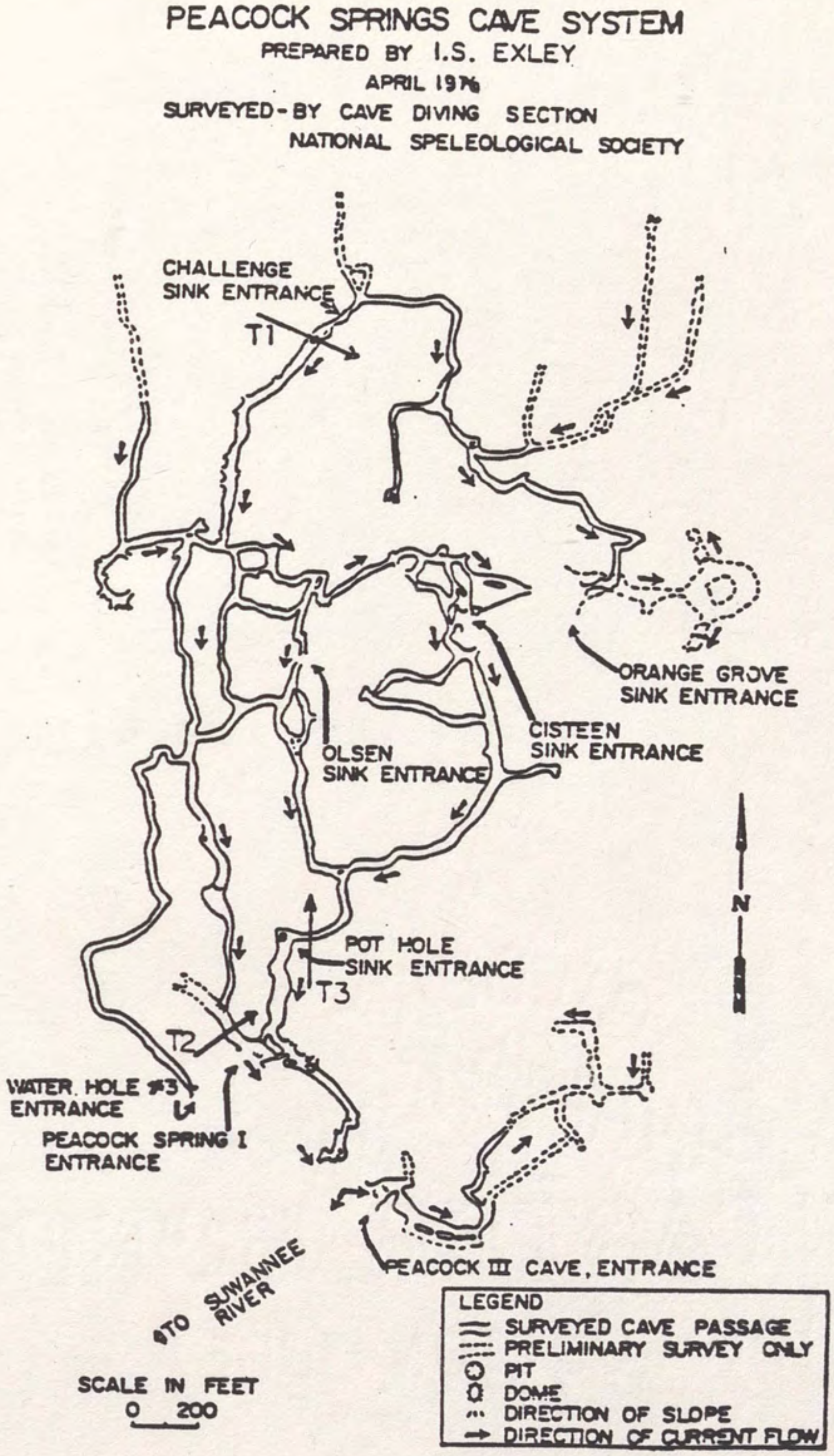


Figure 21. Map of Peacock Springs and the Traverses of Radar Survey.

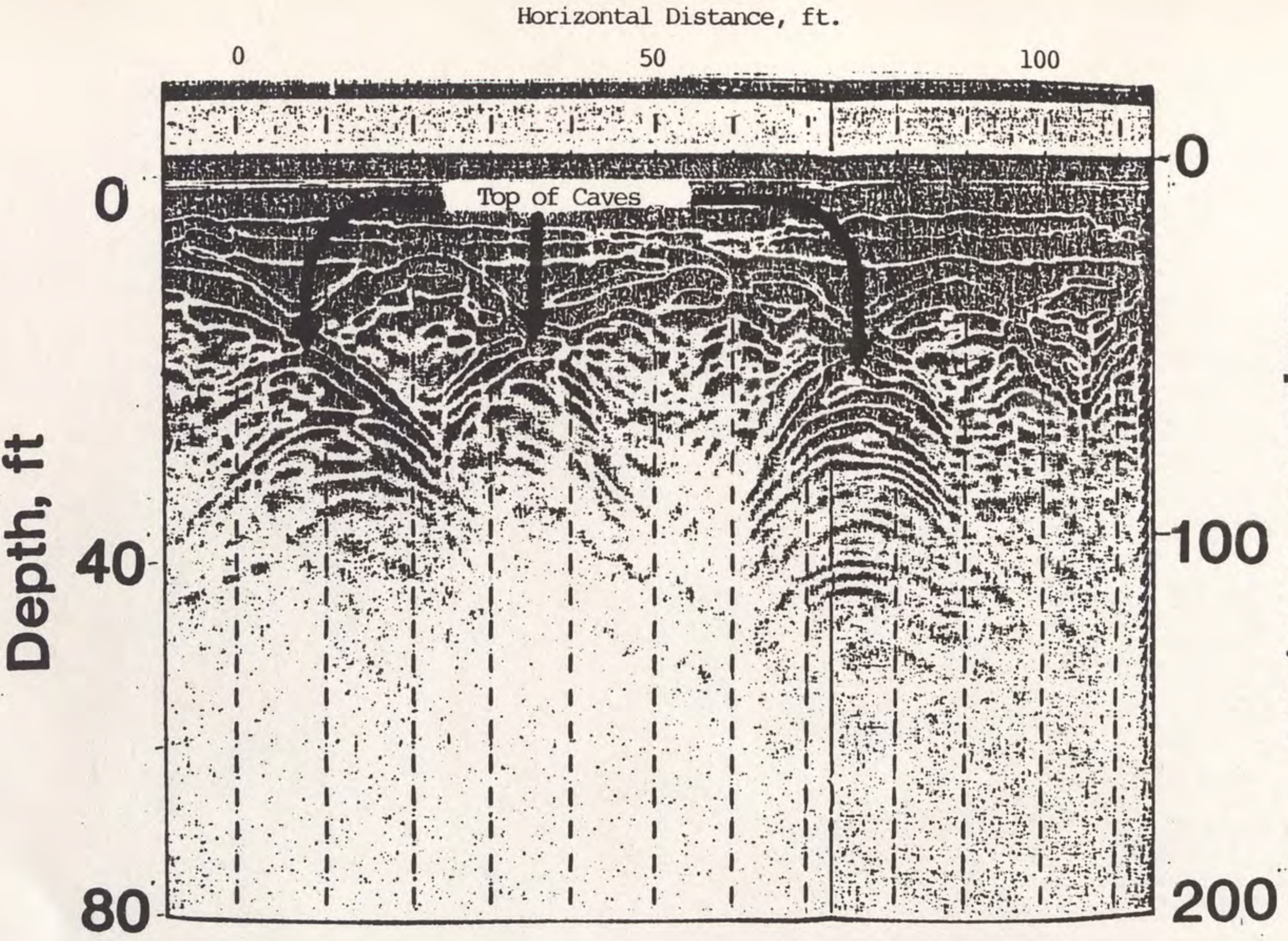


Figure 22. Radar Profile at Peacock Springs, Traverse 1 (999 X4R, System 4, 80 MHz Antenna).

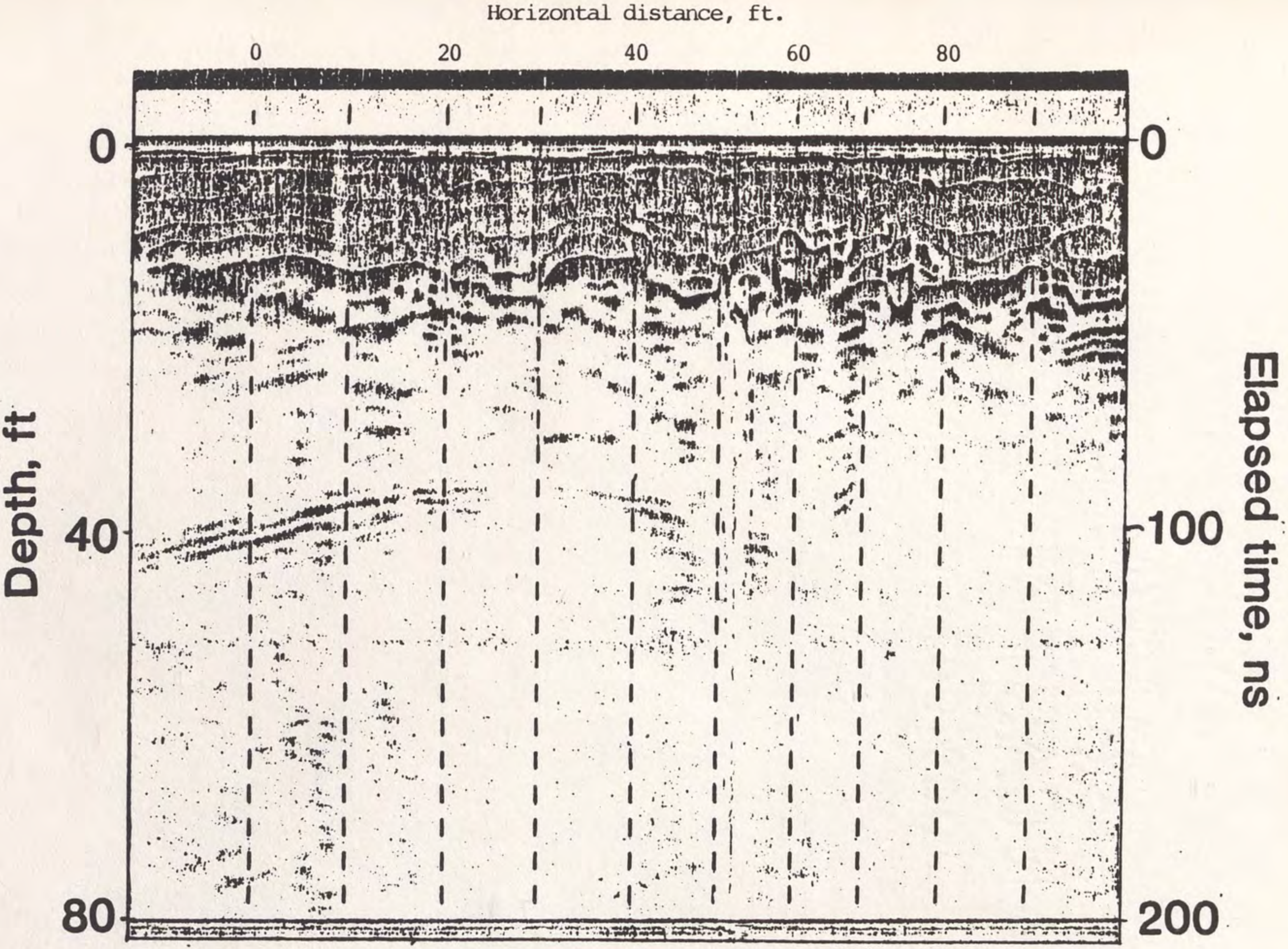


Figure 23. Radar Profile North of Peacock Spring I, Traverse 2 (999 X4L, System 4, 80 MHz Antenna).

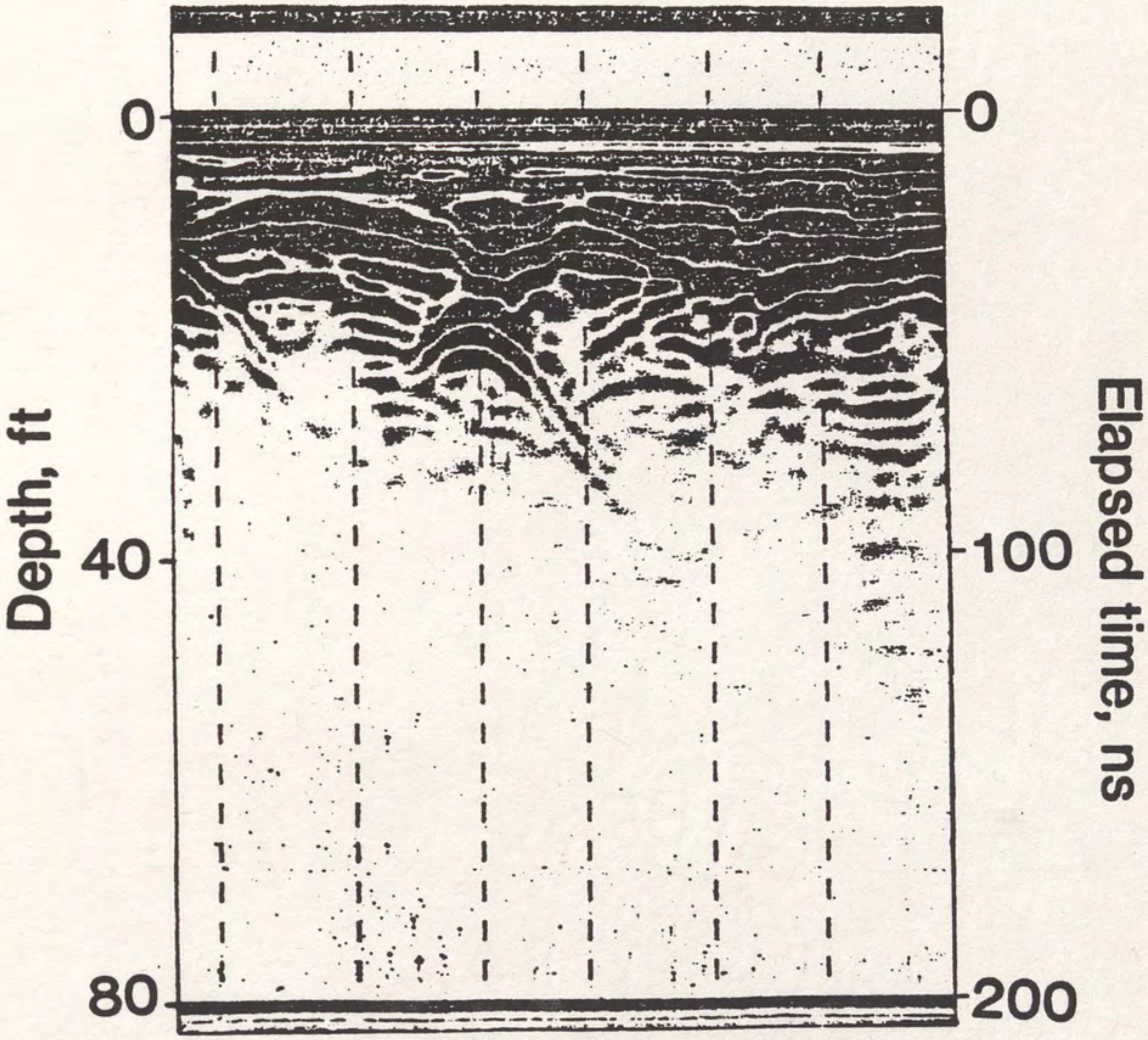


Figure 24. Radar Profile Next to Pothole Sink, Traverse 3. (999 X4R, System 4, 80 MHz Antenna)

exposure around the cave entrance and in the immediate area, which is otherwise covered by clean quartz sand of varying thickness. A map of the cave in Figure 25 shows a maze-like cave system roughly paralleling the water table which is located at approximately 30 to 35 feet. Personal inspection of the cave revealed a highly porous limestone with distinct fractures.

Figure 26 is a complex profile run over the large cavern between the entrances. Radar penetration depth at this site was calibrated at about 55 feet. Signal losses indicate discontinuities in the limestone; however, the caverns were difficult to distinguish due to overlapping reverberations from the very porous limestone formation.

Jerome Sink is a roof collapse sink located a few miles SW of Bat Cave. The sink has a diameter of 9-12 meters with vertical limestone walls. Depth to the clear pool of water at the bottom is about eight meters. A joint in the limestone is apparent on both sides of the sink, and approximately 200 feet away along the line of this crack is a smaller sink also containing water at the bottom.

Several soil borings were made by hand auger along this joint as well as perpendicular to it. Figure 27 gives the locations and logs. These logs revealed limestone at varying depths from less than one foot to over ten feet. In some areas the rock was covered by quartz sand and in other areas by clay or sandy clay. The clay effectively stopped the radar signal. Figure 28 shows a profile perpendicular to the joint in which a cavity in the limestone is

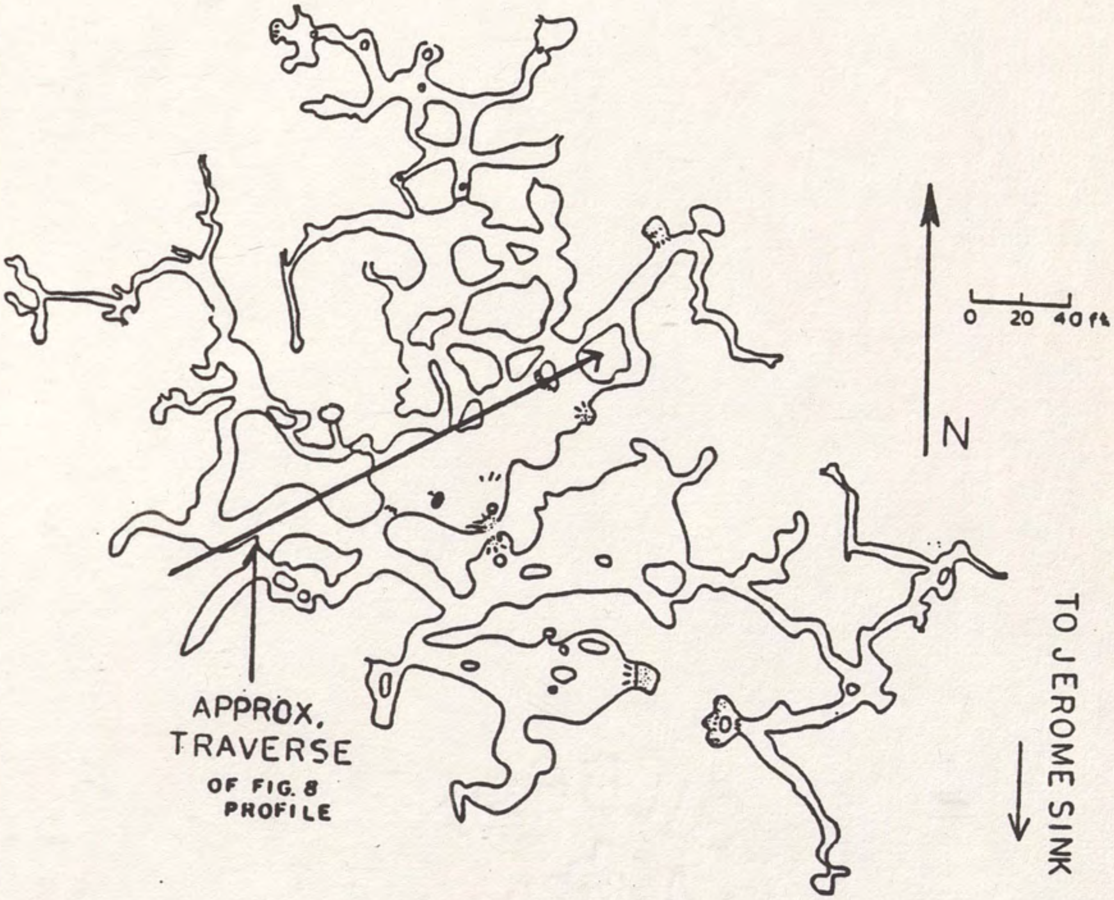


Figure 25. Map of Bat Cave (Paul W. Smith).

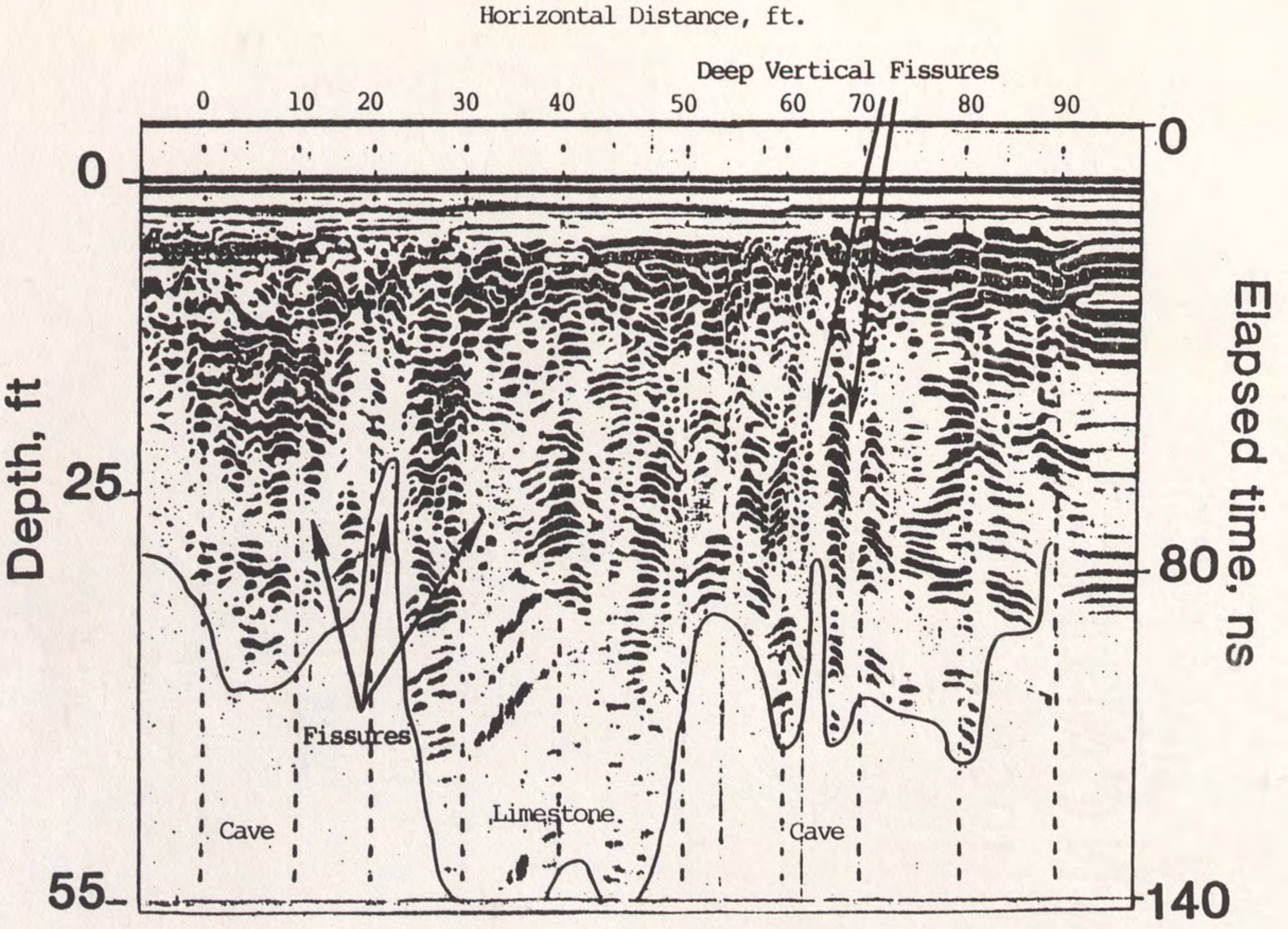


Figure 26. Radar Profile Showing Porous Limestone Formation at Bat Cave.
(700 X4L, System 8, 80 MHz Antenna)

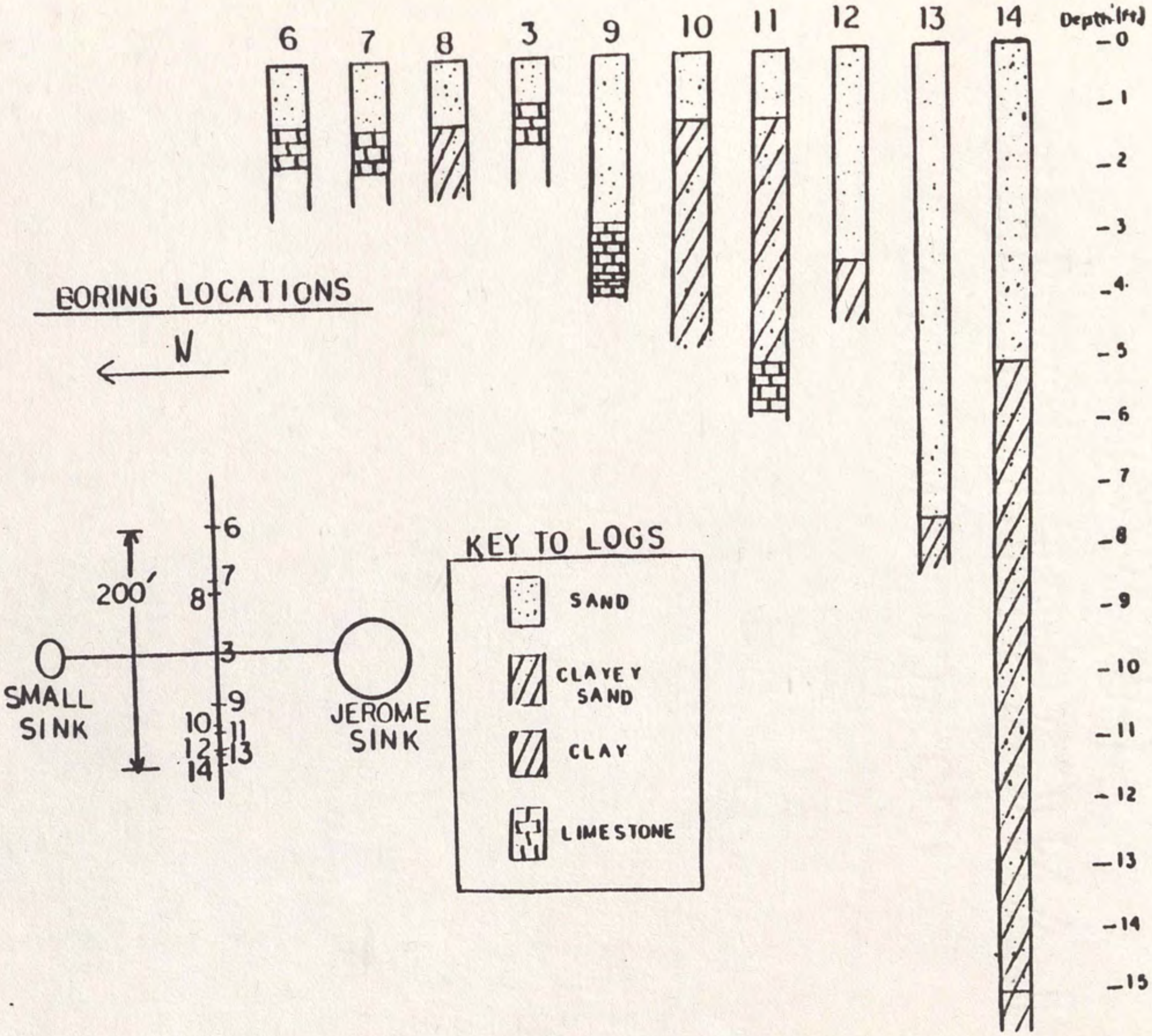


Figure 27. Boring Locations and Logs - Jerome Sink.

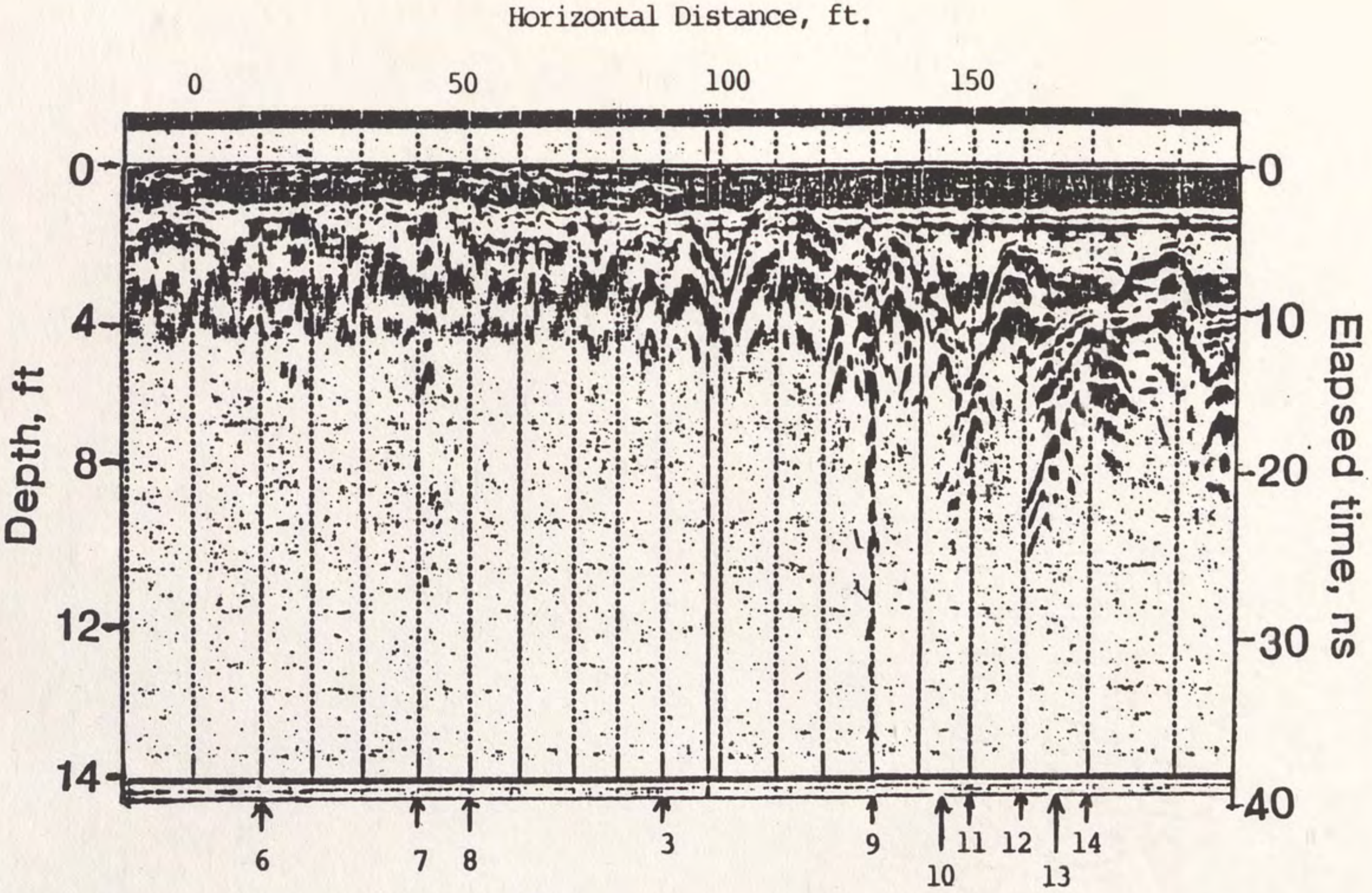


Figure 28. Radar Profile at Jerome Sink (500 X2R, System 4, 300 MHz Antenna).

seen just west of core sample three. This profile was made using the 300 MHz antenna which allows better near-surface resolution.

SITE 6: Ocala, FL

An investigation was conducted at a private residence near Ocala where a sinkhole had opened up in the backyard. This hole had been filled, but radar scans were run around the whole yard to determine if any other cavities existed. Radar surveys indicated a shallow clay layer with no signs of disturbance. One traverse showed a typical limestone pinnacle shown in Figure 29. In order to confirm the limestone peak, a grid pattern was set up with perpendicular traverses run every ten to twenty feet. The profile from Figure 30 was run along this grid. In the area of the limestone peak, auger borings were made at four foot intervals (see boring locations and logs in Figure 31), locating a four foot by eight foot limestone high at one to two feet below the flat ground surface. The overburden was sand and clayey sand. Borings and profiles in other areas of the yard showed the clay layer to be much thicker, causing rapid attenuation of the radar signal.

The GPR System detected clay pockets in the limestone at Haile Quarry, east of Ocala. Thin overburden had been scraped clean, revealing Crystal River limestone pockmarked with clay-filled solution pipes. Most pipes were two to four feet in diameter and from six inches to 75 feet deep. The dark plastic clay blocked the radar signal, which easily penetrated the limestone. However, clay layers less than a foot thick did not affect the signal, as seen in Figure 32.

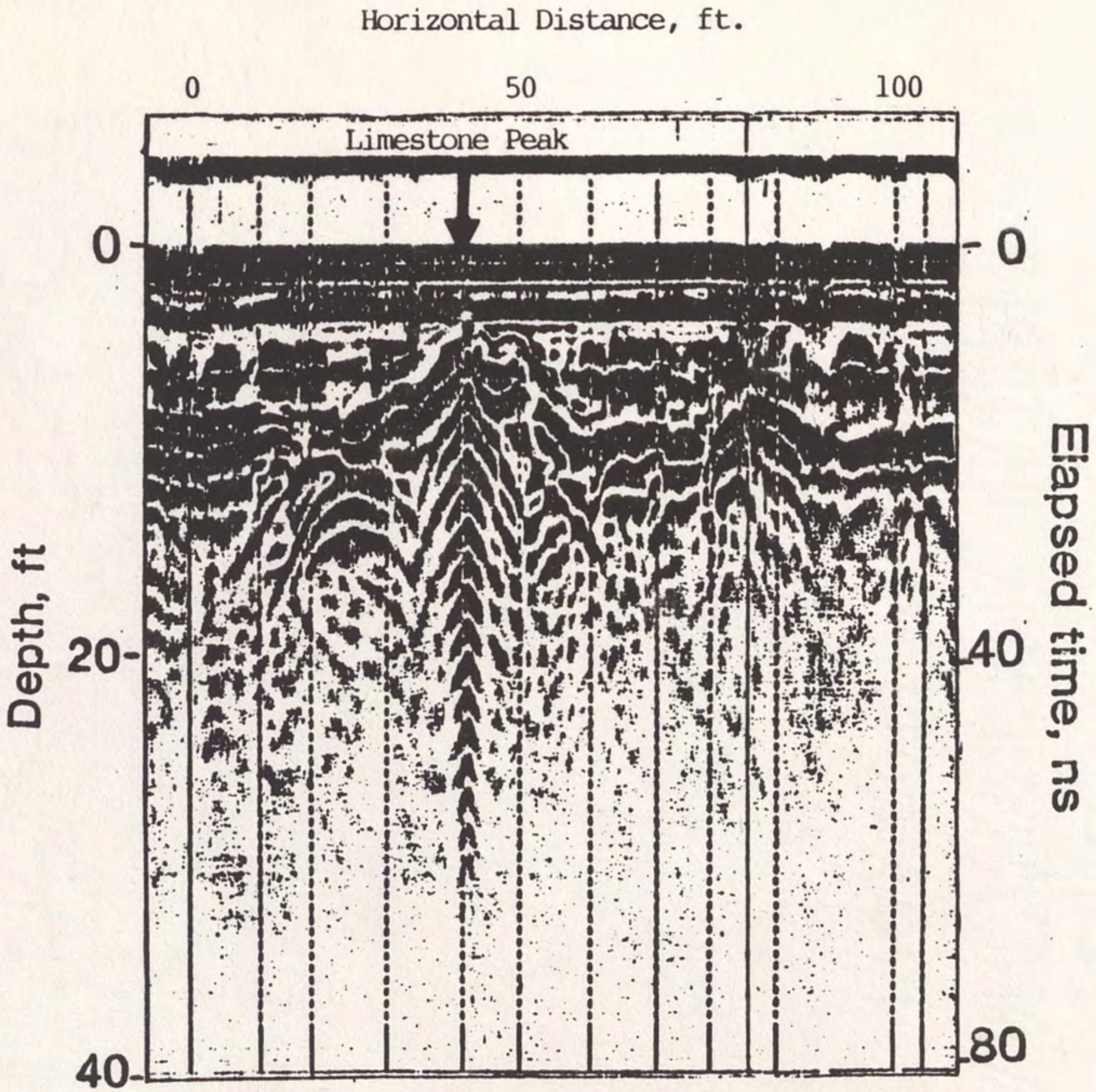


Figure 29. Radar Profile Showing Limestone Signal Near Ocala (600 X4R, System 4, 80 MHz Antenna).

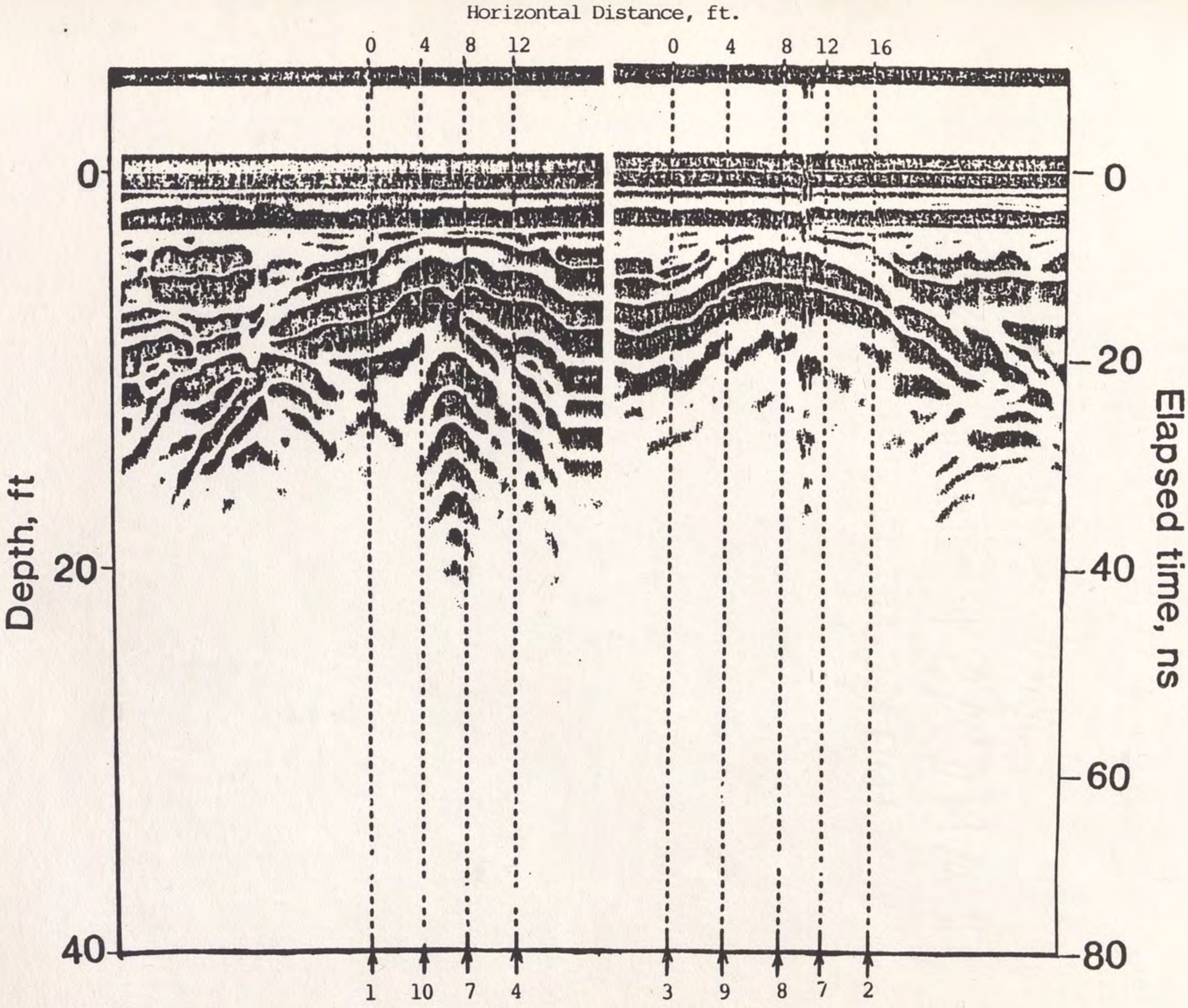


Figure 30. Radar Profile Over Limestone Signal With Auger Locations Marked (600 X4R, System 4, 80 MHz Antenna).

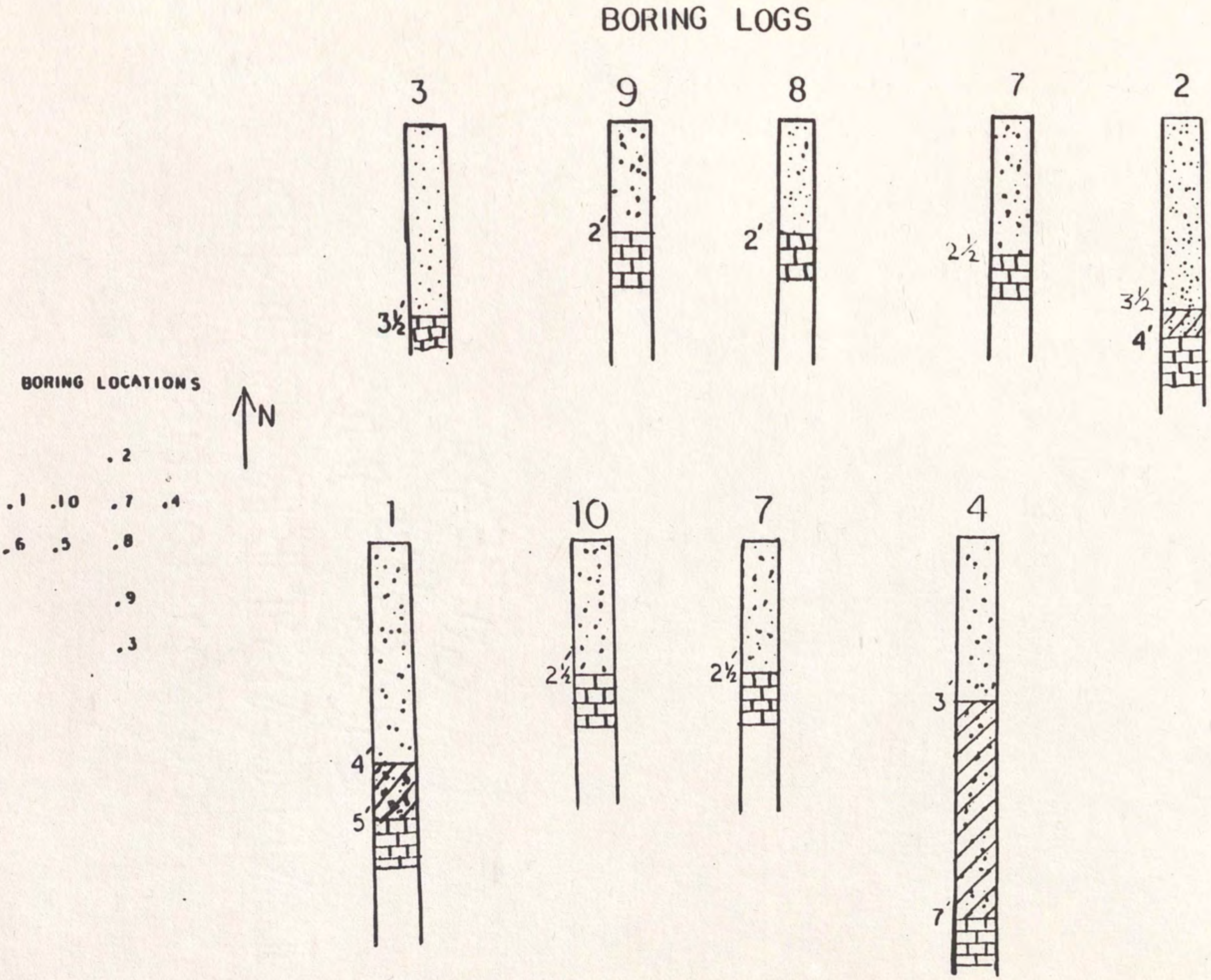


Figure 31. Boring Locations and Logs in Area of Limestone Peak.

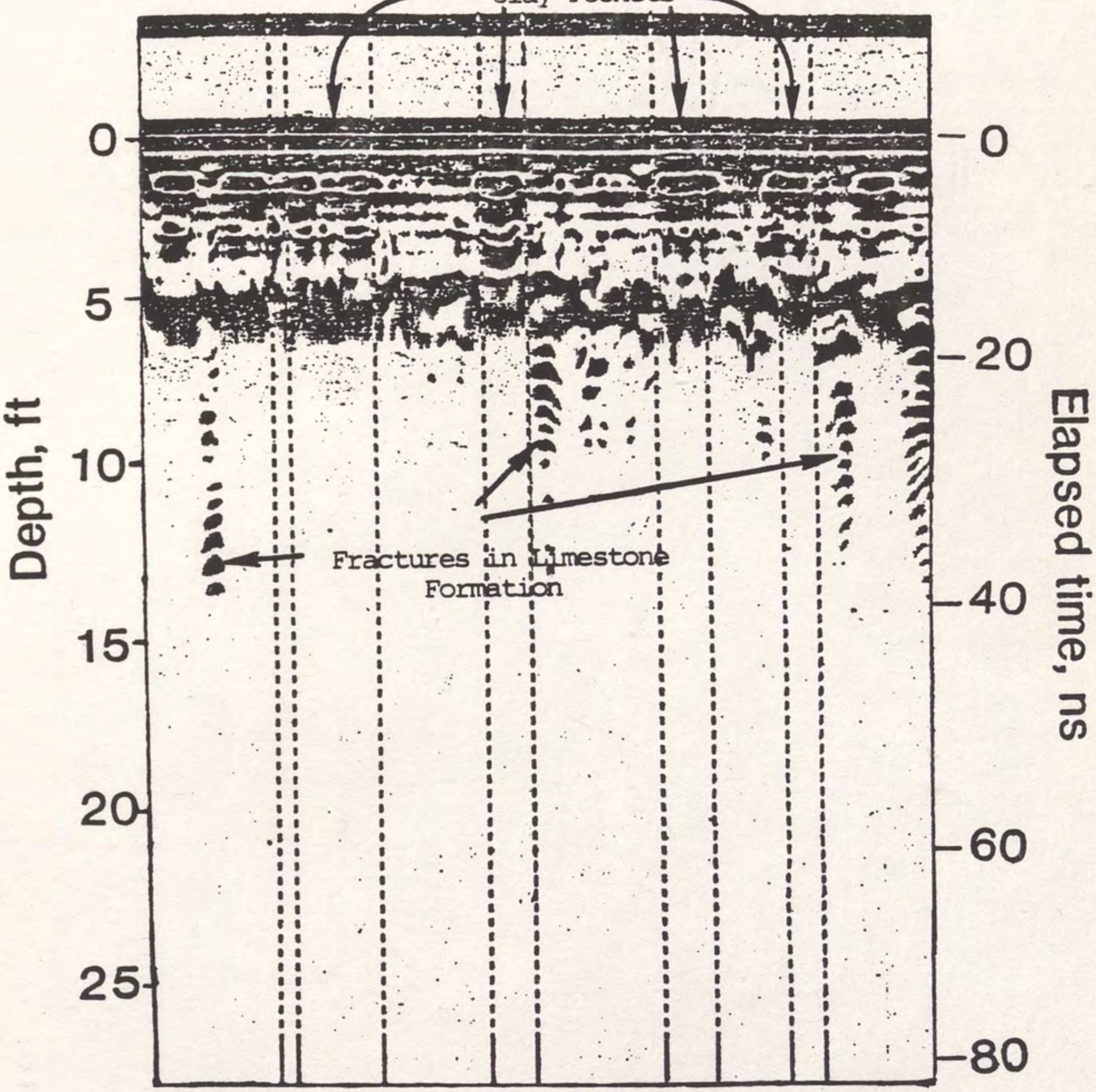


Figure 32. Radar Profile at Haille Quarry (600 X4R, System 8, 300 MHz Antenna).

A change in density was detected at five feet. This is apparent from the profile and was confirmed by a mine foreman. The lack of signal reflections below about five feet is due to the consistency of the limestone extending significantly deep so that there is no interface reflection.

SITE 7: Plant City, FL

Several areas in Plant City were subjected to sinkhole activity related to excessive pumping by strawberry farmers in an effort to protect their crops during a freeze in February 1985 (Ruth, 1985). Thirteen sinkholes occurred within a two mile radius. Two sites on Tanner Road were investigated by radar survey. These were Fletcher Orange Grove and the Beach House.

In the area where sinkholes had collapsed in the orange grove, hand augering revealed that the overburden soil was loose sand with some silt and organics underlain by a thick layer of sandstone at a depth of nine feet. The water table was at a depth of 10 feet. Radar signal penetration was only achieved to approximately 20 feet; therefore no significant features such as subsurface cavities were detected, as can be seen from the radar profile over the top of one sink as shown in Figure 33.

One large collapsed sinkhole approximately 25 to 30 feet in diameter at the backyard of the Beach House across the street from the orange grove had forced the family to move out of their house. Evidence of fracture planes in the subsurface due to the erosion of the soils is seen from the profile of the west side of the hole in Figure 34. No confirming subsurface information was available.

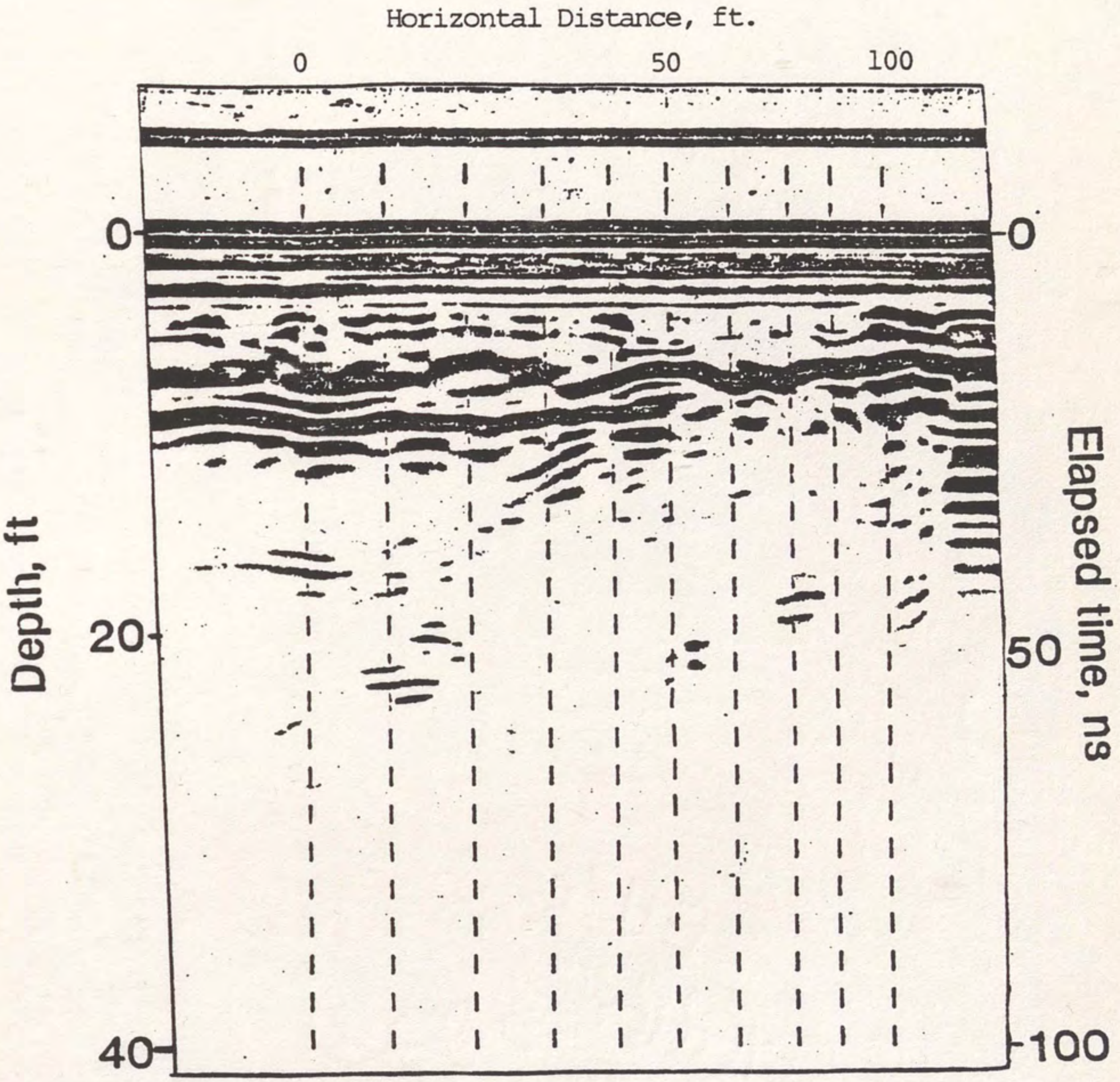


Figure 33. Radar Profile at Fletcher Grove Through Center of Collapsed Area (900 X4R, System 4, 80 MHz Antenna).

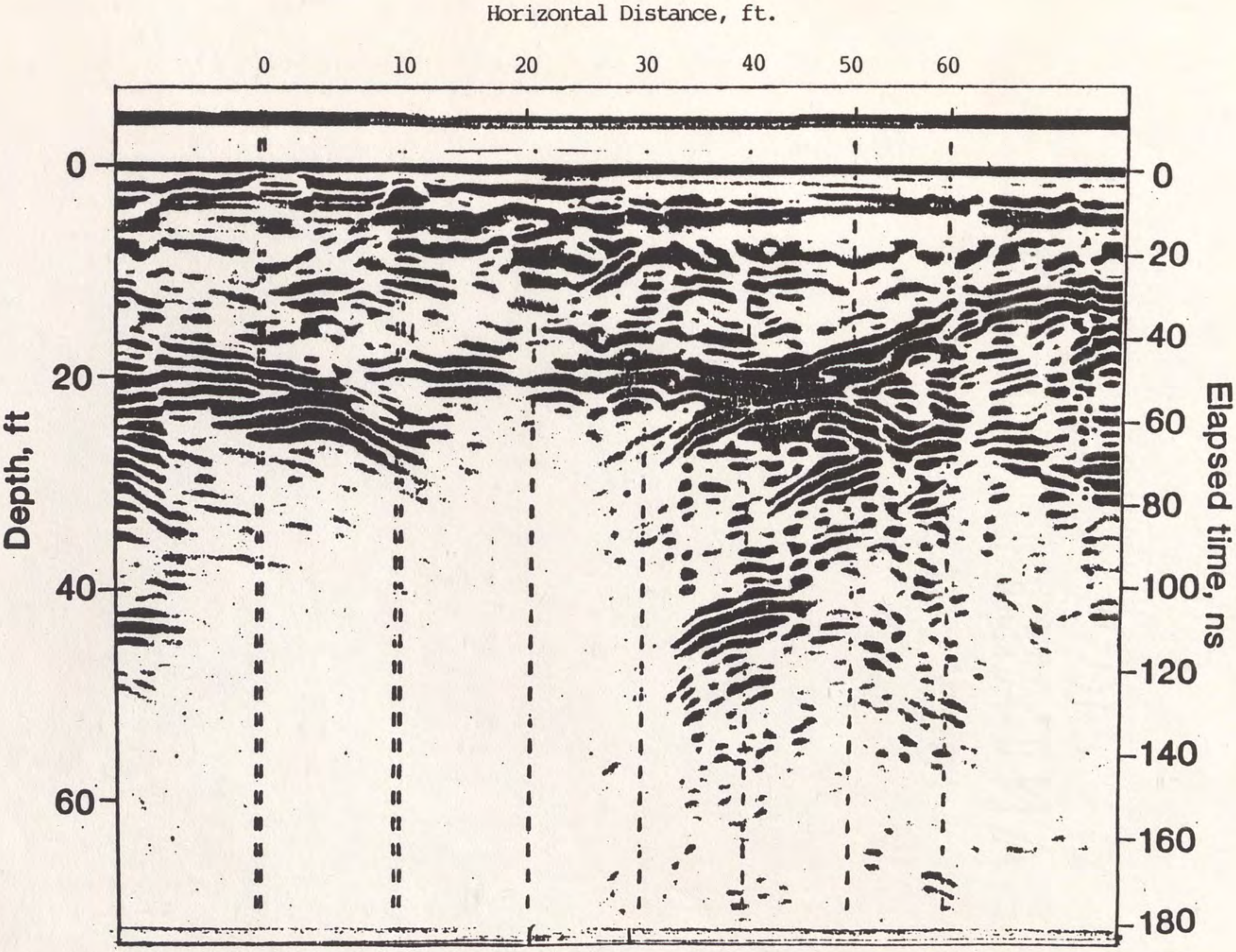


Figure 34. Radar Profile Next to Collapsed Sinkhole in Plant City.
(900 X4R, System 4, 80 MHz Antenna)

SITE 8: Pierson, FL

Pierson Airport is a grass landing strip located in Volusia County. Subsidence in the area due to well drawdown by heavy pumping during freezing weather had caused considerable concern as to the extent of further sinkhole activity. A radar survey was conducted on this site. The range of the control unit was set on 999 x 4L. An estimated dielectric constant of 6 was used for depth calibration. The total penetration depth should be calculated circa 50 feet. A layer of organic soil was located at about 30 feet as seen from the profile shown in Figure 35. This was ground-truthed by shallow auger borings.

SITE 9: Tampa, FL

A survey was conducted at Tampa Airport in an area to be developed for an extension of the existing airport. Boring records show that loss of drilling fluid was reported both above and within the limestone near the surface. From the report, boring 13A showed an 80% loss of drilling fluid at approximately 15 feet. However, no evidence of subsurface cavities could be found from the radar profile presented. in Figure 36. A higher frequency 300 MHz antenna was tried for better resolution but the results were still very poor. Even though a low value of six for the dielectric constant was estimated, penetration was only a few feet. Other antennas and range adjustments were tried but did not offer better resolution or penetration. This is a characteristic site where the application of the radar technique is very limited. The reason for this is either due to high conductivity of

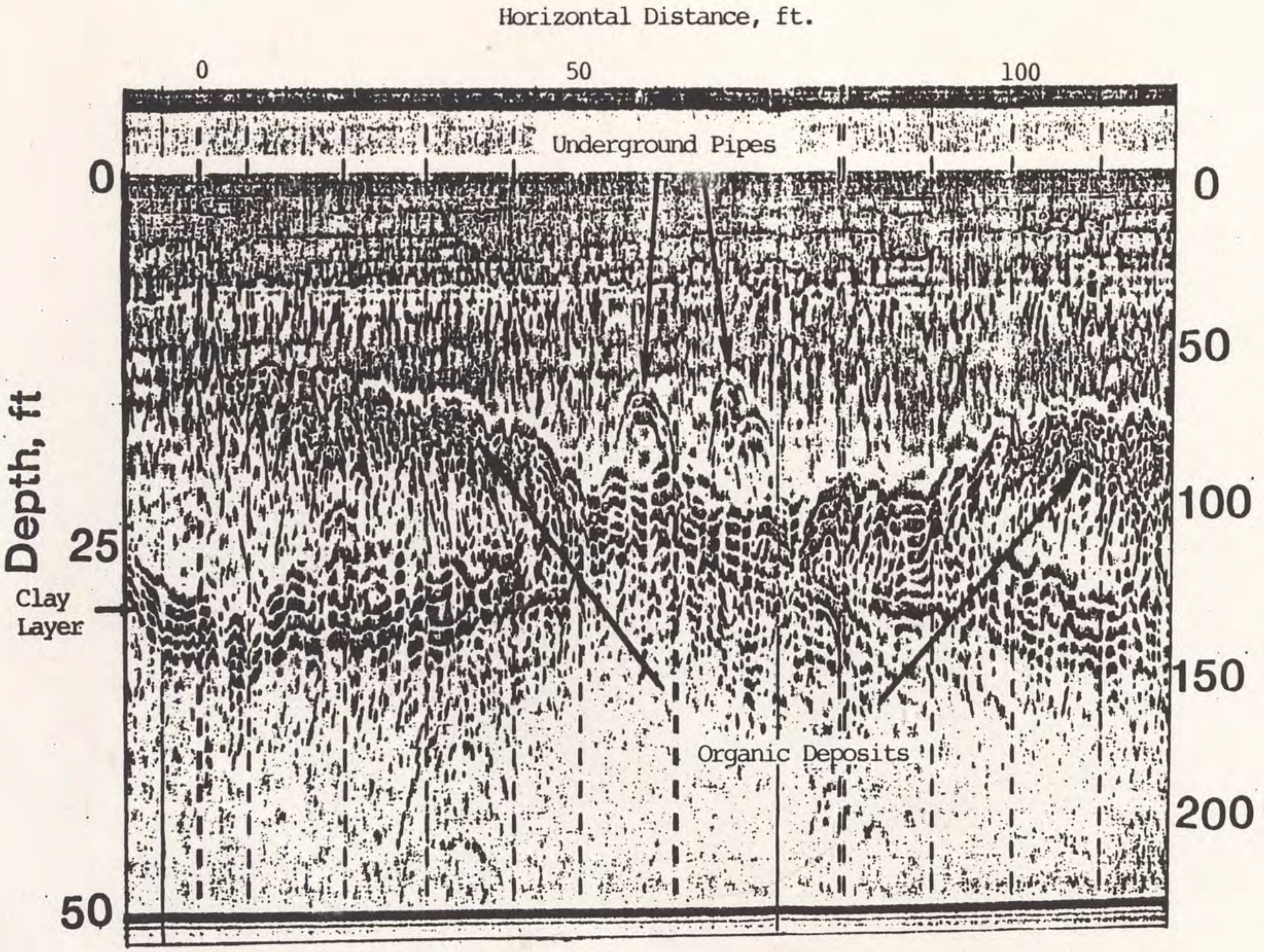


Figure 35. Radar Profile at Pierson Airport Showing Organic Deposits and Clayey Layer. (999 X4L, System 4, 80 MHz Antenna)

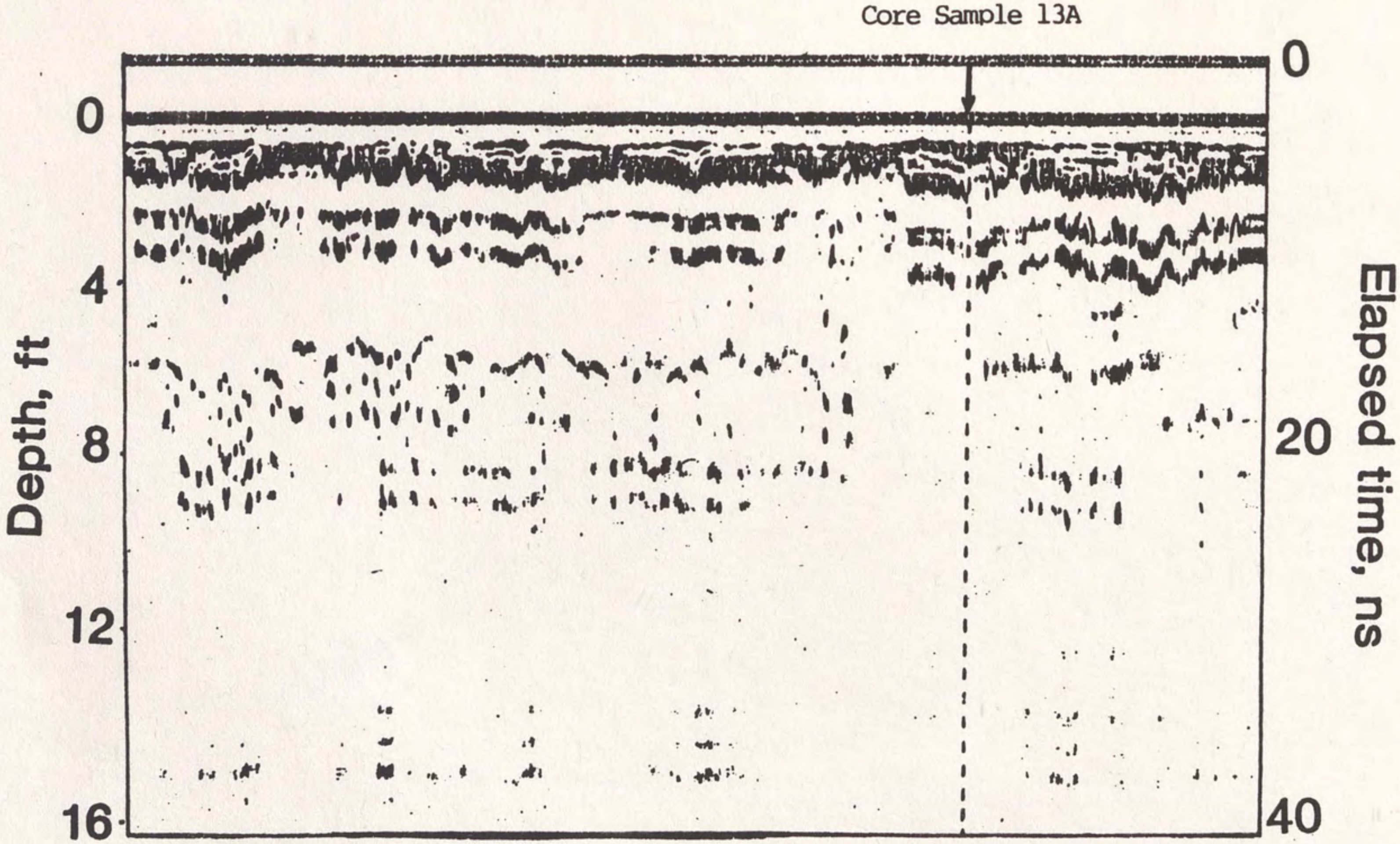


Figure 36. Radar Profile at Tampa Airport (400 X1L, System 8, 300 MHz Antenna).

the overburden soils or shallow groundwater, or a combination of both of these factors.

A profile from St. Petersburg Wellfield just north of Tampa is shown in Figure 37. Borings along this profile show an organic layer at 4.5 feet and the water table at 10 feet. Total penetration depth was calculated at 50 feet, but actual penetration was only about 20 feet.

SITE 10: Crystal River, FL

Radar surveys were conducted at the National Guard Armory at Crystal River. The area had been subjected to shallow depressions of the ground surface. Boring logs showed a very loose fine sand and soft sandy clay overlying hard limestone at depths of 10 to 25 feet. The water table was about six feet deep. Penetration depth was much greater than in the Tampa area. Figure 38 shows a radar profile with the range set on 300 x 4U. Using an average dielectric constant of 10 for saturated silt and limestone, the two cavities shown in the profile of Figure 38 were calculated at a depth of 30 feet.

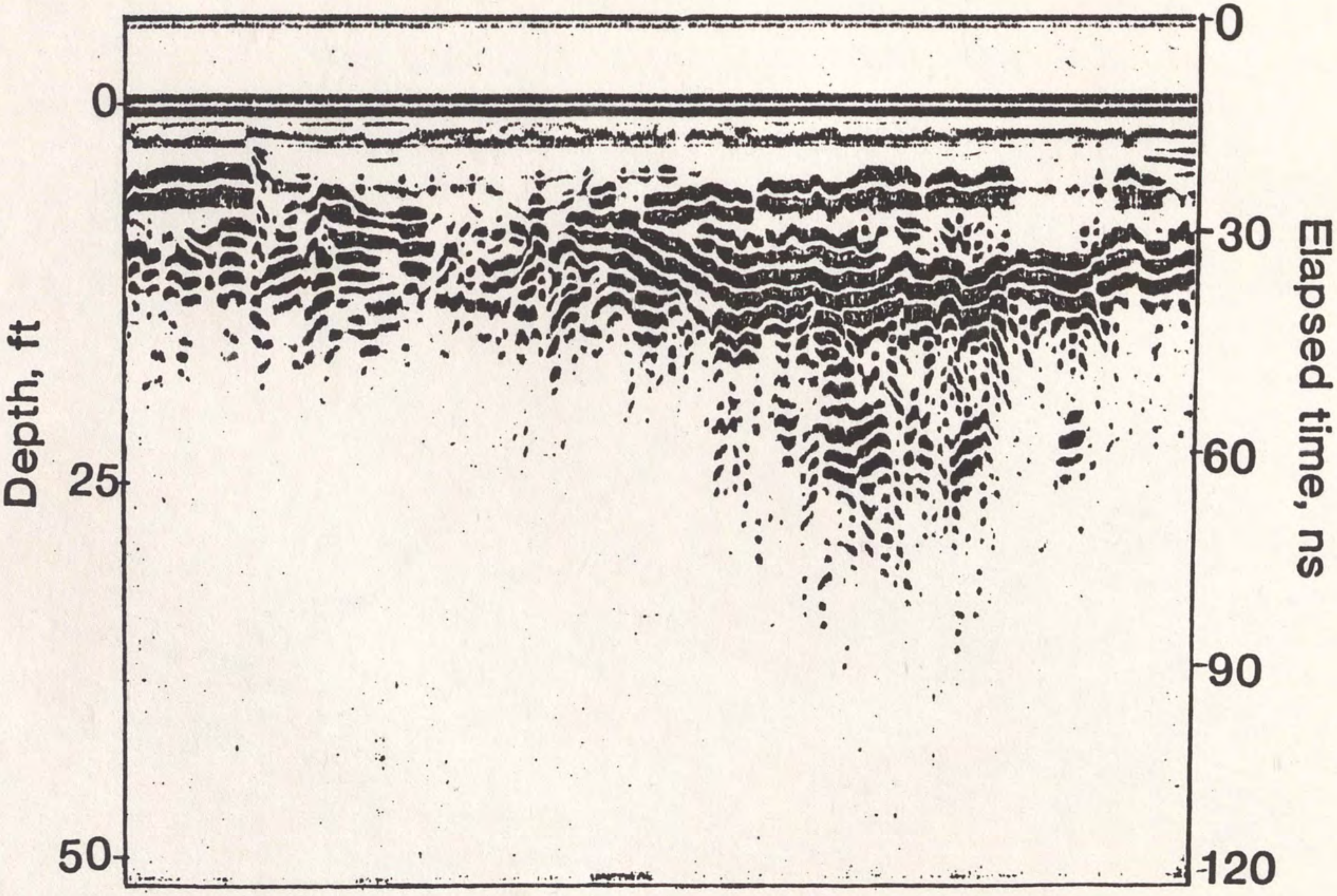


Figure 37. Radar Profile at St. Petersburg Well Field (600 X4R, System 8, 80 MHz Antenna).

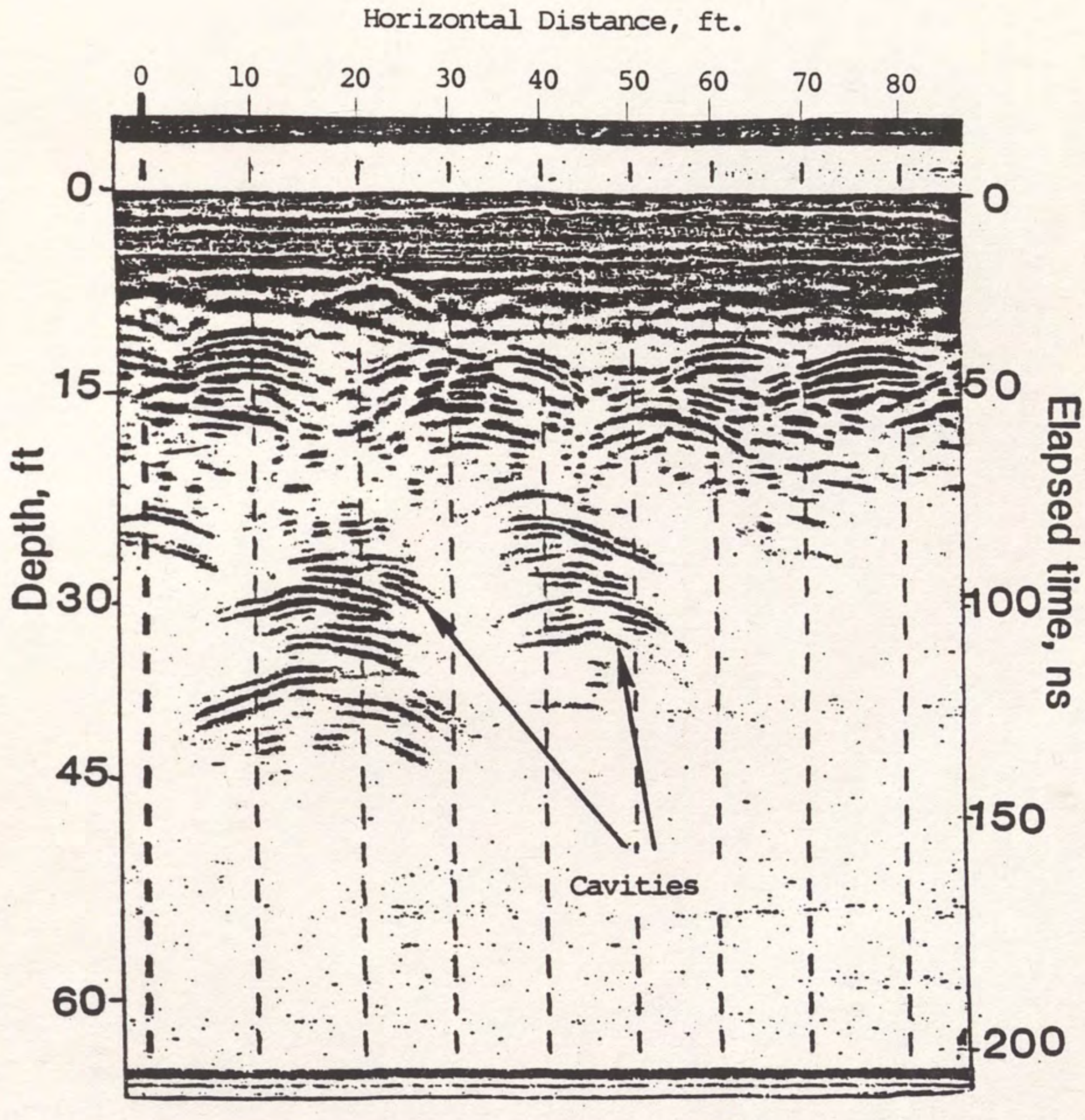


Figure 38. Radar Profile From National Guard Armory at Crystal River (300 X4U, System 4, 80 MHz Antenna.

CHAPTER VI

SUMMARY

This report has demonstrated that GPR can provide useful information for cavity detection by delineating the contours of buried interfaces under favorable conditions. However, limitations in the applicability of this technique under certain geologic conditions limit the usefulness of the equipment.

A summary of the GPR investigations and results are given in Table 2.

TABLE 2

SUMMARY OF SITES SURVEYED

SITE	DATE SURVEYED	SITE DESCRIPTION	RANGE/PENETRATION DEPTH	RADAR RESULTS - COMMENTS
1. Oak Run	11/85	Sand & clay layer, overshallow limestone	800X4L/70'	Cavities at 43' and 38' verified by borings
2. Apopka Blue Sink	6-7/85	Sand and clay over limestone cave system; water 40'	900X4L/65'	Cave system at approx. 35-45' detected well in sandy areas. Thick clay layer blocked signal near mouth of cave.
3. Belleview	3-4/85	Sand and clay over limestone; water table 50'	900X4L/65'	Depressions in clay layer indicate ravelling, cavity penetration out of range.
4. Peacock Springs	3/85	Sandy soil rich in organics over limestone cave system; water table 27'	999X4L	Cave system detected in several areas.
5a. Bat Cave	6/27/85	Clean sand over shallow limestone cave system; water table 30'	700X4L/55'	Strong reflections of limestone shows distinct vertical fissures but no hyperbolic patterns.
5b. Jerome Sink	2/28/85	Sand, sandy clay, limestone	500X2R/15' (300 MHz)	Faults in limestone formation detected.
6a. Ocala (Z House)	12/84	Clayey sand, limestone	600X4R/30'	Detected limestone peak.
6b. Haille Quarry	12/21/84	Clean limestone with clay pockets		Clay blocked radar signal.
7a. Fletcher Grove	1/31/85	Sand (loose)		Disturbance in area, no cavity reflections.
7b. Beach House	6/21/85		999X4R/50'	Fractures in strata apparent.
8. Pierson Airport	4/18/85	Sand with organics	999X4R/50'	Organic and clay layer visible.

SITE	DATE SURVEYED	SITE DESCRIPTION	RANGE/PENETRATION DEPTH	RADAR RESULTS - COMMENTS
9a. Tampa Airport	11/11/85	Sand, clay, limestone; water table 7'	400X2L/16'	Poor penetration. Cavities could not be detected even at shallow depths.
9b. Hillsborough Wellfield	7/11/85	Sand with organics; water table 9-10'	600X4R/40'	Poor penetration. Organic layer detected at 4.5 feet; water table visible at 10'.
10. National Guard Armory at Crystal	4/4/85	Sand, sandy clay, limestone	300X4U/65'	Cavities detected at depths of 30'.

Note: 80 MHz antenna used unless otherwise noted. System 4 prior to May 1985; System 8 after that.

CHAPTER VII

CONCLUSIONS

1. GPR provides a continuous record of subsurface conditions which can indicate trends and inconsistencies in the subsurface strata which are not always apparent from isolated borings. This technique detects changes in material interfaces and presents a two dimensional picture of depth vs. horizontal distance.
2. Ground penetrating radar identifies subsurface features by distinguishing materials with different dielectric constants. Cavities are detected by the variation in electrical properties at interfaces.
3. Depth to an interface is determined by the pulse velocity of the signal and the dielectric constant of the soil. Penetration depths of 80 to 100 feet in the Central Florida area are possible, as seen at Oak Run and Apopka Blue Sink. Penetration depth is adversely affected by highly conductive water or clay, as seen at Tampa Airport.
4. Subsurface cavities of varying size, shape, depth, and content can be detected by GPR systems. The radar signal reflections from cavities with circular or ellipsoidal shapes form a hyperbolic pattern, as seen at Apopka Blue Sink.
5. Not all subsurface cavities are potential sinkholes. Structurally sound cave systems can be identified by little or no indications

of ravelling of the overburden soil, as seen by the reflections from cave systems at Apopka Blue Sink and Peacock Springs.

6. The hyperbolic signal which indicates a subsurface void is not apparent when the cavity is below the penetration depth. Signs of ravelling can indicate a loose area, as seen in profiles from Belleview.
7. The radar survey should be conducted in conjunction with boring tests in order to confirm target depths and investigate suspicious areas as was done at Oak Run.
8. A record of profile locations is useful for relocating suspicious areas. Traverses need to be marked using existing features (natural or manmade) or according to a staked grid system.
9. A great deal remains to be learned concerning the capabilities of GPR. As use of the impulse radar system becomes more widespread, data can be accumulated which will make GPR performance under given subsurface conditions more economical.

APPENDIX A

CALIBRATION CHART FOR SYSTEM 4

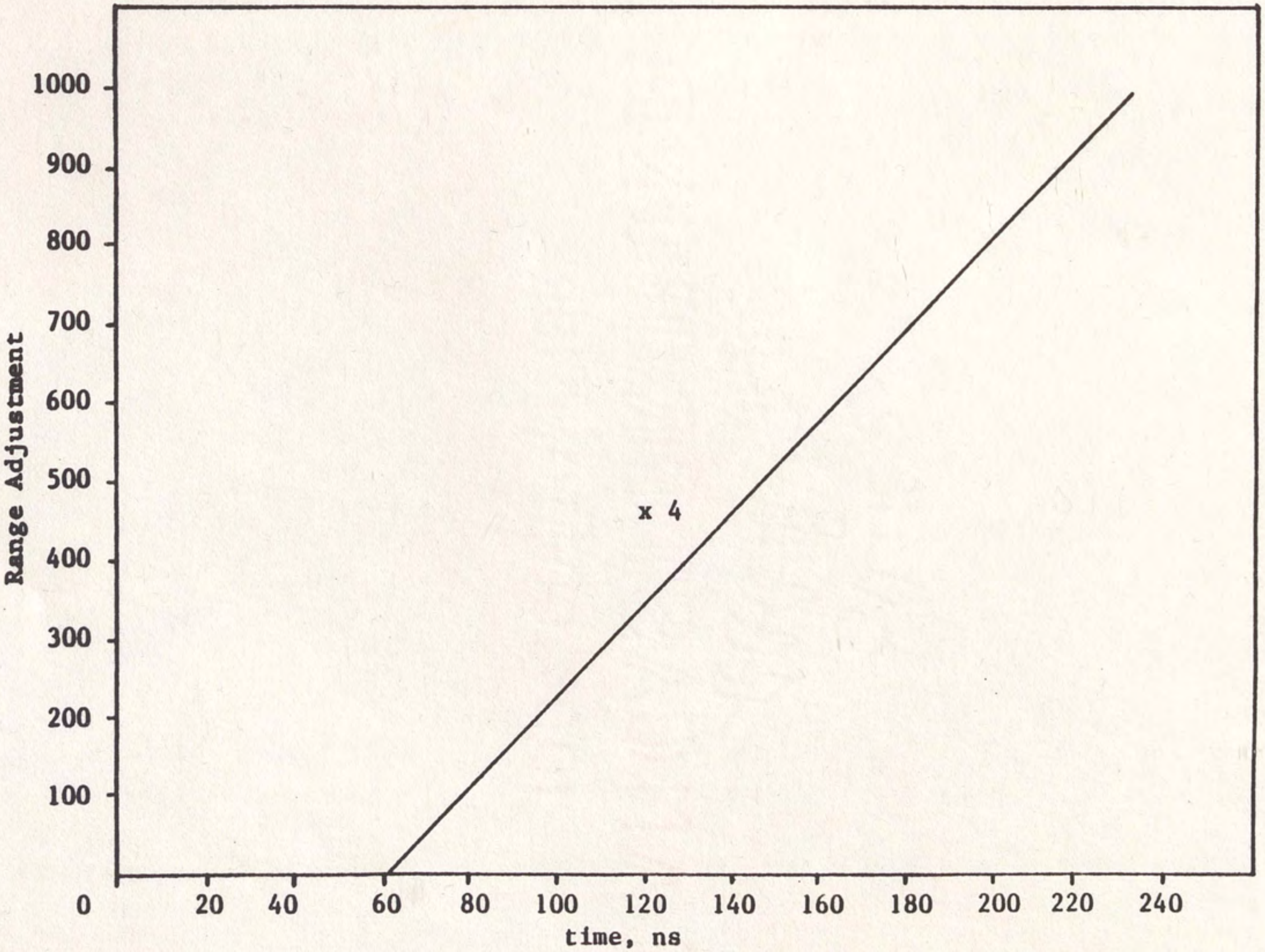


Fig. 39. Normal range calibration chart.

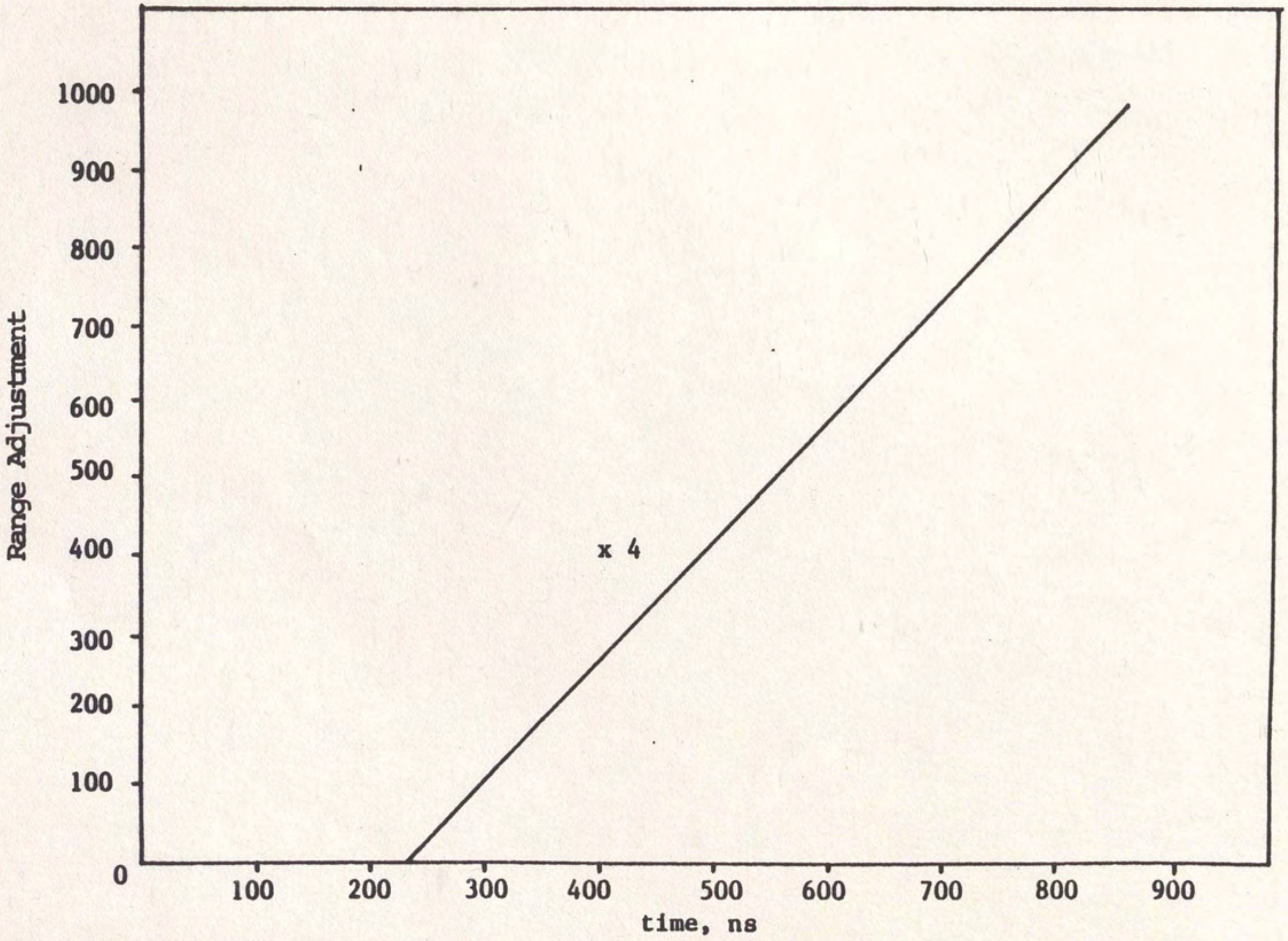


Fig. 40. Ultimate range calibration chart.

REFERENCES

Ballard, Jr., Robert F. Cavity Detection and Delineation Research, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 1983.

Continuous Subsurface Profiling by Impulse Radar. Hudson: Geophysical Survey Systems, Inc., 1984.

Florida Sinkhole Research Institute. Sinkholes: Their Geology, Engineering, and Environmental Impact, Orlando, FL, 1984.

Geophysical Surveys Systems, Inc. Operation Manual Subsurface Interface Radar SIR System 8, Hudson, NH, 1982.

Kuhns, G.L. "Application of Ground Penetrating Radar to the Detection of Subsurface Cavities," Master's thesis, University of Central Florida, 1982.

Kuo, S.S. "Investigation of Underground Pipeline at Iron Bridge Sewage Plant in Orlando, Florida Using GPR," a report to Jammal and Associates, Inc., Winter Park, FL, November, 1984.

Kuo, S.S. "A Rapid Diagnosis of Concrete Pavements by Ground Penetrating Radar," ASCE Annual Meeting - Transportation, 1984.

Nielson, D.M. and Curl, M. Eds. Ground Penetrating Radar Studies on Cape Cod, Worthington: National Well Water Association, 1984.

Nielson, D.M. and Curl, M. Eds. Surface and Borehole Ground Penetrating Radar Surveys for Mapping Geologic Structure, Worthington: National Well Water Association, 1984.

Owen, T.E. "Cavity Detection Using VHF Hole-to-Hole Electromagnetic Techniques," paper presented at Symposium on Tunnel Detection, Colorado School of Mines, Golden, CO, July 21-23, 1981.

Ruth, B.E.; Beggs, T.F.; and Degner, J.D. "Predicting Sinkhole Collapse," ASCE November. 1985: 58-60.

Sowers, G.F. "Failures in Limestone in Humid Subtropics," Journal of the Geotechnical Engineering Division, August, 1975: 771-787.

Stokes, W.L.; Judson, S.; and Picard, M.D. Introduction to Geology, 1978.

Suhler, S.A. "Development of a Prototype Borehole Radar Probe," Paper presented at Symposium on Tunnel Detection, Colorado School of Mines, Golden, CO, July 21-23, 1981.

Tannous, B. "Determination of Electrical Properties Using Ground Penetrating Radar," unpublished raw data, University of Central Florida, 1985.

Ulricksen, C. Peter F. "Application of Impulse Radar to Civil Engineering," Ph.D. dissertation, Lund University of Technology, 1982.

U.S. Army, Chief of Engineers, and U.S. Army Engineer Waterways Experiment Station. Symposium on Detection of Subsurface Cavities, Vicksburg, MS, 1970.