To the Graduate Council:

I am submitting herewith a thesis written by James Denton Bouldin, Jr. entitled "Use of Ground Penetrating Radar to Map Soil Features that Influence Water Content." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Engineering Technology.

Robert S. Freeland, Major Professor

We have read this thesis
and recommend its acceptance:

Accepted for the Council:

Associate Vice Chancellor and
Dean of The Graduate School

Use of Ground Penetrating Radar to Map Soil Features that Influence Water Content

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

James Denton Bouldin, Jr.

December 1997

To:

My mother, Mary Bouldin, for her encouragement, support, and never allowing me to fall short of my goals. To my brother, Michael Bouldin, and to my sister-in-law, Christie Bouldin, for their advice and words of wisdom.

Acknowledgments

I would like to extend my gratitude to the Department of Agricultural Engineering, and Dr. C. Roland Mote for allowing me the opportunity to participate in the Agricultural Engineering Program. I would like to extend a special thanks to Dr. Robert S. Freeland who served as my major professor, without his support this project would have never been completed.

Thanks are also extended to Dr. Ronald E. Yoder and Dr. Donald D. Tyler, committee members, for their time and advice.

Thanks are also extended to the Tennessee Agricultural Experiment Station, Hobart Ames Foundation, and the entire staff at Ames Plantation. Without their guidance and diligent assistance this project would have never been completed.

Special thanks are extended to John Conroy, Joseph C. Reagan, and Jonathan Adamson for contributing their time, effort, and advice.

Finally the author would like to thank Dr. Reed Cripps, Undergraduate Professor at Tennessee Technological University, for preparing me for the stringencies of graduate school. Without his guidance and friendship, I would not have achieved this point in my life.

Abstract

Vadose zone studies are being conducted in the loessial soils at Ames Plantation, which is located near Memphis, Tennessee. The vadose zone beneath two agricultural production fields at this site (one a tilled field and the other a no-tilled field) is heterogeneous. The soil profile consists of two or more parent materials, varying soil textures, and lamella formations. These nonhomogeneous soils can govern solute migration throughout the vadose zone, having an impact on the offsite transport of agrochemicals.

To assist the ongoing vadose zone monitoring studies at Ames Plantation, an interdisciplinary team of scientists from The University of Tennessee is developing innovative applications of Ground Penetrating Radar (GPR) technology. Studies have shown that GPR can provide an accurate and nonintrusive method for mapping and studying nonhomogeneous soil profiles. Research focused on the development of near-surface survey methodologies for identifying and mapping subsurface hydrogeological features. Subsurface features of primary interest include loess/alluvium interfaces, perched water tables, and preferential water flow paths. Successful identification of such features include (1) a shallow water table, (2) coastal plain sediments, and (3) fragipans.

At Ames Plantation newly devised methodologies for data acquisition and GPR settings were incorporated. These new methodologies allowed researchers to map the loess/alluvium interface, giving insight to the offsite transport of agrochemicals from a no-till site and a tillage site. Other subsurface features successfully mapped by GPR at Ames Plantation were a fragipan and increases in soil moisture content.

Table of Contents

Chapter		Page
1.	Introduction and Objectives	1
	Justification	1
	GPR Basics	2
	Radar Profile	3
	Instrumentation Settings	4
	Radar Wave Penetration and Resolution	6
	Objectives	7
2.	Literature Review	9
	Vadose Zone Monitoring and Sampling	9
	Perched Water Tables	10
	Ames Plantation Water Quality Project	11
	GPR Imaging	18
3.	Materials and Methods	20
	Equipment Summary	20
	Site Preparation	22
	Conventional Survey Summary	23
	Lab Hardware and Software	23
	GPR Surveys	27
	Data Set One	27
	Data Set Two	29
	Data Set Three	31
4.	Results and Discussion	33
	Data Set One	33
	Coastal Plain Sediments	33
	Shallow Water Table	35
	Fragipan Data	35
	Data Set Two	39
	Hancock Tract Data	39
	West Pasture Data	42
	Data Set Three	50
	Centennial Field	50
	Discussion	53

Chapter		Page

5. Recommendations 58
GPR System Operation 58
Calibration 58
Data Collection 58
Transect Surveys 59
Statistical Model 60
Future Data Collection 60

6. Summary 62

Bibliography 64

Appendices 68
Appendix A 69
Appendix B 71

Vita 73

List of Tables

Table | Page
4.1 GPR calibration settings for Ames Plantation data acquisition 34
4.2 Ground-truth depths compared with GPR depths 34
4.3 Mainframe settings used under wet conditions 46
4.4 Average mean difference between GPR data and field observation, and results from a linear regression 52
4.5 Conventional soil surveying method compared with GPR interpreter methods 52

List of Figures

Figure		Page
1.1	Color scale used to compare reflection intensity of GPR images	5
2.1	Map of Hancock Tract and concentric circle configuration of vadose zone wells (Rainwater, 1996)	12
2.2	Map of West Pasture and concentric circle configuration of vadose zone wells (Rainwater, 1996)	13
2.3	Stream terrace locations of West Pasture and Hancock Tract (Livingston, 1993)	14
2.4	Order 1 soil map of Hancock Tract (Livingston, 1993)	16
2.5	Order 1 soil map of West Pasture (Livingston, 1993)	17
3.1	Transect lines A, B, C, D, E, and F's orientation at Hancock Tract	24
3.2	Transect lines A, B, C, D, E, and F's orientation at West Pasture	25
3.3	Locations of GPR data taken at the West Tennessee Experiment Station	28
3.4	Shallow well orientation and order 1 soil classification at Centennial Field (Carter, 1995).	32
4.1	GPR data of coastal plain sediments taken at the West Tennessee Experiment Station	36
4.2	900-MHz image of a shallow water table	37
4.3	Filtered 900-MHz image of a shallow water table	38

Figure		Page

4.4 GPR image of a fragipan taken at the Milan Experiment Station 40

4.5 GPR data showing the loess/alluvium interface at Hancock Tract 41

4.6 Map of the loess/alluvium interface at Hancock Tract taken from GPR data 43

4.7 GPR image of a depression in the loessial material at Hancock Tract 44

4.8 GPR image of increased soil moisture content at West Pasture 47

4.9 GPR image of a discontinuous fragipan 48

4.10 Map of the loess/alluvium interface at West Pasture taken from GPR data 49

4.11 Filtered data of increased soil moisture content at West Pasture 51

4.12 Affects of moisture and clay content on GPR interpretations 55

4.13 Apparent pockets or cracks at the loess/alluvium interface 57

List of Abbreviations

λ	Wavelength
σ	Relative Dielectric Constant
CDP	Common Depth Point
DSP	Digital Signal Processor
EM	Electromagnetic Conductivity Meter
FFZ	First Fresnal Zone
GSSI	Geophysical Survey System, Inc.
GPR	Ground Penetration Radar
GPS	Global Positioning System
SIR	Subsurface Interface Radar
TT	Two Way Travel Time

Chapter 1

Introduction and Objectives

1. Justification

The detection of agrochemicals in drinking water wells is a concern to rural America. Many farmers and rural communities use drinking water wells as their primary source of water. Not only is the rural farmer's water supply in question, but as our society's environmental awareness increases, the use of agrochemicals and standard agricultural practices is being questioned by the public and special interest groups (Michna and Bourodimos, 1973).

Challenges to traditional farming practices, coupled with farmers' economic concerns, are prompting increased vadose zone research and monitoring. Monitoring of the vadose zone is a formidable challenge, and is sometimes alluded to as a "hit and miss science." These challenges are due to the many unseen and unpredictable variables that govern the transport of solutes in the vadose zone. Some variables that influence solute transport include perched water tables, differing soil layers, and macropore flow.

Identifying these parameters is both time-consuming and labor intensive. Backhoes, hand augers, drill rigs, and picks are the primary tools available for such research (Doolittle, 1987). Although these tools are effective for identifying homogeneities in the soil profile, they may physically alter many parameters governing soil water movement (i.e., hydraulic conductivity, total porosity, and soil structure). Thus, measurement methodologies that do not physically alter soil water movement are essential for vadose zone investigations.

One promising noninvasive technology that is available for vadose zone investigations is Ground Penetrating Radar (GPR). Near surface images from GPR are formed by electromagnetic reflections that are influenced by the dielectric contrasts of different subsurface media and features. The sharper the contrast between the dielectric properties of the media, the stronger the reflection. A medium with high conductive properties, such as wet clay, provides a poor image when surveyed. In contrast, a medium with lower conductive properties, such as coarse grained materials provides a sharper image (The Finnish Geotechnical Society, 1992).

2. GPR Basics

GPR is a broadband, impulse radar system that is specifically designed to penetrate earthen materials (Doolittle, 1987). When a radar pulse is transmitted through a nonhomogeneous material, it encounters an area of contrasting electromagnetic properties, and a portion of the pulse returns to the antenna (Doolittle, 1987). The amount of energy that reflects back to the antenna is directly proportional to the electromagnetic change in the boundary.

The dielectric constant (σ) is a measure of how well a material stores an electrical charge. Air has a dielectric constant of one, and water has a dielectric constant of 81, while other materials have a dielectric constant somewhere in between. The primary factor affecting the σ of a soil profile is moisture content.

The σ of a soil can be determined by the common depth point method (CDP). This method requires the use of two antennas and a flat surface. One antenna is used as a receiver and the other antenna is used as a transmitter. As the two antennas are pulled from a common point at equal distances, the depth to a reflector is found using triangulation. This method allows the velocity of the wave moving through the material to be determined with the antenna separation set to zero (Ulrikson, 1982).

Two way travel time (TT) is another technique for determining the velocity of the radar wave. The TT requires the depth of an object to be known. As the radar wave passes materials of varying σ, the TT is recorded by the radar wave reflecting off a known object. An average σ for the medium is calculated using equation 1.1.

$$\sigma = \frac{(ns/m)^2}{43.56} \qquad \text{(eq. 1.1)}$$

where

σ = overall relative dielectric constant of the medium
ns = two way travel time of radar wave in nanoseconds
m = distance in meters

Radar Profile

A radar image is composed of three primary parts. The first reflection of a radar image is a result of the radar wave traveling through the air to the receiver. The second reflection in the radar profile is caused by the surface of the medium. The third and subsequent reflections in the radar profile are a result of electrical boundaries within the medium.

The TT and intensity of a signal are analyzed by the instrumentation. Multiple scans are taken consecutively to create a continuous image of the σ profile. This allows digitized information to be viewed on a monitor, written to disk, or printed upon demand.

Once the radar images are analyzed by the instrumentation, they can be viewed in two different formats: wiggle or line scan. A radar image in wiggle format consists of lines or curves that are representative of each pulse of energy. The higher the amplitude of the reflection the larger the curve. Line scan format assigns a color to each electrical change in the medium. The color scale of a GPR image ranges from positive to negative (Figure 1.1).

The more a color representing a reflection intensity deviates from zero, the stronger the reflection or changes in σ. Colors or reflections that are situated close to zero represent weak reflections or small changes in σ. These scans are displayed close together to form a continuous representation of the electrical boundaries in the medium.

4. Instrumentation Settings

The GPR unit is configured based on: antenna model number, horizontal filters, vertical filters, range gain, trace position, range, and display parameters. Descriptions of these settings and other radar parameters are presented in SIR System-10A Training Notes

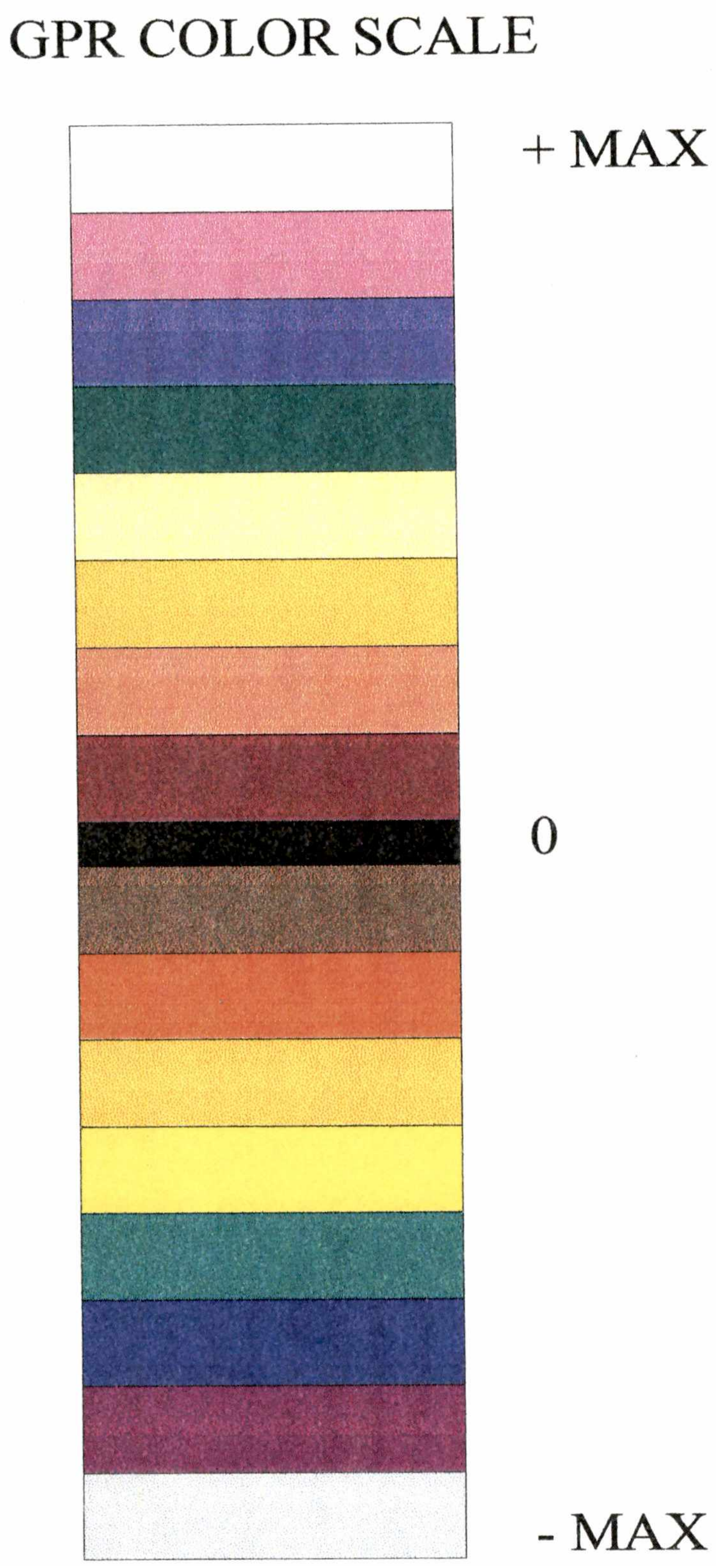


Figure 1.1: Color scale used to compare reflection intensity of GPR images.

(GSSI, 1992b) and SIR System-10A User's Manual (GSSI, 1993). Many preset parameters are loaded by entering the antenna model number. These parameters vary with differing antennas. Range selection is based on the length of time returning waves are sampled; if a range of 110 ns is selected, the returning radar wave is sampled for 110 ns after the pulse is emitted. This allows the GPR operator to view depths of interest.

Range gain configures the amount of amplification applied to certain depths within the medium. There are up to five gain settings that are manually controlled by the operator. These five settings allow relative features to be targeted in the subsurface. With the beginning scan set to 0 ns, the beginning reflection in the image is the surface. With the surface of the media at the beginning of the scan, the TT can be converted to depth if the average σ of the media is known.

SIR System-10A Training Notes delineate filter settings that remove unwanted noise from radar images (GSSI, 1992b). High pass filters pass high frequencies within a certain range while removing low frequency noise. The low pass filters pass low frequencies within a certain range while removing high frequency noise. These settings are site-specific and can be adjusted with varying field conditions.

5. Radar Wave Penetration and Resolution

Penetration depth of the radar wave is limited by several variables: electrical conductivity of the medium, number and strength of the electrical interfaces, and the angle at which the radar waves travel from the antenna to the earth. Of the limiting variables, conductivity of the medium is the primary factor that affects the penetration of the radar image. A medium with high conductivity (e.g., wet clay, soils with high salinity) diminishes radar waves more readily than a medium with low conductivity (e.g., dry sand). A medium with many sharp electrical interfaces reflects more of a radar wave's energy than a medium with fewer interfaces.

Radar waves enter the medium in a cone. As the penetration depth of the radar wave increases, the cone becomes larger. GPR data are collected from a smaller cone within this cone called the First Fresnal Zone (FFZ). As the cone becomes too large, the radar signal becomes noncontiguous, and a portion of the radar signal cannot reflect from the FFZ to the antenna. If the radar wave enters the profile at an angle, the cone will attenuate at shallower depths than a radar wave entering the profile vertically.

Resolution and penetration depths of the radar image are affected by the wavelength (λ) of the radar signal, which is a function of the antenna. The effects of these two variables can be reduced with proper antenna selection. Antenna selection is based upon the desired surveying depths. Antennas that transmit high frequencies resolve more distinct electrical properties of the medium, but penetration depths are limited. Antennas that transmit lower frequencies increase penetration depths but have reduced resolution of horizon thickness.

6. Objectives

Vadose zone studies are being conducted in the loessial soils at Ames Plantation, which is located near Memphis, Tennessee. The vadose zone beneath two agricultural production fields at this site is heterogeneous. The soil profile consists of two or more parent materials, varying soil textures, and lamella formations. These varying soil parameters govern solute migration throughout the vadose zone, having an impact on the off-site transport of agrochemicals. Research focused on developing near-surface survey methodologies that identify and map these subsurface hydrogeological features. Subsurface features of primary interest include the loess/alluvium interface, paleosol surface, perched water tables, and preferential water flow paths. Survey results were statistically compared with established intrusive soil survey methods that gave insight to possible error when the newly devised GPR methodologies were used at Ames Plantation.

Chapter 2

Literature Review

1. Vadose Zone Monitoring & Sampling

To better understand the offsite environmental impact of agrochemicals, more precise methodologies in predicting the movement of these solutes through the vadose zone are needed (Jaynes et al., 1988). Many techniques have been developed to monitor solute transportation through the vadose zone. Of these techniques, core sampling is the most commonly used methodology for characterizing the downward migration of surface-applied chemicals (Ghodrati and Jury, 1990).

The major imperfection of these monitoring techniques is the intrusion associated with gathering these samples. When soil corings are taken or trenches are excavated to monitor soil water movement, the soil profile is disturbed (Ghodrati and Jury, 1990). This disturbance affects soil water movement by altering soil hydraulic properties in a controlled area. Nonintrusive surveying techniques that do not physically alter soil-water movement are essential for vadose zone investigations. Such methodologies that are traditionally employed by geologists are GPR and the Electromagnetic Conductivity Meter (EM).

EM utilizes electromagnetic energy to measure apparent conductivity of earthen materials (Doolittle et al., 1994). This noninvasive technology has had most of its success in relative homogeneous media, where the properties of one variable dominate over the properties of other variables (Cook et al., 1989). Data being gathered in these areas are normally based on the dominant electrical subsurface feature while assumptions are made on less dominant features (Cook et al., 1989). In contrast, GPR is a broadband, high frequency, impulse radar that uses short bursts of energy through earthen materials (Doolittle, 1987). These pulses travel through the earth until they encounter a layer with a contrasting dielectric constant. These contrasting layers are the major variables controlling the signal that reflects back to the antenna (Ulriksen, 1982).

2. Perched Water Tables

Areas of perched water can provide saturated lateral flow of pollutants throughout the vadose zone to local streams and water supplies (Hammermeister et al., 1982). Little information is available about the development and longevity of perched water tables, but the identification of such layers is critical to vadose zone water quality studies. These temporary layers of saturation provide areas where relatively large samples of soil-water can be retrieved and monitored for agrochemicals. Such layers tend to form above restrictive layers in the soil profile. These areas of lower hydraulic conductivity slow the advancing wetting front and sometimes cause the wetting front to move laterally. A good indicator of the lateral movement of soil-water is the presence of an E horizon overlying a less permeable layer (Miller et al., 1971). Other good indicators of lateral movement of water in the subsurface are gleyed areas and low chroma mottles within the soil profile.

Areas of low hydraulic conductivity discussed above usually form above pedogenic layers such as fragipans or dense argillic horizons (McDaniel and Falen, 1994). Fragipans have been identified in approximately 138,000 km^2 of soils mapped in the United States

(McDaniel and Falen, 1994). Franzmeier et al. (1989) found that the presence of fragipans within the soil profile causes very anisotropic water movement. They also noted that the permeability of the fragipan layer was reduced 100-fold in comparison with surrounding soil layers and caused water to advance laterally until reaching a layer of increased permeability. Daniels and Fritton (1994) also observed lateral movement of soil-water over a Typic Fragiudalf in Pennsylvania.

3. Ames Plantation Water Quality Project

A KBr tracer was broadcasted to two different field sites at Ames Plantation (Hancock Tract and West Pasture) to aid in the development of vadose monitoring equipment and sampling methodologies (Figures 2.1 and 2.2). Both Hancock Tract and West Pasture are 10-ha field sites that are part of the 994-ha watershed within Ames Plantation.

The geology of Ames Plantation is representative of much of West Tennessee, in that it consists of aeolian-deposited loess overlying the Tertiary-aged Claiborne and Wilcox formations. The two sites are separated by an ephemeral stream and are located on two different stream terraces (Figure 2.3) (Livingston, 1993).

Since 1990, the 10-ha field site north of the stream has been under a no-tillage practice while the 10-ha field site south of the stream has been under tillage practices. Each of the field sites encompass a 0.4-ha square test plot bounded by an earthen berm to measure runoff and to prevent surface runoff.

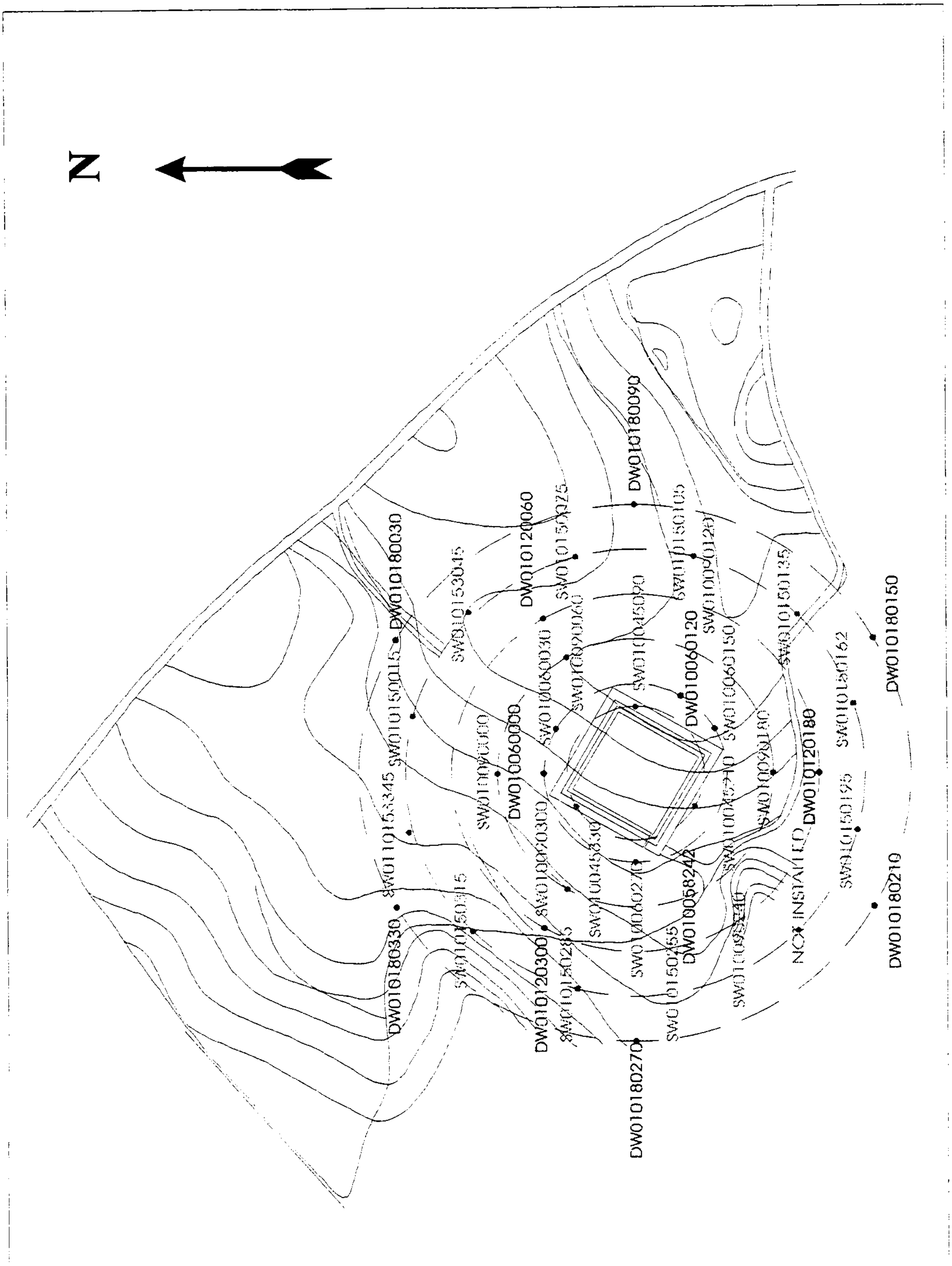


Figure 2.1: Map of Hancock Tract and concentric circle configuration of vadose zone wells (Rainwater, 1996).

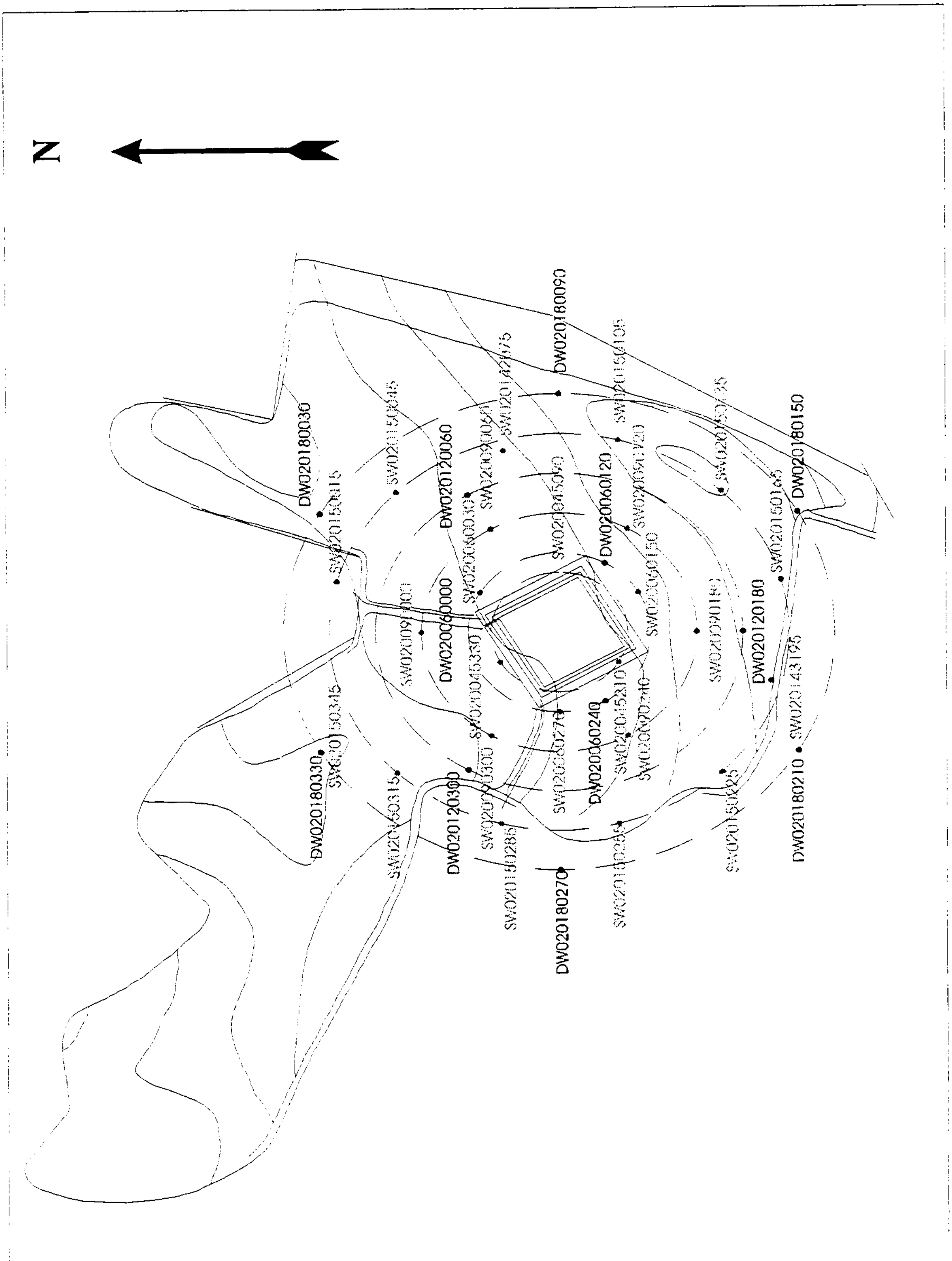


Figure 2.2: Map of West Pasture and concentric circle configuration of vadose zone wells (Rainwater, 1996).

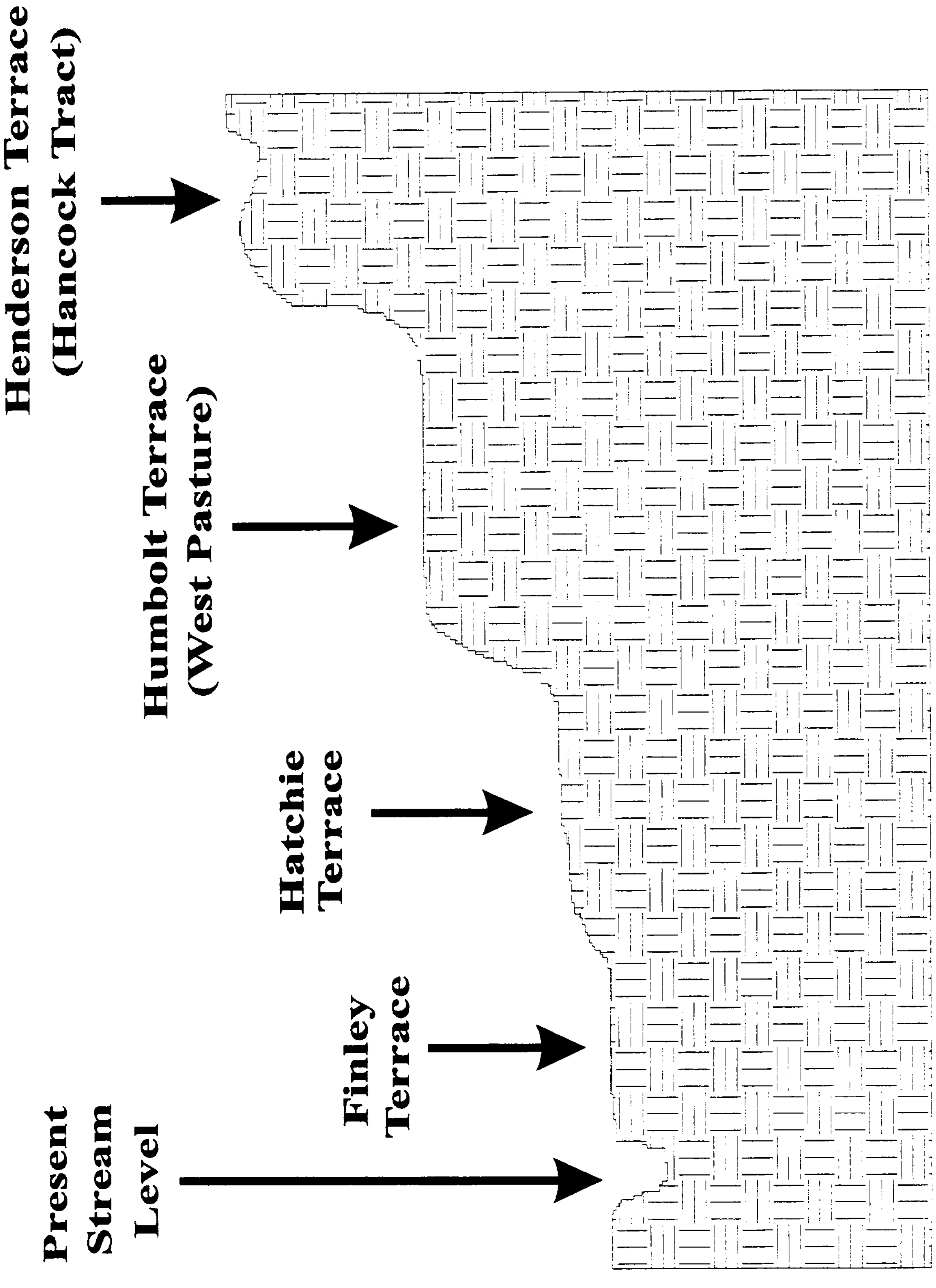


Figure 2.3: Stream terrace locations of West Pasture and Hancock Tract (Livingston, 1993).

To obtain samples from the upper 1.20 m of the vadose zone, pan lysimeters and solution samplers were installed. In each 0.4-ha plot, three tension-free pan lysimeters were installed at a depth of 1 m to collect integrated water samples over a surface area of 0.46 m^2. On two sides of each pan lysimeter, a cluster of five solution samplers was installed to collect soil-water through porous ceramic cups at depths of 0.15, 0.30, 0.60, 0.90, and 1.20 m. In total, the two field sites contain 60 vacuum operated solution samplers and six tension-free pan lysimeters (Yoder and Mote, 1994).

Shallow wells were installed with a 0.23-m length of well screen at the paleosol interface to collect perching water (Ammons, 1997). The shallow wells were installed at 24 locations surrounding the 0.4-ha tillage test plot and at 23 locations surrounding the 0.4-ha no-till test plot. To sample for possible solute migration into the aquifer underlying the two field plots, twelve groundwater wells were also installed at each location (Yoder, 1996).

While the shallow wells were being installed, Livingston (1993) derived an Order 1 soil survey for each of the two field sites. Soils were classified to the family level using the soil descriptions taken from forty-seven sites. Seven soil families were classified on the two field plots: thermic Fragic Haplaudalfs, thermic Ultic Haplaudalfs, thermic Typic Fragiudalfs, thermic Ultic Haludalfs, thermic Glossaquic Fragiudalfs, thermic Typic Paleudults, and Dystric Eutrochrepths (Figures, 2.4 and 2.5).

Soil family classifications have given researchers clues to the hydraulic properties of different soil profiles at Ames Plantation. Three of the seven soil pedons were classified

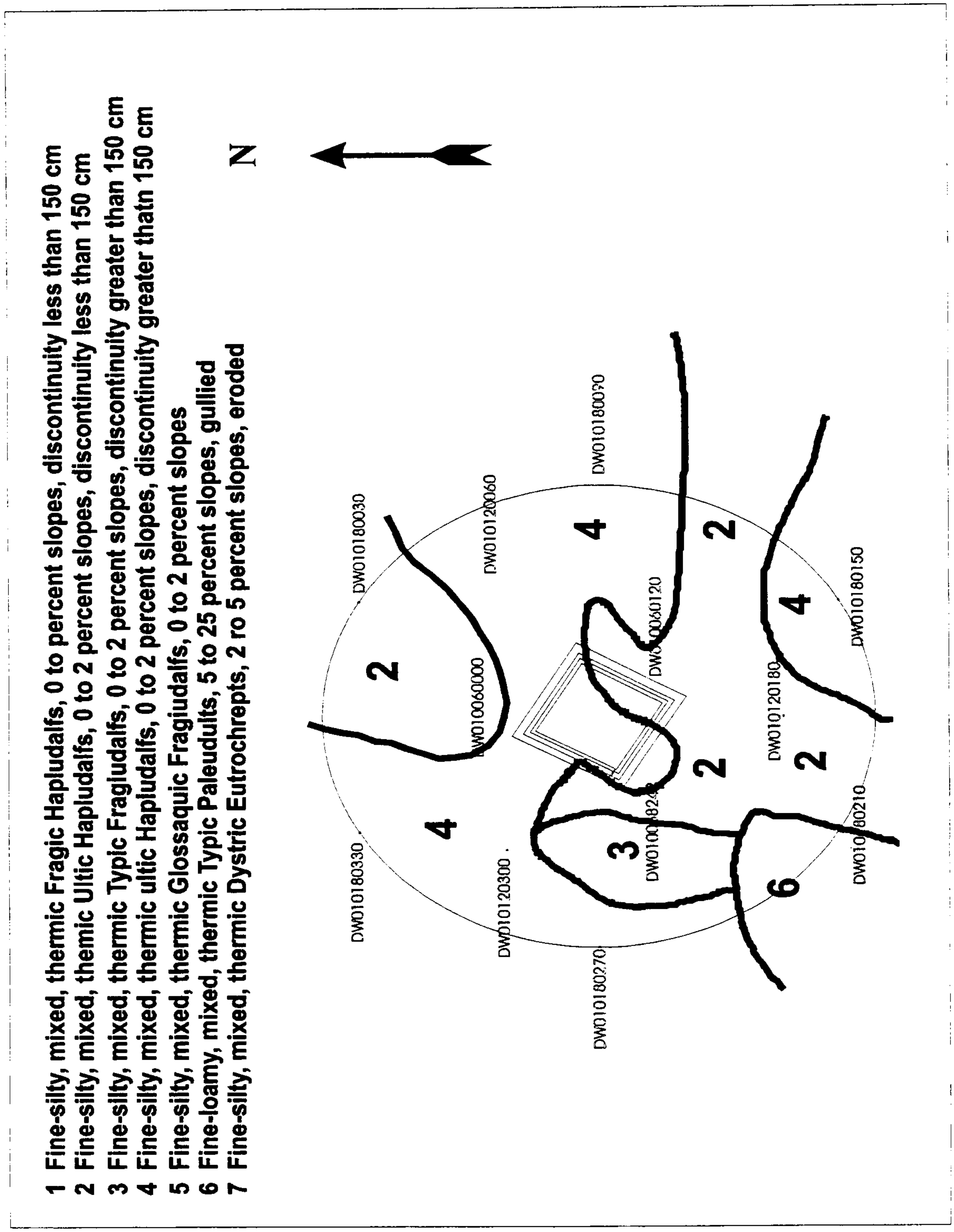


Figure 2.4: Order 1 soil map of Hancock Tract (Livingston, 1993).

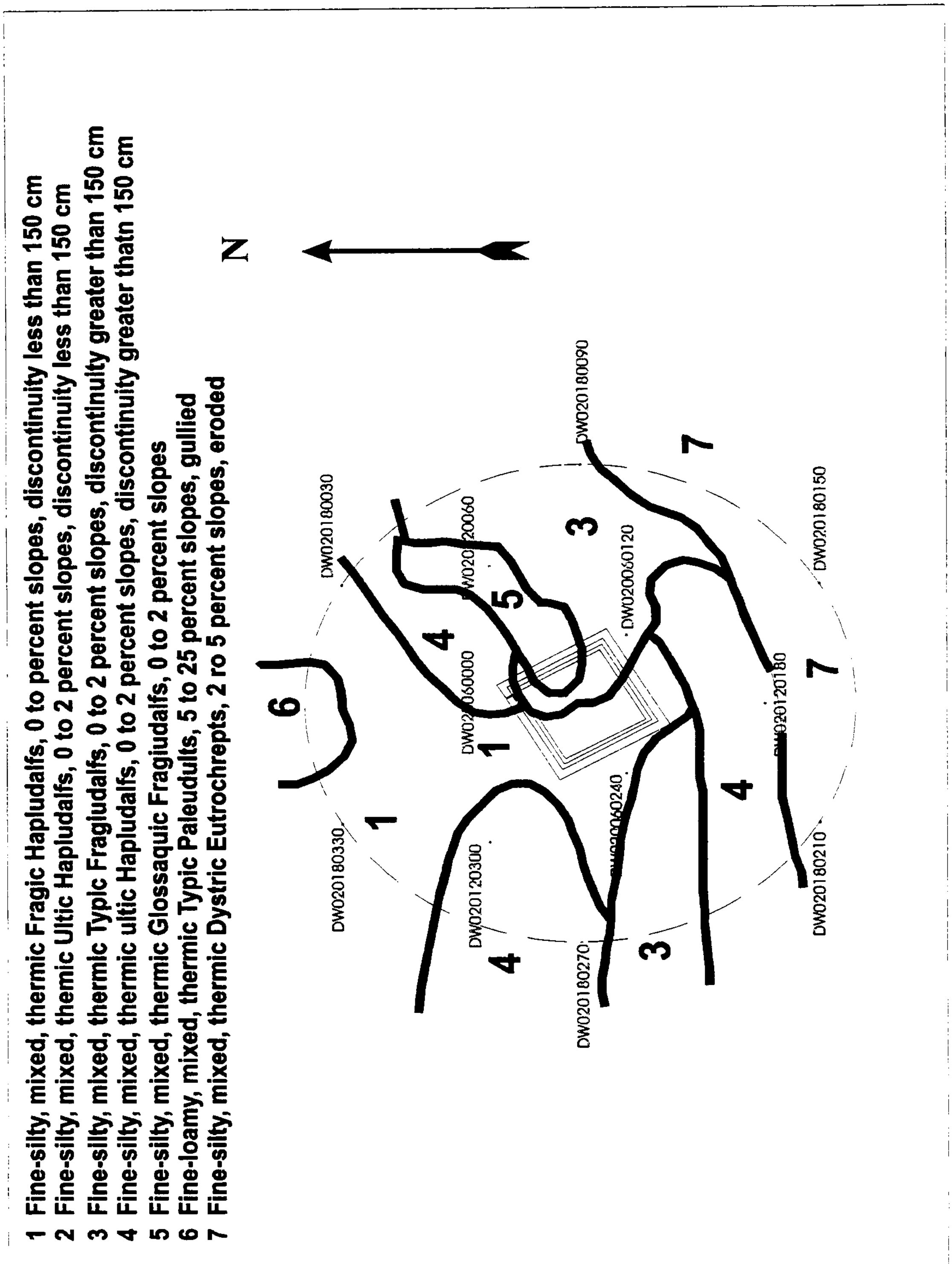


Figure 2.5: Order 1 soil map of West Pasture (Livingston, 1993).

as having one or more fragipan layers in the soil profile (Livingston, 1993). Researchers have found that fragic horizons can decrease the hydraulic conductivity of a soil by 100-fold (McDaniel and Falen, 1994).

The entire soil profile at Ames Plantation could affect soil-water movement because loess overlies a finer textured paleosol. Whenever a wetting front, moving in response to the matrix potential of a soil layer and the combined gravitational potential, reaches a finer textured soil horizon, perching of the wetting front occurs (Miller and Gardner, 1962). Since water has a σ of 81 and dry soil has a σ of approximately six, this situation provides an ideal situation to detect moisture regimes in the vadose zone using GPR imaging (GSSI, 1992b).

The distinct boundary conditions at Ames Plantation caused by differing depositional environments also provide a good situation to detect pedologic discontinuities and differing soil horizons with GPR imaging. Kung and Donohue (1991) were able to locate such distinct soil horizon boundaries using GPR imaging, allowing a team of researchers to increase solute concentrations in their vadose zone samples.

4. GPR Imaging

In the past, GPR imaging has provided the following information to geologists and engineers (Benson and Glaccum, 1979):

1) Detection and mapping of soil horizons, permeable zones, clay lenses, organics, water tables, and soil types.

2) Geotechnical assessments of soil cementation (hard pan), soil/rock contacts, rock fractures and bedding, lateral continuity, and subtle geologic transitions.

3) Location of natural or induced hazards including cavities in karst areas, soil piping, voids in or under structures or roads, and general subsidence features.

4) Detection and mapping of buried hazardous materials such as low level nuclear and industrial wastes, whether they be confined in containers or occur as seeping effluents.

GPR has been implemented in soil reconnaissance for its speed of operation and its ability to gather large quantities of continuous, high resolution subsurface data. GPR methodologies when compared with conventional soil surveying methods have proven to be economical and less likely to miss subsurface features (Doolittle and Collins, 1995). Doolittle (1987) compared conventional soil reconnaissance cost with GPR methods and found that GPR could reduce field costs by 70%, while increasing productivity by 210%.

Chapter 3

Materials and Methods

1. Equipment Summary

The Ames Plantation Water Quality Project used a Subsurface Interface Radar System-10A (SIR-10A)[1] designed by Geophysical Survey Systems, Inc. (GSSI) (North Salem, NH, USA). The SIR-10A is comprised of a 486SLC Cyrix motherboard with an 80387 math coprocessor, which used a 20-MHz Motorola DSP 56001 digital signal processor (DSP) for high speed signal processing. Proprietary system software, stored in the firmware, was used to control the radar system when conducting field data acquisition.

Inputs to the system were controlled by a standard AT keyboard and a hand-held marker attached to the antenna. Inputs to the system by the hand-held marker were used to place marks at discrete locations within the data acquisition set. These marks could later be used for site specific locations of certain subsurface anomalies and to normalize each data set for 3-D software analysis.

To analyze and view radar data, a VGA color monitor was used in the field. Data sets

1

The use of brand names in this report does not imply endorsement of these products by The University of Tennessee.

were written to an internal 2.3-GB Exabyte 8-mm tape drive, to be viewed and analyzed in the lab. The 2.3-GB Exabyte 8-mm tapes not only provided a method to store large data sets, but they also provided a permanent archive for each sequence of data acquisition.

A variety of antennas are available for use with the SIR-10A. Antenna models ranged from 10-1000 MHz. To obtain data from depths pertinent to Ames Plantation Water Quality Project, a 200-MHz antenna (Model # 5106) was utilized. A 15-m antenna control cable was attached from the 200-MHz antenna to the SIR-10A for data transfer.

For mobility under field conditions the radar unit was powered by a Mobile 110-VAC system using a Model PV 1200 FC Tripp-Lite DC/AC Power Inverter and two Nationwide deep cycle marine 12-VDC batteries. Two deep-cycle marine batteries were wired in parallel to supply additional power to the system. This configuration allowed data collection of approximately eight hours under optimal field conditions.

Many possibilities were considered for mobilization of the radar equipment in the field during data collection. One method used was based on (Doolittle, 1982). He towed the antenna behind a pick-up truck at rates of 5 to 8 km/hr. This method provided a weatherproof environment for the radar unit. When GPR data were viewed and processed in the lab, the speeds were determined to be too fast and inconsistent for detailed radar imaging.

The best mobility methodology for the precise data needed from the long continuous radar scans at the Ames Plantation Water Quality Project was the utilization of a Model 770 John Deere tractor. A small trailer was attached to the tractor to provide a stable platform for the SIR-10A, VGA monitor, DC/AC power inverter, and batteries. With the tractor in low range, third gear, and the engine operated at 1400 rpm, continuous radar imaging at a slow, continual pace was achieved.

2. Site Preparation

Before precise GPR surveys could be obtained at the two field sites, a combination of certain environmental and field conditions had to occur. GPR surveys could not be conducted under harsh environmental conditions. If the ambient temperature fell below 0^0 C, the electronic equipment would not function properly. Rain also presented difficulties when operating the electronic equipment.

Surface conditions also presented challenges when conducting GPR surveys. Rough surfaces cause irregular antenna movement along transects. These irregular movements generated false signals in the GPR images.

To prevent equipment damage and inadequate data collection, field conditions had to be assessed before satisfactory GPR images could be acquired. A smooth surface for precise data acquisition had to be achieved for antenna mobilization. To provide a smooth surface at the two field sites, each transect line was mowed with a Murray push mower. The tillage site presented a greater challenge, due to gullies in the field from surface erosion. Each transect line at the tillage site had to be disced and smoothed with a soil pulverizer. After the field surface was smoothed by the soil pulverizer, a roller was pulled across the transect lines several times.

3. Conventional Survey Summary

Soil corings were taken at the two field sites with 5-cm dia. bucket augers to confirm depths to major subsurface interfaces reported by Livingston (1993). In this same area, transects were configured by placing surveying flags every 10 m along the transects and 5 m within the bermed area, using a Pentax Model PTS Total Sation , an electronic surveying device. At the no-till site there was a total of 330 flags, and at the tillage site there were 275 flags. These transects paralleled the berm at all four sides (Figure 3.1 and 3.2). After the transects were completed, topographic data were taken at each flag location using the Pentax Model PTS Total Station and the data were downloaded to a Hewlett Packard Calculator. The topographic data were then downloaded from the calculator to a personal computer. This allowed the topographic data to be entered into a spreadsheet and used to simulate a topographical map of the two sites.

4. Lab Hardware and Software

Raw GPR data files were downloaded from 2.3-GB Exabyte 8-mm tapes to a 1-GB SCSI drive. The data files were then transferred to a P5-166 personal computer with 32 MB of RAM and 4 GB of hard disk space.

RADAN™ III and RADAN™ for Windows were the primary software packages used for the annotation of the radar images. Each data file was horizontally normalized to allow data processing by the many filters provided by RADAN III. These filters were used to refine radar images and to establish depths to important features in the soil profile.

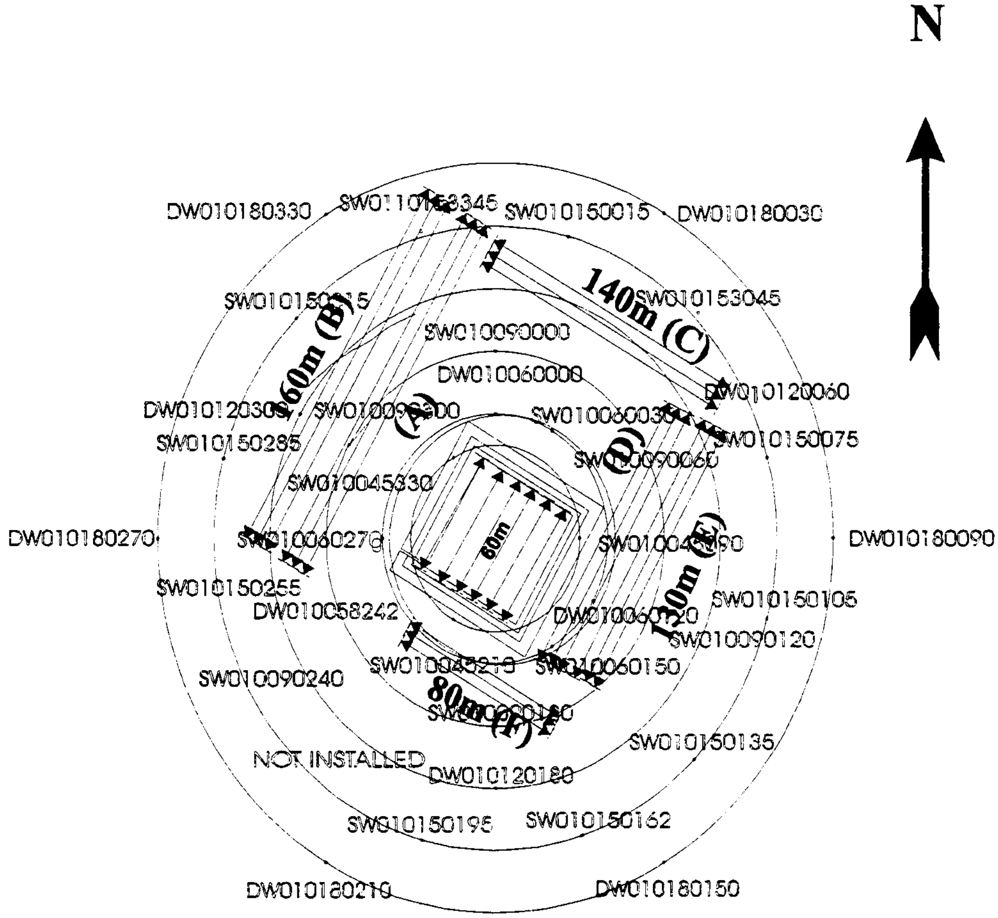


Figure 3.1: Transect lines A, B, C, D, E, and F's orientation at Hancock Tract.

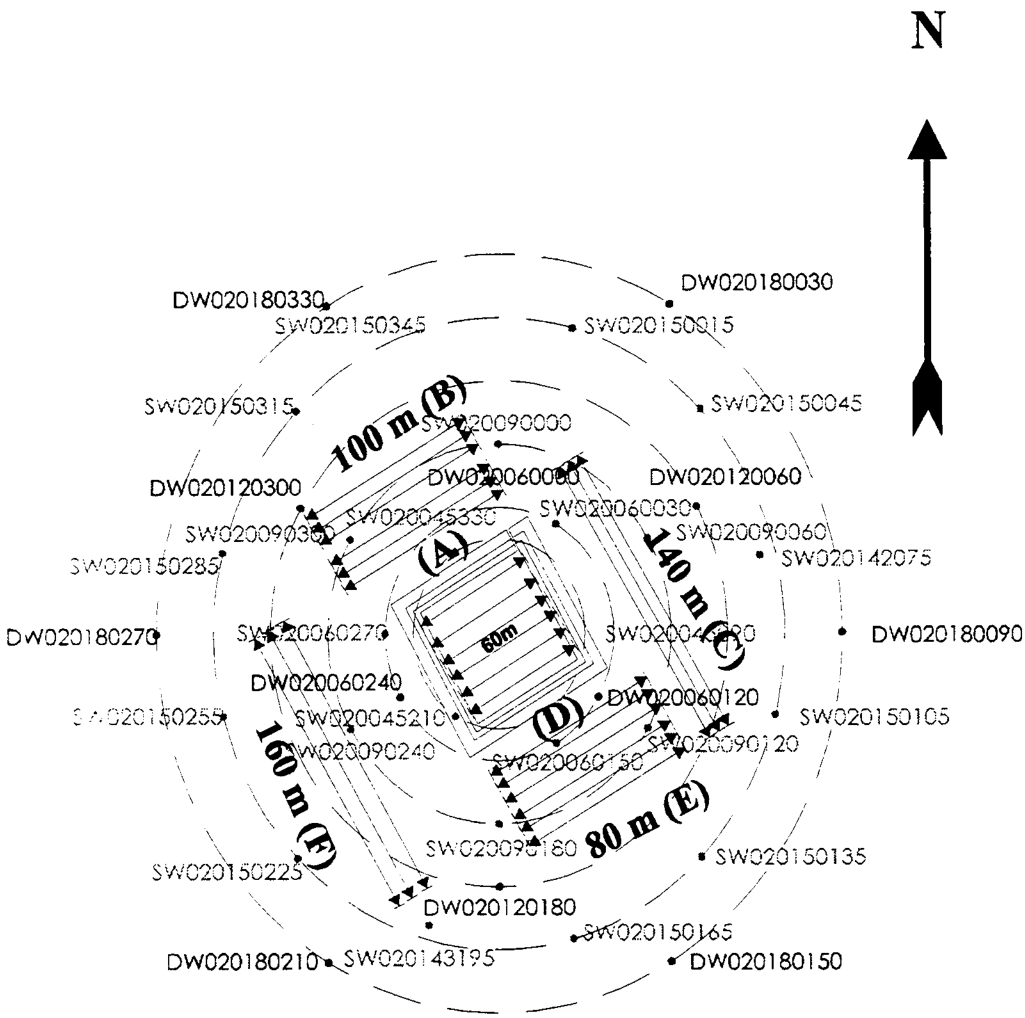


Figure 3.2: Transect lines A, B, C, D, E, and F's orientation at West Pasture.

The raw or processed data files from RADAN III were imported into Adobe Photoshop™ Version 3.0 or Corel Presentations Version 7. These Window compatible software packages allowed the radar files to be converted and handled by most Window software packages.

Corel Draw7™ was used for the final annotations of the radar images. This software package allowed subsurface features to be outlined and labeled for presentation. From this information, 3-D images of the surface and subsurface were generated using Surfer™ version 5.01.

Depths to prominent subsurface interfaces were interpolated using radar imaging and conventional soil surveying methods. These two methodologies were statistically compared using SAS® for Windows. The SAS® program written for this comparison involved the following steps:

Step 1 The difference between each datum point was computed to analyze the variance associated with each methodology (i.e., well logs and GPR imaging).

Step 2 A "proc univariate" was conducted on the variances (this procedure performed a paired T-test and showed the mean of the variance).

Step 3 A "proc reg" was performed to analyze overall variances associated with depths to subsurface features.

Before statistical analyses were conducted on the two data sets, each datum point was examined for any discrepancies. These discrepancies included over-saturated GPR data or false signals within the GPR data file due to inadequate field surfaces. These discrepancies were considered detrimental to the statistical analysis of the data sets (Saxton, 1997).

5. GPR Surveys

Data Set One

Data set one was taken August 7, 1996 with a 300-MHz antenna (Model # 3105). This data set was conducted primarily for calibration purposes. The locales for the data set were chosen by Dr. Donald D. Tyler. These sites consisted of soil profiles that were similar to soil profiles encountered at Ames Plantation. The field sites included the West Tennessee Experiment Station and the Milan Experiment Station. The primary goals of this data acquisition set were to:

(1) Ground-truth GPR images.

(2) Identify reflective characteristics of certain soil layers.

(3) Distinguish optimal antenna settings for loessial soils.

(4) Obtain data sets for comparison with Ames Plantation data.

Calibration processes used conventional soil surveying methods (i.e., bucket augers) to locate depths to coastal plain sediments, a fragipan, and a shallow water table. From these radar images, these features were correlated with the conventional soil surveying method used. Once these correlations were made, a suitable σ was calculated using equation 1.1.

The first data were taken at the West Tennessee Experiment Station in an area with varying depths of coastal plain sediments (Figure 3.3). These depths were acquired using a

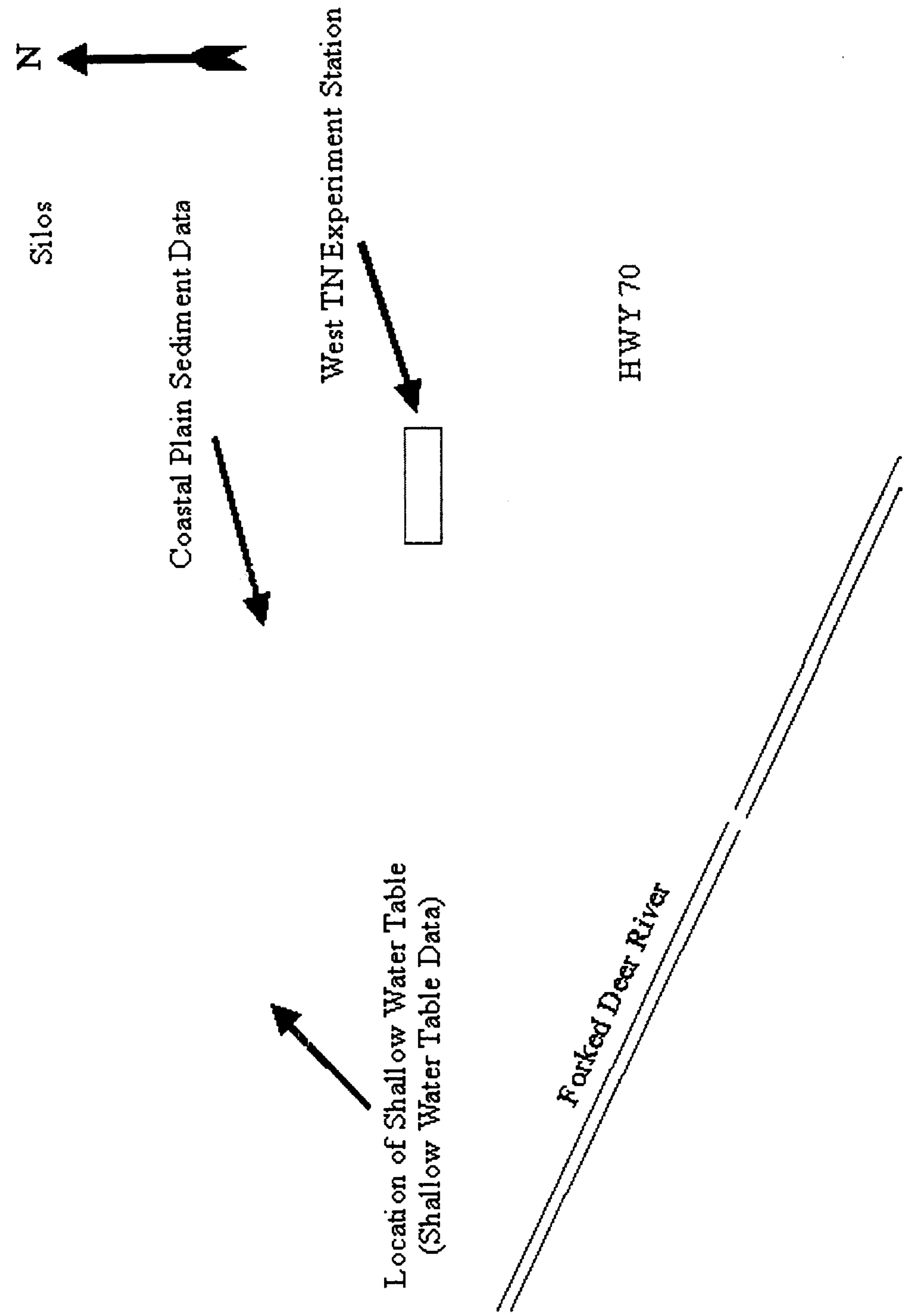


Figure 3.3: Locations of GPR data taken at the West Tennessee Experiment Station.

hand-held bucket auger. One depth was logged at the beginning of the transect line, the second in the middle of the transect, and the third at the end of the transect.

Varying depths of coastal plain sediments allowed a change in the radar image to be viewed by the GPR operator. From the logged depths, a suitable σ was calculated using equation 1.1. Once a σ was calculated, depths were later determined in the lab using the radar image.

Data were also taken along a bottomland at the West Tennessee Experiment Station (Figure 3.3). This data set provided a shallow water table for GPR imaging. A 30-m transect line was configured with flags placed every 3 m. Soil corings were taken until free-water was present in the boreholes. Depths to free-water logged in the field were later compared with depths obtained from radar images.

Data acquired at the Milan Experiment Station were obtained in Field A-11. A site was chosen that provided a location with a fragipan. Not only was there a fragipan present, but due to differences in topography at this site, the fragipan was discontinuous. The transect line at this field site was situated to provide a data set showing the presence of a fragipan and where the fragipan was no longer present. The transect line was 24 m long, with flags placed every 3 m. Again, soil corings were taken and later compared with GPR imaging.

Data Set Two

Data set two was acquired on March 3, 1997 at the no-till site at the Ames Plantation. For this data set a 200-MHz antenna (GSSI Model 5106) was chosen. Each transect line consisted of two data sets. The first data set for each transect line began nearest the bermed area with the next data set starting in the reverse direction, on the opposite side of the transect line farthest from the bermed area. The transect lines oriented along the east and west side of the bermed area were started on the south side of the transect line and continued northward. The transects placed on the north and south side of the bermed area were started on the west side of the transect line and pulled northward. The transects established inside the bermed area were started on the east side of each transect line with the reverse pull on the west side of each transect line. Data acquisition within the bermed area was started at its south side and continued northward (Figures 3.1 and 3.2).

Due to inclement weather conditions, data set two could not be completed at the tillage site until March 25, 1997. At the beginning of data acquisition of the tillage site, the instrumentation was configured differently than that of the no-till site, due to extremely wet field conditions. The wet conditions encountered at the tillage site required the gain settings of the instrumentation to be reduced. These settings were utilized on the transect lines situated inside the berm and transect F (Figure 3.2). These settings were replaced with original settings as the field began to dry.

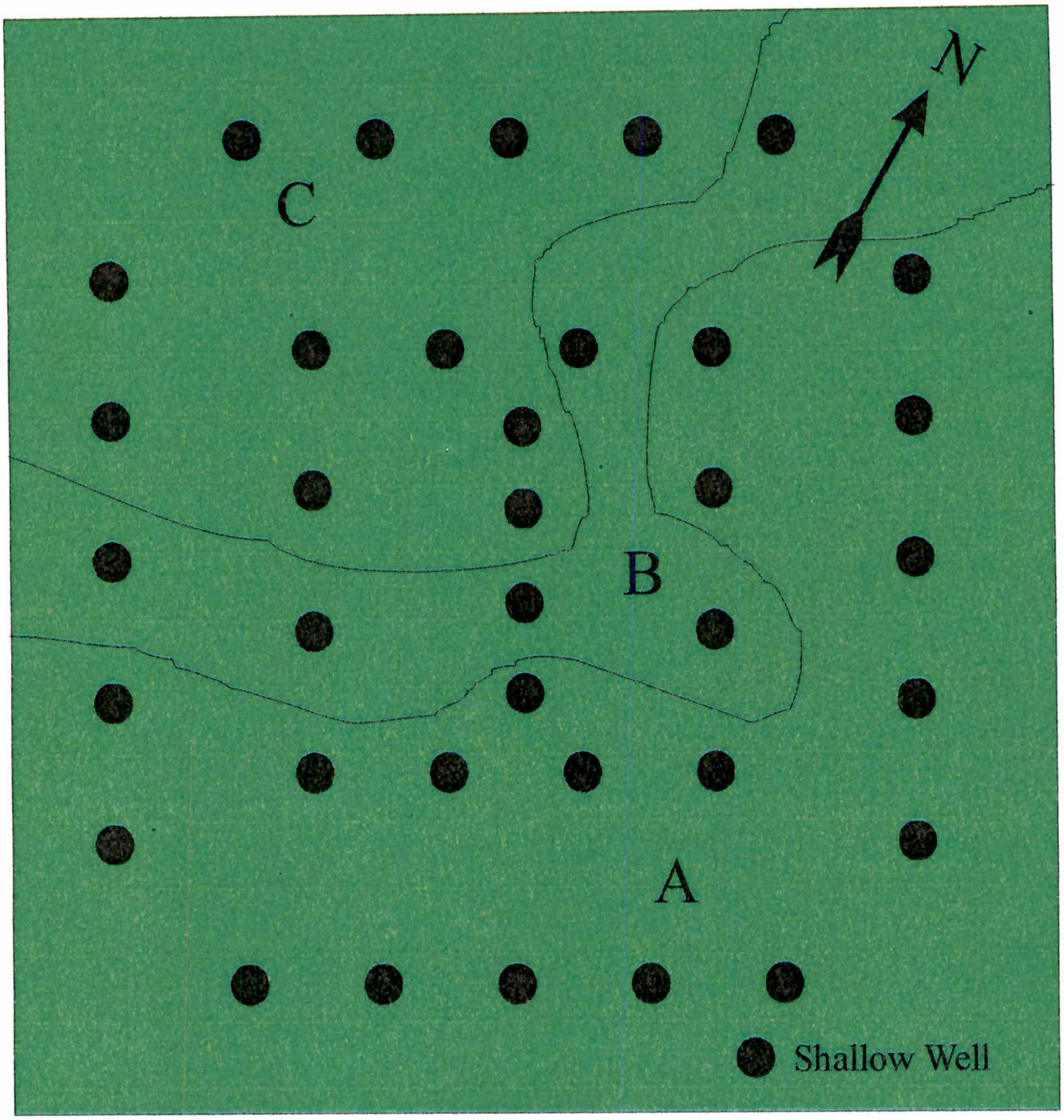
Each transect line was begun nearest the bermed area, with the consecutive data set on the opposite side of the transect line, farthest from the bermed area. Data acquisition for the transect lines oriented east and west of the bermed area were started on the south side and continued northward. The transect lines oriented south of the bermed area were begun to the west and continued eastward. The transect lines oriented north of the bermed area were begun to the east and continued westward. Data acquisition within the bermed area was started on the west side of each transect line with the consecutive data set started on the east side of each transect line. GPR imaging of the bermed area began to the north and continued southward.

The wet conditions encountered at the tillage site prevented acquisition of a complete data set. A1, A1r, D3r, E3, and E3r were not taken due to wet conditions of the field (Figure 3.2). Data were taken at C1, but the tractor became stuck halfway through the transect.

Data Set Three

Data were taken April 22, 1997, at Ames Plantation's Centennial Field for statistical comparisons (Figure 3.4). At Centennial Field there are 32 vadose wells installed around a small berm. As the shallow wells were installed, core samples were taken of the soil profile (Carter, 1996). These soil corings were statistically compared with depths to the alluvium interface acquired from GPR images.

Possible inadvertent bias interpretation of the data set was prevented by prohibiting well logs to be viewed by the GPR operator. The GPR operator was allowed to view one shallow well log for calibration purposes. Once the radar images were calibrated, the remaining 31 depths were obtained based on GPR images alone. Data obtained at this site employed the same mobilization and GPR system settings as data acquired at Hancock Tract and West Pasture.



Key

A - fine-silty, mixed, thermic, Typic Hapludalf
(paleosol ranging from 140 cm to 200 cm)
B - fine-silty, mixed, thermic, Typic Hapludalf
(paleosol > 200 cm)
C - fine-silty, mixed, thermic, Typic Hapludalf
(separated because paleosol consisted of more sand and clay)

Figure 3.4: Shallow well orientation and order 1 soil classification at Centennial Field (Carter, 1996).

Chapter 4

Results and Discussion

1. Data Set One

Coastal Plain Sediments

Data set one was taken at the West Tennessee Experiment Station and the Milan Experiment Station. This data set was used for calibration purposes and for comparison with data acquired for the Ames Plantation Water Quality Project. The calibration process involved conventional soil surveying methods (i.e., bucket augers) to locate depths to certain soil horizons considered relevant to soil-water movement. From these radar images relevant soil horizons were correlated with the conventional soil surveying method used. Once these correlations were made, a suitable σ was calculated using equation 1.1. Soil characteristics of interest were depths to coastal plain sediments, depths to water tables, and the presence of fragipans. Not only were GPR operators able to view these characteristics but the data taken allowed GPR system settings to be maximized for West Tennessee soils (Table 4.1).

The first data were taken at the West Tennessee Experiment Station, using a 300-MHz antenna. This locale was designated by Dr. Donald D. Tyler because of varying depths to the coastal plain sediments. These depths were acquired using a handheld bucket auger. One depth was logged at the beginning of the transect line, the second in the middle of the transect line, and the third at the end of the transect line (Table 4.2).

Table 4.1: GPR calibration settings for Ames Plantation data acquisition.

200 MHz Antenna Model # 5106	
Settings	**Value**
Range	110 ns
Number of gain settings	5
Gain Settings	1. 12 2. 61 3. 70 4. 76 5. 77
Samples per scan	512
High Pass Filter	
Poles	2
Frequency	4
Low Pass Filter	
Poles	2
Frequency	66

Table 4.2: Ground-truth depths compared with GPR depths.

Depths to Coastal Plain Sediments		
Location	Bucket Auger Depths	GPR Depths
Beginning	1.37	1.42
Middle	1.32	1.31
End	1.06	1.14

Varying depths to coastal plain sediments allowed a change in the radar image to be viewed by the GPR operator (Figure 4.1). From the depths logged, a suitable σ was calculated using equation 1.1. Once a σ was calculated, depths were later determined in the lab using the radar image.

Shallow Water Table

Data taken at the West Tennessee Experiment Station also utilized a 900-MHz antenna. A transect line was placed in a bottomland along a tree line south of the West Tennessee Experiment Station. Soil corings showed a shallow water table to be within 0.32 m of the soil surface. Due to the shallow nature of the water table a 900-MHz antenna was chosen over a 300-MHz antenna.

A change in the GPR image could be viewed in the field from raw data processed by the GPR mainframe. This change was interpreted as the top of the water table in the GPR image, based on the dielectric difference of water and soil. This interpreted depth did not correlate with the conventional soil surveying method used (Figure 4.2).

The data were later processed in the lab using a low pass filter provided by RADAN III. The low pass filter separated the image into two distinct boundaries, which not only correlated better with the conventional method used but was easier to interpret. (Figure 4.3).

Fragipan Data

Milan Experiment Station's field A-11 was chosen for GPR surveys of a fragipan. At this location, a fragipan had formed in the soil profile at a discontinuity between two

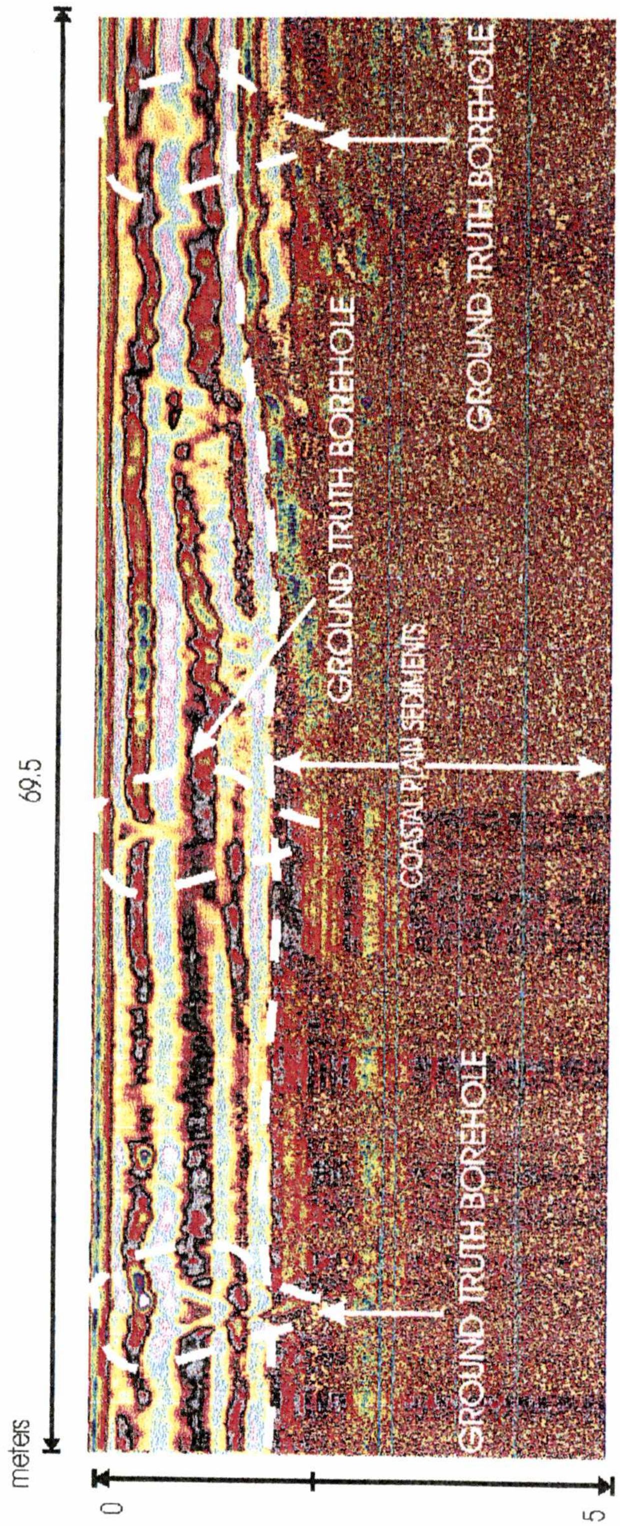


Figure 4.1: GPR data of coastal plain sediments taken at the West Tennessee Experiment Station.

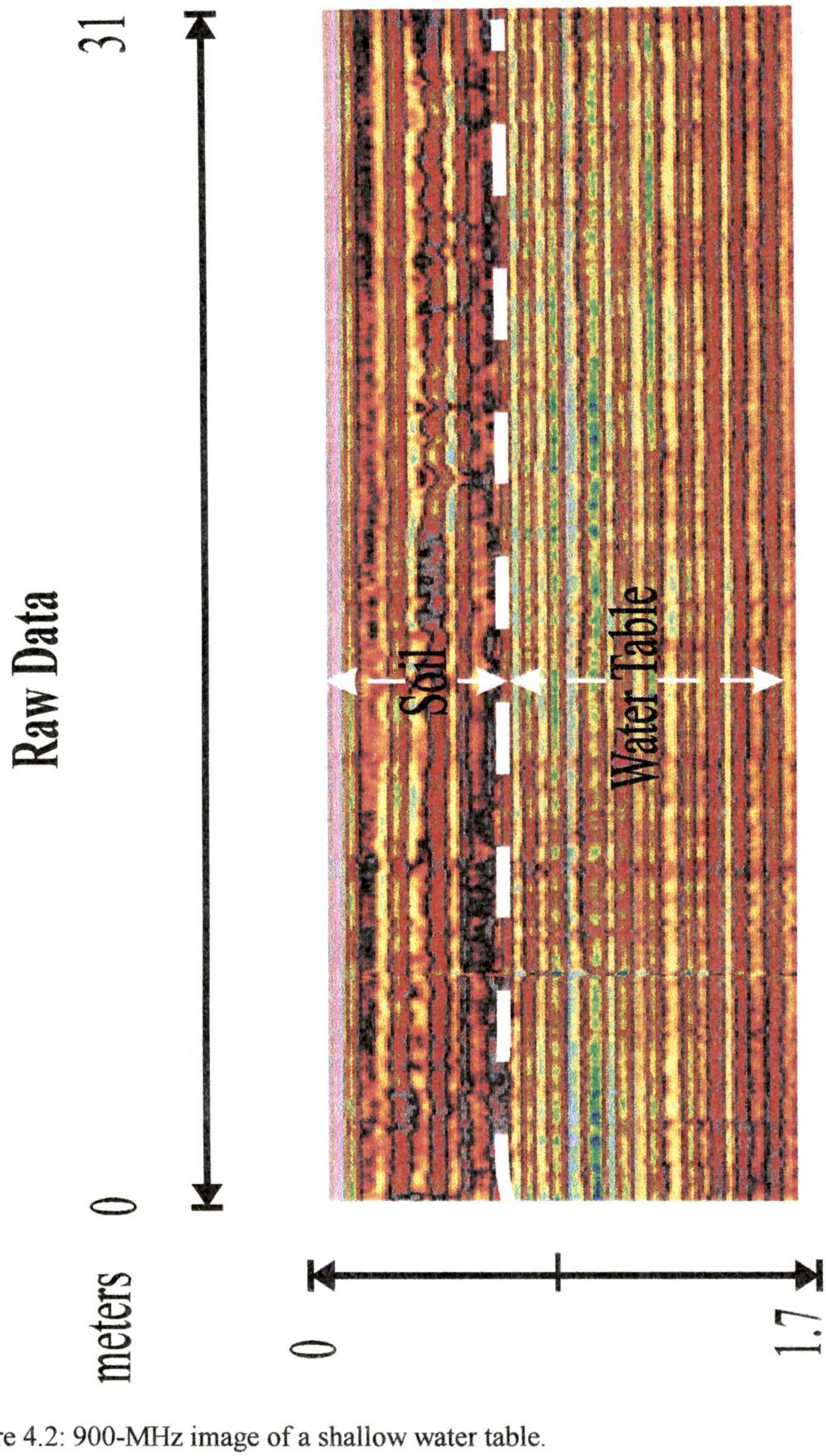


Figure 4.2: 900-MHz image of a shallow water table.

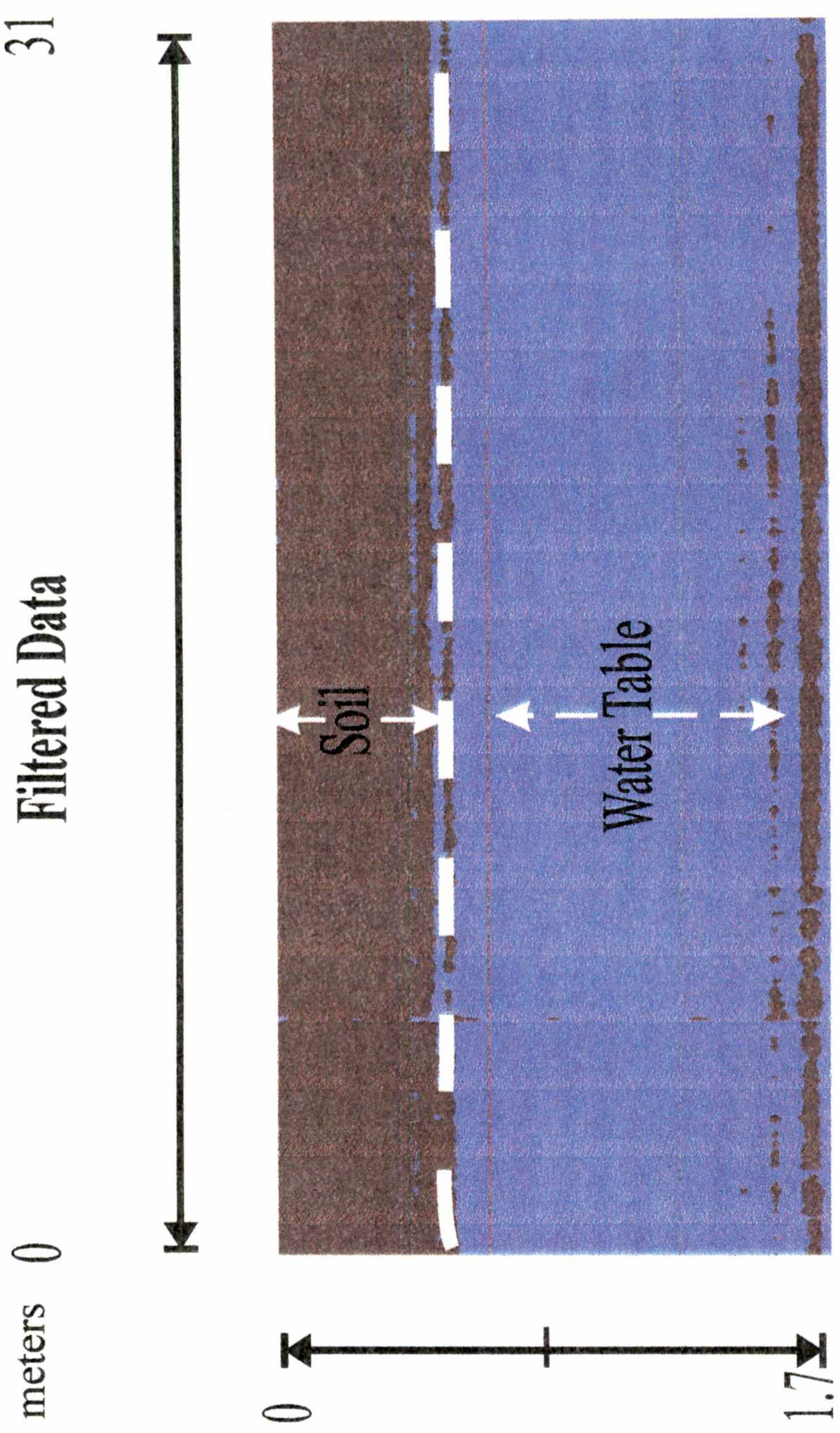


Figure 4.3: Filtered 900-MHz image of a shallow water table.

different loessial deposits at approximately 0.95 m. Soil corings taken along this transect line confirmed that due to a topography change the fragipan became discontinuous.

GPR data were taken along this same transect line after the soil corings were taken. This gave the GPR operator a chance to view a reflection that could be associated with a fragipan. When GPR data were taken along this same transect line, a distinct reflection that became discontinuous could be viewed in the GPR image (Figure 4.4).

2. Data Set Two

Hancock Tract Data

The calibration data taken at the West Tennessee Experiment Station gave researchers a permanent archive of GPR data. This data contained GPR images of subsurface features that affected soil-water content and movement. The data also gave researchers the ability to compare reflections of these features with data taken at Ames Plantation.

GPR system settings used at the West Tennessee Experiment Station were also utilized at Ames Plantation (Table 4.1). Sometimes small adjustments were made to gain settings to focus on the loess/alluvium interface.

The loess/alluvium interface was the subsurface feature of primary interest. This interface was the first strong reflection viewed in GPR data (Figure 4.5). This strong reflection resulted from an increase in clay content and moisture at this interface (Freeland et al., 1995).

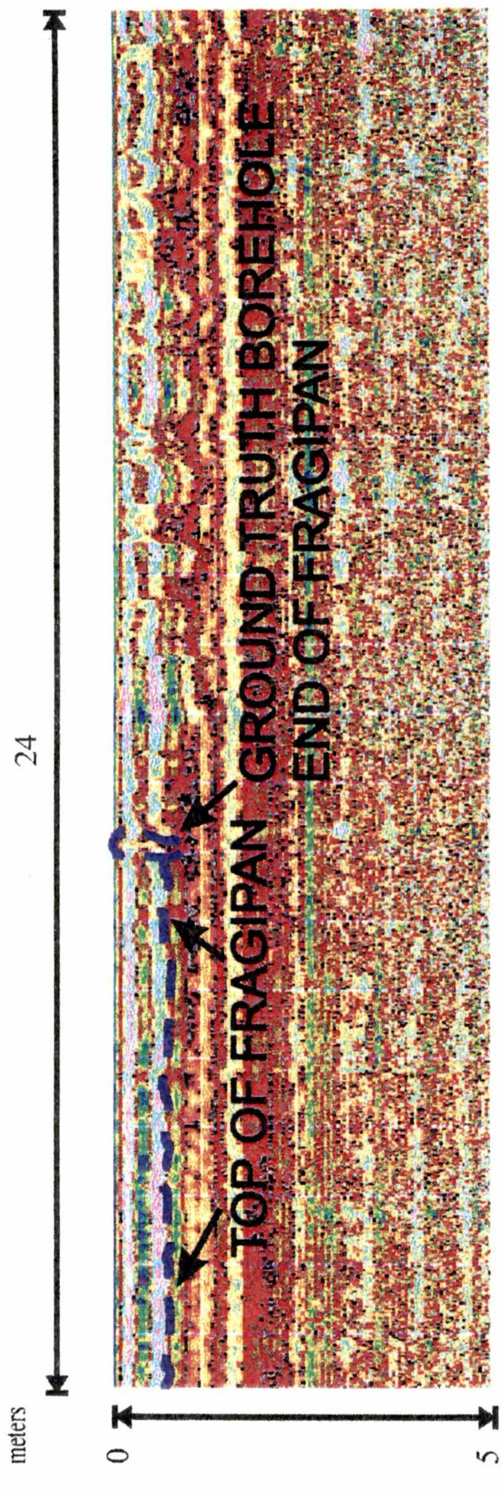


Figure 4.4: GPR image of a fragipan taken at the Milan Experiment Station.

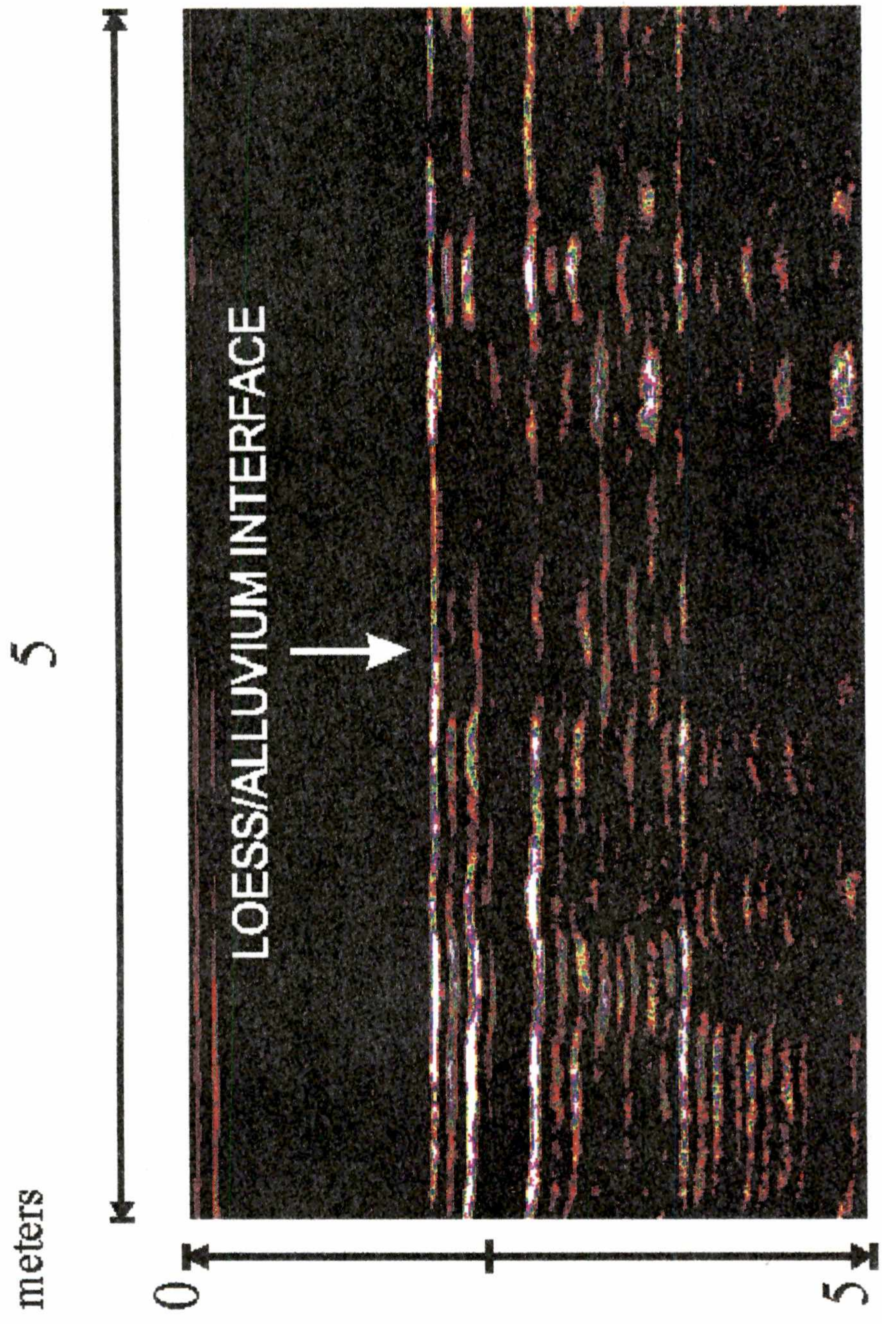


Figure 4.5: GPR data showing the loess/alluvium interface at Hancock Tract.

GPR data taken at Hancock Tract revealed to researchers that the paleosol surface (loess/alluvium interface) did not look exactly like the present surface (Figure 4.6). A total of 336 GPR data points were used to generate Figure 4.6. These 336 data points revealed "channels" that could affect the movement of solutes and soil-water at this interface. The most influential channel started northeast of Figure 4.6 and ran southward, the other began west of the berm and continued westward.

Heterogeneity was also discovered in the loessial material that could alter the vertical movement of soil-water. An apparent depression was discovered in the loessial material within transect lines A and B (Figure 3.1). After closer examination of the 3-D map, this depression seemed to extend into the alluvial material (Figure 4.6).

This small channel can be seen running east and west along the west side of the berm (Figure 4.6). GPR imaging also demonstrated apparent pockets of soil-water within this depression (Figure 4.7).

West Pasture Data

Settings for the GPR unit were configured according to Table 4.1 except when relatively wet conditions were encountered or gain settings needed to be adjusted to focus on the loess/alluvium interface. At these locations GPR settings were adjusted to compensate

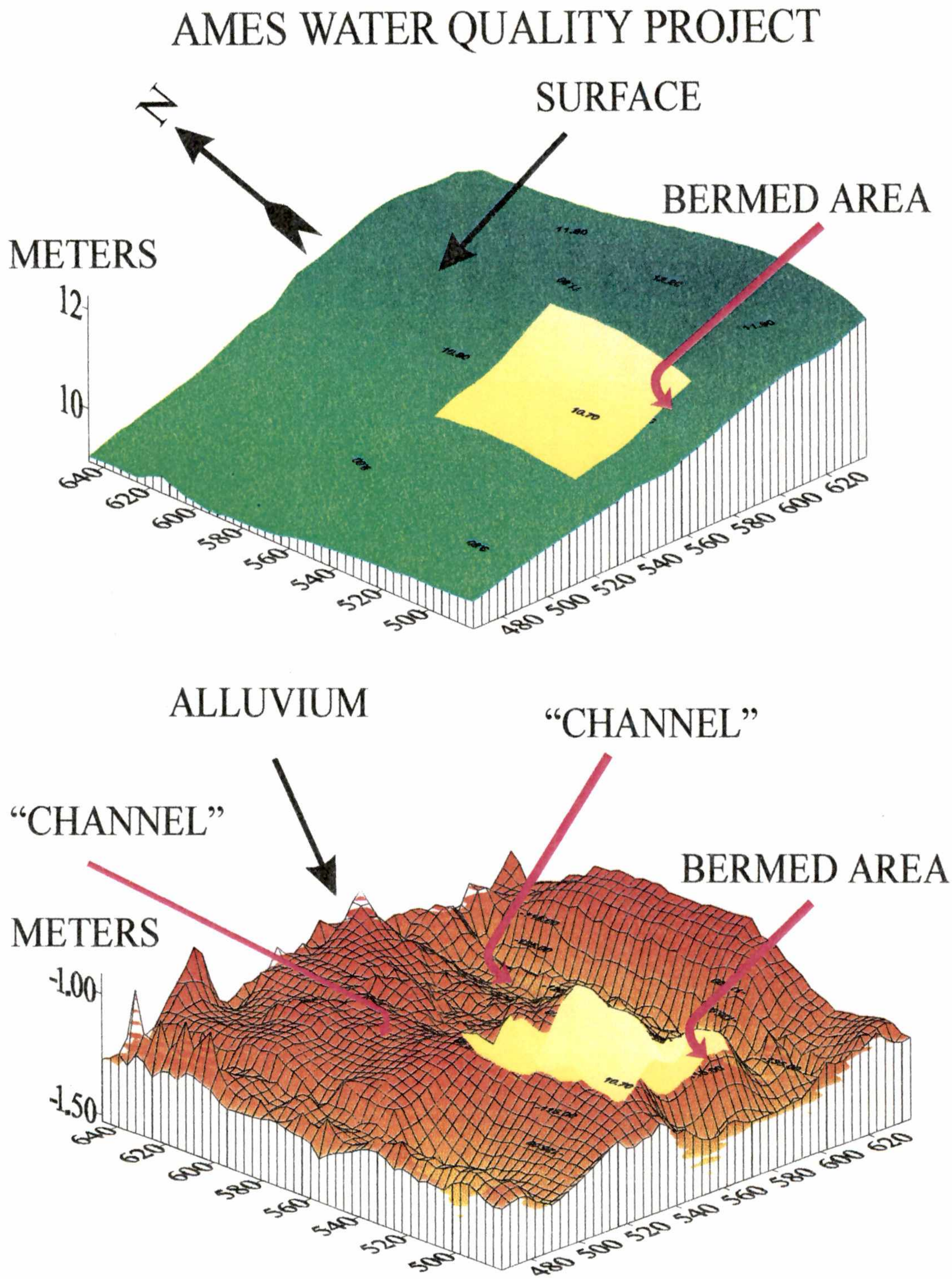


Figure 4.6: Map of the loess/alluvium interface at Hancock Tract taken from GPR data.

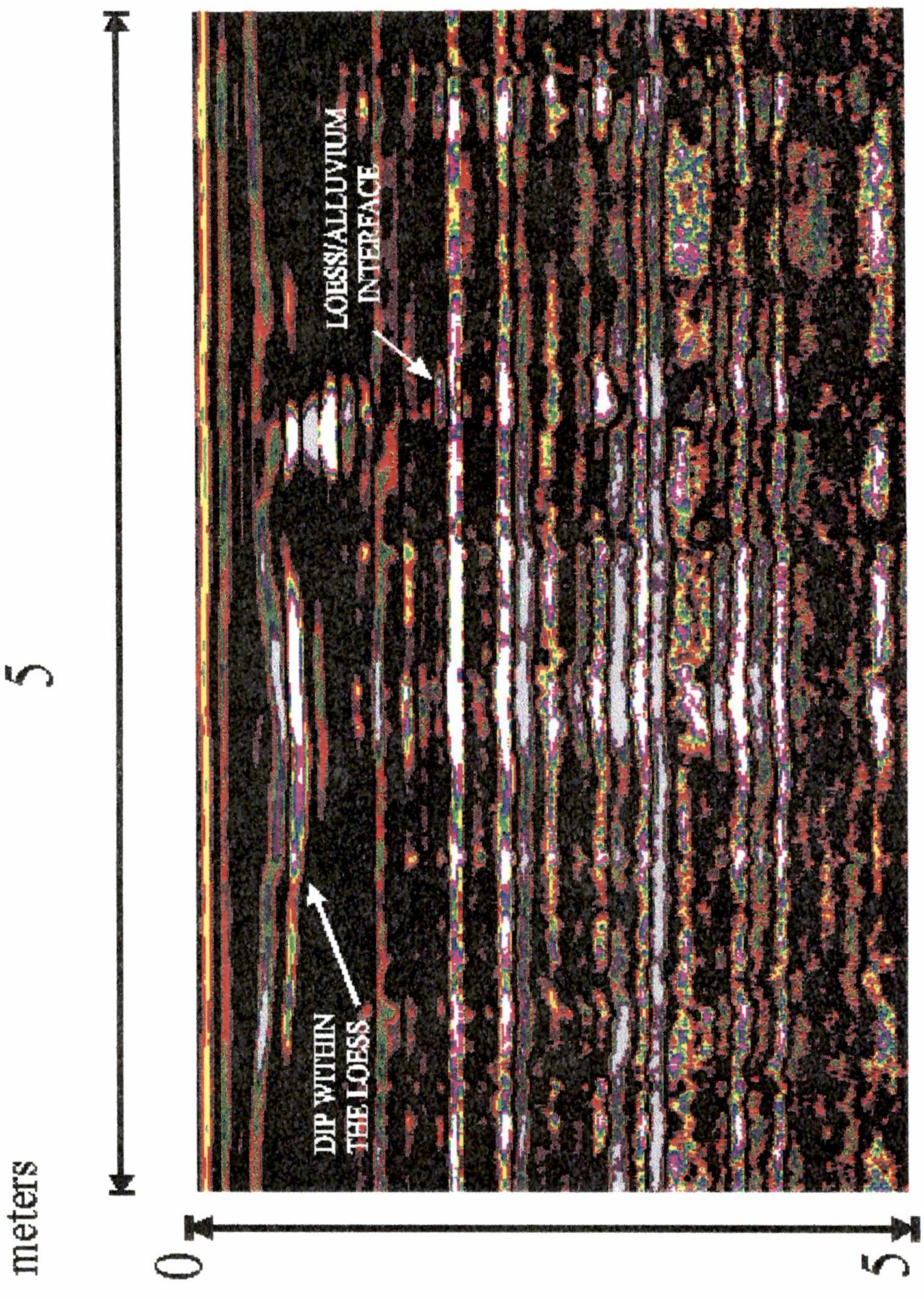


Figure 4.7: GPR image of a depression in the loessial material at Hancock Tract.

for the higher σ associated with water (Table 4.3). GPR data acquired at West Pasture established many features in the subsurface that could alter the movement of soil-water. North of the berm a relatively large area of soil with increased moisture content was discovered (Figure 4.8). This area of increased soil moisture content was also evident to Livingston (1993), where he classified the soil as a Glossaquic Fragiudalfs (Figure 2.5). Fragic properties that appeared discontinuous were evident in GPR data throughout West Pasture (Livingston, 1993) (Figure 4.9). The surface of the loess/alluvium interface at West Pasture was sloping southward, with the actual surface topography sloping northward (Figure 4.10).

If the assumption were made that the loess/alluvium interface was the controlling factor of soil-water movement at West Pasture, a pattern of this movement could easily be made from Figure 4.10. There are two possible channels located to the east and west side of the berm, and the topography of the loess/alluvium interface slopes southward, all of these factors could have an impact on soil-water movement.

With all of the heterogeneity discovered throughout the soil profile at West Pasture, it was determined that there were other variables altering soil-water movement before reaching the loess/alluvium interface (e.g., fragipans).

Data taken at West Pasture have given researchers insight in the many capabilities of GPR for soil reconnaissance. Variations in the profile that not only altered soil-water movement but also determined how soils were classified were mapped by GPR imaging. Three transect lines at West Pasture had fragipans in the soil profile that seemed to perch

Table 4.3: Mainframe settings used under wet conditions.

200 MHz Antenna Model # 5106	
Settings	**Value**
Range	110 ns
Number of gain settings	5
Gain Settings	1. 12 2. 58 3. 67 4. 70 5. 73
Samples per scan	512
High Pass Filter	
Poles	2
Frequency	4
Low Pass Filter	
Poles	2
Frequency	66

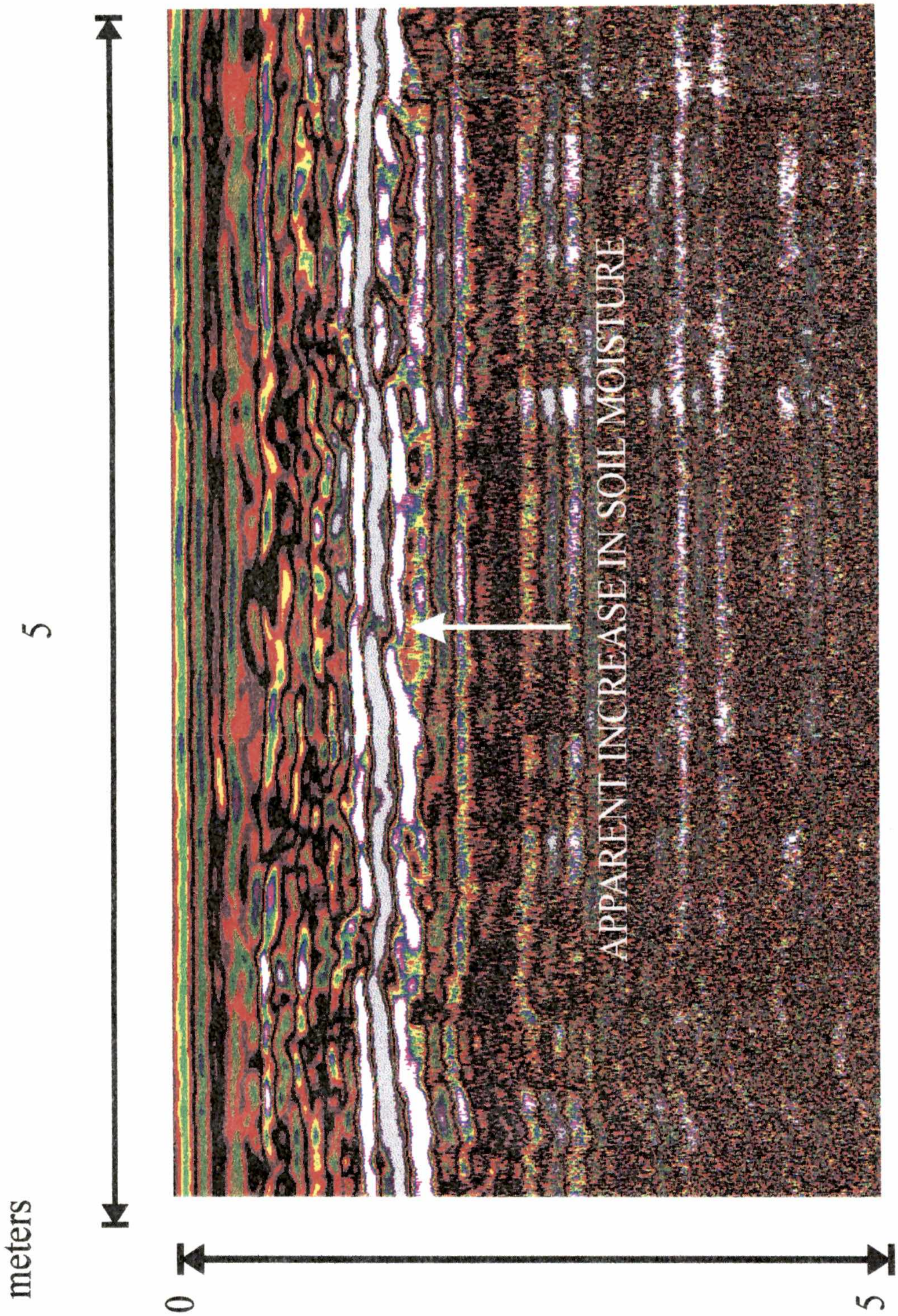


Figure 4.8: GPR image of increased soil moisture content at West Pasture.

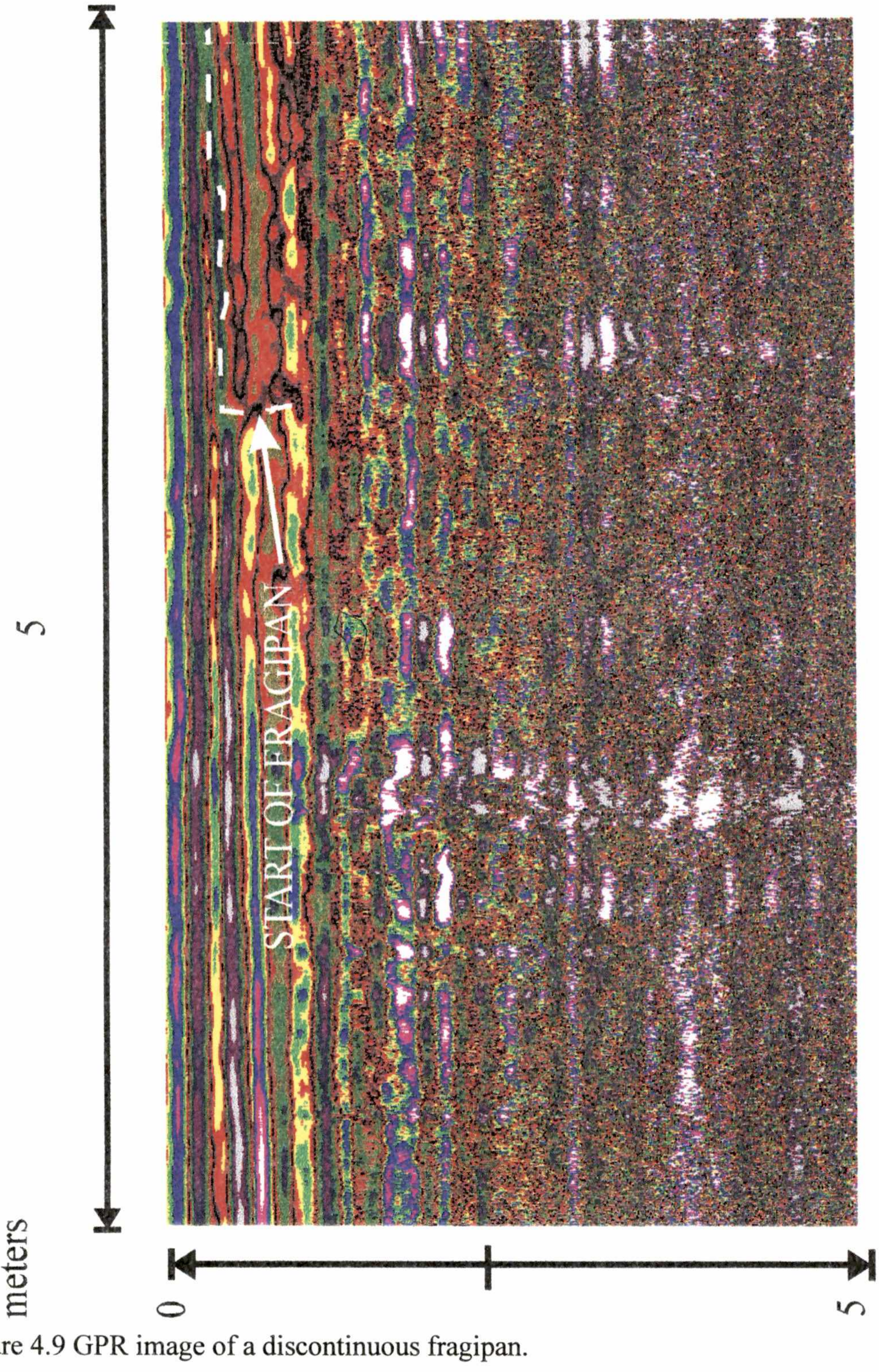


Figure 4.9 GPR image of a discontinuous fragipan.

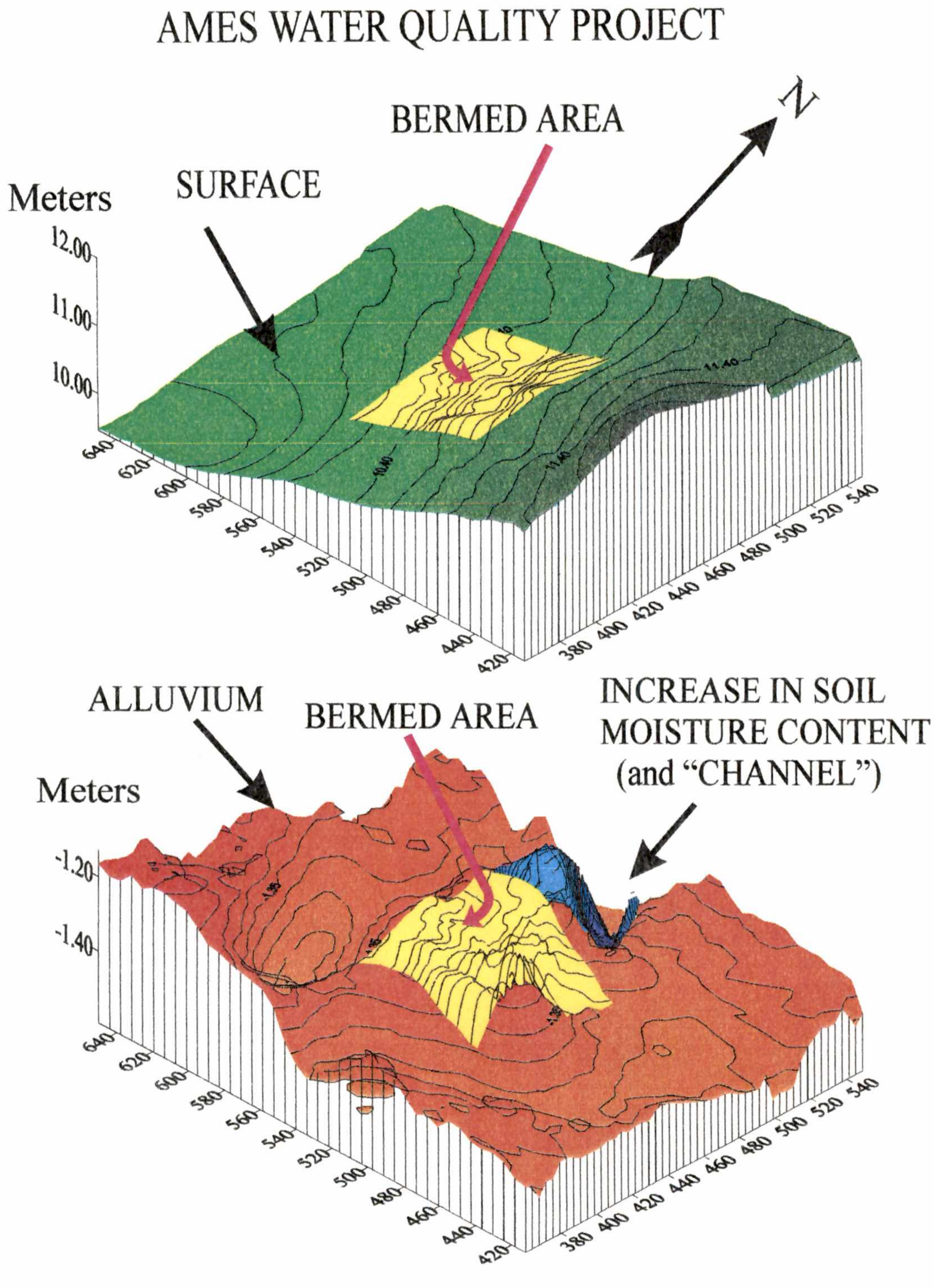


Figure 4.10: Map of the loess/alluvium interface at West Pasture taken from GPR data.

water (Figure 4.8). The area of increased soil moisture was highlighted using the same filter, utilized on the calibration data of the shallow water table, taken at the West Tennessee Experiment Station (Figure 4.11).

Soil surveys taken at West Pasture revealed the presence of fragipans that became discontinuous along these transects. This soil morphological situation was attributed to the fact that many soil profiles at Ames Plantation exhibited fragic characteristics, but did not alter soil-water movement enough to form sufficient redoximorphic features associated with fragipans (Lindbo et al., 1994).

The presence of these fragipans was viewed as the major variable controlling soil-water movement at West Pasture. This gave researchers insight to the possibility that in some areas of West Pasture, fragipans were altering vertical soil-water movement before advancing soil-water reached the loess/alluvium interface.

3. Data Set Three

Centennial Field

Centennial Field was chosen to determine if GPR interpretations of depths to the loess/alluvium interface were statistically different than field observations. The statistical model found the two methods to be statistically different when determining depths to the interface (Table 4.4). The statistical comparison also revealed that the two methodologies had a mean average difference of 5 cm when determining the depth to the loess/alluvium interface (Table 4.4). The interpreted data points for each method can be found in Table 4.5.

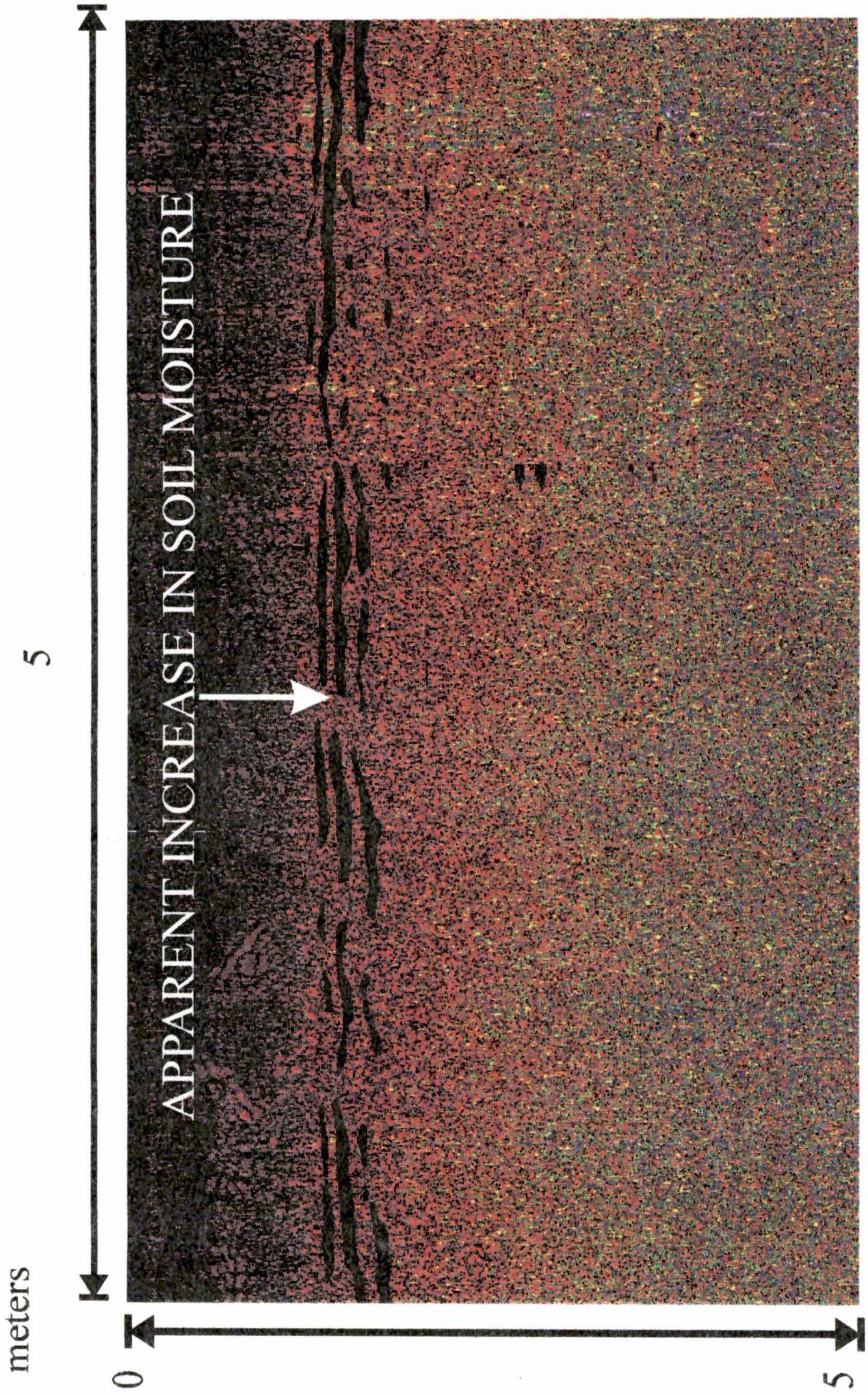


Figure 4.11: Filtered data of increased soil moisture content at West Pasture.

Table 4.4: Average mean difference between GPR data and field observation, and results from a linear regression.

Univariate Procedure	Linear Regression		
Average Mean (cm)	**Slope**	**Y-intercept**	**r^2**
5.625	.0393	0.1622	0.134

Table 4.5: Conventional soil surveying method compared with GPR interpreter methods.

Depths to the loess/alluvium interface

Well #	GPR Depth (cm)	Soil Survey Depth (cm)
1	197	190
2	199	200
3	198	202
4	199	195
5	198	185
6	199	180
7	199	185
9	198	216
10	202	200
11	197	208
12	197	203
13	201	193
14	200	195
15	198	188
16	199	188
17	200	195
18	203	189
19	**199**	**150**
20	**195**	**157**
21	**195**	**140**
22	**197**	**145**
23	198	200
24	197	200
25	200	210
26	195	225
27	202	223
28	203	198
29	206	213
30	**205**	**205 (known)**
31	202	185
32	200	202

The loess/alluvium interface at Centennial Field was interpreted by the GPR operator as being relatively flat, with a minimum depth from the surface of 195 cm and a maximum depth from the surface of 205 cm. Soil morphology data taken during well installation showed the loess/alluvium interface reaching a shallower depth at four locations than the GPR interpretation (Table 4.5). According to well log data, there was a rise at the loess/alluvium interface, located at the southeast corner of the plot (Carter, 1996).

The GPR interpreter did not locate this rise with GPR imaging. Although this rise was not interpreted from GPR data, Table 4.5 illustrates the relative accuracy of GPR imaging when mapping the loess/alluvium interface. Researchers also noted that in 32 observations, the GPR data interpretations were within 20 cm of the field observation 28 times.

Discussion

A Giddings drill rig (Model # GSRP-S-M) was used to verify the GPR interpretation and the field observation data taken at Centennial Field. GPR data and the soil survey data taken at Centennial Field disagreed by more than 20 cm, when determining depths to the loess/alluvium interface, at well numbers 19, 20, 21 , and 22 (Table 4.5). Two possibilities were explored to explain why the GPR interpreter and soil scientists had disagreed at the four locations.

The first possibility was that GPR had missed the loess/alluvium interface and reflected off another strong electrical boundary. Increases in clay and water content within

1997). To determine if GPR had missed the loess/alluvium interface due to increases in clay and moisture content, well logs taken at Centennial Field along the outer edge of the field plot were used (Figure 3.4).

Figure 4.12 contains three graphs: Graph (a) illustrates the GPR interpretation and the field observation depths to the loess/alluvium interface plotted by well number. There is a discrepancy between the two methodologies of more than 20 cm at well numbers 19, 20, 21, and 22. Graph (b) adjusts the field observation depths based on a soil textural change of silt loam (SiL) to silty-clay loam (SiCL), and graph (c) adjusts the field observation depths based on an apparent increase in moisture (Carter, 1996).

From these graphs, the possible effects of clay and moisture content on GPR imaging can be seen. The difference between the field observation and the GPR interpretation at well number 19 could not be explained by these results (Figure 4.12).

The other possibility that might explain the discrepancy between GPR data and the field observation is GPR data interpretation. More in-depth interpretations were made of the data, after the statistical model failed. In previous interpretations of the Centennial Field data, the first continuous strong reflection was interpreted as the loess/alluvium interface. There is a strong reflection, which was discontinuous, above the reflection interpreted as the loess/alluvium interface.This discontinuous reflection was interpreted by the GPR operator as a mixing zone, based on data reported by Livingston (1993).

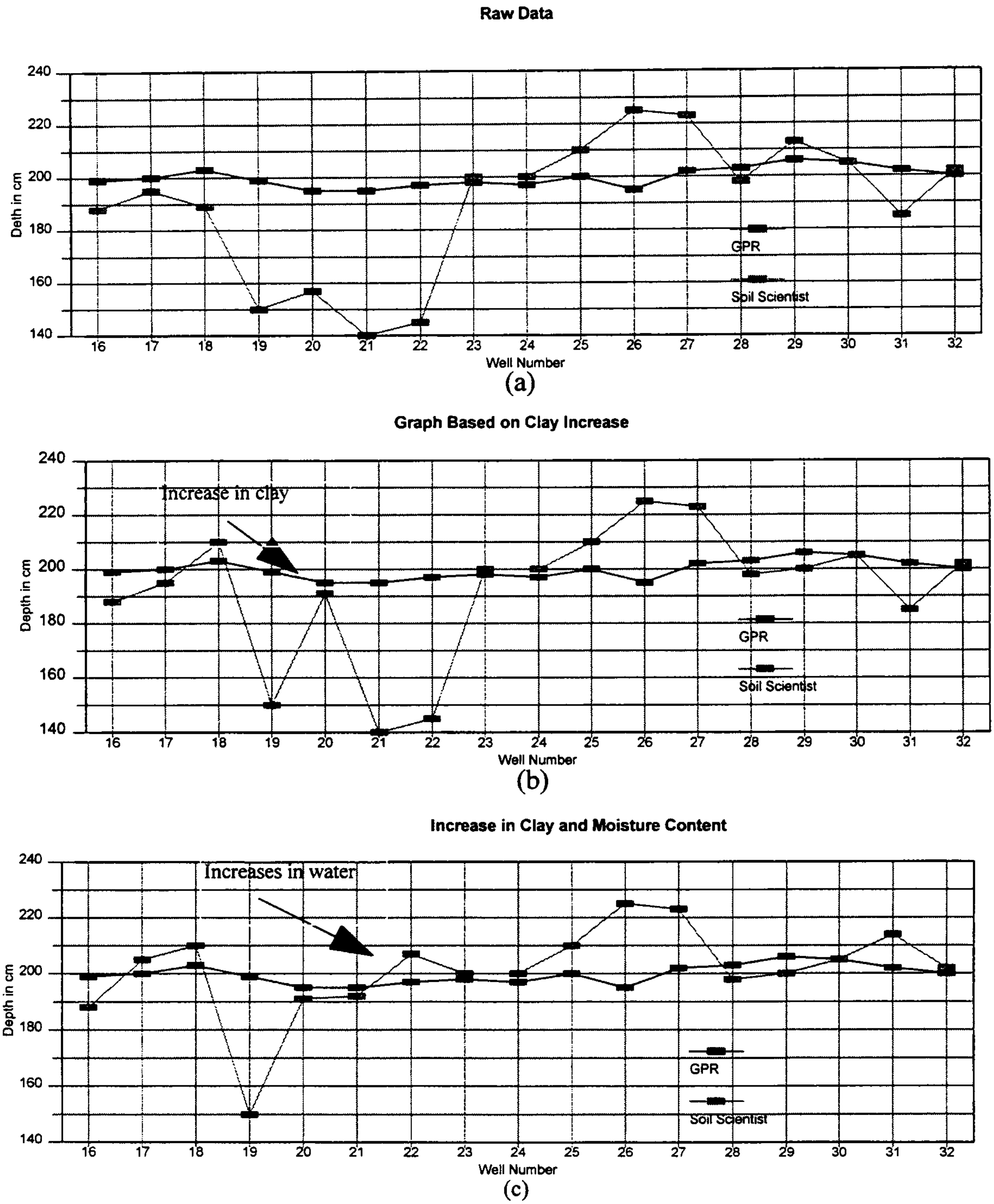


Figure 4.12: Affects of moisture and clay content on GPR interpretations.

If this noncontiguous reflection was the actual loess/alluvium interface, it would explain the rise in the soil survey data. If soil corings were taken in the mixing zones or depressions, field observations would reveal rises and valleys at the loess/alluvium interface. This would mean that GPR data of the loess/alluvium interface would need to be interpreted very carefully, because these depressions could be very easily overlooked (Figure, 4.13).

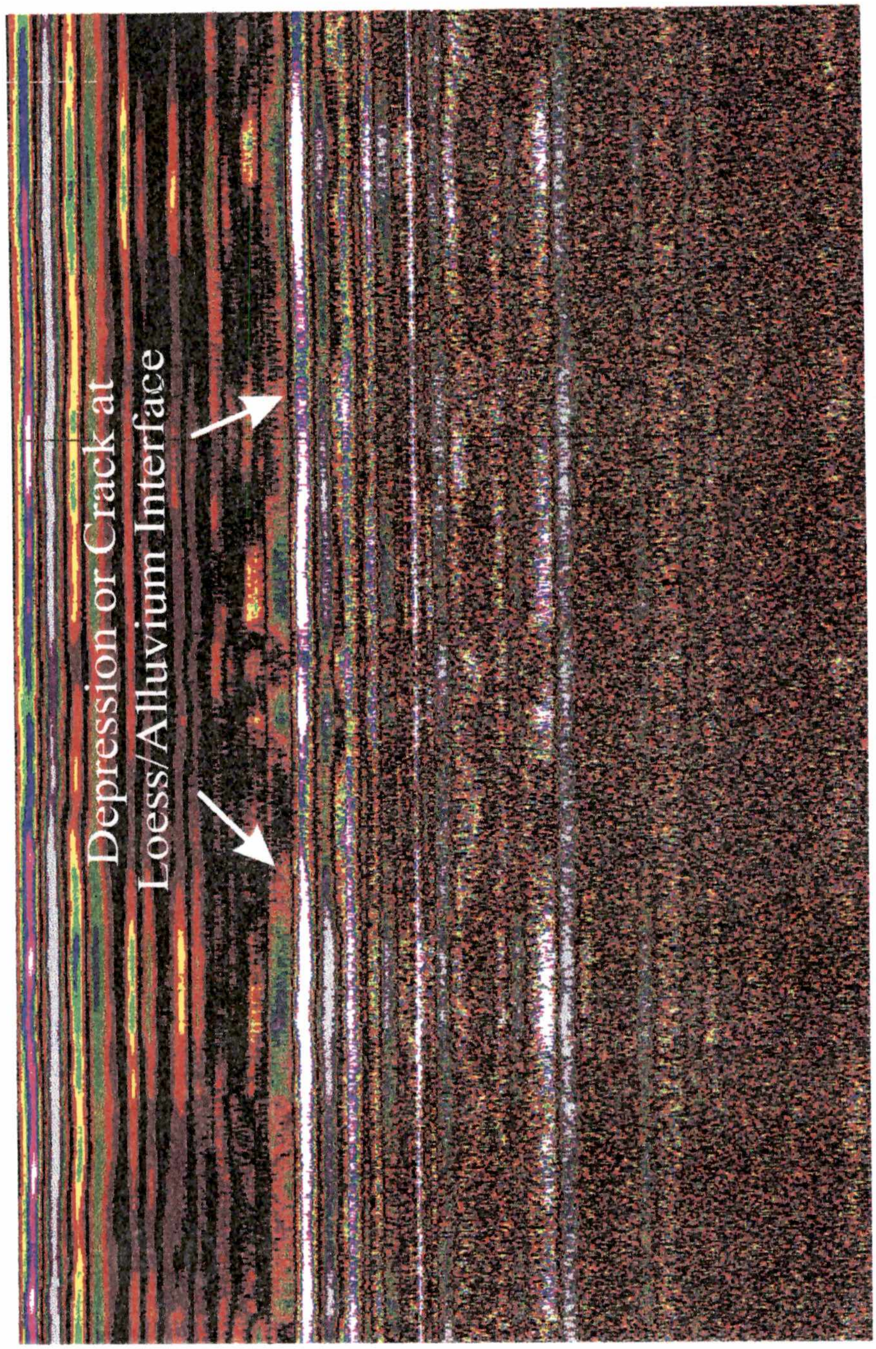


Figure 4.13: Apparent pockets or cracks at the loess/alluvium interface.

Chapter 5

Recommendations

1. GPR System Operation

Calibration

Antenna selection is one of the most important variables in GPR research. To select the proper antenna, GPR operators should be aware of the morphology being surveyed. Not only is the geology important, but depths to prominent features are critical. When the morpholgy and depths to prominent features are determined, the proper antenna can be selected. An antenna with the highest frequency that can achieve the depths needed should be used. This will allow optimal resolution for GPR data.

Before successful GPR data can be obtained, GPR operators should be aware of prominent subsurface features and how these features will attenuate the radar wave. This can be accomplished by ground-truthing GPR surveys. These ground-truths enable the GPR operator to determine features that produce stronger reflections and features that produce weaker reflections. Once these features have been determined, GPR operators can pinpoint optimal system settings that will produce precise GPR data.

Data Collection

Implementation of GPR technology in an agricultural production field usually requires GPR data to be obtained after crops have been harvested, thus reducing damage to crops. For most production fields this means that GPR data acquisition must be conducted in winter months. GPR data taken at the Ames Plantation Water Quality Project gave much insight in field limitations of the GPR unit used by The University of Tennessee during the winter months of 1996-97.

To overcome these limitations, a method of GPR data collection should be developed that will protect the GPR unit from the environment. Protection of the system will allow GPR data to be taken when temperatures fall below 0^0 C, or when rain is present. Not only will this increase data obtained but will reduce costs, by limiting time spent waiting for optimal environmental conditions.

2. Transect Surveys

GPR's most substantial benefit to research is the ability to gather large quantities of continuous, nonintrusive data of the subsurface. This capability allows tremendous amounts of subsurface data to be gathered in relatively short periods of time, thus reducing costs to researchers. Costs of GPR surveys could be reduced even more by eliminating time spent surveying transect lines for GPR data acquisition.

One way to eliminate transect line configurations is to implement Global Positioning Systems (GPS) methodologies with GPR methodologies. With the combination of these two technologies surveying data could be gathered by a GPS receiver as subsurface data are acquired by GPR.

3. Statistical Model

The statistical model used for GPR research at the Ames Plantation Water Quality Research Project gave much insight regarding GPR capabilities in resolving the loess/alluvium interface at Centennial Field. After GPR data of Centennial Field were interpreted, ground-truth data were gathered by field observations to compare differences in the two methods.

Ground-truth data would be more beneficial if acquired first. From this information researchers would have a better understanding of the homogeneities in the subsurface that cause stronger GPR reflections, thus allowing researchers to calibrate GPR settings accordingly. Knowing this information prior to actual data collection would also allow GPR operators to better determine the number of ground-truths needed for each data set.

Differences in GPR data and the field observation data may never be determined with point source sampling (i.e., boreholes). To truly determine the discrepancies in field observations and GPR interpretations, a trench should be excavated. This would give researchers the opportunity to view and examine a contiguous soil profile and to have a contiguous view of the loess/alluvium interface.

4. Future Data Collection

The possible differences in GPR data and ground truth data at Centennial Field have prompted many questions about the heterogeneity within the soil profile that GPR can actually detect. Research is needed to determine if GPR is pinpointing moisture increases in the soil profile due to the large difference in the σ of soil and water, or if GPR is pinpointing textural changes due to small differences in soil texture σ. The other possibility is that all of these factors are related since increases or decreases in clay, sand, and silt are usually related to increases or decreases in moisture content.

This research would be very beneficial to future GPR use. One approach would be to design a soil bed where researchers could control moisture content and soil textures. This would allow GPR data to be taken in the lab, where all variables within the soil matrix are known and controlled by the researchers.

Chapter 6

Summary

The primary objective of this research was to assist the ongoing Ames Plantation Water Quality Project, in West Tennessee. Completion of this goal was based on the following objectives:

1. Evaluate GPR for agricultural soil reconnaissance.
2. Develop calibration and survey techniques.
3. Implement new GPR methodologies for the Ames Plantation Water Quality Project.
4. Design a non biased statistical model that determines the accuracy of GPR data based on conventional methods.

The first objective was to evaluate GPR for agricultural soil reconnaissance and to develop calibration and survey techniques. This objective was accomplished at the West Tennessee and the Milan Experiment Stations. These locations provided soil profiles similar to those encountered at Ames Plantation. At these two locations GPR was used to successfully map coastal plain sediments, a shallow water table, and a fragipan.

Calibration data and system settings obtained from the calibration data were used at the Ames Plantation Water Quality Project. Calibration data were used for comparison with data obtained at the Ames Plantation and system settings were used to shorten time spent calibrating the instrumentation for West Tennessee soils.

Many subsurface features were mapped by GPR incorporating these newly devised methodologies. Subsurface features successfully identified were the loess/alluvium interface, areas of increased moisture content within the soil profile, and the presence of fragipans. These GPR images have given insight to the possible offsite transport of agrochemicals and the potential of GPR imaging as a nonintrusive surveying tool.

When GPR results were statistically compared with conventional soil surveying methods, the two methods were determined to be statistically different. Although the two methods were statistically different, the conventional method used and the GPR interpretation were within 20 cm, 28 of 32 times.

It was determined from field observations that GPR could resolve boundaries or discontinuities within the soil profile that could affect soil-water movement and content at the Ames Plantation. These boundaries were viewed as strong reflections within the GPR image. It was also determined that GPR interpretations are subjective and could easily be misinterpreted without preliminary knowledge of the subsurface.

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Appendices

Appendix A

Raw Data File Names

Date	File Name
8/97	Jack8_96
3/97	WP3_97
3/97	HC3_97
4/97	Cent4_97

Corel Data File

Figure	Corel 7 File
1.1	Color.cdr
2.1	Han.cdr
2.2	Wp.cdr
2.3	Terrace.cdr
2.4	Hansoil.cdr
2.5	Wpsoil.cdr
3.1	Hantran.cdr
3.2	Wptran.cdr
3.3	Map.cdr
3.4	Cent.cdr

GPR Data Used in Figures

Figure	Raw Data	Processed Data
4.1	Sand.dzt	Sand.cdr
4.2	Wet1.dzt	Water.cdr
4.3	Wet1.dzt	Water.cdr
4.4	Pan1.dzt	Pan.cdr
4.5	F1.dzt	Loess.cdr
4.7	B1.dzt	Dep.cdr
4.8	C2.dzt	Wperch.cdr
4.9	A2.dzt	Wpan.cdr
4.11	C2.dzt	Wperchfil.cdr
4.12	Cent1.dzt	Cent1.cdr

Survey Data

Figure	Surfer File	Processed data	Corel Presentation
4.6	Hpsub.srf	Hpsub.cdr	Hpsub.wpg
4.10	Wpsub.srf	Wpsub.cdr	Wpsub.wpg

Quattro Pro File

Figure	Quattro Pro 8 File
4.11	Wet.wb3

Appendix B

SAS Program

```
options ls=64 ps=72;
data Cent;
input gpr physical;
diff=gpr-physical;
cards;

;

proc print data=Cent;
 title 'Difference Between GPR Depths and Physical Depths';
proc univariate data=Cent;
var diff;
run;
proc reg;
model physical=gpr;
run;
proc plot; plot physical*gpr;
run;
```

Vita

James Denton Bouldin, Jr. was born in Sparta, Tennessee on March 16, 1972. He attended White County High School and was graduated in May 1990. He enrolled at Tennessee Technological University in August 1990. There he received a Bachelor of Science degree in Agriculture with a concentration in Soil Science and Geology in December 1995. He was employed as a Graduate Research Assistant at The University of Tennessee at Knoxville in January 1996 and began study toward the Master of Science degree in Agricultural Engineering Technology. Upon completion of his course work and research, he was employed by Wiedeman and Singleton, Inc., a civil engineering firm located in Atlanta, Georgia.