Report of
3-D Ground-Penetrating Radar Survey
for the
Manufactured Gas Plant Sites
Innovative Technologies Demonstration Project
Binghamton, New York

Prepared for

New York State Electric and Gas Company
Contract No. 98-226

June 13, 1999

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
(614) 421-7944 tel, (614) 421-2688 fax

Table of Contents

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
(614) 421-7944 tel, (614) 421-2688 fax

LEGAL NOTICE

This report was prepared by *Grumman Exploration, Inc.* pursuant to a Demonstration Project and neither *NYSEG*, nor any of its subcontractors nor the co-funders, nor any person acting on behalf of either:

- Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in the Report, or that the use of any information, apparatus, method, or process disclosed in this Report may not infringe privately-owned rights; or

- Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this Report.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or favoring by any Party. The views and opinions of the authors expressed herein do not necessarily state or reflect those of *NYSEG* or the co-funders.

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
(614) 421-7944 tel, (614) 421-2688 fax

Report of
3-D Ground-Penetrating Radar Survey
for the
Manufactured Gas Plant Sites
Innovative Technologies Demonstration Project
Binghamton, New York

Executive Summary

A survey using 3-D Ground-Penetrating Radar (GPR) was used to non-destructively explore the shallow subsurface at a Manufactured Gas Plant (MGP) site in downtown Binghamton, New York during November 1998. The 3-D GPR methodology is a recently developed enhancement to the conventional GPR survey approach and uses existing, commercially available instrumentation, computers and software. 3-D GPR can provide the investigator a means to rapidly visualize and interpret high-resolution three-dimensional GPR images of the subsurface. The results of this survey appear to show the location of several MGP related buildings and gas holder foundations, backfilled excavations, utility trenches and piping as well as other anomalous features that may have relevance for future site investigations. The lateral resolution of subsurface features appears to be relatively high, although the overall exploration depth appears to have been limited to less than ten feet across the site. It should be noted that the 3-D GPR survey detected a wide range of subsurface targets and that these interpretations were made using only minimal prior site information. 3-D GPR, when used in combination with other available information, geophysical tools or conventional, invasive site investigation methods, can provide an effective means to non-destructively explore the shallow subsurface at environmentally complicated MGP sites in urban and industrial settings.

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
(614) 421-7944 tel, (614) 421-2688 fax

1.0 Project Overview and Objectives

The legacy of Manufactured Gas Plant (MGP) sites remains in many urban and industrialized areas of the United States. The limitations of characterizing these sites using conventional site exploration tools has prompted the *New York State Electric and Gas Company (NYSEG)*, the *Electric Power Research Institute (EPRI)*, the *US Environmental Protection Agency (USEPA)* and other project participants to examine several newer, promising technologies that could help with the task of exploring and remediating remaining MGP sites. *Grumman Exploration, Inc.* was selected to demonstrate the 3-D GPR site exploration method at the Court Street MGP site located along the Susquehanna River in downtown Binghamton, New York.

Given the age and complex usage of many former MGP locations, there are many questions regarding what and how much remains below ground and where. The types of subsurface information that are needed to promote effective site characterization and remediation fall into several broad categories including: geologic/hydrogeologic investigation, buried structure and utility detection and location, and contamination identification and mapping. The original MGP Project Request for Proposal (RFQ) lists specific subsurface data needs that are to be examined on this project.

GPR is a subsurface exploration tool that has been used for decades to non-destructively investigate many of the subsurface conditions noted above. The advantages of GPR include its relative speed and apparent high resolution. GPR also provides a quasi-2-D cross-section of the subsurface that gives the initial impression of ease of interpretation. The well-known disadvantages of GPR include (1) its limited depth penetration and resolution, particularly in wet, clay-rich environments, (2) large amounts of data, (3) interference, and (4) difficulties with interpreting GPR responses in complicated settings. 3-D GPR was developed in part to overcome the limitations of working at complex sites and offers an improved means to observe the shallow subsurface in three dimensions. Although 3-D GPR does not overcome some of the limitations of GPR, the 3-D GPR methodology can improve the effectiveness of GPR. 3-D GPR is well suited for non-destructively exploring many of the problematic shallow subsurface conditions present at MGP locations and other urban and industrial sites.

The objective of this 3-D GPR survey was to demonstrate the operation and use of the technique for non-destructively exploring as many relevant conditions and features as possible at the Court Street site. A primary Demonstration-Test Area was surveyed followed by supplemental surveys at several other areas on site. Selected lines were designated as reference lines and an additional test area near the gas control building was surveyed. Follow-up site explorations by *NYSEG* will be used by *NYSEG* and others to evaluate the 3-D GPR survey findings. One of the challenges for the 3-D GPR survey was to explore the site for a wide range of targets with very limited starting information.

This report is structured to describe the method, performance and findings of the 3-D GPR survey at the Court Street MGP site. The following sections of this report include:

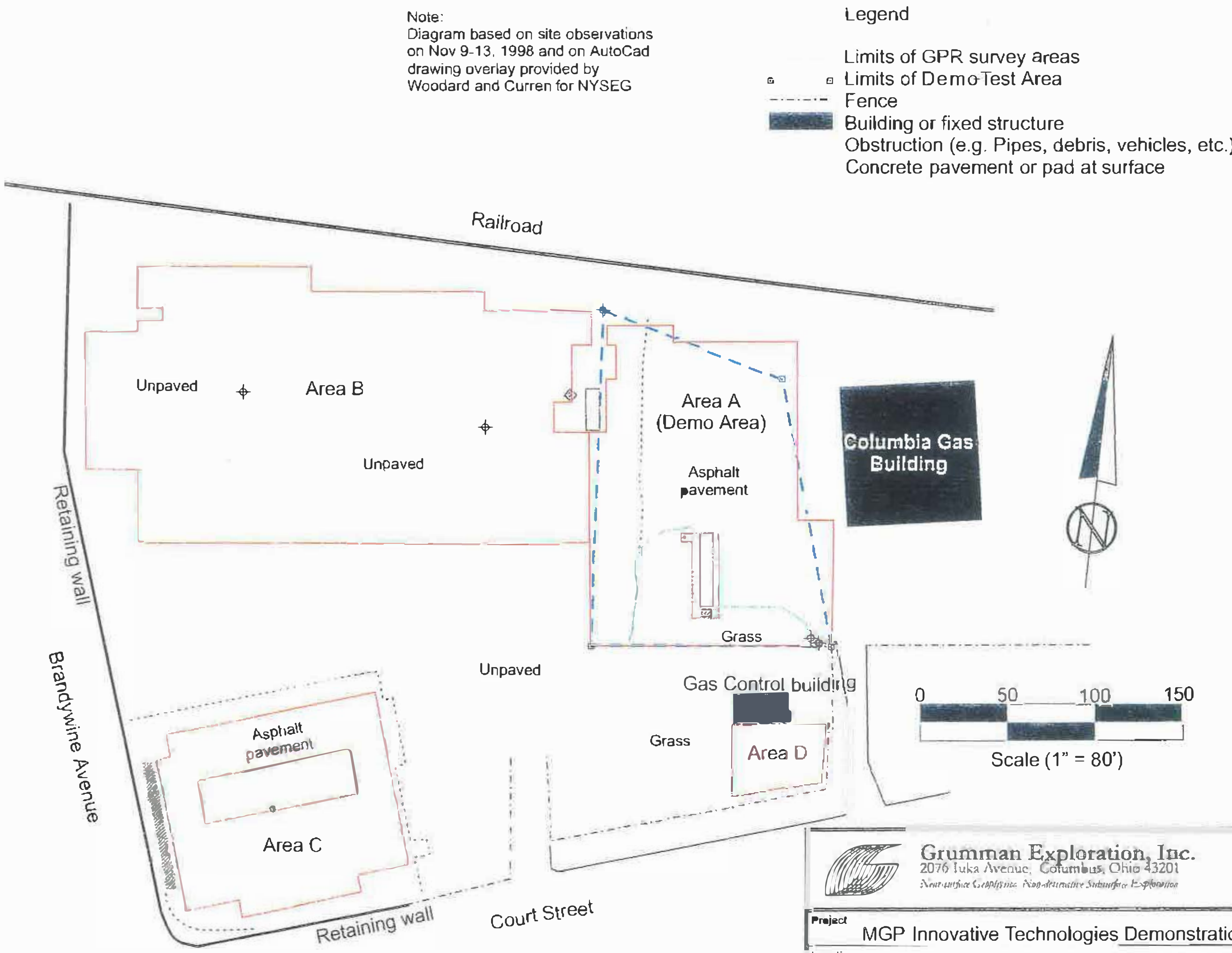
- Descriptions of the site and areas surveyed (Section 2),
- Review of the 3-D GPR methodology (Section 3),
- Summary of the results from the four areas surveyed (Section 4),
- Conclusions regarding the use of 3-D GPR for MGP site exploration (Section 5).

Included are over 30 figures and tables that illustrate and summarize the 3-D GPR methodology, the areas surveyed, the results and many of the important findings. Many of the significant interpretations are noted on the figures in order to minimize potentially lengthy written descriptions of the findings. Supporting materials that are included in the Appendices include an overview of GPR, Standard Operating Procedures (SOP), and a summary of the time requirements and costs associated with the survey and various alternative survey scenarios.

2.0 Site Description and Survey Conditions

The study site is located at the northeast corner of Court Street and Brandywine Avenue, east of downtown Binghamton, New York. According to information provided by *NYSEG*, the Court Street site has a long, complicated history of manufactured gas production dating from the late 19th century through the 1950's. This information included a historical review of the site usage and manufacturing processes used and a site diagram illustrating the approximate locations of former structures based on available fire insurance maps. No information regarding known subsurface soil, geologic, groundwater or possible contamination conditions was provided. Based on inference and experience at similar sites, it is suspected that the shallow subsurface generally consists of a veneer of soil, stone and rubble fill overlying a heterogeneous mix of river bank and river floodplain silt, clay, sand and gravel. The water table is assumed to be relatively shallow, on the order of 5-ft to 10-ft below ground surface, reflecting the Court Street site's valley location and proximity to the Susquehanna River. It is believed that this shallow subsurface soil and geologic setting is generally similar to that found at many urban, industrial and MGP sites located in the East, Northeast and Midwest.

The Court Street site is currently open and used for equipment, material and vehicle storage by *NYSEG*. The overall MGP site covers approximately 4 acres of which approximately 3.2 acres is owned by *NYSEG*, according to site diagrams provided by *NYSEG*. Figure 1 illustrates the overall site boundaries, site features and limits of the 3-D GPR survey areas. A retaining wall delineates the western and southwestern corner of the site, a railroad defines the northern boundary and the reminder of the site is fenced. The eastern third of the site and southwest corner are asphalt paved. The remaining majority of the site is unpaved and covered with crushed stone except for the southeast corner, which is grass covered. A gas control building, *Columbia Gas* services building and associated vehicle parking and stored equipment occupy the eastern edge of the former MGP site. Other smaller structures (dumpsters, containers), parked vehicles, pipes and equipment were present at the time of the survey in the areas indicated on Figure 1. The outline of a foundation wall was noted in the asphalt pavement near the *Columbia Gas* building and two concrete pads were present near the dumpsters. Figures 5, 15, 23, and 28 illustrate conditions present within each of the four survey areas. As a consequence of a significant rainfall on November 10, several areas of shallow ponded water persisted during the latter half of the survey.



Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-destructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client	NYSEG	By Dlg	Date 1/12/99
Project No	01-98027	Checked Dlg	Scale 1"=80'

Figure 1

Title Site Diagram Showing 3-D GPR Demonstration Survey Areas

3.0 3-D Ground-Penetrating Radar Method Description

3.1 Introduction

Ground-Penetrating Radar (GPR) has been used as a site investigation tool for diverse applications for several decades. The 3-D GPR approach is not so much a new geophysical technique as it is an interpretation enhancement to conventional GPR procedures. The goal of 3-D GPR is to help visualize and interpret complicated subsurface features and their spatial relationships using conventional GPR field data. By taking advantage of recent technological innovations, such as through the use of advanced data processing techniques and 3-D visualization methods, 3-D GPR can be an effective tool for developing high-resolution images of the shallow subsurface. The three critical components of a GPR survey that uses 3-D imaging include:

- Field Data Acquisition procedures,
- Data Processing (enhancement) methods, and
- Computerized Data Visualization using powerful graphics computers and software.

A simplified introduction to GPR principles and limitations is contained in Appendix A. The following paragraphs briefly summarize 3-D visualization of GPR data.

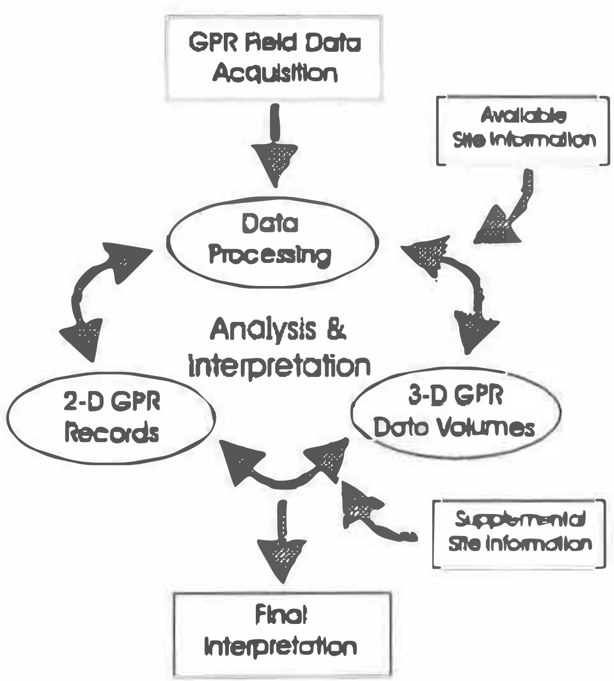


Figure 2. Schematic Sequence of a 3-D GPR Survey

3-D GPR is a relatively new advancement that is described in Annan and Daniels (1998) and mentioned in Conyers and Goodman (1997), both of which include references to other published examples of 3-D GPR. Daniels and others (1998) present examples of the recent effective use of 3-D GPR for environmental site characterization. Because the 3-D GPR technique is relatively new, there exist several valid approaches and no generally accepted standards of practice have been established. The 3-D GPR methodology described herein is one possible approach and is described in Daniels and Grumman (1996). Figures 2 and 3 illustrate the basic steps used in 3-D GPR. Photographs of the 3-D GPR system components used on this project are shown in Figure B.1 in Appendix B.

3-D GPR uses conventional GPR data acquired across a gridded, two-dimensional ground surface to create a three-dimensional (3-D) data volume representing the subsurface. The time (depth) axis is used to represent the third dimension. In most cases the field survey consists of surveying a site along closely spaced parallel survey lines, thereby acquiring a dense sequence of 2-D GPR records that span the site. The process of creating the 3-D volume consists of combining the series of 2-D records or 'slices' into a larger data set. To be efficient and economical, all the field data must be acquired digitally. Additionally, powerful computers and software are required to create and view the resultant 3-D data volume. Most 3-D visualization software programs allow the interpreter to view the entire data volume, sub-volumes or slices from any angle using any amplitude color scheme.

The three essential components of the 3-D GPR approach include:

(1) Field data acquisition procedures,
(2) Advanced and rapid digital data processing, and
(3) Data analysis and interpretation using 2-D and 3-D representations of the processed GPR data.

A Standard Operating Procedure (SOP) for the 3-D GPR survey performed for this project is contained in Appendix B.

3.2 Field Data Acquisition

The recommended field acquisition procedures consist of using distance triggered GPR records and closely spaced, parallel survey lines. The survey line separation and trace spacing depends on the size of the anticipated GPR target(s). In general, a survey line spacing of 1-ft to 2-ft (0.3-m to 0.6-m) with a trace spacing of 5 to 20 traces per-ft are suitable for most high-resolution environmental site investigations. Additionally, the survey area must be relatively open with minimal topographic variation and surface obstructions. Perpendicular crossing lines are recommended. The position, distance traversed and coordinates of each survey line must be carefully monitored and documented.

3.3 Data Analysis

The data analysis begins in the field during acquisition and continues through subsequent processing stages. From the beginning, well-defined survey objectives and favorable survey conditions help the interpretation process. As illustrated in Figures 2 and 3, the data processing and interpretation approach is iterative, whereby GPR records and 3-D volumes are observed and refined multiple times before the final interpretation is reached. Since tens to hundreds of individual GPR records are involved, much of the processing is performed in batch, or simultaneously in large groups. A typical processing sequence consists of applying one or more filters, viewing selected records, reapplying filters, generating and viewing a 3-D data volume, and repeating this sequence until a satisfactory interpretation is obtained.

The completed 3-D data set is often used to highlight sub-areas within the larger data set that deserve more focused attention – similar to first viewing the forest in order to determine which trees to examine. Viewing the 3-D data volume never eliminates the need to examine individual 2-D records and both data types contribute to the final interpretation. The whole process can require a few hours to a day or more depending on the size and complexity of the data set. Figure 3 graphically illustrates the overall process of data acquisition, and interpretation using processed GPR records and 3-D images.

3.4 3-D Visualization and Interpretation of GPR Data

In practice, viewing and manipulating 3-D GPR data on the computer involves using the computer mouse to select, move, rotate and scale the 3-D image as well as change color amplitude assignments. Rendering, viewing and interpreting each 3-D image is highly interactive. Creating each 3-D image requires as little as a few seconds to a few minutes. The entire volume of data or any sub-volume or data slice may be scaled and viewed from any angle using any color amplitude assignment. One popular approach is to observe thin slices of the data set in plan-view at different time (or depth) intervals, termed timeslices (see Figure 8). Proper scaling of the 3-D volume helps to maintain the same relative spatial relationships as are present in the survey area. Interpretation usually involves observing and recognizing the spatial position(s) and type(s) of reflection responses. Pipes and foundation walls often appear as linear reflectors and backfilled excavations often appear as irregularly shaped regions of chaotic reflections.

3.5 Limitations

Among the limitations of the 3-D GPR approach (and GPR in general) are that: (1) 3-D GPR is an interpretation enhancement – it does not improve already poor GPR data or overcome the existing limitations of GPR signal penetration and target detection or resolution, (2) 3-D GPR is not necessarily appropriate for all sites or targets, and (3) the quality and reliability of 3-D GPR interpretation relies in part on the availability of corroborating site information (e.g., boring logs, historical information, etc.) and interpreter experience. Antenna and target ringing effects can give the false appearance of an object or condition being present deeper that it actually is. Because the data volumes tend to be large, there can be some loss of visual resolution. The use of some color mapping schemes can result in some weaker or smaller reflection patterns being overlooked.

3.6 New and Evolving Technology

Currently there are several software programs and computer platforms that can perform 3-D GPR. Additionally, there exist different procedural approaches to the field data acquisition, processing and visualization of the data. These multiple approaches all have unique advantages and disadvantages that consider a range of technical, practical and economic factors. The 3-D GPR method used at the MGP site is one of the available methods that has been in use for over four years on environmental site investigations in the Midwest. The field equipment, data processing and 3-D visualization computers are all commercially available and use popular, inexpensive and/or freely available software. The rapid pace of computer hardware and software innovation suggests that 3-D GPR is only in its infancy. Software modifications since the time of the field survey now allow the 3-D visualization program to run on a standard *Intel*-based PC or laptop that uses the *Linux* operating system. Improvements in the areas of field data acquisition hardware, data and image processing, and computerized 3-D visualization will elevate the capabilities and usefulness of 3-D GPR.

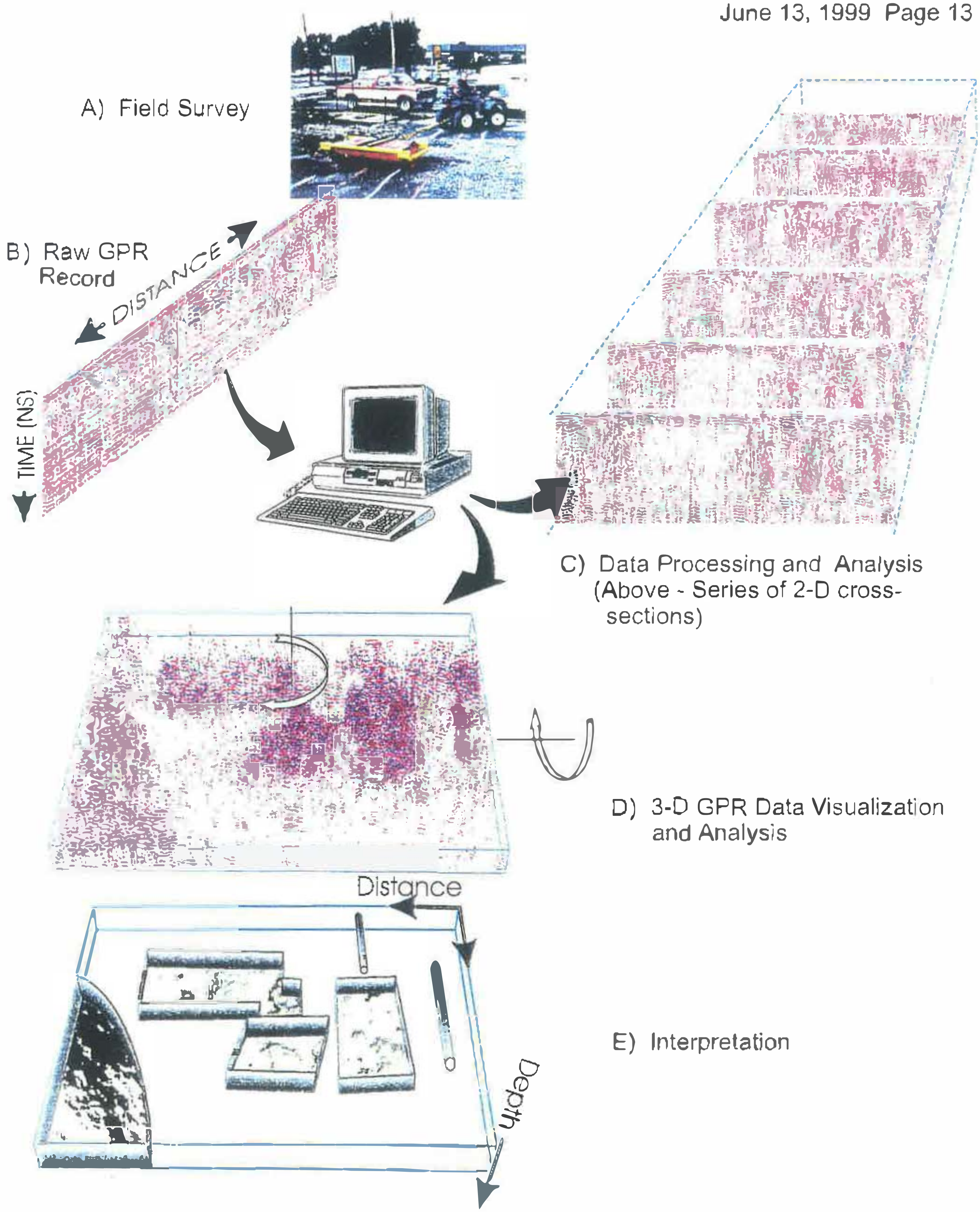
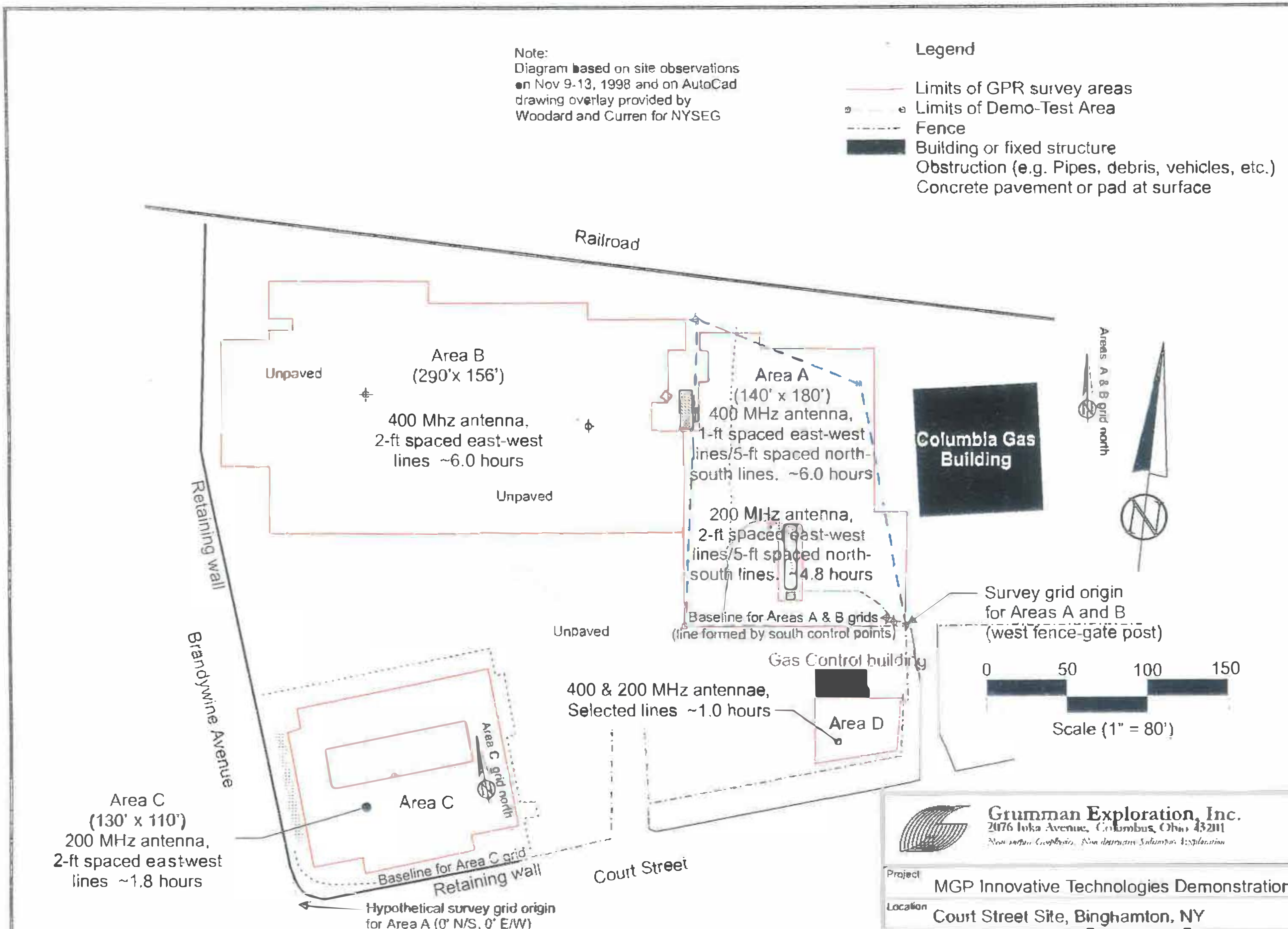


Figure 3 - Simplified example of procedures used to develop 2-D and 3-D GPR images and interpretations. (images selected from MGP project data).



Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201

Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client	NYSEG	By: Dig	Date: 1/12/99
Project No	01-98027	Checked: Dig	Scale: 1"=80'

Figure 4 — Title: Survey Grid Summaries

4.0 Field Survey, Data Analysis and 3-D Visualization Procedures

4.1 Survey Areas Summary

The GPR field survey was conducted by *Grumman Exploration, Inc.* on November 9 –13, 1998 using a two-person field crew. A total of four areas were surveyed as indicated on Figure 3 and summarized below:

- Area A Demonstration-Test Area, Northeast-East Central area,
- Area B Northwest and North Central area of property,
- Area C Southwest Comer, within paved pipe storage area, and
- Area D South of Gas Control Building – pipe location test area

Table 1 and Figure 4 summarize the surveys performed at each area, and indicate limits of coverage, field time, and antennas used. Figures 5, 15, 23 and 28 illustrate the generalized conditions within each survey area. Additionally, two "Reference" lines were performed within the Demonstration Area (Area A) – these are presented in Figure 30.

4.2 Field Survey Grids

Simple survey grids were established over each survey area using fixed locations as reference. The grid reference points and baselines are indicated on Figures 4, 5, 15, 23, and 28. The field survey grids were established using measuring tapes, triangulation, chalk and spray-paint. Area B is contiguous with and uses the same coordinate system as that used for the Demonstration Area (Area A). The positions of all survey grid lines, selected features and interpreted subsurface conditions within each survey area as indicated on the included figures are with respect to the field grids. The location of other, larger site features as shown on these figures were based on the *AutoCad* drawing, and some of these objects may be offset slightly from their true position with respect to the field grid used. Minor to moderate positional discrepancies were noted between some field measured locations and the *AutoCad* drawing, including the following: *Columbia Gas* building, Gas Control building, some site fences, retaining wall, railroad, and several monitoring wells and peizometers.

4.3 Field Survey

The field survey of the four areas required approximately 4.5 days, acquired 678 GPR records, and covered approximately 2.5 acres and 56,000 linear feet (includes some overlap). The survey was suspended for several hours by rain on November 10 and was interrupted periodically for demonstrations of the preliminary 3-D GPR results and for conducting another type of geophysical survey over the Demonstration Area. Work was limited to daylight hours, which during the month of November was approximately 9 hours per day.

Survey Area (antenna used)	Line/Trace Spacing (ft)	Dimensions (ft)/ (Area [acres])	No. of data files (File #s + direction)	Data Set Size (Megabytes)	Start Time/Day	End Time/Day	Net Time (hrs)[1]
Area A – 400 MHz (Demo-Test Area)	1.0/0.1	140'x180' (0.58)	260 (1-229 e-w, 350-380 n-s)	245.9	1:37 M 7:16 T 3:57 W	5:07 M 8:46 T 4:50 W	5:53
Area A – 200 MHz (Demo-Test Area)	2.0/0.1	140'x180' (0.58)	117 (232-318 e-w, 320-349 n-s)	103.9	3:46 T 7:59 W	4:56 T 11:31 W	4:43
Area B – 400 MHz (north-central)	2.0/0.1	290'x156' (1.04)	216 (100-315)	164.4	10:36 Th	4:29 Th	5:53
Area C – 200 MHz (southwest corner)	2.0/0.1	130'x78' (0.23)	68 (327-394)	55.7	10:01 F	11:47 F	1:46
Area D – 400 & 200 MHz – Gas Control	5.0/0.1	~50'x50'	11 (316-325)	5.3	7:49 F	8:41 F	0:52
Long Lines	N/A	430'	4 (397-400)	4.1	12:06 F	12:09 F	0:03
Reference Lines	N/A	~300'	2 (360 & 144)	~1 ea	--	--	<0:01
Totals		~56,000 ft = 10.6 miles (~2.5 acres)	678	579.3			19:07

[1] Does not include set-up or tear-down time, but does include survey pauses and breaks – based on data file time stamps.

Table 1. Field Survey Summary Statistics

4.3.1 Field Instrumentation

Table 2 summarizes the field instrumentation used during the field survey. The field instrumentation used are all commercially available either through the GPR manufacturer (*Geophysical Survey Systems, Inc.* [*GSSI*] of North Salem, NH) or from various retail sources (e.g., automotive, electronics or hardware stores, etc.).

Item	Manufacturer/ Source	Model	Dimensions and Weight	Description
GPR System Control Unit	*GSSI*	SIR-2	11.4"x10.6"x5.5" 14 lbs	Field ruggedized, *Intel* 486 DX2 PC, Color VGA Display, 0.5 GB Hard disk, Standard I/O Ports
GPR Antenna (400 MHz)	*GSSI*	#5103	12"x12x6.5" 12 lbs.	Bistatic dipole antenna, shielded
GPR Antenna (200 MHz)	*GSSI*	#5106	24"x24"x24" 42 lbs.	Bistatic dipole antenna, shielded
Control Cables and Accessories	*GSSI*	---	—	GPR-antenna cables + misc.
Survey Wheel	Custom built	---	---	
Field Data Download/Archive	*Iomega* (Computer store)	*Zip* Drive	—	Archive/download field data
Power	(various retail stores)	---	~8"x3"x7" ~ 10 lbs.	12-v Lead Acid Battery

Table 2. Field Survey Instrumentation Summary Table

4.3.2 Survey Set-up

The GPR system used requires only minimal system calibration and check-out procedures. The initial survey set-up consisted of performing simple system checks (power, connections, etc.) followed by running several test scans. During the performance of the test lines, selected data acquisition parameters were adjusted. Calibrating the survey wheel using a fixed distance as reference followed this. The initial set-up process on November 9, 1999 required approximately 1.5 hours, not including the prior survey grid set-up.

No depth/velocity calibration procedures were performed prior to or during the field survey. The reasons for this included (1) limited availability of depth information to known targets onsite (e.g., pipes), (2) likelihood of highly variable subsurface electrical properties both laterally and vertically (heterogeneity), and (3) no identifiable reflecting surfaces at depth (for walk-away testing).

4.3.3 Data Acquisition Parameters

The field data were acquired using the following parameters: 16 bits (2 bytes) per sample, 512 samples per trace, and approximately 10.0 traces per-ft with a maximum acquisition rate of 64 samples per second. This resulted in data files that were approximately 1.0 Megabytes in size for a 100 foot long survey line. Time windows (ranges) of 70 nanoseconds (ns) and 110 ns were used for the 400 MHz and 200 MHz antennas, respectively. Different time-variable grain curves were used for the 400 and 200 MHz antennas, and broad bandpass filters were applied during acquisition to reduce extraneous interference. The field records were displayed in real time and observed in the field during acquisition. All data were recorded electronically on the internal hard disk in the field and later transferred to a desktop or laptop PC computer and *Silicon Graphics, Inc. Indy* workstation for subsequent processing, display and analysis. Photographs of these components are presented on Figure B.1 in Appendix B.

Figure 4 and Table 1 summarize the antennas used, line spacing and directions for each survey grid. 1-ft spaced east-west lines were used over the Demonstration-Test grid (Area A) and 2-ft spaced east-west lines were used on the other grids. 5-ft spaced north-south crossing lines using the 400 MHz antenna were acquired over Area A. North-south crossing lines were not collected over the other grids due to time constraints. The 200 MHz antenna was used for comparison over the Demonstration-Test grid and over Area C. The results of the 200 MHz survey are not presented herein since the data appeared to show similar features as noted on the 400 MHz survey but at a lower resolution and without a useful increase in overall exploration depth (see Figure 31).

4.4 Data Processing, Analysis and Interpretation

While many of the significant GPR features were apparent on the raw GPR field records, supplemental data processing was performed to enhance the interpretation and presentation of these features. Table 3 summarizes the computer platforms and software programs that were used in the field data acquisition, data analysis, including 3-D visualization and report development. An overview of GPR principles, including data processing and analysis, is contained in Appendix A.

Figures 2 and 3 illustrate the generalized 3-D GPR data processing and interpretation flow. The data processing and interpretation approach was iterative, whereby multiple stages of GPR records and 3-D volumes were prepared and reviewed to refine the final interpretation. The data processing consisted of amplitude gain adjustment, bandpass filtering, and spatial filtering (f-k) to suppress horizontal banding (antenna coupling) within the GPR records. Using the processed GPR records, three-dimensional (3-D) representations of the GPR data were developed to help visualize the data.

The data processing and 3-D visualization were performed using a *Silicon Graphics, Inc. Indy R-5000* workstation. The data processing program is named *Radacal* and was developed by David Grumman at *The Ohio State University* (Daniels and Grumman 1996). *Radacal*'s capabilities include simple data editing, bandpass and spatial filtering, amplitude gain adjustment, trace averaging, GPR trace and color record display, and 3-D data volume generation. The 3-D visualization program is named *BOB* for 'brick-of-bytes' and is available over the Internet (www.arc.umn.edu/GVL/Software/*BOB*.htm). *BOB* is a voxel-based volume-rendering program that includes color map and time-lapse movie rendering functions. *BOB* renders single byte, unstructured data volumes using an alpha-blending scheme. By selecting various amplitude color assignments, one can create the impression of translucency within the volume of data. A typical approach is to assign strong, high amplitude reflections non-translucent colors (e.g., red, green blue, white), and low amplitude signals, such as from weak reflections and noise, to more translucent colors (e.g., black).

Images of the 3-D volumes and GPR records were taken using standard screen image capturing tools and the image acquisition function in *Radacal*. The images are compressed and saved in the standard Tagged Image File Format (TIFF), a format that is widely supported by popular and commercial drawing and word processing programs (e.g., *Microsoft Word, Word Perfect, Adobe Illustrator, Corel*, etc.). The saved data images were directly imported into the drawing program that was used to develop the report figures.

The interpretation of the survey data involved examining selected GPR records and 3-D data volumes. Various subsurface features were interpreted based on the recognition of characteristic GPR reflection response patterns and their spatial configuration. Many complicated reflection responses apparent on the 2-D records became readily identifiable using 3-D GPR slices of the data. Among the interpreted features were pipes, foundation walls, backfilled excavations, buried pavement and subgrade interfaces, and reinforced concrete. Other reflection responses could not be categorized and are identified as significant but anomalous.

Hardware	**Platform (Manufacturer)**	**Operating System**	**Description**
GPR System Control Unit	Customized *Intel* 486DX2 PC (*GSSI*)	*Dos 6.2*	Field data acquisition instrumentation
3-D Graphics Visualization Workstation	*Silicon Graphics, Inc. Indy R-5000* Workstation	*Irix 6.2* (Unix)	Data processing, image analysis and interpretation, 3-D visualization
Field Laptop/ Desktop Personal Computers (PC)	Standard Intel Pentium PCs	*Win 95/98/NT*	Data interpretation, figure and report preparation, data management, networked to workstation & PCs
Software	**Manufacturer or Author**	**Platform/ Oper. System**	**Description (cost/availability)**
BOB (Brick-of-Bytes)	*AHPCRC*	*SGI Irix 4.0-6.2*	3-D Data visualization program. Freely available on Internet: www.arc.umn.edu/GVL/Software/BOB.htm
Radacal	D. Grumman	*SGI Irix 4.0-6.2*	Processing, display, image acquisition, data management program. Freely available from *The Ohio State University*
Word 97	*Microsoft Corp.*	PC *Win 95/98/NT*	Report Preparation (<$400)
Corel Draw 8	*Corel* Corp.	PC *Win 95/98/NT*	Report figure preparation (<$400)

Table 3. Computer Platforms and Software Programs Used on the MGP Project

4.5 Data Management

Following each day of fieldwork, the GPR data were downloaded and archived onto a *Zip* drive and checked for errors and consistency. Some data were processed and displayed for demonstration purposes at the *NYSEG* offices during the survey performance. Following the fieldwork all data were returned to *Grumman Exploration, Inc.*'s offices for further processing and analysis. After completing the data processing and analysis, all raw, intermediate and final processed GPR data, including 3-D data volumes, were archived on CD-ROM disks.

5.0 Results and Interpretations

5.1 General Findings

A number of buried structures, backfilled excavations, pipes, pipe trenches and other anomalous features were interpreted using the 3-D GPR methodology. Many of these features would have been difficult or impossible to recognize using the GPR records alone without the assistance of the 3-D images. The following paragraphs describe some of the general findings and discuss the more specific results from each survey area. The 3-D GPR results and interpretations are shown on the following figures:

- Site Overview — Figures 1 and 4
- Area A — Demonstration-Test Area — Figures 5 through 14
- Area B — North-Northwest Central — Figures 15 through 22
- Area C — Southwest Corner — Figures 23 through 27
- Area D — Gas Control Building Pipes — Figures 28 and 29
- Reference Lines — Demonstration-Test Area — Figure 30
- Long Lines — Antenna Comparison — Figure 31

The set of figures for each survey area includes: (1) survey area diagram(s), (2) interpretation diagrams, and (3) representative 3-D timeslices, 3-D images, and GPR records that illustrate various response patterns used to interpret the results. Table 4 summarizes some of the targets and conditions that were interpreted from each of the four survey areas. The following paragraphs describe some of the important interpretations and are devoted mainly to summarizing the general findings observed over all four survey areas.

	Survey Area			
Subsurface Target or Condition	**A**	**B**	**C**	**D**
Backfilled excavation, disturbed/altered soil/fill	X	X	X	
Buried Structures, buildings, foundations, etc.	X		p	
Pipes/conduits	X	X	p	X
Trenches	X	X	p	X
Reinforced pavement/floor (shallow)	X	X		
Buried pavement/floor or subgrade interface	p	X		
Contamination	p	p		
Lateral changes in soil/fill	X	X	X	X
Water Table				
Geologic/soil profile				
Unrecognized/Anomalous Response(s)	X	X	X	

X=High confidence, p=Possible, lower confidence

Table 4. Summary of Interpreted Features and Conditions

5.2 Interpretations

Because little historical or subsurface information regarding actual subsurface conditions on site were available to *Grumman Exploration, Inc.*, the findings presented below describe interpreted conditions that may (or possibly, or appear to, or could) be present on site. These interpretations take into consideration our experience at similar sites and our understanding of some of the expected response(s) from various conditions that can be anticipated within the areas surveyed. An additional consequence is that some of the observed responses noted on several of the included figures are termed anomalous and do not correspond to a recognized response pattern without additional diagnostic information. If questions or uncertainties exist regarding the presence, depth, configuration, material properties, or absence of interpreted subsurface features, such as structures, pipes, stratigraphic layering and other targets, supplemental invasive explorations, such as test pit excavations or borings are the recommended way to document actual subsurface conditions. Supplemental subsurface and historical information can be used to help refine some of the 3-D GPR interpretations and help clarify additional issues regarding the subsurface on site.

5.2.1 General Results and Interpretations

5.2.1.1 Quality of Results and Interpreted Subsurface Setting

The GPR results were best over the Demonstration Test Area (Area A). However, for most of the areas surveyed, the results appear to indicate subsurface soil and fill materials that are generally not considered favorable for deep GPR exploration. The apparent high attenuation of the late-time signals, over-amplified system noise and antenna ringing are general indications of moderate to highly conductive near surface materials, such as silt and clay, and possibly conductive fill materials such as weathered shale, cinders, fly ash and slag. Antenna ringing can indicate inefficient antenna-ground coupling (electrical mismatch), and ringing often occurs over conductive soil, fill and densely reinforced pavement (see Appendix A.4). It is notable that some ringing is both present and absent on some of the raw GPR records from the Demonstration Test Area. This may indicate a lateral transition from moderate to high conductivity soil/fill into lower conductivity soil/fill in the north. This suggests the presence of more coarse-grained or lower conductivity materials (e.g., sand, gravel, crushed limestone) in the northern third of the Demonstration Test Area, and the good results from this sector of the site may support this conclusion. Figure A.1 in Appendix A presents one record from this area that illustrates this response.

The GPR results were poorer over much of Areas B and C, where the data showed high signal attenuation and generally poor antenna-ground coupling. Among the possible explanations for this response include: higher conductivity silt, clay and/or fill throughout these areas, the prior application and accumulation of road salt in these areas, moist to wet shallow soil conditions compounded by (a) an elevated water table and thick capillary fringe, and/or (b) precipitation soaking into the unpaved survey areas during the survey. One or more of these conditions may be present and working in combination. An extensive shallow reflective interface noted in Area B also may have limited the amount of radar energy that could penetrate this interface and reach deeper into the subsurface.

Reflections from the water table or other geologic boundaries were not observed. Because these interfaces are likely to be relatively horizontal across the site, it is possible that some of the data processing (spatial filtering) reduced the reflection(s) from a flat-lying water table or stratigraphic boundary (if these reflections are at all present in the data). Conductive near surface soil and fill and a gradational water table interface would likely make reflections from and penetration through the water table difficult or impossible regardless of the GPR antenna used. A general lack of reflections or reflecting interfaces from an area may occur because of: (a) high signal attenuation caused by conductive soil conditions, and/or (b) no detectable targets or reflecting interfaces. A general lack of reflections was noted within the central region of the Demonstration-Test area.

5.2.1.2 Depth of Exploration

The overall exploration depth appeared to be relatively shallow throughout most of the four areas surveyed. It is estimated that the overall effective exploration depth across the site ranged between 5-ft and 10-ft for the 400 MHz antenna and may have been slightly greater or less in some areas depending on the soil/fill conditions. Overall, the majority of the interpreted subsurface features appear to be located within the upper 2-ft to 6-ft of the subsurface. Only a few deeper structures and anomalous responses were noted, mainly in the north and northeast comer of the Demonstration-Test area (Area A). It is likely that there are objects and conditions beyond the attainable GPR exploration depth, and that none of these targets can be interpreted from the GPR records.

The simplest depth interpretations involve relative reflection time (depth) comparisons. This is the primary approach used for differentiating target depths on this project. Reflections occurring at a greater time will likely be from deeper targets compared to adjacent, shorter time reflections (shallower). For this project, the interpretations were grouped in terms of shallow, intermediate depth and deeper. Because it appears that only the uppermost 10-ft or less of the subsurface can be considered for most of the areas surveyed, it would be difficult to further subdivide these relative depth ranges.

Using Table A.1 in Appendix A as a guide, generalized exploration/target depth categories for a range of two-way travel times are as follows:

Subsurface Region	Two-way travel time (ns)	Approx. Depth Range (ft)
Shallow	5-15	1-3
Intermediate	15-25	3-6
Deep	>25	5-10 (+/-)

Table 5. Generalized Exploration/Target Depth Ranges for various travel times for subsurface materials believed to be present on site (e.g., silt, clay, sand and fill)

Pulse velocity 'calibrations' were not made because of the overall subsurface heterogeneity apparent in some areas and the lack of suitable calibration locations or interfaces (e.g., pipes at known depths or well defined, horizontal interfaces at depth). Consequently, no depth or velocity calibrations using specific subsurface features were performed.

The lower frequency (deeper-sensing) 200 MHz antenna results from the Demonstration-Test area provided a similar but considerably lower resolution response compared to the 400 MHz results. The lower resolution response is apparent on the GPR records and 3-D timeslices from Survey Area C (southwest comer, Figures 25 through 27) and in the 200 MHz/400 MHz comparison shown on Figure 31. The 200 MHz results only appeared to achieve slightly greater exploration depths compared to the 400 MHz results.

5.2.1.3 Lateral Resolution

The positional accuracy of the interpreted results will be assessed during subsequent site exploration work by *NYSEG*. Lateral resolution varies with respect to the direction the GPR scan is taken (Appendix A.6). In general, the in-line (in the direction of the GPR traverse) accuracy is on the order of 2 to 3 inches, while the cross-line accuracy is on the order of 1-ft to 2-ft. Higher confidence is placed in the interpreted position of highly reflective targets, such as pipes and foundations. Less confidence is placed on the interpreted positions and boundaries of less reflective targets, particularly in cases where there exist low electrical property contrasts or gradational boundaries, or in areas complicated by dense or multiple, overlapping GPR reflections. Additional positioning errors can be introduced by a rough, uneven ground surface and long survey lines. The actual 2-D GPR records provide the most accurate indication of the lateral position of a target, with slightly decreasing accuracy in the derived 3-D images and subsequent interpretations.

5.2.2 Interpreted Subsurface Targets and Conditions

5.2.2.1 Pipes and Trenches

Only a few distinctive pipe runs were noted within the four survey areas, although several linear features that could indicate trenches were recognized. A typical pipe response on a GPR record is a narrow, inverted hyperbola or parabola-shaped reflection. The gas pipes detected in Area D near the gas control building illustrate pipe responses (Figures 28 and 29). In 3-D, pipes often stand out as narrow, linear reflectors. Pipes could be present in some of the interpreted trenches, although the pipes themselves, if present, may have been too deep to detect. Metallic pipes are often easier to identify using their strong reflectivity and associated antenna or target ringing effects. PVC or ceramic pipes are more difficult to detect using GPR except under favorable circumstances.

Trenches often appear in 3-D as narrow, linear gaps (Figures 9, 19 and 20). Pipes within trenches are sometimes noted on deeper timeslices, although deep pipes may elude detection if beyond the exploration depth. On the GPR records, trenches often appear as narrow, vertical gaps that exhibit steeply dipping trench backfill reflections that extend into the trench from the ground surface. In other instances, the backfill within trenches appears as a narrow zone of chaotic reflections, possibly indicating some backfill heterogeneity or differences in moisture content or compaction above and surrounding a pipe.

The 3-D GPR approach was not used in Area D because of an oversight during the field survey, although, based on the GPR records alone (Figure 28), it is believed that 3-D GPR data would have simplified the interpretation for this area.

5.2.2.2 Buried Structures

The strongest indications of backfilled structures were from Area A (Figures 6 through 15). Here the structures appeared to include foundations, building walls and backfilled, below-grade rooms. The 3-D plan-view shape of these structures provided the simplest means of identification. These interpretations would have been extremely difficult and tedious using the GPR records alone. Two interpreted gas holders appeared as circular areas ringed by a narrow reflection band (interpreted foundation wall). Figures 10 through 13 illustrate the apparent limits of the gas holder foundations.

Two possible levels of buildings were interpreted from the northern third of Area A. The faint outline of a possible building(s) was noted on the shallowest timeslices from Area A (Figure 9). A group of deeper former buildings become apparent in Figures 10 and 11. These buildings are recognized by their consistent, strong reflection response and rectangular shape. The strong reflection and ringdown (see Appendix A.4) response from the northern buildings may indicate that the building walls contain metal, such as structural beams, siding, or reinforcing bars. The chaotic reflections between and surrounding these interpreted building walls appear to show a jumbled mix of soil and rubble that fills several former below-grade rooms or basements.

It appears that several additional structures and areas of deeper disturbed soil extend further to the north and northeast beyond the Area A survey boundaries. Additionally, several other possible structures were recognized in Areas A, B and C, although these structures could not be easily categorized and would require further exploration to confirm their presence.

5.2.2.3 Contamination

No clear indications of subsurface contamination on site were observed, although observable contaminant effects could be present within portions of the GPR data. Under favorable circumstances, it is possible that shallow, concentrated amounts of some organic contaminants, such as tar, heavy waste oils and other common NAPL compounds, can create a distinctive and detectable GPR reflection response. In a complex subsurface environment, there can exist many explanations for a particular GPR response and it is usually difficult to diagnostically identify contaminants using GPR without additional subsurface information. Additionally, several different GPR response(s) can occur for different contaminants in different settings, thus further emphasizing the need for corroborating contaminant data. In general, detecting and mapping organic contaminants in the subsurface using GPR is site specific and difficult except under favorable, and often rare and unpredictable, circumstances (Grumman and Daniels, [1995], Olhoeft [1992]).

One possible (and speculative) interpretation of the intermediate depth reflective interface observed across the south-south central region of Area B (Figures 17, 18, 20 and 21, anomalous surface on Figure 22d and e) is that it represents a very shallow (3-ft to 6-ft deep or less) region of heavy oil and tar contamination positioned above or within the capillary fringe or above some other interface (e.g., pavement, former ground surface). A somewhat similar GPR response has been observed by researchers and GPR professionals at locations with heavy oil or tar floating on the water table. Additional subsurface information or exploration in this area would be required to document the nature and configuration of this interface. Other possible GPR-contamination response candidate areas could include below former gas holders or in known spill areas. Access to information regarding the presence and distribution of contamination onsite would allow a follow-up analysis of the 3-D GPR data set to determine whether a detectable GPR-contaminant response is present.

5.2.2.4 Backfilled Excavations, Disturbed or Altered Soil

Areas of deeper, more chaotic reflections characterize backfilled excavations or disturbed soil. Unexcavated, undisturbed and natural layered soils tend to show little variation on the GPR records. An area of deep filling appears to be present surrounding and within the interpreted Area A building structures (Figures 11,12 and 13). Localized regions in Area B also show a similar response, possibly indicating more deeply disturbed or excavated materials. The chaotic response is probably caused by a combination heterogeneous fill type (soil, rubble, general debris), and variations in moisture, compaction and voiding. Reflections from the sloping surfaces created by the backfill placement and sometimes the excavation floor can be used to identify the limits of filling. Examples of this are noted in Area A, near the northeast corner of the site (Figure 13a). It appears that additional backfilled excavations and buried structures may extend east and north beyond the Demonstration Test Area.

3-D GPR images showing circular-shaped areas of moderately strong chaotic reflections helped to delineate the interpreted locations of two former gas holders in Area A (Figures 11-14). The chaotic reflections below these structures could indicate engineered foundation and subgrade materials or possibly the effects of chemical alteration of the soil or fill below the former gas holders.

5.2.2.5 Reinforced Pavement and Flooring

A wire-mesh reinforced floor immediately below the asphalt pavement was noted below and east of the storage container in Area A. Several elongated, steel reinforced concrete pads were also noted in Areas A and B. The different near surface GPR response and apparent rebar reflections identify the limits of these pads. Higher frequency GPR antennas (> 400 MHz) can often penetrate through ground-level reinforced pavement, although the clarity of results is sometimes compromised in these areas. More deeply buried reinforced pavement or floors cannot be penetrated because of the reduced aperture with respect to a more distant antenna.

Deeper reinforced pavement and floors often appear as a strong reflective band on the GPR record. This kind of response was noted across much of the southwestern region of Area A and over much of Area B, and consequently it was suggested that these areas may contain buried floors or pavement. The 3-D GPR plan-view outline can sometimes be used to identify and delineate these surfaces. This proved difficult for portions of Areas A and B, although it is believed that one or more buried building floors may be present within the west-central to southwestern regions of Area A. Additional subsurface exploration would be required to correlate particular response patterns with deeper reinforced concrete floors or pavement. Lower frequency antennas are not able to penetrate ground-level reinforced concrete and often respond to reinforced pavement with strong antenna ringing that can extend down the entire record (Figure 31).

5.2.2.6 Buried Pavement, Subgrade and Reflective Subsurface Interfaces

As noted above, large portions of Areas A and B indicated very shallow to mid-depth reflective interfaces. These interfaces are believed to indicate one or more conditions including buried floor, pavement, subgrade interface (former) ground surface or other kind of thin or layered anomalous material (e.g., contamination – see 5.2.2.3). The shallow depth and apparent minimal slope of these surfaces tends to support the interpretation that most of these surfaces may represent buried pavement or unpaved ground surfaces. The 3-D GPR interpretation provides a simplified way to map the lateral extent(s) of these areas and use the different response characteristics to categorize the areas. A stronger reflective interface accompanied by antenna ringing ('ringdown' - see Appendix A.4) indicates more reflective surfaces, such as may be caused by reinforced pavement or floors. Figure 13d identifies two examples of this kind of shallow reflective surface.

The slightly deeper, more discontinuous and undulating interface reflections observed in the central to south-central region of Area B could indicate one or more conditions, including: (1) a buried pavement or floor surface, former excavation base or relic ground surface overlain by rubble fill and debris, or (2) a shallow veneer of heavy oil and tar contamination lying on a stratigraphic interface, such as a soil stratum, above the shallow water table, or within the capillary fringe (see Section 5.2.2.3). Gaps in this interface could indicate changes in fill types, weakly reflective, buried structures or former trenches or excavations. Additional subsurface information (e.g., drilling or excavation observations) would be required to develop a more reliable interpretation(s) of these shallow interfaces.

6.0 Conclusions

A geophysical survey conducted at the Court Street MGP site in Binghamton, New York demonstrated the 3-D Ground-Penetrating Radar method for three-dimensional visualization of the shallow subsurface. The method is suitable for non-destructively exploring the shallow subsurface at challenging, environmentally complex sites.

3-D GPR is an interpretive tool that enhances conventional GPR survey results and requires only slight modifications to normal GPR field survey and data analysis methods. Recent innovations in computer technology allow one to create 3-D images of GPR data that give the interpreter a more complete, full site perspective of the shallow subsurface. Field productivity ranges from about one-half to one acre per day, depending on the level of detail required and the complexity of the survey setting. Data analysis and visualization of the data requires anywhere from several hours to several days, depending on the project objectives and data analysis requirements. The 3-D GPR system demonstrated at the Court Street MGP site by *Grumman Exploration, Inc.* represents existing technology that is currently in commercial use. All of the field instruments and computers are commercially available. The required software is either inexpensive or freely available and operates on standard computer platforms. *Grumman Exploration, Inc.* has used this system for over three years for non-destructive environmental site exploration.

In general, it is believed that the geologic, environmental and historical setting of the Court Street site encompasses many of the same conditions found at MGP sites throughout the Northeast, East and Midwest. Among the buried conditions that appear to have been successfully detected and mapped using 3-D GPR at this MGP demonstration site include:

- Foundations, walls and other building structures,
- Pipes,
- Trenches,
- Backfilled excavations/ disturbed soil,
- Pavement, floor and former ground surfaces,
- Reinforced concrete pads, floor and pavement, and
- Various other anomalous/unidentified objects and conditions

It is worth noting that these interpretations were developed using minimal historical information and no data regarding known subsurface conditions. Additional information regarding known soil contamination along with a reassessment of the 3-D GPR data could add to the list of interpreted features or refine and improve the existing interpretations. In particular, additional subsurface data could help with identifying and mapping more subtle GPR targets such as filled, altered or contaminated areas.

The hypothesized soil and geologic conditions on site are believed to have limited the depth of exploration to between 5-ft and 10-ft, although no specific depth calibrations could be performed. Consequently, only relative and approximate target depth estimates could be provided. The in-line lateral resolution of interpreted targets appears to be on the order of ½-ft or less.

3-D GPR surveys can be strengthened when used in conjunction with available historical information, other complementary geophysical data (e.g., Electromagnetic [EM] surveys, metal detection) and other conventional subsurface information such as soil borings, excavation and chemical testing data. Although GPR has been used successfully by researchers to explore many of the kinds of conditions found at MGP sites, the capabilities of GPR remain site- and project-specific. 3-D GPR can help to reveal more of the subsurface non-destructively, although success depends on the careful consideration of factors such as site conditions, objectives, expectations and economics in addition to the technical issues specific to GPR. If one considers that much of the legacy of human activity is concentrated in the upper 10-ft of the subsurface, 3-D GPR and GPR in general are well suited for high-resolution, non-destructive site characterization.

7.0 Selected References

BOB 3-D Volume Rendering Program, 1992, Army Research Contract No. DAAL03-89-C-0038, Army High Performance Computer Research Center (*AHPCRC*) – Graphics Visualization Laboratory, Minneapolis, MN (available from www.arc.umn.edu/GVL/Software/*BOB*.htm)

Annan, A.P. and J.J. Daniels, 1998, Foundations of GPR for Three dimensions, Short-course Reference Guide, March 30, 1998, Chicago, IL, Symposium on the Application of Geophysics to Environmental and Engineering Problems, EEGS, Englewood, Colorado, 226p.

Conyers, B. L. and D.Goodman, Ground-Penetrating Radar – An Introduction for Archaeologists, AltaMira Press, Walnut Creek, CA, 232 p.

Daniels, J. J., 1989, Fundamentals of Ground Penetrating Radar, Proc. of the Symposium on the Application of Geophysics to Environmental and Engineering Problems, EEGS, Englewood, Colorado, p. 62 - 142.

Daniels, J. J., Roberts, R. L., Vendl, M., 1992, Site Studies of Ground Penetrating Radar for Monitoring Petroleum Product Contaminants, Proc. of the Symposium on the Application of Geophysics to Environmental and Engineering Problems, EEGS, Englewood, Colorado, p. 597-609.

Daniels, J. J., Grumman, D.L., 1996, Development of a Three Dimensional Subsurface Imaging Computer Display System for Using Ground Penetrating Radar to Locate Buried Substances, Final Report for USEPA Research Grant No. V995876-01-3, USEPA-Region V, Chicago, IL, 123 p.

Daniels, J.J.,, J. Brower and F. Baumgartner, 1998, High Resolution GPR at Brookhaven National Laboratory to Delineate Complex Subsurface Targets, J. of Environmental and Engineering Geophysics, v. 3, No. 1, p. 1-6.

Davis, J.L. and Annan, A.P., 1989, Ground Penetrating Radar for High Resolution Mapping of Soil and Rock Stratigraphy, Geophysical Prospecting, v.37, p. 531 - 550.

Grumman, D.J. and Daniels, J.J., 1995, Experiments on the Detection of Organic Contaminants in the Vadose Zone, J. of Environmental and Engineering Geophysics, v. 0, No. 1, p. 31-38.

Maxwell, M., Schmock, J., 1995, Detection and Mapping of an LNAPL Plume Using GPR: A Case Study, Proc. of the Symposium on the Application of Geophysics to Environmental and Engineering Problems, EEGS, Englewood, Colorado, p. 15-23.

Olhoeft, G. R., 1992, Geophysical Detection of Hydrocarbon and Organic Chemical Contamination, Proc. of the Symposium on the Application of Geophysics to Environmental and Engineering Problems, EEGS, Englewood, Colorado, p. 587-595.

Powers, M.H., Dispersive Ground Penetrating Radar Modeling in 2D, 1995, Ph.D. Thesis, Dept. of Geophysics, Colorado School of Mines, T-4820. 198 p.

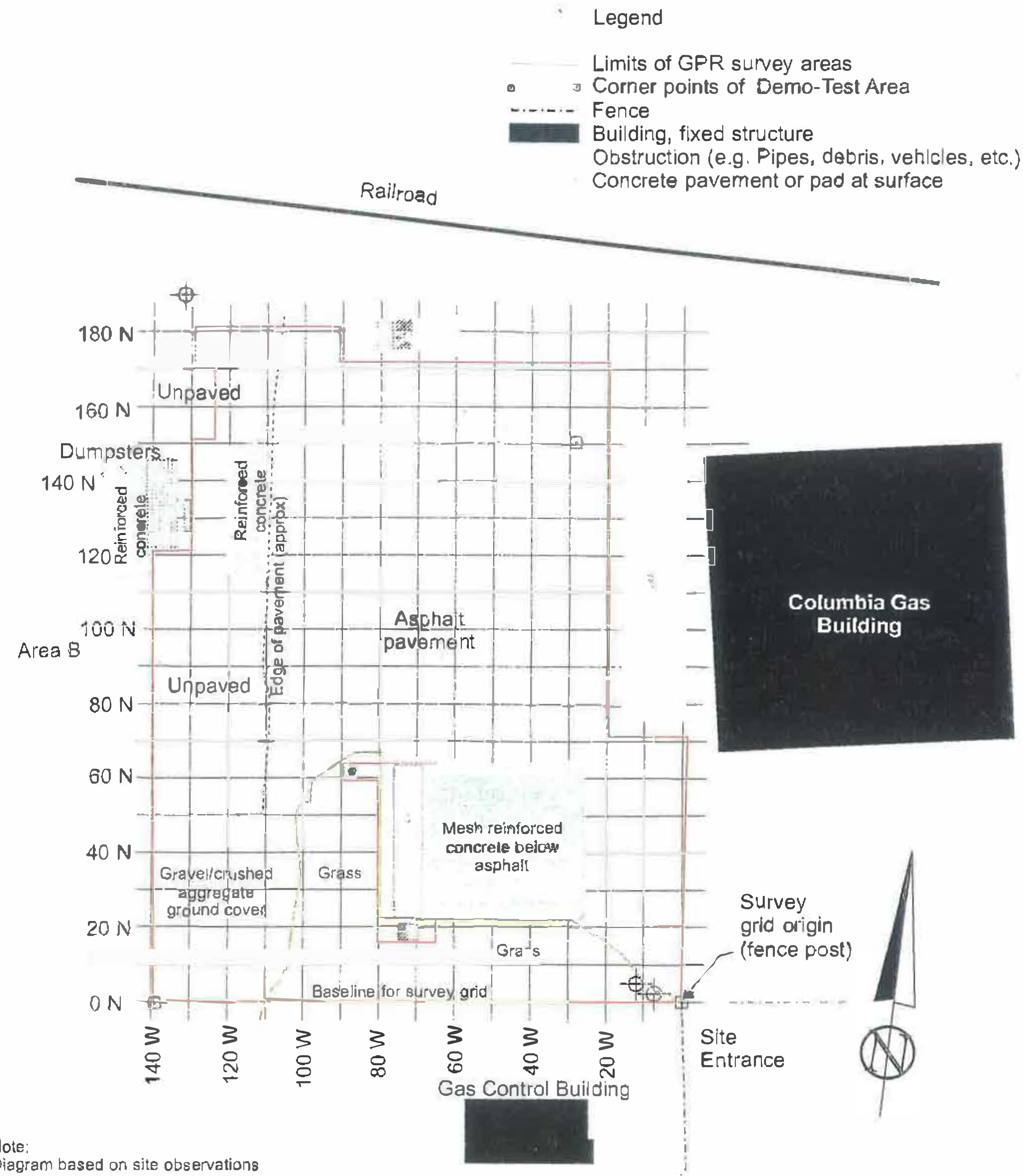
Internet Sites:

www.arc.umn.edu/GVL/Software/*BOB*.htm
www.g-p-r.com
www.geophysical.com
www.sensoft.on.ca
www.ldeo.columbia.edu/eeg/gpr.links/gpr.links.html
www.agu.org/revgeophys/phillj01/node11.html

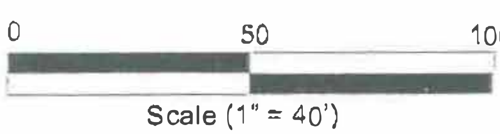
Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
(614) 421-7944 tel, (614) 421-2688 fax

FIGURES

Figure Numbers
5 though 31



Note:
Diagram based on site observations on Nov 9-13, 1998 and on AutoCad drawing overlay provided by Woodard and Curren for NYSEG

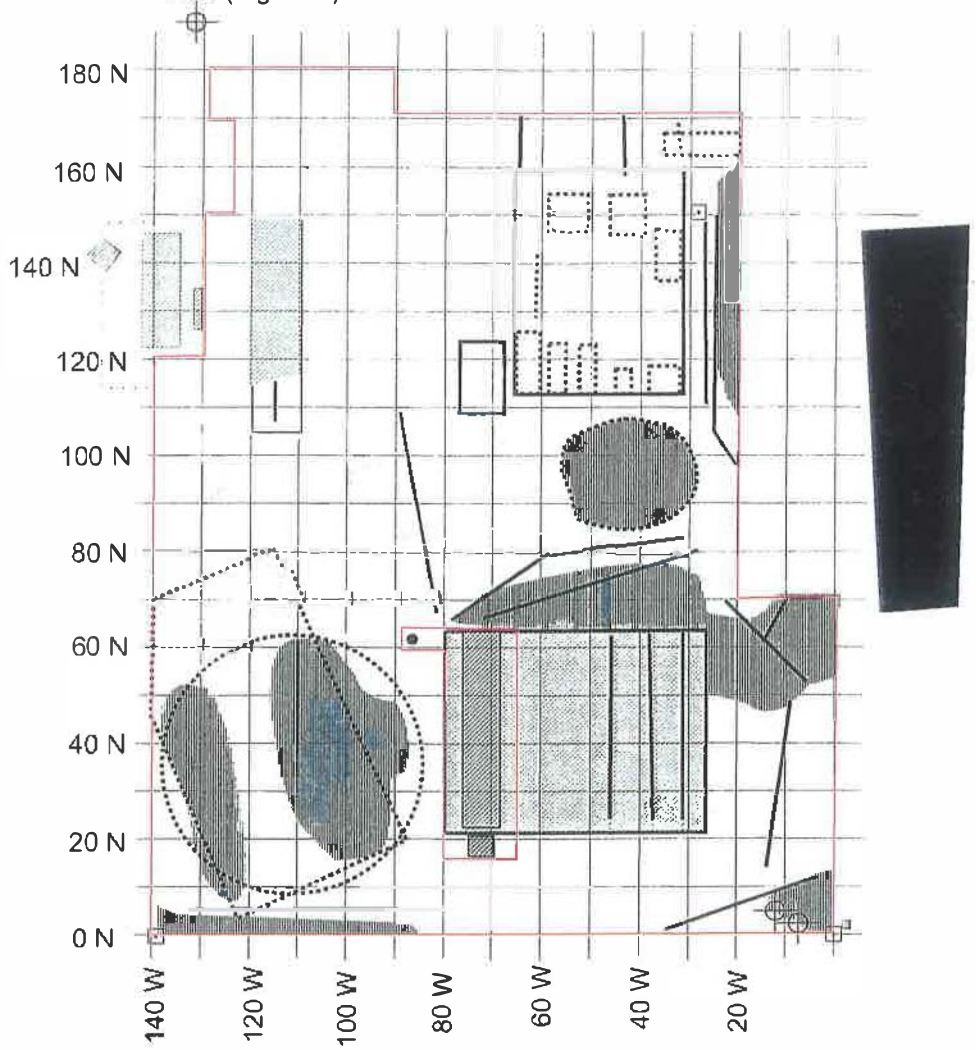


Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Nonsurface Geophysics, Nondestructive Subsurface Exploration

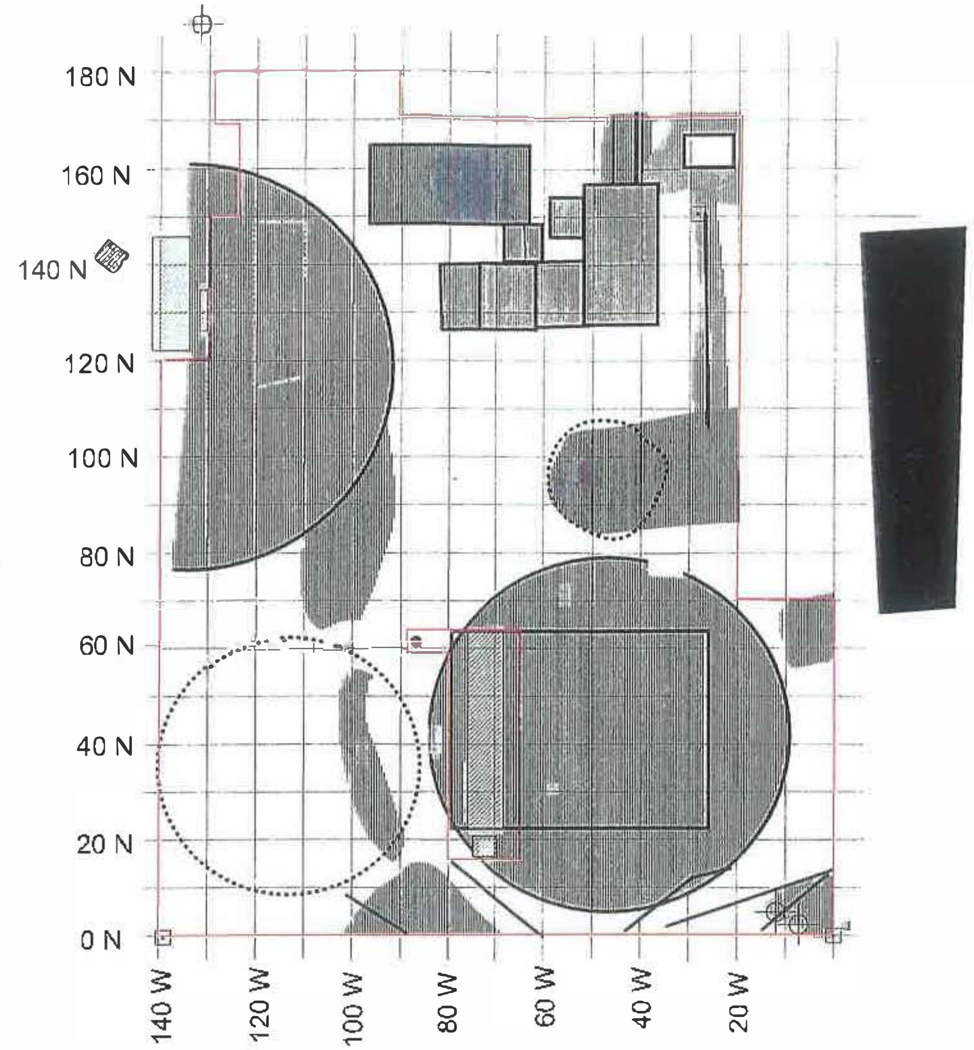
Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client	NYSEG	By Dlg	Date 1/12/99
Project No.	01-98027	Checked Dlg	Scale 1"=40'

Figure 5 Title Area A -(Demo-Test Area) - Site Diagram Showing

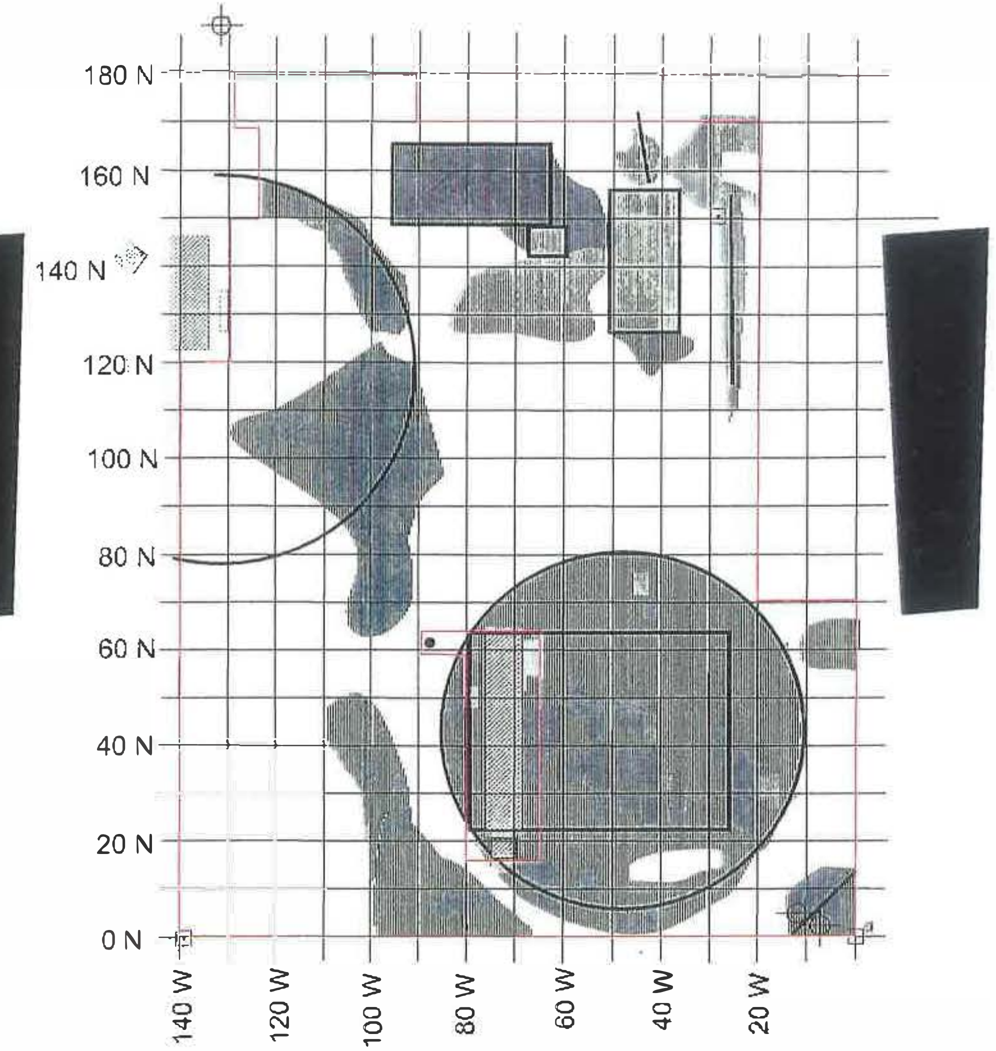
A) Composite Interpretations for Shallow Depth (5 -13 ns) Timeslices (Figure 9)



B) Composite Interpretations for Intermediate Depth (15 - 25 ns) Timeslices (Figure 10)



C) Composite Interpretations for Deeper (30 - 50 ns) Timeslices (Figure 11)



Interpretation Legend

- Interpreted/possible pipe, conduit or linear structure
- Interpreted building or other structure - foundations, walls, floor, etc. (Outline)
- Possible structure (inconclusive)
- Subsurface object or surface/interface (pavement, pad, subgrade, etc)
- Possible disturbed, altered, contaminated or backfilled soil/fill
- Building or fixed structure
- Above-ground obstruction (equipment, vehicles, container, etc.)

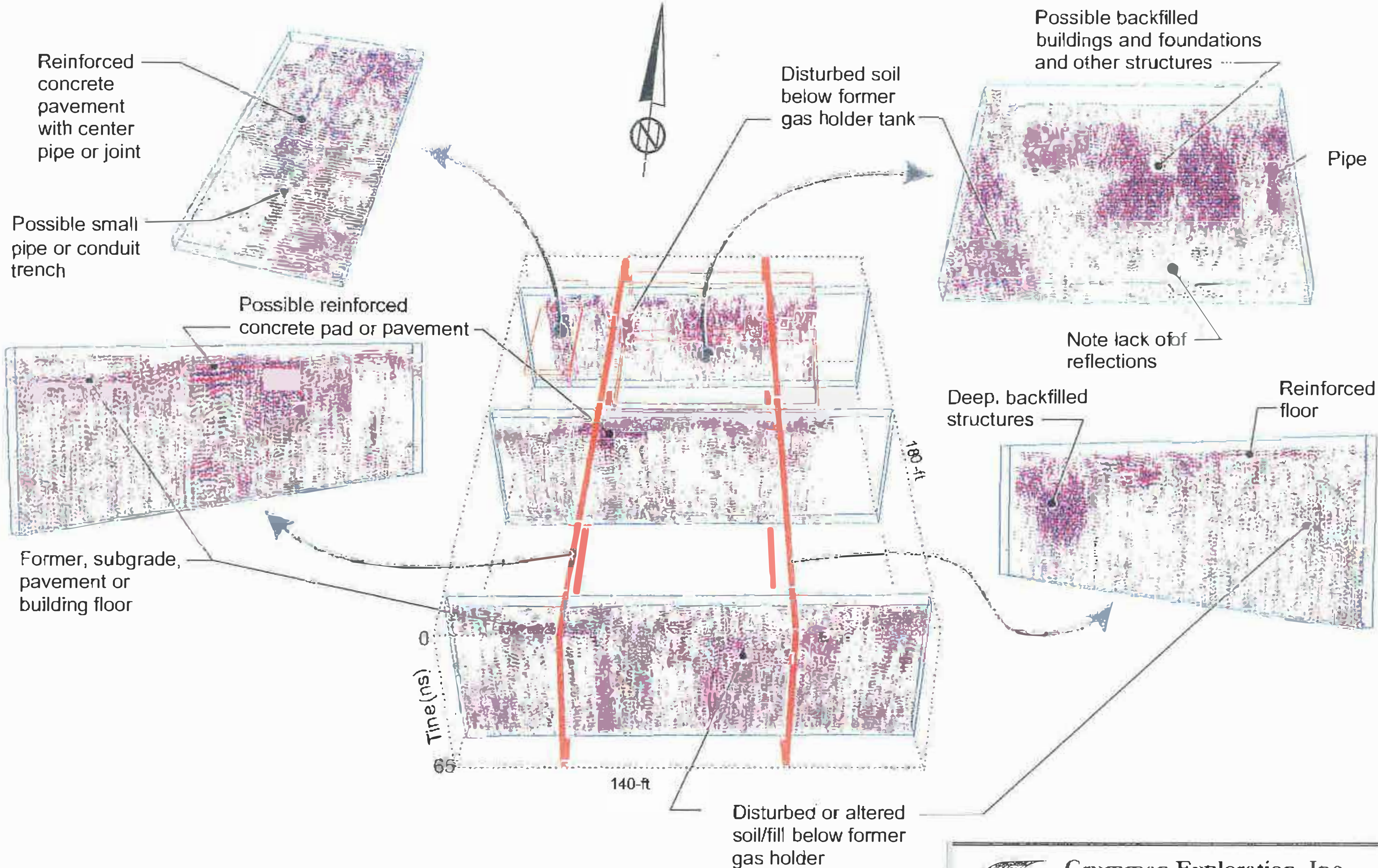
Notes:
Compare interpretations to 3-D GPR timeslices - Figures 8 - 10
400 Mhz antenna, 512 samples/trace, 10 traces/ft.
Survey date: November 9 -10 , 1998
Refer to Figures 1 and 3 for additional location information.

0 50 100
Scale (1" = 40')

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-Intrusive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client NYSEG	By Dlg	Date 1/12/99	
Project No. 01-98027	Checked Dlg	Scale 1"=40'	

Figure 6 Title Composite Interpretations of Timeslices for three depth ranges for Area A (Demonstration Test Area)

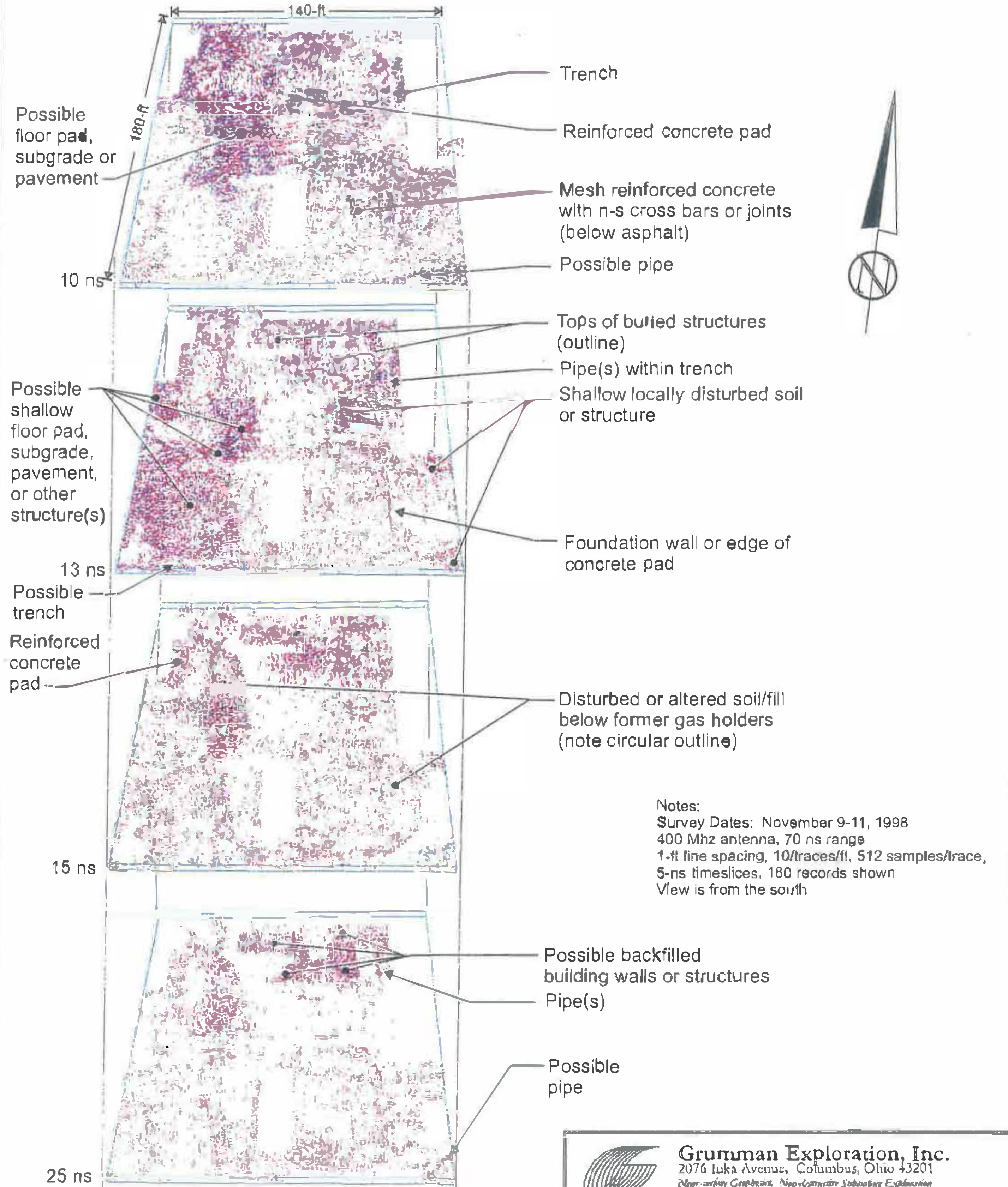


Notes:
Survey Dates: November 9-11, 1998
400 Mhz antenna
1-ft line spacing, 10/traces/ft, 512 samples/trace,

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201

Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client	NYSEG	By: Dlg	Date: 1/15/99
Project No	01-98027	Checked: Dlg	Scale: NTS

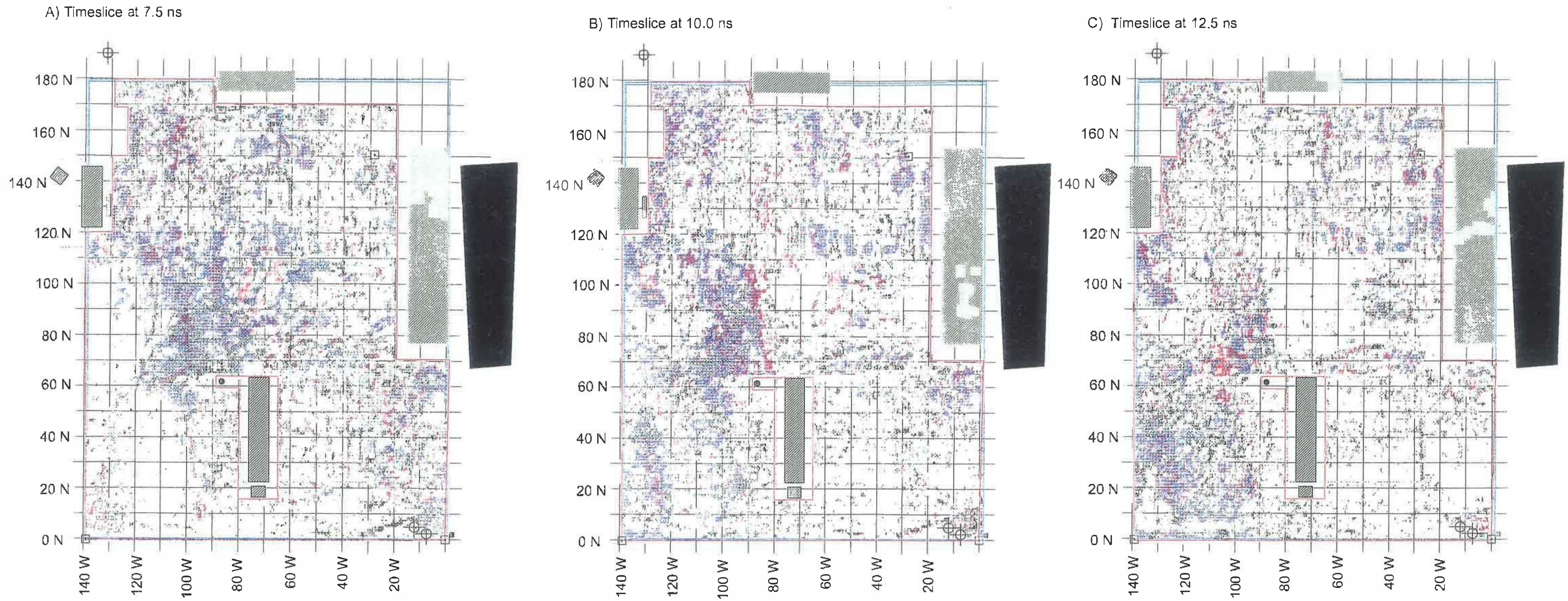
Figure 7 — Title: Examples of 3-D Images of GPR Data used for Area A Interpretations



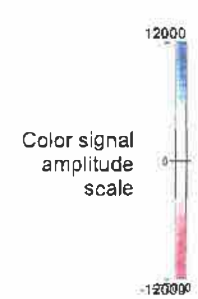
Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201

Project	MGP Innovative Technologies Demonstration				
Location	Court Street Site, Binghamton, NY				
Client	NYSEG	By	Dig	Date	1/12/99
Project No.	01-98027	Checked	Dig	Scale	NTS

Figure 8 Title Selected Stacked Timeslices from Area A



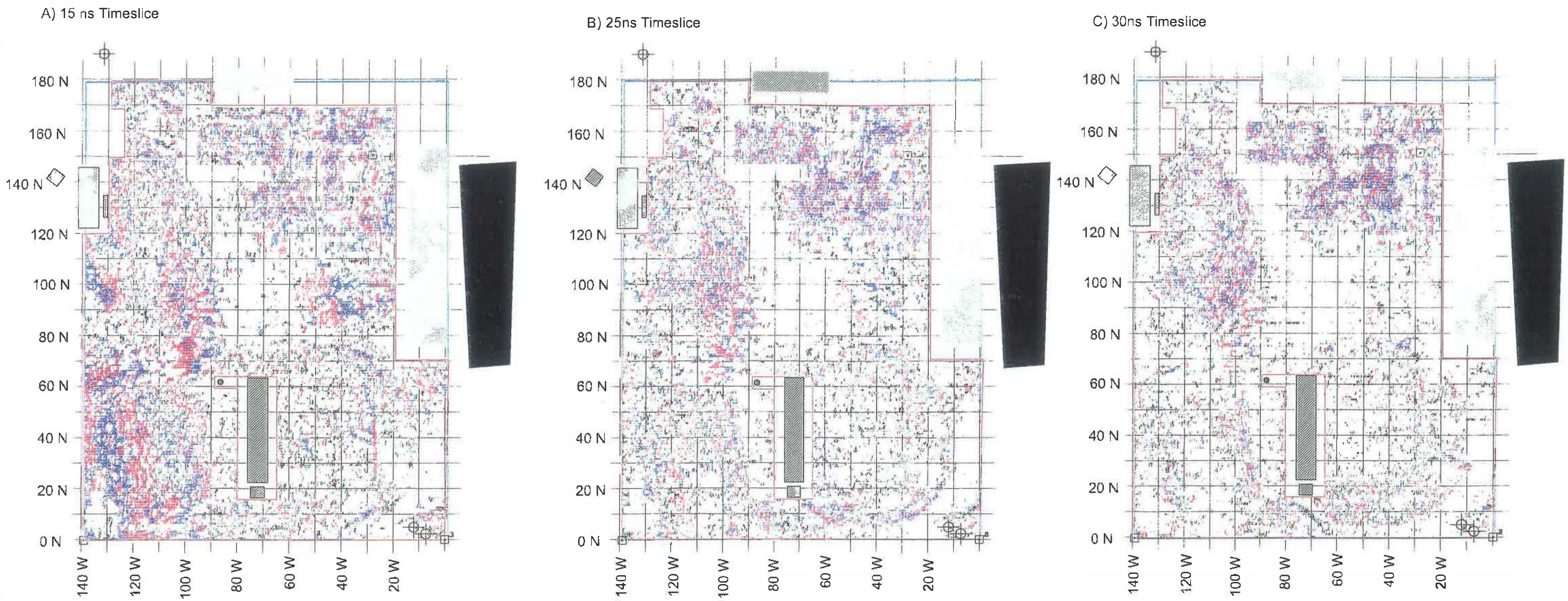
Notes:
All timeslices represent 5 ns thickness, centered at time indicated.
400 Mhz antenna, 512 samples/trace, 10 traces/ft.
1-ft line spacing (east-west), 180 records shown
Survey date: November 9 -10 , 1998
Refer to Figures 1, 4 and 5 for additional location information.



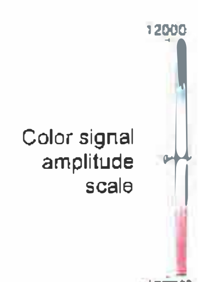
0 50 100
Scale (1" = 40')

Grumman Exploration, Inc. 2076 Luka Avenue, Columbus, Ohio 43201 Near-surface Geophysics, Nondestructive Subsurface Exploration	
Project MGP Innovative Technologies Demonstration	
Location Court Street Site, Binghamton, NY	
Client NYSEG	By Dig · Date 1/12/99
Project No. 01-98027	Checked Dig · Scale 1"=40'

Figure 9 — Title 3-D GPR Timeslices for Area A - 7 - 13 ns (shallow depth)



Notes:
All timeslices represent 5 ns thickness, centered at time indicated.
400 Mhz antenna, 512 samples/trace, 10 traces/ft.
1-ft line spacing (east-west), 180 records shown
Survey date: November 9 -10 , 1998
Refer to Figures 1, 4 and 5 for additional location information.

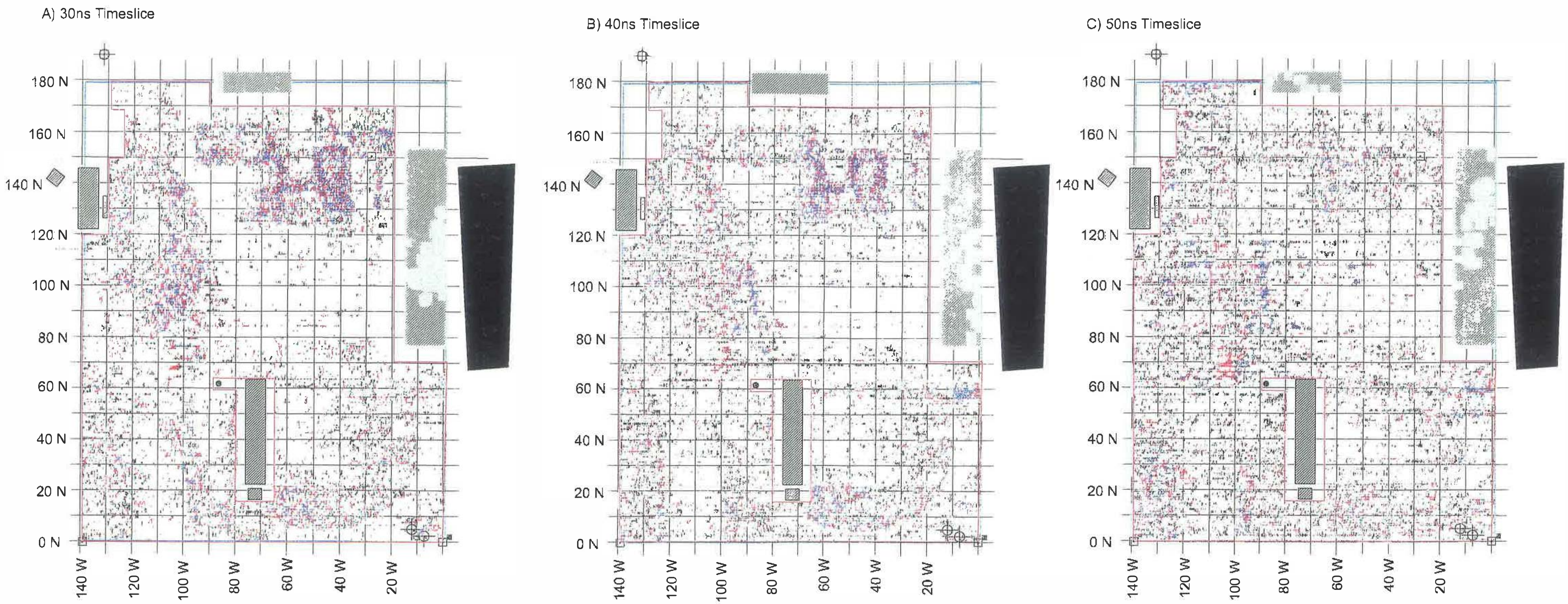


0 50 100
Scale (1" = 40')

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201

Project	MGP Innovative Technologies Demonstration
Location	Court Street Site, Binghamton, NY
Client	NYSEG
By	Dlg
Date	1/12/99
Project No.	01-98027
Checked	Dlg
Scale	1"=40'

Figure 10 Title 3-D GPR Timeslices for Area A - 15 - 25 ns (intermediate depth)



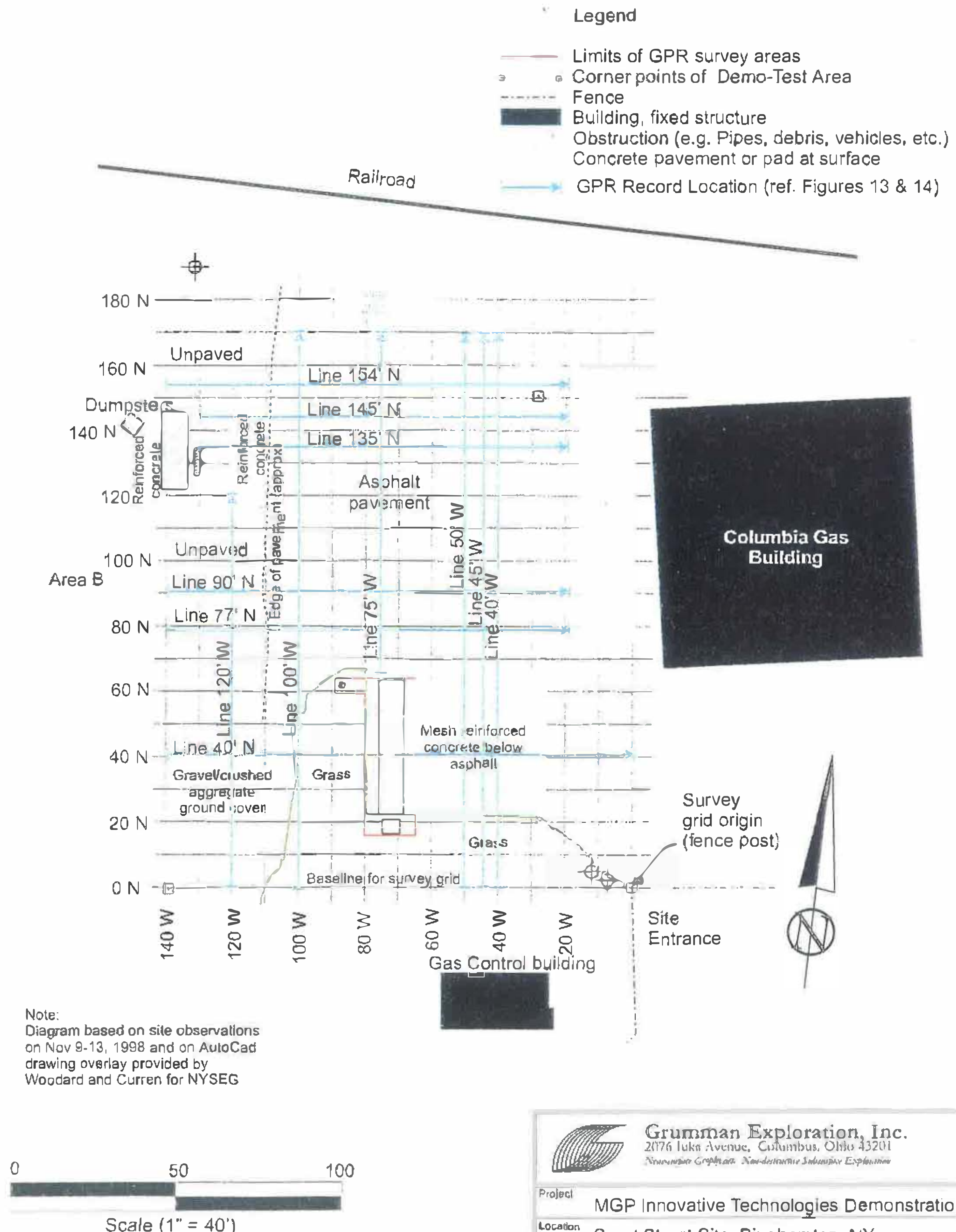
Notes:
All timeslices represent 5 ns thickness, centered at time indicated.
400 Mhz antenna, 512 samples/trace, 10 traces/ft.
1-ft line spacing (east-west), 180 records shown
Survey date: November 9 -10 , 1998
Refer to Figures 1, 4 and 5 for additional location information.

Color signal amplitude scale: 12000 / 0 / -12000

Scale: 0 50 100 — Scale (1" = 40')

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics. Non-destructive Subsurface Exploration

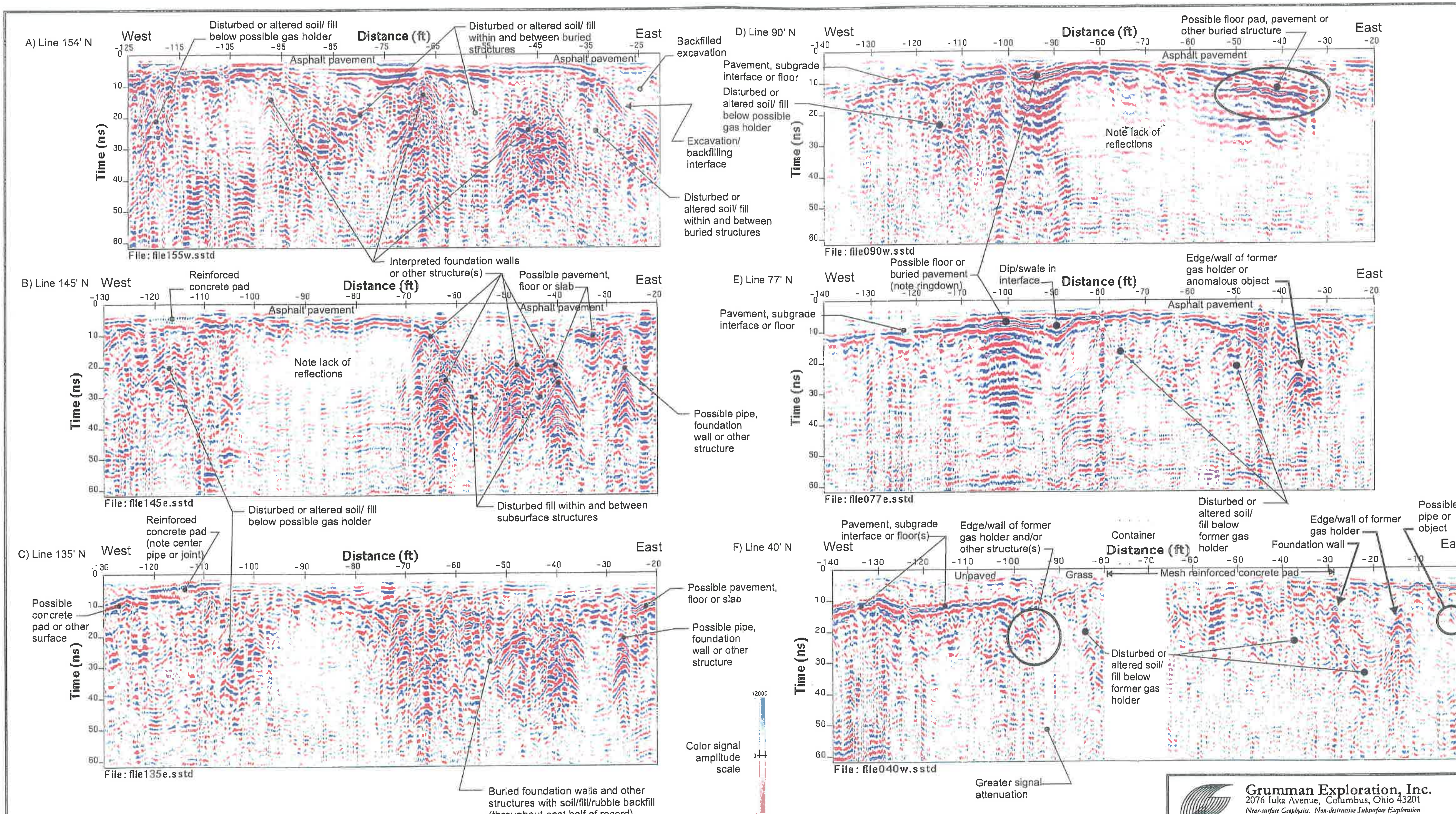
Project	MGP Innovative Technologies Demonstration
Location	Court Street Site, Binghamton, NY
Client	NYSEG
By	Dlg
Date	1/12/99
Project No.	01-98027
Checked	Dlg
Scale	1"=40'
Figure	11
Title	3-D GPR Timeslices for Area A - 30 - 50 ns (deeper)



Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Nonintrusive Geophysics Non-destructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration
Location	Court Street Site, Binghamton, NY
Client	NYSEG
By	Dlg
Date	1/12/99
Project No	01-98027
Checked	Dlg
Scale	1"=40'

Figure 12 Title Area A -Site Diagram with GPR Record Locations

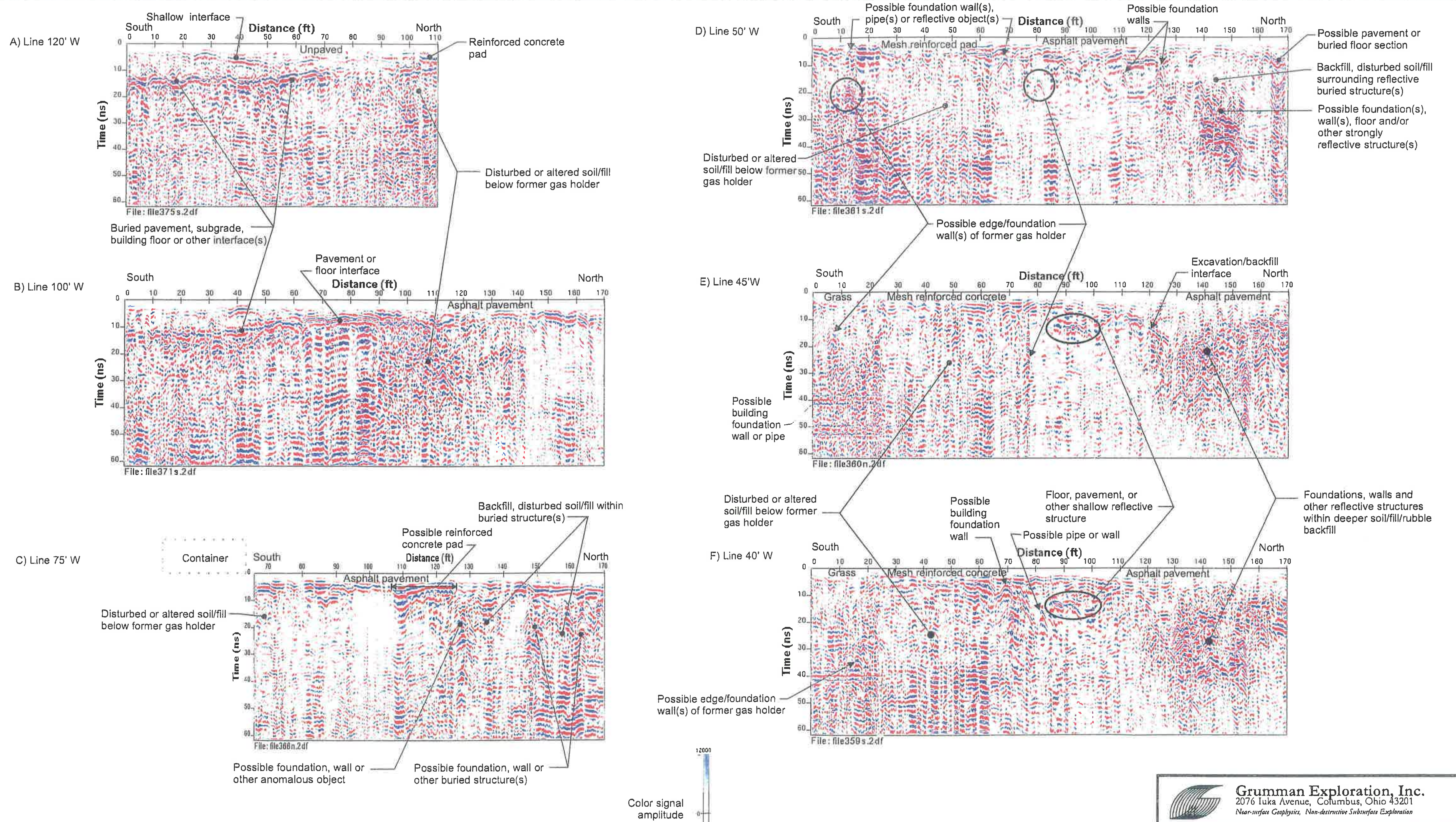


Notes:
400 Mhz antenna,70 ns range, 512 samples/trace, 10 traces/ft.
Survey date: November 9 -11 , 1998
Refer to Figure 12 for survey line location information.

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-destructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration
Location	Court Street Site, Binghamton, NY
Client	NYSEG
By	Dlg
Date	1/12/99
Project No.	01-98027
Checked	Dlg
Scale	As shown

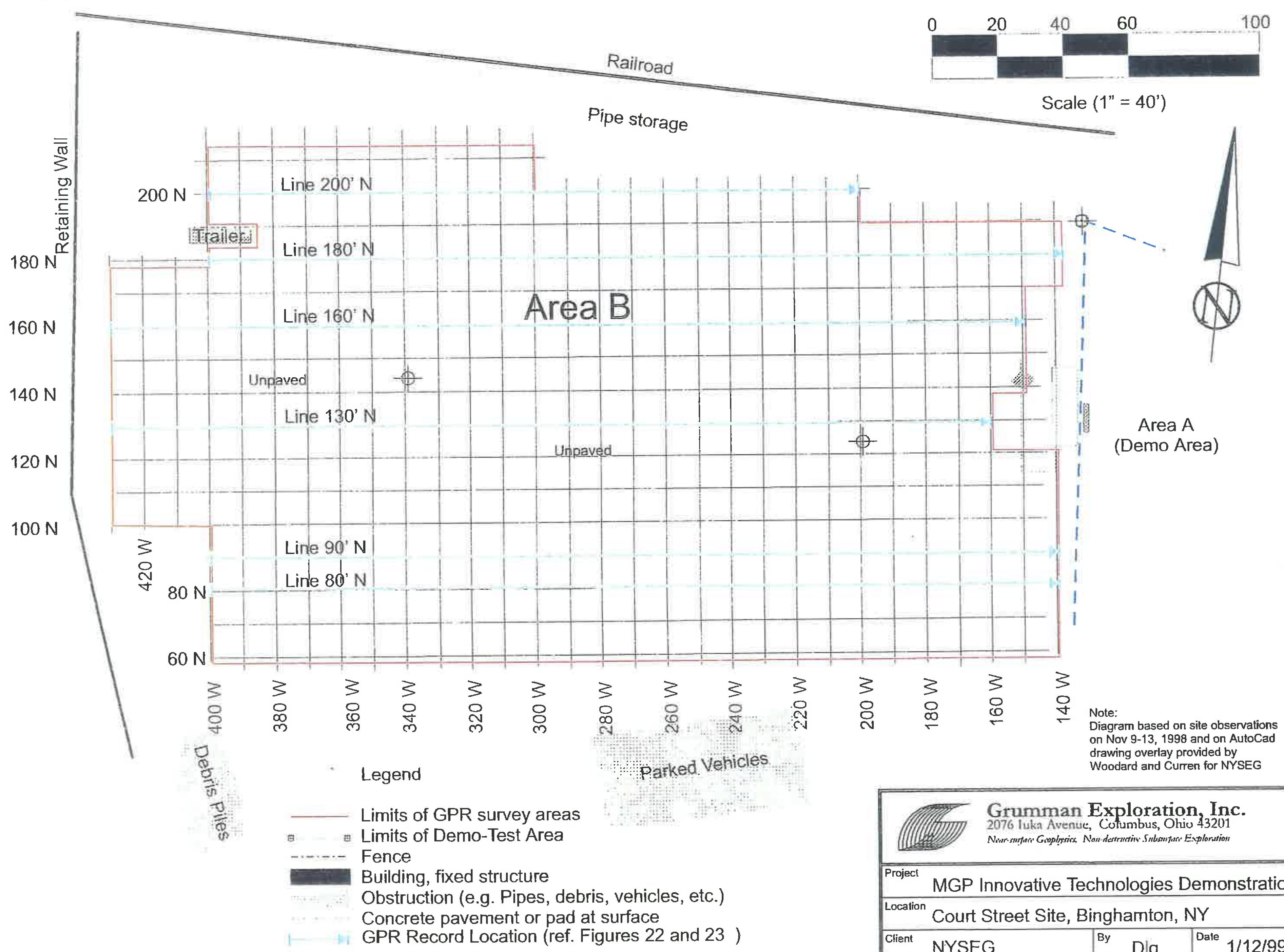
Figure 13 — Title: Representative Annotated GPR Records from Area A - east-west survey lines



Notes:
400 Mhz antenna,70 ns range, 512 samples/trace, 10 traces/ft.
Survey date: November 9 -11 , 1998
Refer to Figure 12 for survey linel location information.

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-destructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration
Location	Court Street Site, Binghamton, NY
Client	NYSEG
By	Dlg
Date	1/12/99
Project No.	01-98027
Checked	Dlg
Scale	As shown
Figure	14
Title	Representative Annotated GPR Records from Area A - north-south survey lines

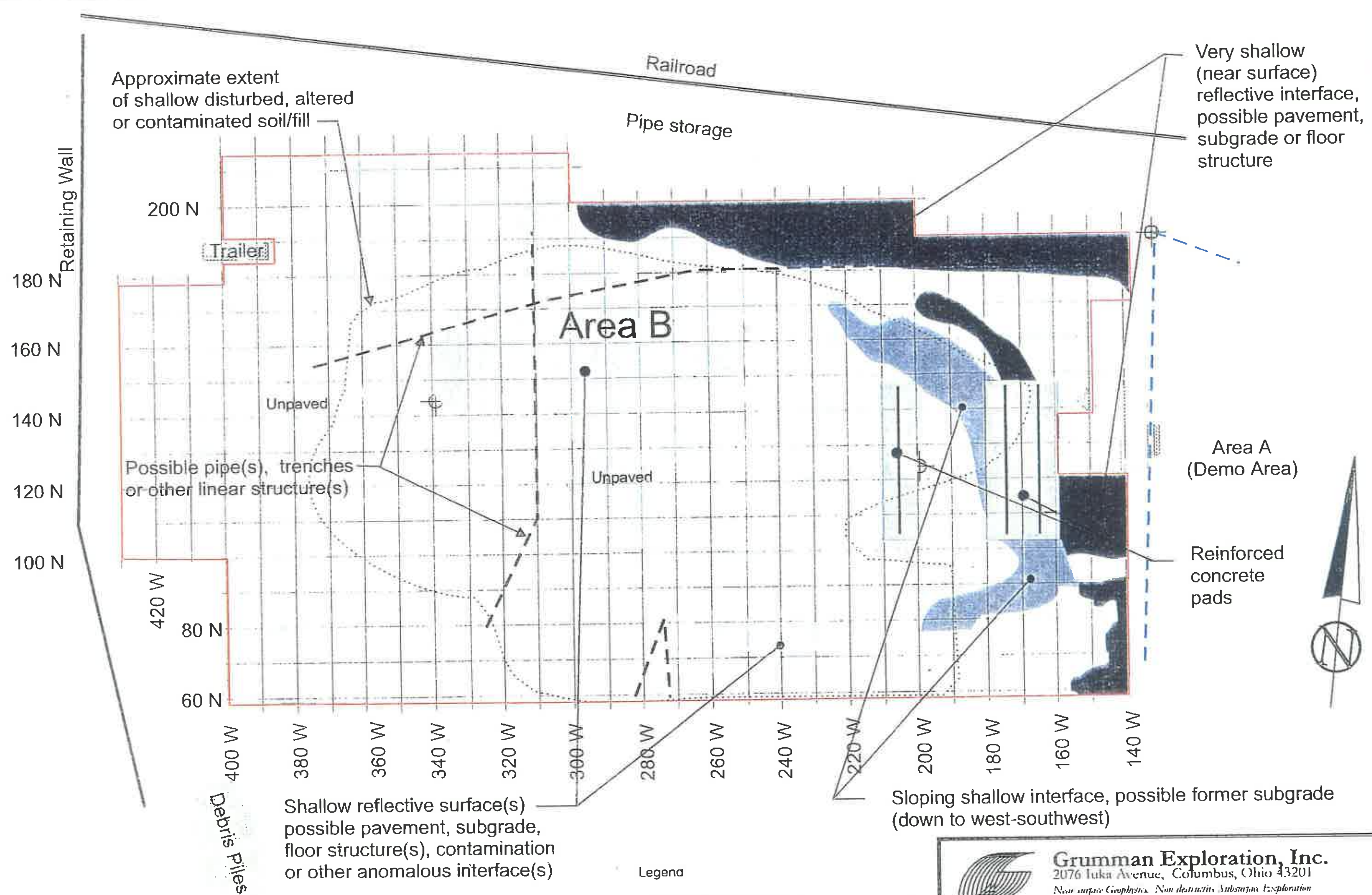


Note:
Diagram based on site observations on Nov 9-13, 1998 and on AutoCad drawing overlay provided by Woodard and Curren for NYSEG

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-destructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client	NYSEG	By Dlg	Date 1/12/99
Project No.	01-98027	Checked Dlg	Scale 1"=40'

Figure 15 — Title: Site Diagram Showing 3-D GPR Survey Extent for Area B



0 20 40 60 100

Scale (1" = 40')

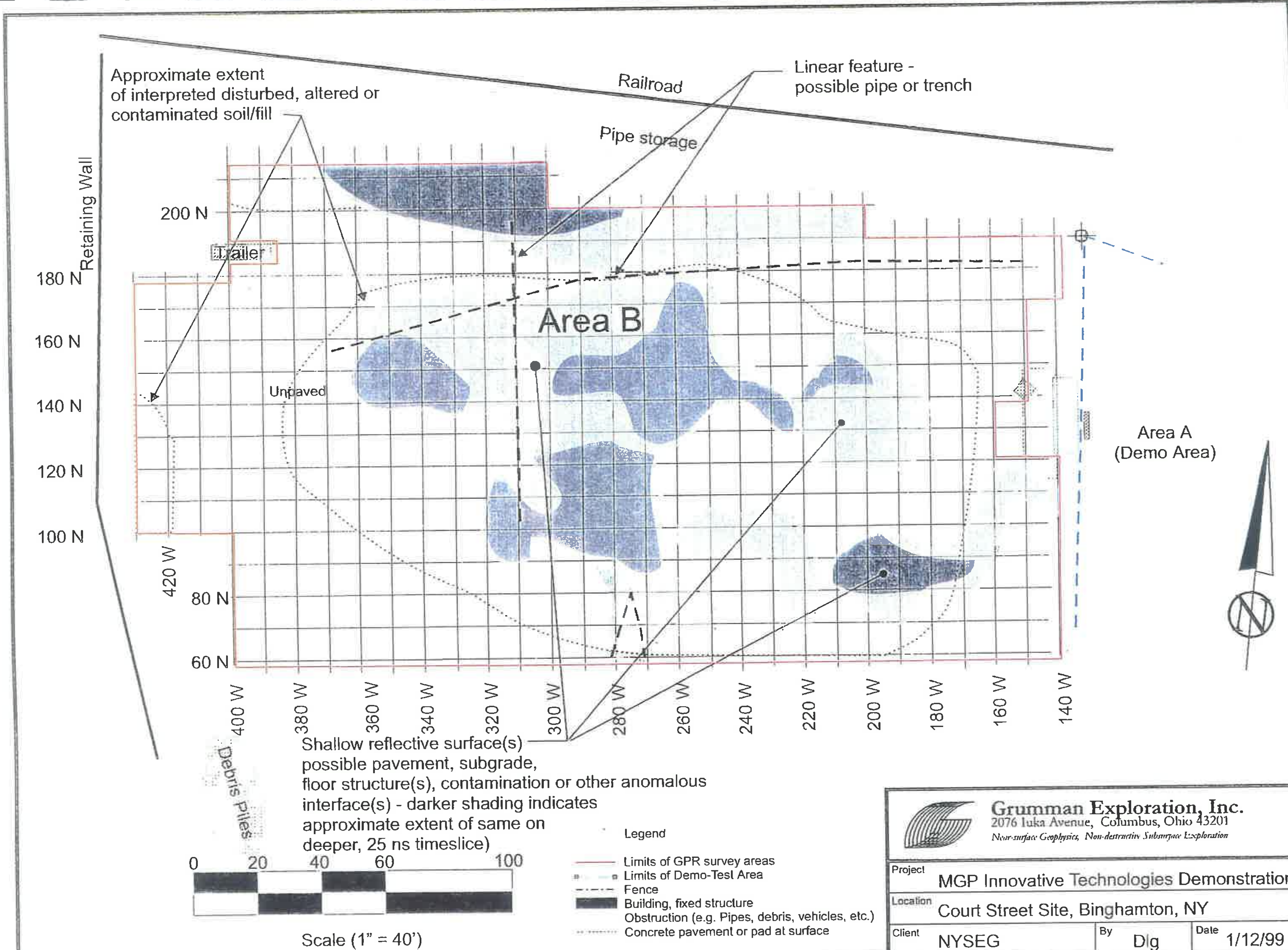
Legend

- Limits of GPR survey areas
- Limits of Demo-Test Area
- Fence
- Building, fixed structure
- Obstruction (e.g. Pipes, debris, vehicles, etc.)
- Concrete pavement or pad at surface

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near surface Geophysics. Non destructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client	NYSEG	By Dlg	Date 1/12/99
Project No	01-98027	Checked Dlg	Scale 1"=40'

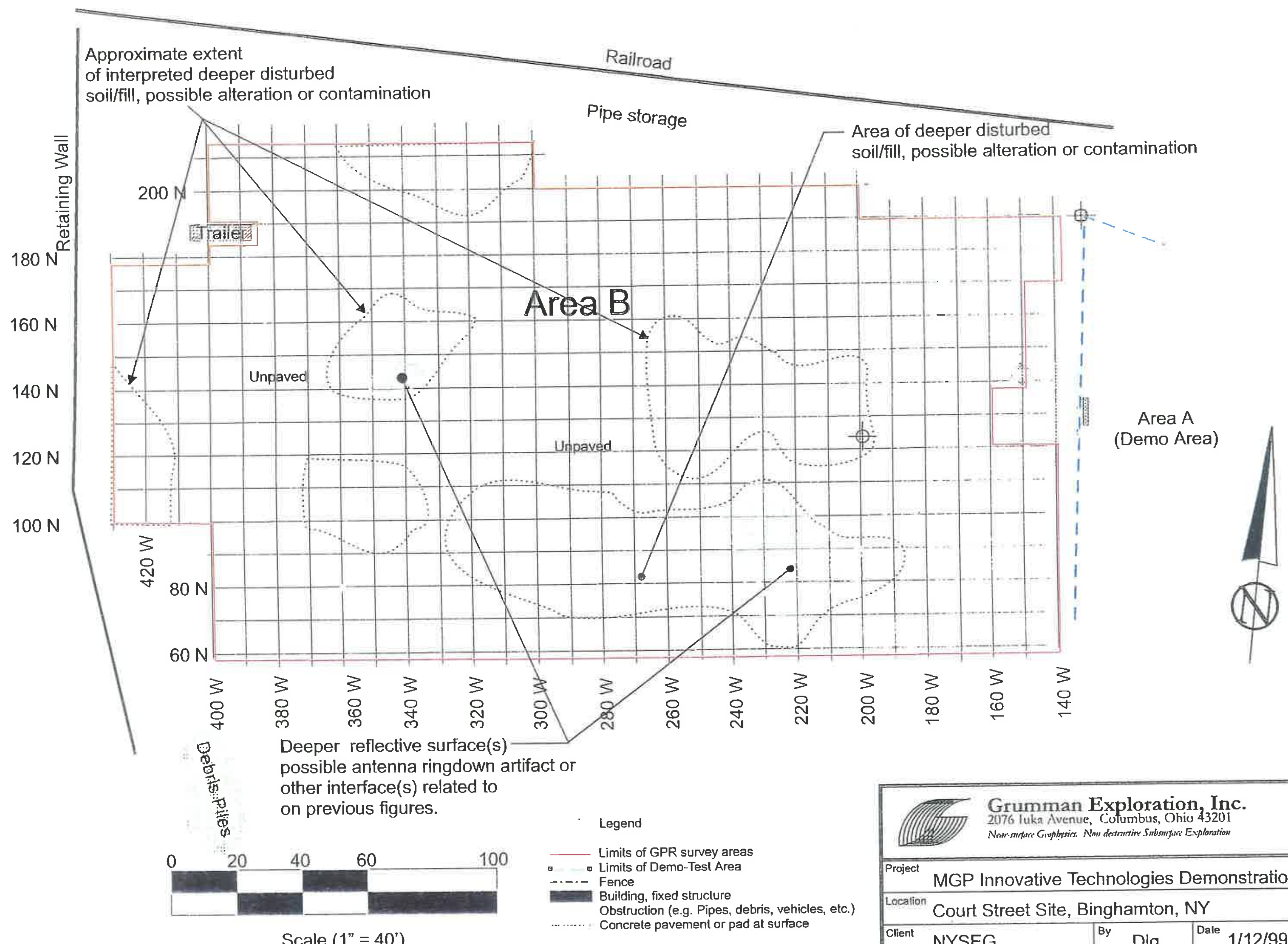
Figure	Title
16	Composite Interpretation of 10-15 ns Timeslices (Shallow Depth) for Area B



Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-destructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client	NYSEG	By: Dlg	Date: 1/12/99
Project No.	01-98027	Checked: Dlg	Scale: 1"=40'

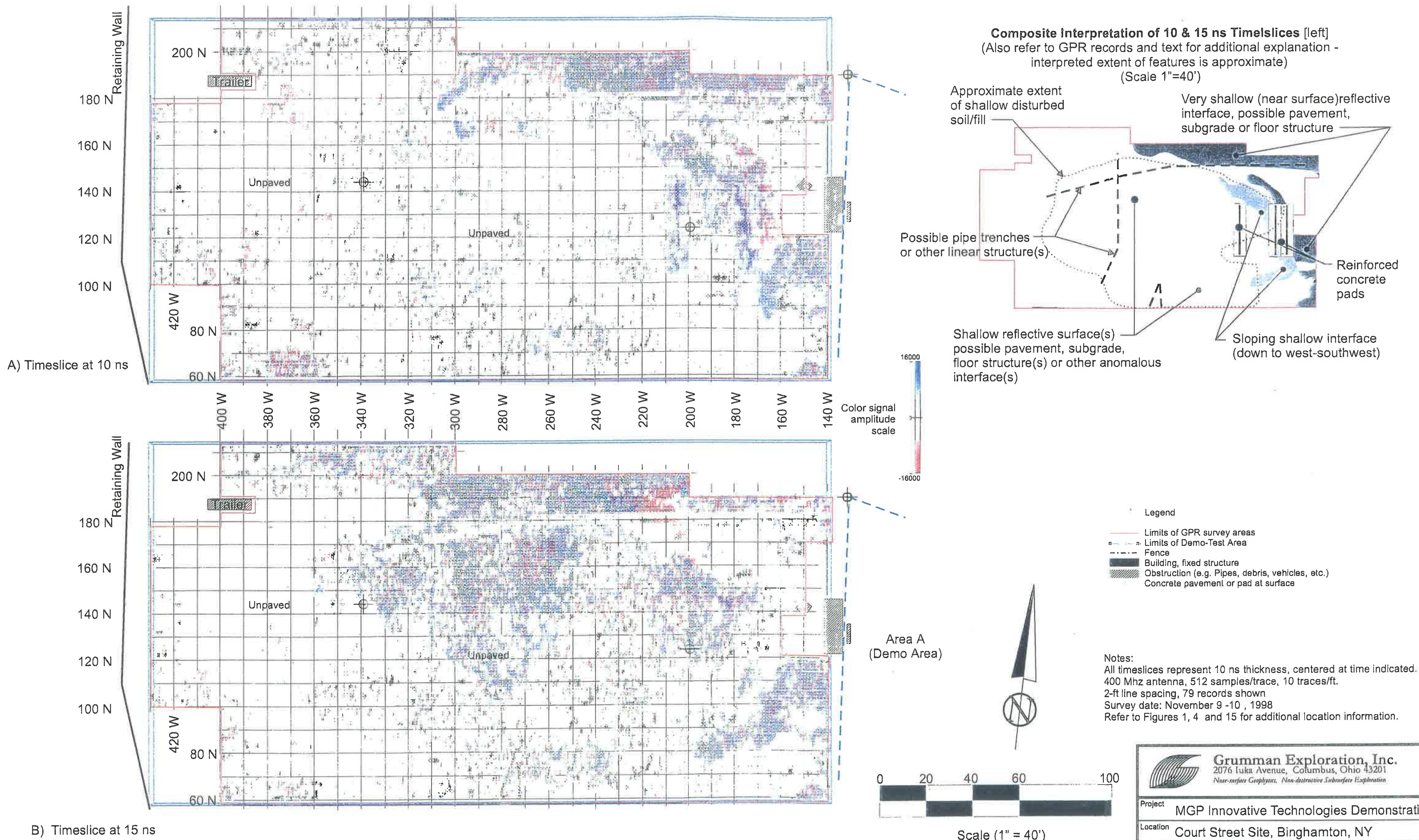
Figure 17 — Title: Composite Interpretation of 20-30 ns Timeslices (Intermediate Depth) for Area B



Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics. Non destructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration				
Location	Court Street Site, Binghamton, NY				
Client	NYSEG	By	Dlg	Date	1/12/99
Project No.	01-98027	Checked	Dlg	Scale	1"=40'

Figure	18	Title	Composite Interpretation of 30-40 ns Timeslices (Deeper) for Area B

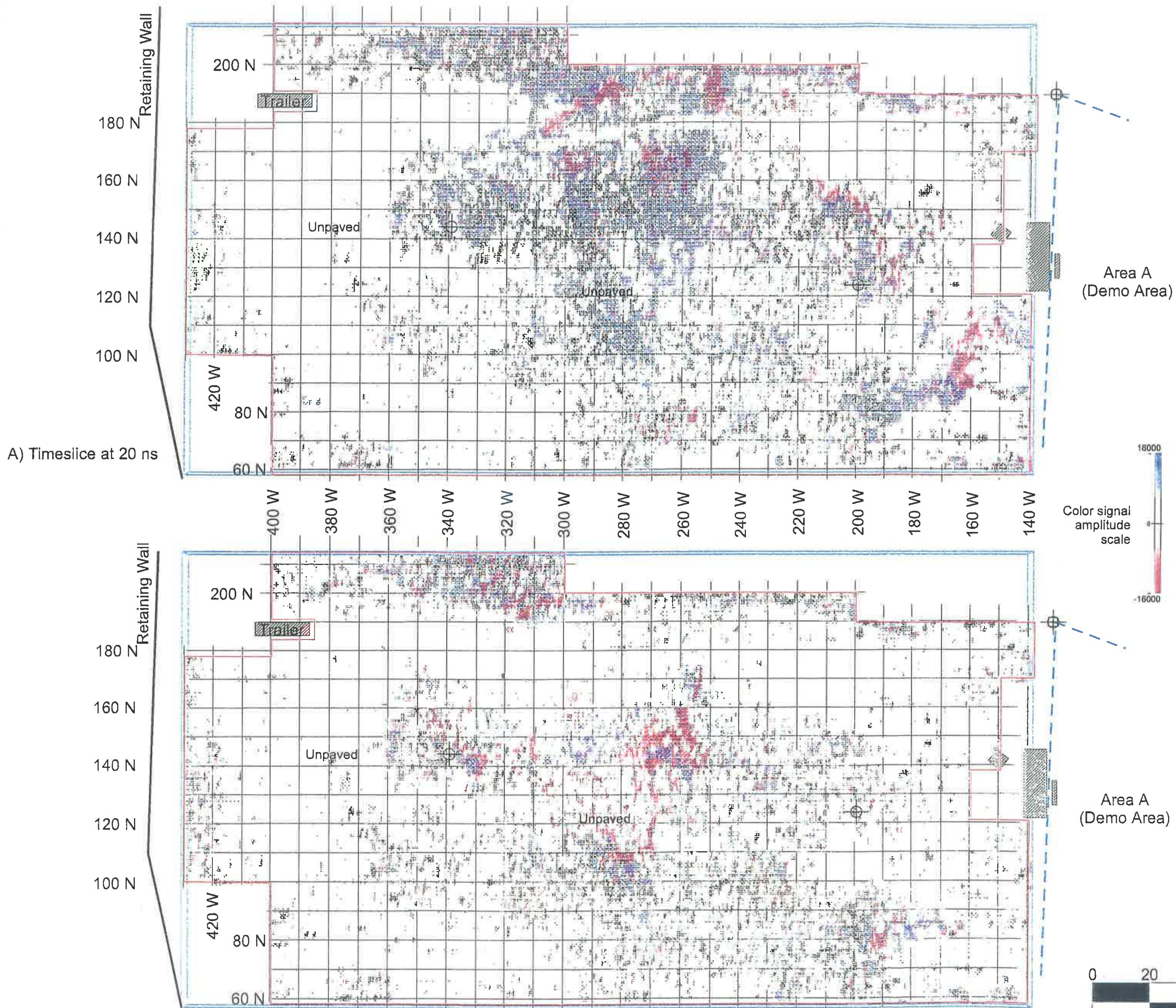


Notes:
All timeslices represent 10 ns thickness, centered at time indicated.
400 Mhz antenna, 512 samples/trace, 10 traces/ft.
2-ft line spacing, 79 records shown
Survey date: November 9 -10 , 1998
Refer to Figures 1, 4 and 15 for additional location information.

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-destructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration
Location	Court Street Site, Binghamton, NY
Client	NYSEG; By: Dlg; Date: 1/12/99
Project No.	01-98027; Checked: Dlg; Scale: 1"=40'

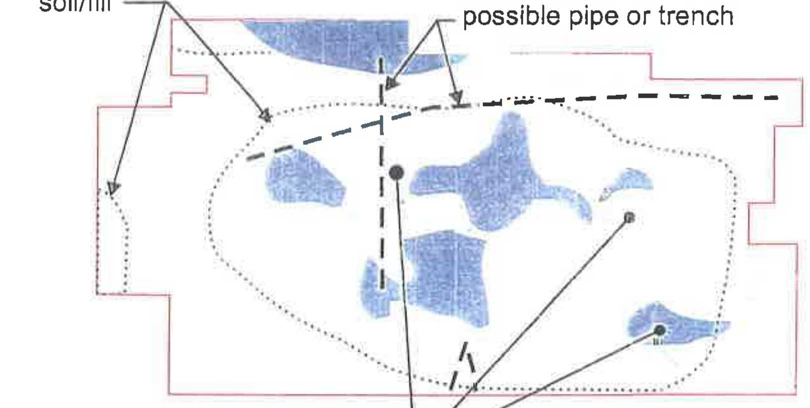
Figure 19 Title 3-D GPR Timeslices for Area B - 10 and 15 ns (shallow depth)



A) Timeslice at 20 ns

B) Timeslice at 25 ns

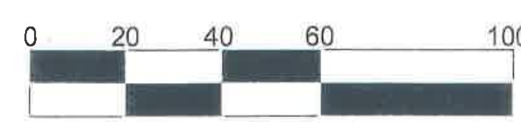
Composite Interpretation of 20 & 25 ns Timelslices [left]
(Also refer to GPR records and text for additional explanation - interpreted extent of features is approximate)
(Scale 1"=40')



Legend

- Limits of GPR survey areas
- Limits of Demo-Test Area
- Fence
- Building, fixed structure
- Obstruction (e.g. Pipes, debris, vehicles, etc.)
- Concrete pavement or pad at surface

Notes:
All timeslices represent 10 ns thickness, centered at time indicated.
400 Mhz antenna, 512 samples/trace, 10 traces/ft.
2-ft line spacing, 79 records shown
Survey date: November 9 -10 , 1998
Refer to Figures 1, 4 and 15 for additional location information.

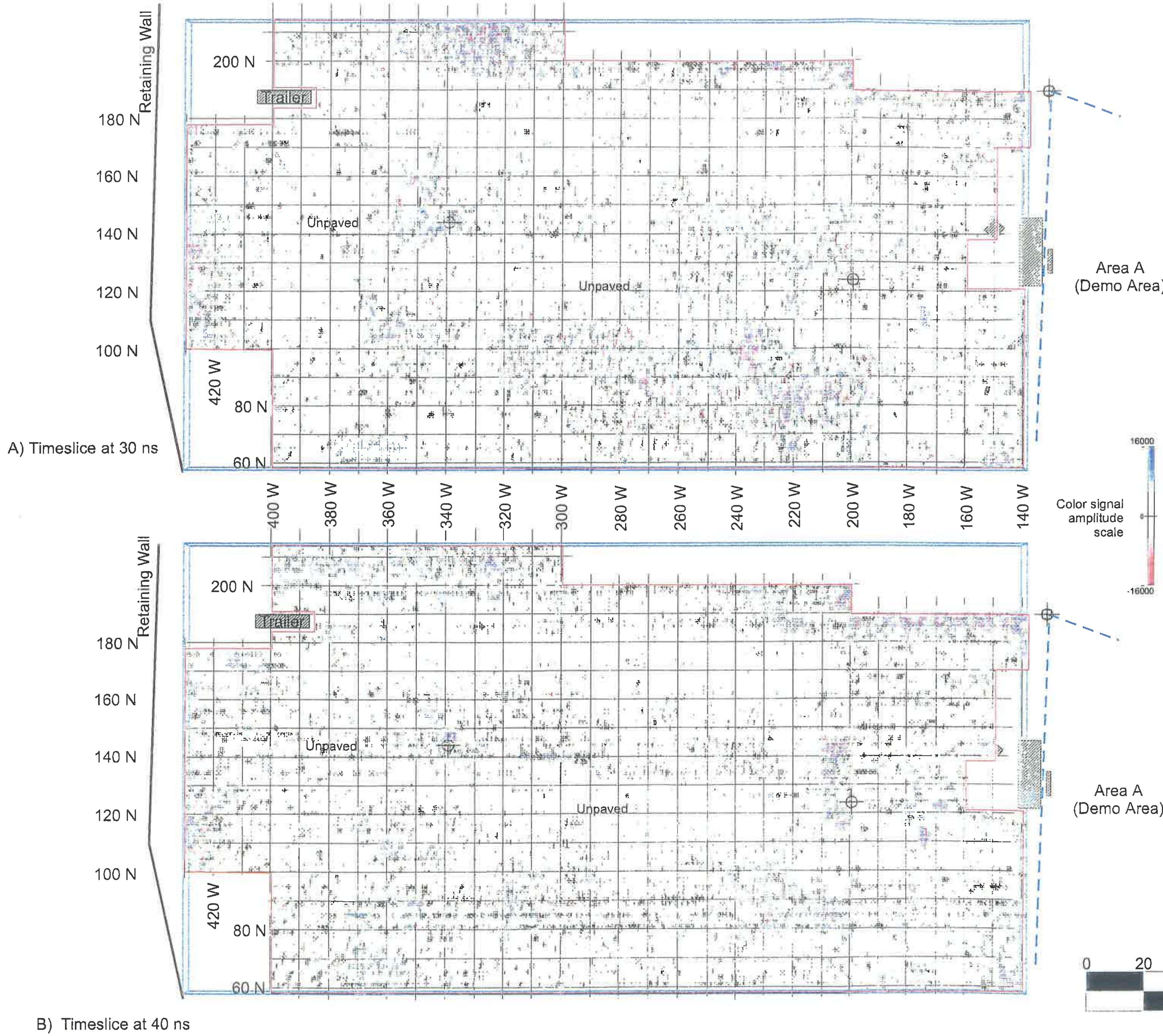


Scale (1" = 40')

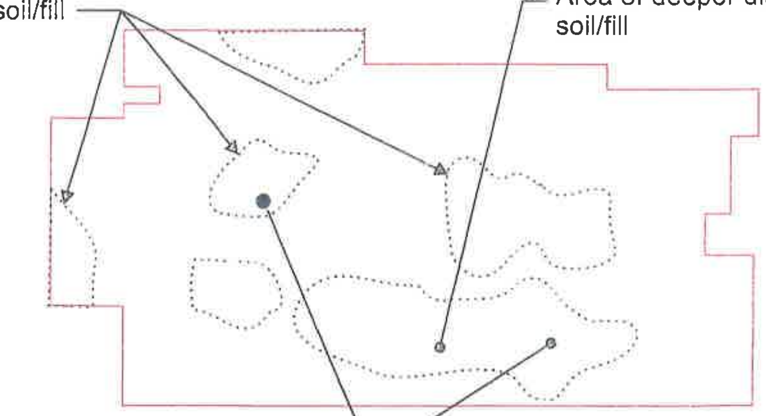
Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-destructive Subsurface Exploration

Project: MGP Innovative Technologies Demonstration			
Location: Court Street Site, Binghamton, NY			
Client: NYSEG	By: Dlg	Date: 1/12/99	
Project No.: 01-98027	Checked: Dlg	Scale: 1"=40'	

Figure: 20 | Title: 3-D GPR Timeslices for Area B - 20 and 25 ns (intermediate depth)



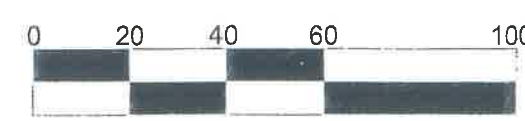
Composite Interpretation of 30 & 40 ns Timelslices [left]
(Also refer to GPR records and text for additional explanation - interpreted extent of features is approximate)
(Scale 1"=40')



Legend

- Limits of GPR survey areas
- Limits of Demo-Test Area
- Fence
- Building, fixed structure
- Obstruction (e.g. Pipes, debris, vehicles, etc.)
- Concrete pavement or pad at surface

Notes:
All timeslices represent 10 ns thickness, centered at time indicated.
400 Mhz antenna, 512 samples/trace, 10 traces/ft.
2-ft line spacing, 79 records shown
Survey date: November 9 -10 , 1998
Refer to Figures 1, 4 and 15 for additional location information.

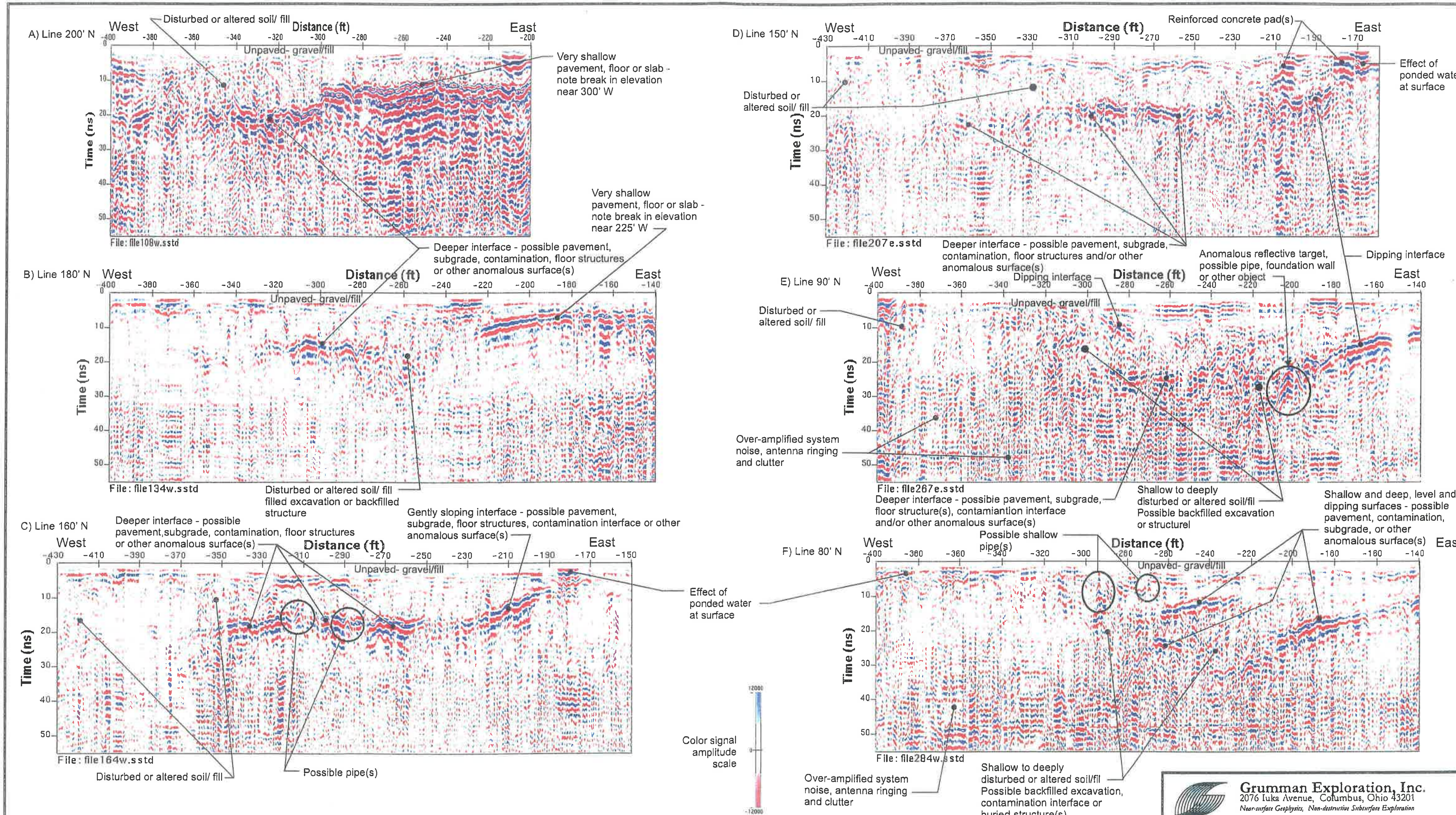


Scale (1" = 40')

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-destructive Subsurface Exploration

Project: MGP Innovative Technologies Demonstration			
Location: Court Street Site, Binghamton, NY			
Client: NYSEG		By: Dlg	Date: 1/12/99
Project No.: 01-98027		Checked: Dlg	Scale: 1"=40'

Figure 21 | Title: 3-D GPR Timeslices for Area B - 30 and 40 ns (deepest depth)

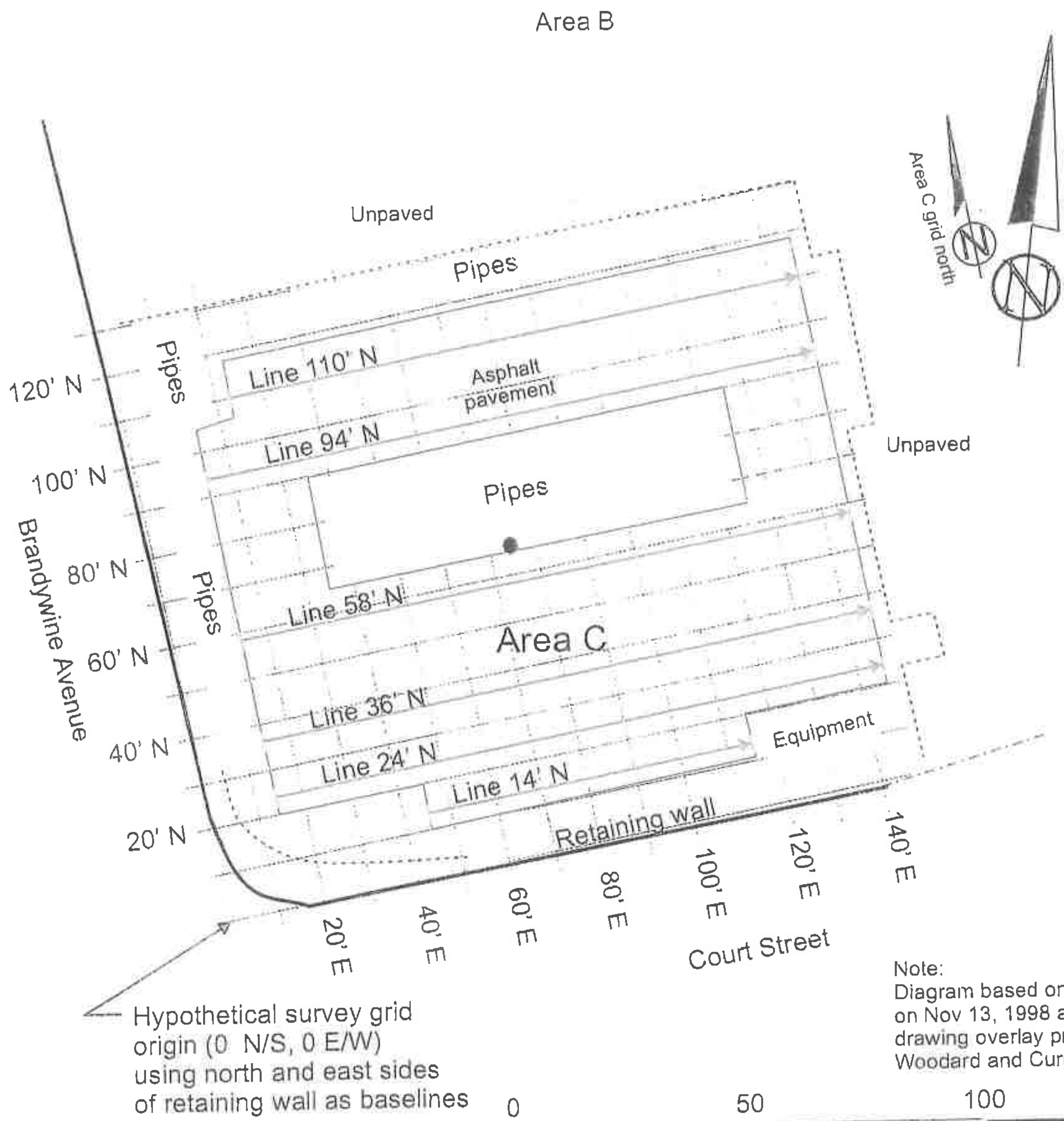


Notes:
400 Mhz antenna,70 ns range, 512 samples/trace, 10 traces/ft.
Survey date: November 12 , 1998
Refer to Figure -15 for additional location information.

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-destructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client NYSEG	By Dlg	Date 1/12/99	
Project No. 01-98027	Checked Dlg	Scale As shown	

Figure 22 Title Representative Annotated GPR Records from Area B - east-west survey lines



Note:
Diagram based on site observations on Nov 13, 1998 and on AutoCad drawing overlay provided by Woodard and Curren for NYSEG

0 50 100 150

Scale (1" = 40')

Legend

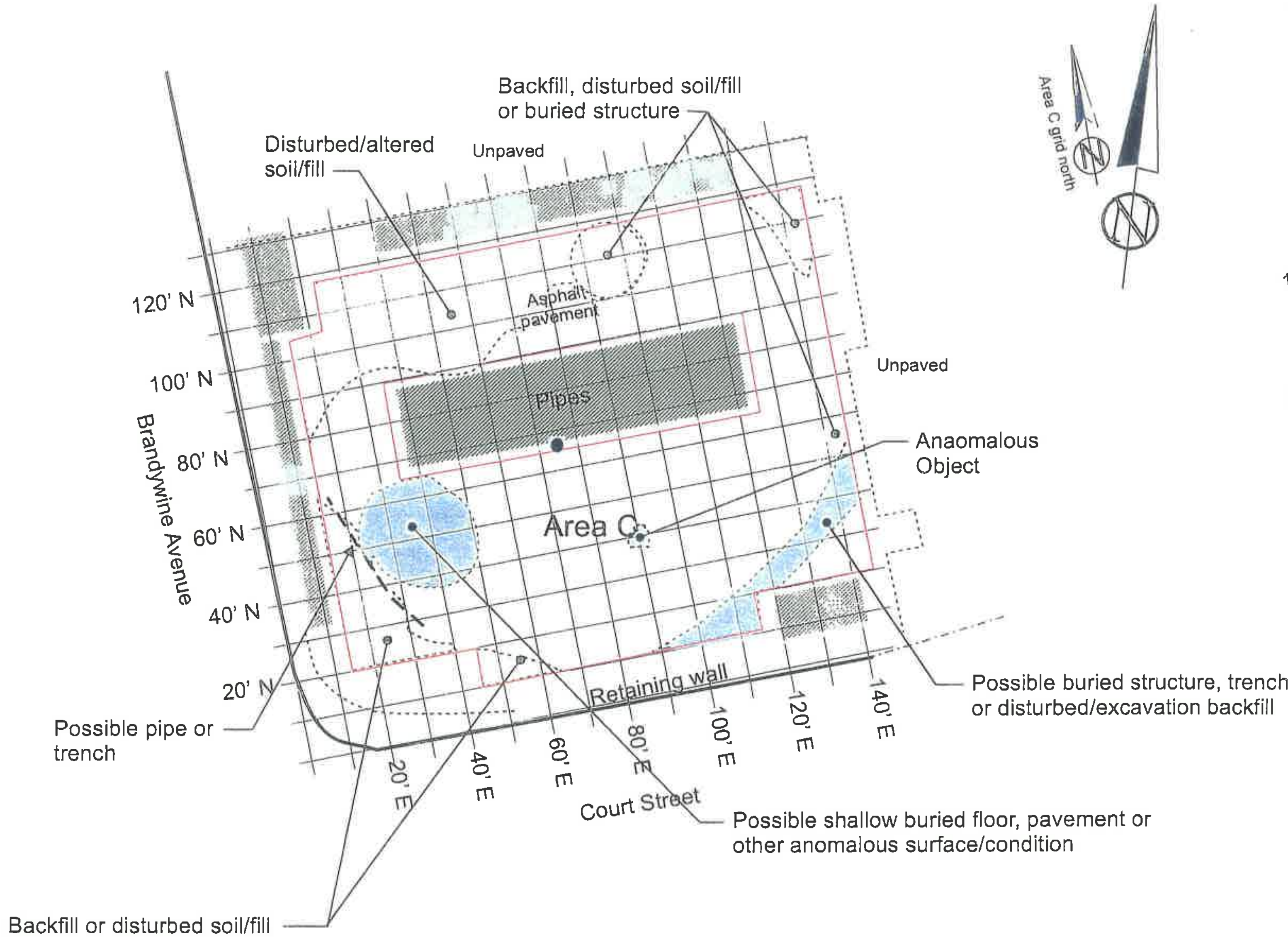
- Limits of GPR survey areas
- Corner points of Demo-Test Area
- Fence
- Building, fixed structure
- Obstruction (e.g. Pipes, debris, vehicles, etc.)
- Concrete pavement or pad at surface
- GPR Record Location (ref. Figure 27)

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-destructive Subsurface Exploration

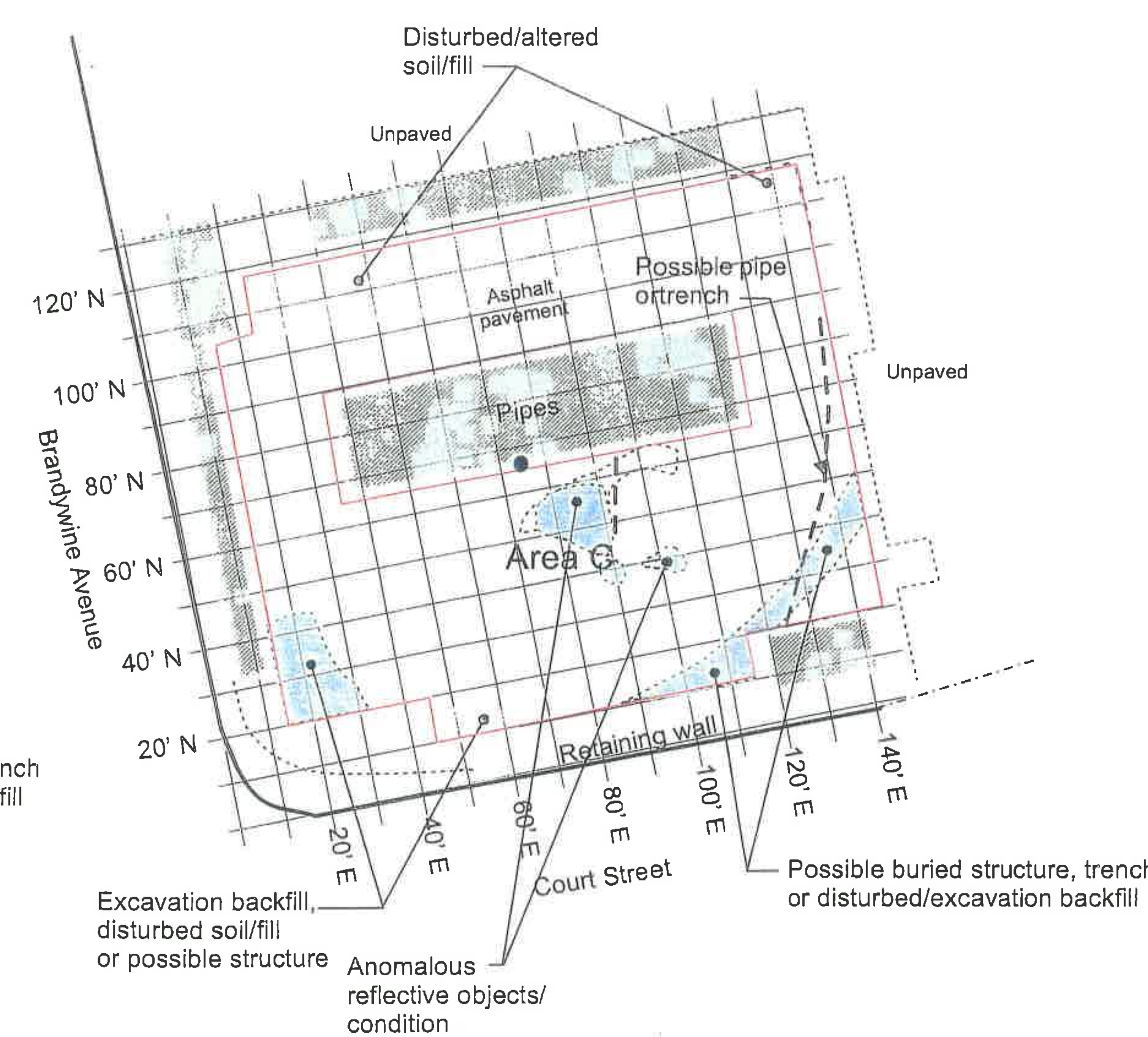
Project: MGP Innovative Technologies Demonstration			
Location: Court Street Site, Binghamton, NY			
Client: NYSEG	By: Dlg	Date: 1/19/98	
Project No.: 01-98027	Checked: Dlg	Scale: 1"=40'	

Figure 23 Title: Area C - Survey Area Diagram

A) Composite Interpretation of 15-30 ns Timeslices
(shallow to intermediate depth)



B) Composite Interpretation of 35 - -55 ns Timeslices
(intermediate to deep)



0 50 100

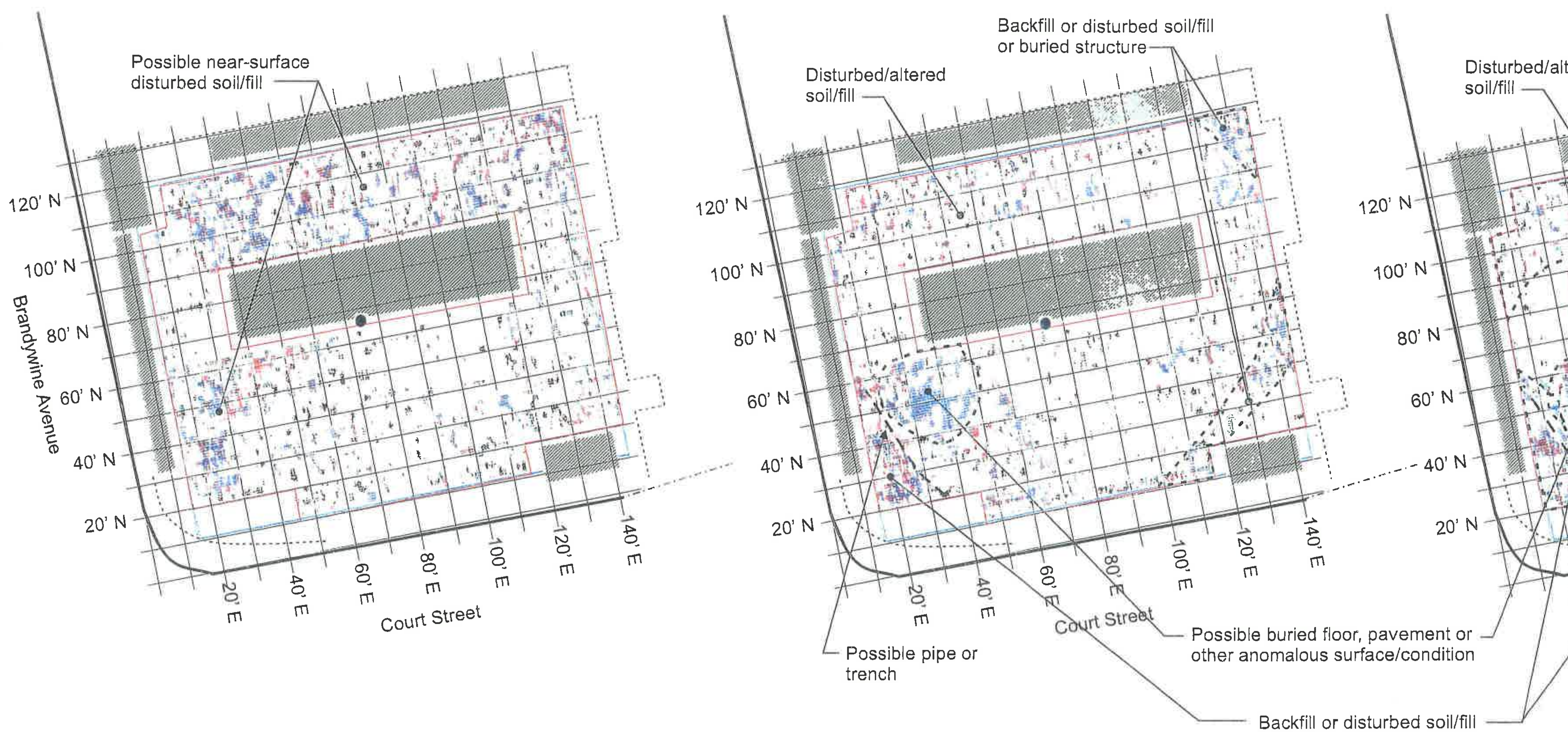
Scale (1" = 40')

Notes:
Compare interpretations to 3-D GPR timeslices and records -- Figures 24-26
200 Mhz antenna, 512 samples/trace, 10 traces/ft.
Survey date: November 13 , 1998
Refer to Figures 1, 4 and 23 for additional location information.

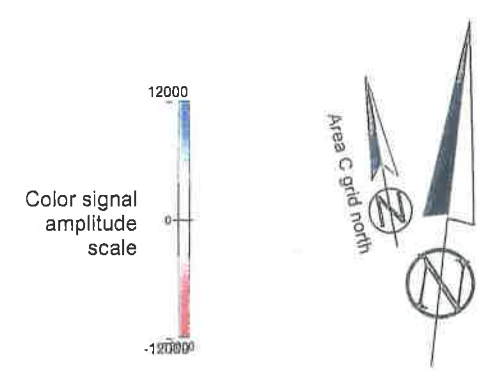
Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-destructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client	NYSEG	By Dlg	Date 1/12/99
Project No.	01-98027	Checked Dlg	Scale 1"=40'

Figure 24 Title Composite Interpretations of Timeslices for two depth ranges for Area C (Southwest corner)



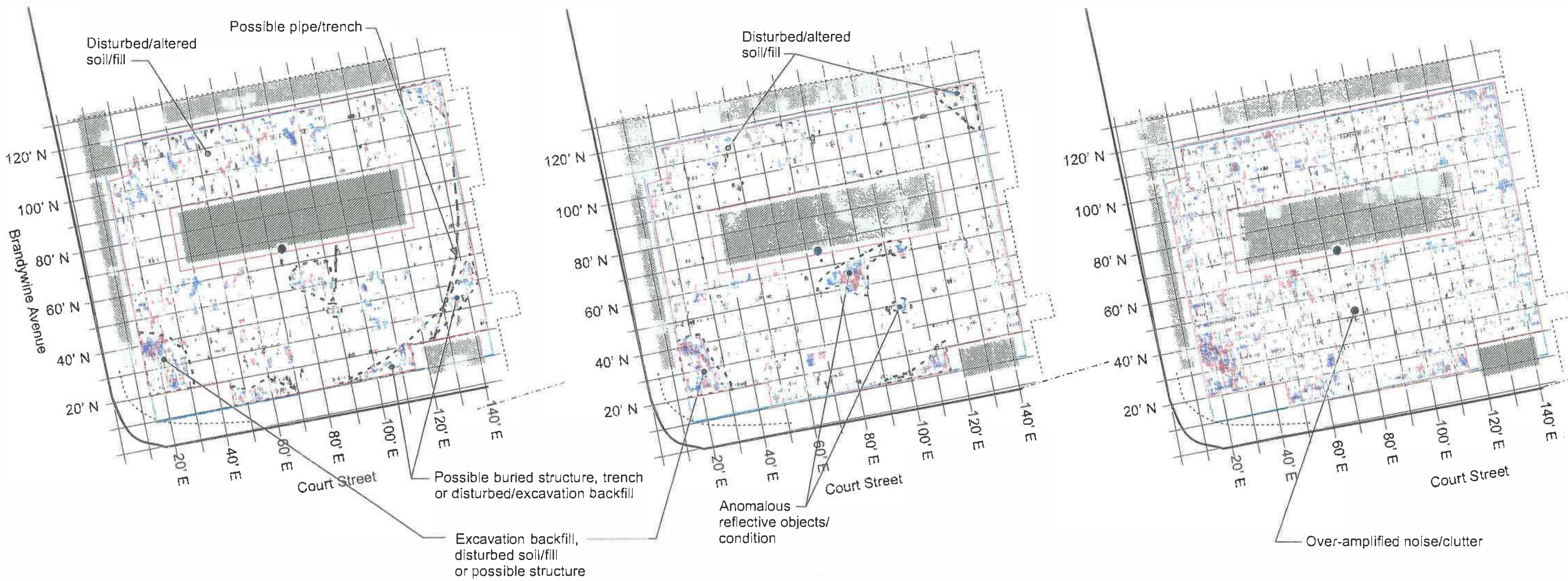
Notes:
Compare interpretations to 3-D GPR timeslices and records -- Figures 24-27
200 Mhz antenna, 512 samples/trace, 10 traces/ft.
Survey date: November 13 , 1998
Refer to Figures 1, 4 and 23 for additional location information.



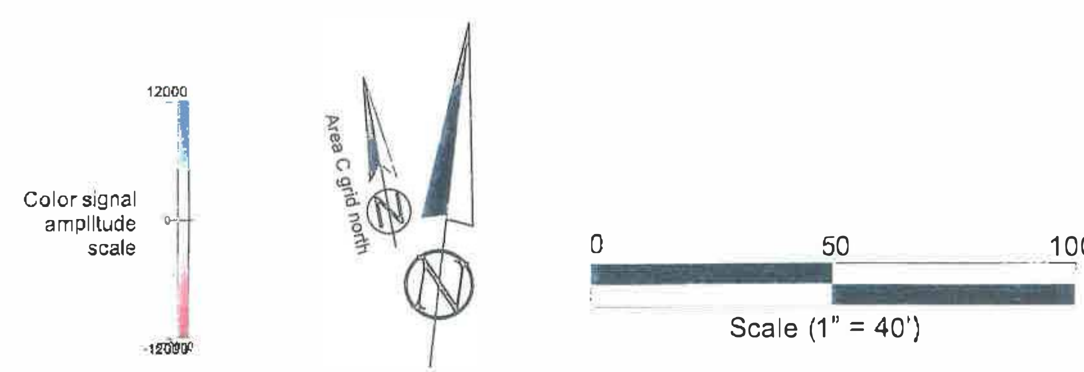
0 50 100
Scale (1" = 40')

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-destructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration
Location	Court Street Site, Binghamton, NY
Client	NYSEG
By	Dlg
Date	1/12/99
Project No.	01-98027
Checked	Dlg
Scale	1"=40'
Figure	25
Title	GPR Timeslices for threeshallow to intermediate depth ranges (15 - 30 ns) for Area C (Southwest corner)



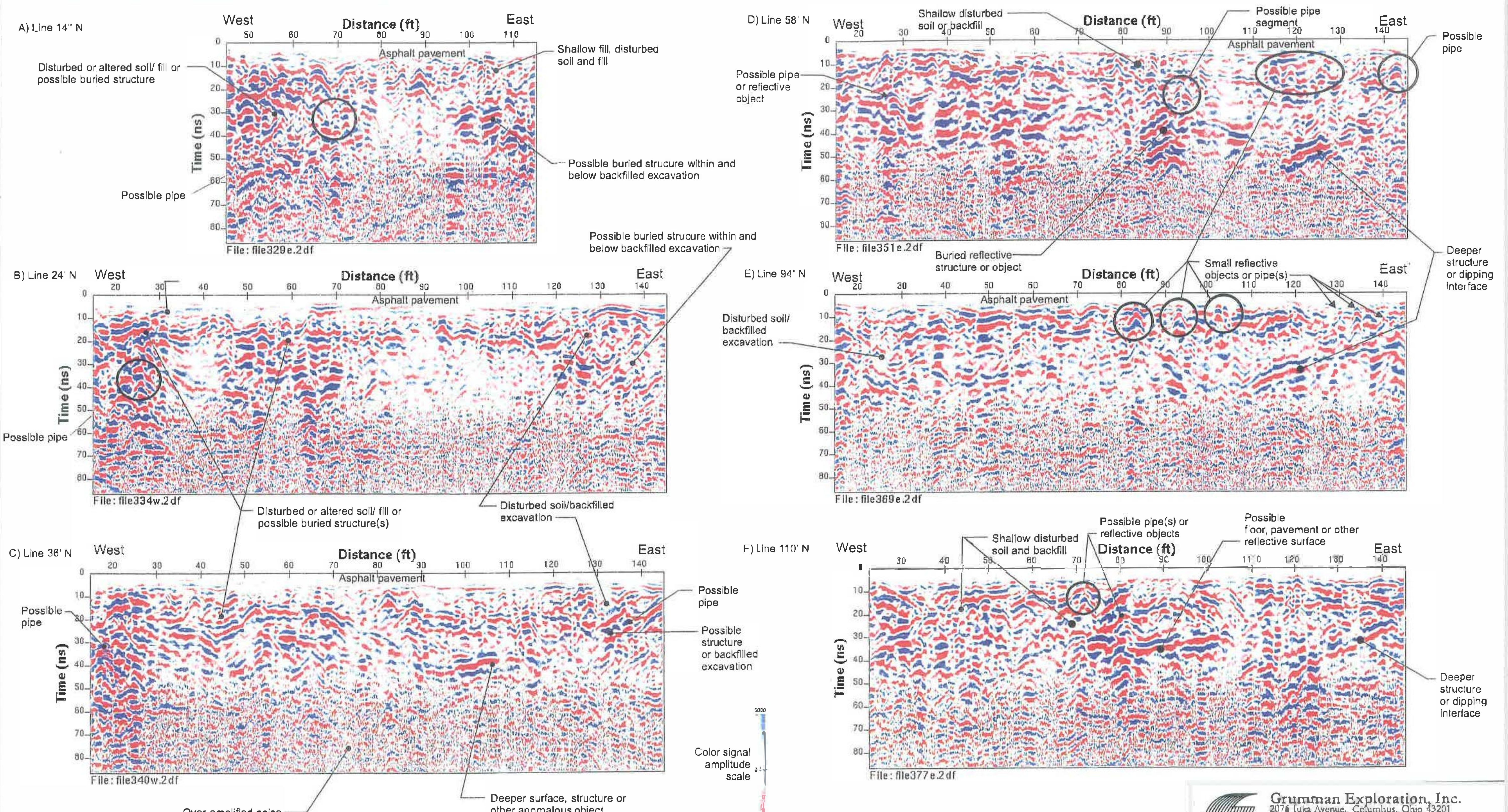
Notes:
All timeslices represent 5 ns thickness, centered at time indicated.
200 Mhz antenna, 512 samples/trace, 10 traces/ft.
2-ft line spacing (east-west), 68 records shown
Survey date: November 13, 1998
Refer to Figures 1, 4 and 23 for additional location information.



Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-destructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration
Location	Court Street Site, Binghamton, NY
Client	NYSEG
By	Dlg
Date	1/12/99
Project No.	01-98027
Checked	Dlg
Scale	1"=40'

Figure 26 Title GPR Timeslices for three intermediate to deep depth ranges (35-55 ns) for Area C (Southwest corner)

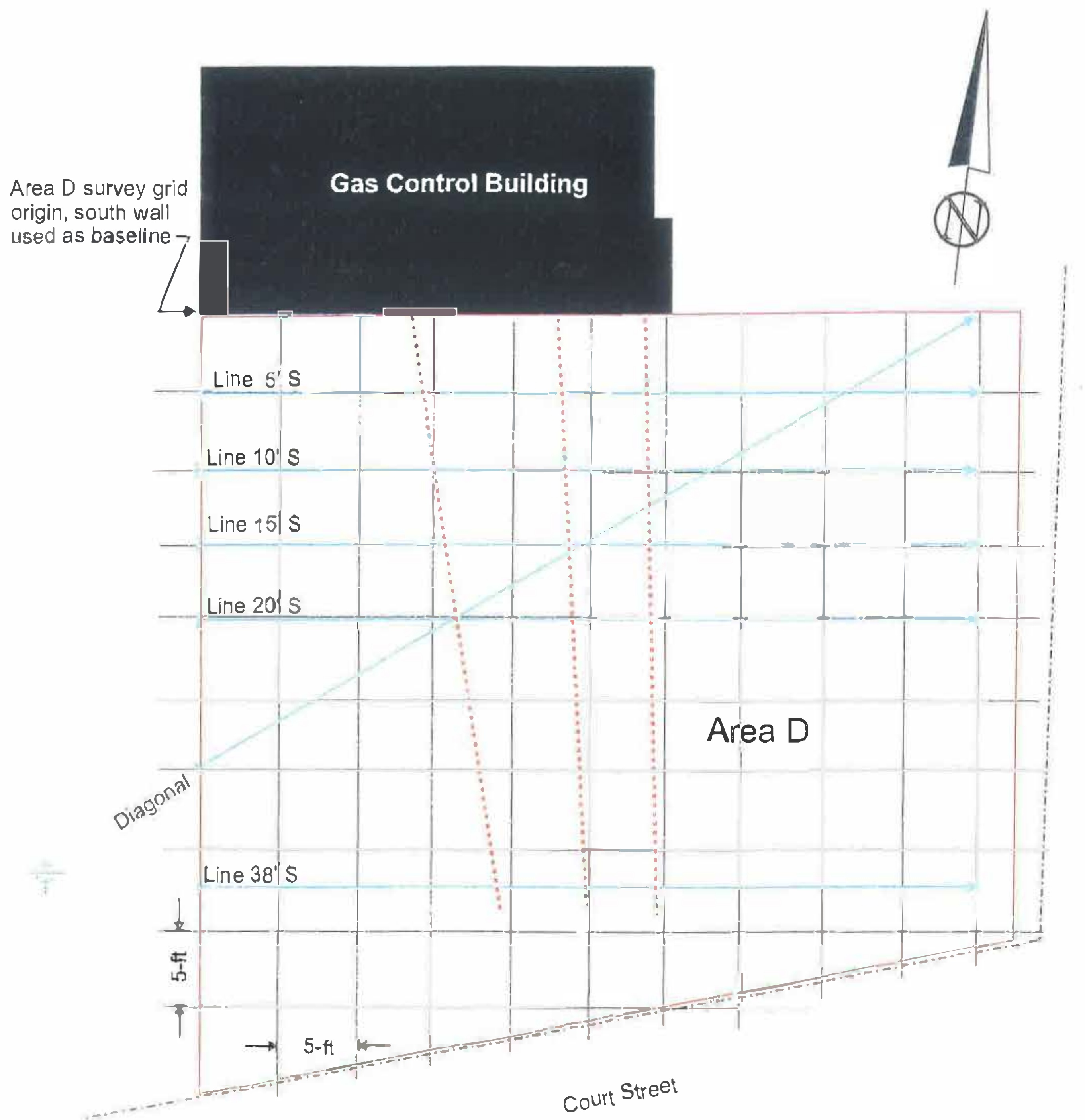


Notes:
200 Mhz antenna,110 ns range, 512 samples/trace,
10 traces/ft, 2-ft line spacing
Survey date: November 13 , 1998
Refer to Figure 23 for survey line location information.

Grumman Exploration, Inc.
2078 Tuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Non-destructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client	NYSEG	By Dig	Date 1/12/99
Project No.	01-98027	Checked Dig	Scale As shown

Figure 27 Title Representative Annotated GPR Records from Area C - east-west survey lines



0 10 20

Scale (1" = 10')

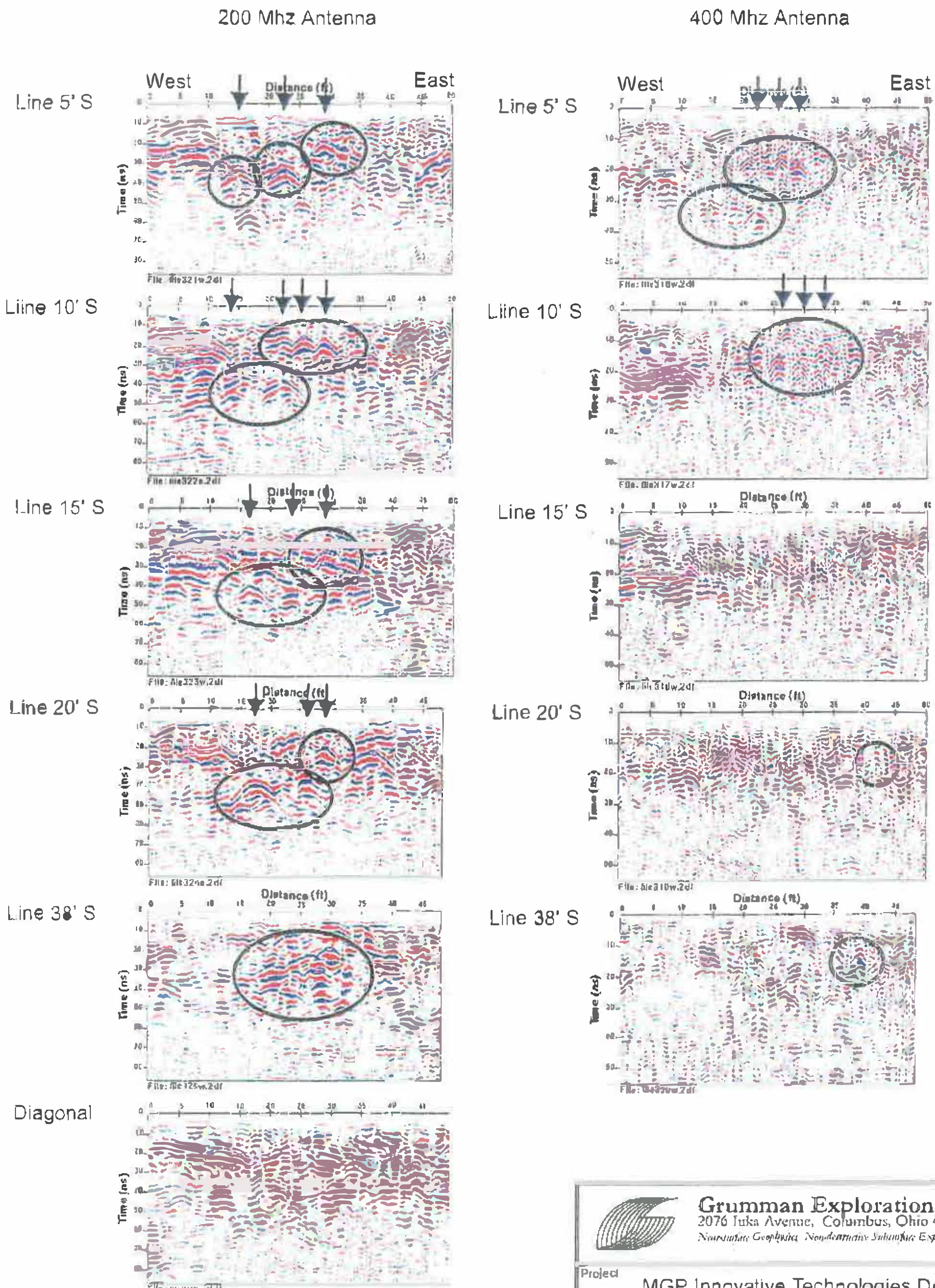
Legend

- Limits of GPR survey areas
- Corner points of Demo-Test Area
- Fence
- Building or fixed structure
- Obstruction (e.g. Pipes, debris, vehicles, etc.)
- Concrete pavement or pad at surface
- GPR Record Location (ref. Figures)
- Interpreted Pipe/Conduit

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Noninvasive Geophysics, Nondestructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client	NYSEG	By Dig	Date 1/123/98
Project No.	01-98027	Checked Dig	Scale 1"=10'

Figure 28 Title Area D - Gas Control Building Test Area

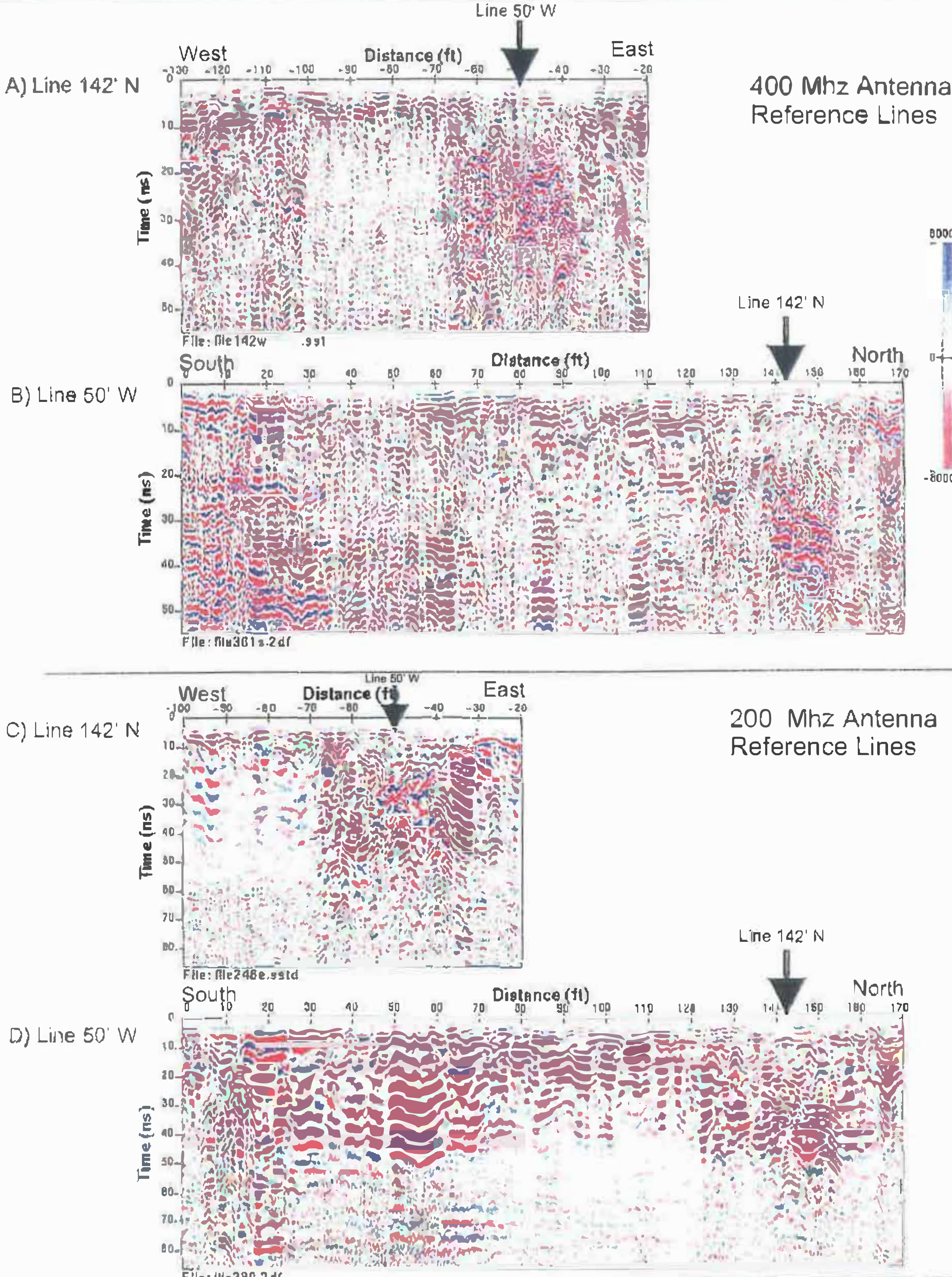


Refer to Figure 28 for line locations

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201

Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client	NYSEG	By Dig	Date 1/123/98
Project No.	01-98027	Checked Dig	Scale NTS

Figure 29 Title Area D - Gas Building Test Area GPR Records



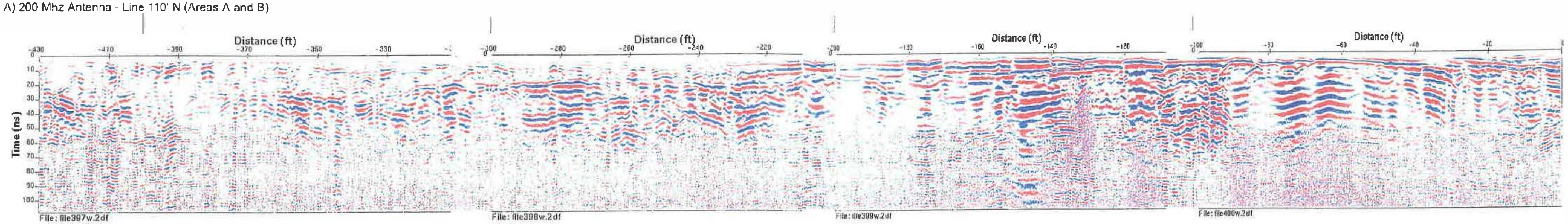
Notes:
Survey Dates: November 9-11, 1998
400 Mhz antenna :70 ns range, 200 Mhz antenna: 100 ns range
1-ft/2-ft line spacing, 10/traces/ft, 512 samples/trace
Line locations with respect to Demo-Test Area survey grid
Refer to Figure 5 for survey area and line locations

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Nonintrusive Geophysics Non destructive Subsurface Exploration

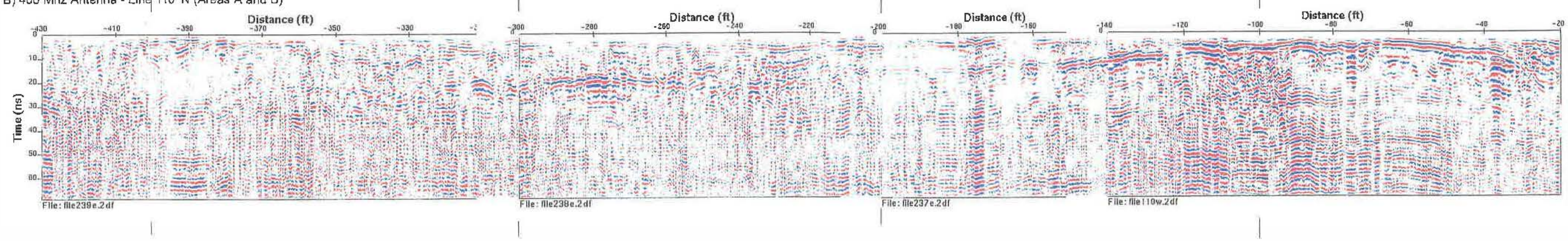
Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client NYSEG	By Dlg	Date 1/123/98	
Project No 01-98027	Checked Dlg	Scale NTS	

Figure 30 Title Reference Lines GPR Records - Demo-Test Area

A) 200 Mhz Antenna - Line 110' N (Areas A and B)



B) 400 Mhz Antenna - Line 110' N (Areas A and B)



Notes:
400 Mhz antenna,70 ns range, 512 samples/trace, 10 traces/ft.
200 Mhz antenna,110 ns range, 512 samples/trace, 10 traces/ft.
Survey date: November 9 -11 , 1998
Line location with respect to Areas A & B survey grid
Refer to Figure s 5 and 15 for survey line location.

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
Near-surface Geophysics, Nondestructive Subsurface Exploration

Project	MGP Innovative Technologies Demonstration		
Location	Court Street Site, Binghamton, NY		
Client	NYSEG	By Dlg	Date 1/12/99
Project No.	01-98027	Checked Dlg	Scale As shown

Figure 31 Title Long Survey Lines - Comparison of 200 and 400 Mhz Antenna Processed Results for Survey Line 110' That Crosses Areas A and B

APPENDICIES

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
(614) 421-7944 tel, (614) 421-2688 fax

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
(614) 421-7944 tel, (614) 421-2688 fax

APPENDIX A

Overview of Ground-Penetrating Radar

A.1 Introduction

Ground-Penetrating Radar (GPR) operates by transmitting and receiving microwave electromagnetic impulses. By moving a broadband, dipole antenna across the ground surface, an approximate two-dimensional cross-section of the subsurface can be displayed on the GPR system unit. GPR is sometimes described as a kind of pulse-echo device, not unlike sonar or an acoustic fish finder. In contrast to these acoustic devices, however, GPR operates by using electromagnetic signals that are governed by the principles of electromagnetic wave propagation through the subsurface. Transmitted GPR impulses propagate downward through the subsurface, reflect off buried target boundaries and return to the receiver antenna. Contrasts in the electrical properties of a target will cause some of the GPR signal to reflect back toward the ground surface. Interfaces between electrically distinctive materials such as sand and clay, backfill and steel, concrete and soil, and the water table can be detected using GPR under favorable survey conditions. The technical basis for GPR is described in Daniels (1989), Davis and Annan (1989), Powers (1995), and Conyers and Goodman (1997). A comprehensive review of GPR is also available on the Internet at www.g-p-r.com.

The preceding simplified description belies much of the complexity of GPR. Among the interdependent variables that affect GPR performance include: the electrical properties of the subsurface and targets, the spatial configuration of the subsurface and targets, the GPR system hardware and performance, above ground and below ground conditions, and electrical interference. Also important are subjective variables such as exploration objectives, expectations and the experience of the person(s) conducting the survey and interpreting the results. As an electrical method, the basis for understanding GPR lies in the principles of electromagnetic wave propagation (e.g., Maxwell's Equations, Radar Equation, etc). The references noted above summarize the theoretical basis for GPR more completely. The following paragraphs provide a simplified summary of some of the basic concepts useful for understanding GPR.

A.2 Applications

GPR is credited with successfully exploring a wide variety of buried targets and subsurface conditions. Popular applications of GPR span the fields of environmental, geologic and civil engineering and generally involve buried target characterization, detection and mapping. Published examples of the application of GPR for environmental site characterization including NAPL contaminant exploration include: Daniels and others (1992), Grumman and others (1995), Maxwell & Schmock (1995), and Olhoeft (1992).

There exist few published reports of GPR used at MGP sites in the geophysical literature, although many of the conditions found at MGP sites have been successfully explored using a number of geophysical methods, including GPR, at other similarly complex and contaminated sites.

A.3 GPR System Components and Operation

A basic GPR system consists of a system control unit and recording instrumentation connected to transmitter and receiver antennas (see photographs in Figure B.1 in Appendix B). The transmit and receive antennas may be separate components or housed together in a single container or antenna box. Both antenna elements are placed in close proximity to the ground surface to efficiently transmit and receive the GPR signal. Several different GPR antenna designs are used, although most commercial systems use a dual dipole antenna configuration. High-frequency, short duration impulses that originate on the transmit antenna radiate outward in a pattern determined by the impulse characteristics, antenna design and near surface electrical properties. At the moment the transmit pulse begins, the second receiver antenna 'listens for' (measures) the returning signal. The received waveforms are displayed on the system unit and may be recorded digitally. By moving the antennas across the ground surface, the series of recorded impulses responding to horizontal and vertical changes in the subsurface create the impression of a two-dimensional cross-section of the subsurface. The recording is actually a quasi 2-D representation of the configuration of electrically different materials within the subsurface (Figure A.1).

A.4 Electrical Properties, Signal Reflection and Attenuation

The electrical properties that affect GPR signal propagation and reflection are: conductivity (charge transport), permittivity (dielectric, related to charge storage), and permeability (related to magnetic properties). Electrical conductivity strongly affects the attenuation of the GPR signal, with higher electrical conductivity causing higher levels of signal loss. Higher conductivity clay soils tend to severely reduce signal penetration, sometimes to as little as a few feet. In contrast, low conductivity sand often results in low signal loss and deeper penetration, often on the order of 15-ft to 30-ft. Permittivity is also a source of signal loss similar to the effect of conductivity. However, it is the contrast in permittivity between materials that is responsible for causing reflections, and permittivity can be used to estimate the depth of exploration. Permittivity is sometimes referred to as the dielectric characteristic of a material and is often termed the 'dielectric constant'. Magnetic permeability tends to have a minimal influence on GPR except in materials with elevated iron or magnetic mineral content. Other signal loss mechanisms are described in the references noted previously.

In order for reflection to occur, there must be a sufficient permittivity contrast across the reflecting interface, and the interface must be spatially well defined (i.e., sharp). A buried concrete surface or the water table in a coarse grained soil (e.g., sand and gravel) are often good reflecting surfaces. A gradational boundary, such as a thick capillary fringe above the water table in a finer grained soil (e.g., silt or clay) may not be sufficiently distinct to produce any reflection. The larger the permittivity contrast between materials, the stronger the reflected energy will be. Many metals, being nearly perfect reflectors, generate strong reflections and often a distinctive 'ringing' response on the GPR record. A general lack of reflections or reflecting interfaces from an area may occur because of: (a) high signal attenuation caused by conductive soil conditions, and/or (b) no detectable targets or reflecting interfaces.

How efficiently an antenna radiates energy into the subsurface (termed antenna-ground coupling) depends in part on the similarity of the electrical characteristics of the antenna and the subsurface. The greatest transfer of energy into the subsurface occurs when the electrical impedance of the antenna and that of the ground are approximately the same. When a mismatch occurs (such as over conductive or clay-rich soils), some of the radiated energy remains and resonates within the antenna and causes a distinctive 'ringing' pattern on the GPR record. Antenna ringing (poor antenna-ground coupling) is often apparent as a series of moderate to strong horizontal bands that extend across the record (see Figure A.1). A similar ringing effect can occur in response to some reflective targets or interfaces whereby electrical currents resonate within a target or antenna. In this case, targets often appear with a series of strong, parallel bands that appear to shadow the target farther down the record ('ringdown'). Buried reinforced pavement, steel pipes and other metal objects often show this response.

A.5 Depth of Exploration

Each GPR trace is a measure of the amount of time for a transmitted impulse to propagate down through the subsurface, reflect off an interface, and travel back to the receiver antenna. Consequently, the recorded time is a two-way travel time – down and back. Travel time is recorded in units of nanoseconds (ns: 1 ns = 1 billionth of a second). The travel time of a reflected impulse is related to the depth of the reflector by the permittivity of the subsurface through which the pulse travels. Specifically, the velocity (v) of a GPR signal through some medium is the speed of light (c) divided by the square root of the medium's permittivity (ε).

$$v = \frac{c}{\sqrt{\varepsilon}}$$

Using the 'pulse' velocity of a subsurface medium and the observed two-way travel time to a reflector, one can calculate depth to the reflecting interface. The derivation of reliable depth estimates tends to be more complicated in practice. The effective depth of exploration may actually vary across a site as a function of the spatial variation in the electrical properties of the subsurface.

Electrical permittivity is not a commonly reported field parameter. However, there are several methods to derive the velocity of a material and subsequently depth or permittivity.

One simple 'depth calibration' method involves measuring the travel time required to reflect off a target or interface (e.g., a pipe or stratigraphic surface) at a known depth and then calculate a velocity. Another procedure (walk-away test) involves using transmit and receive antennas separated by fixed distances to reflect off a horizontal subsurface interface (e.g., water table or stratigraphic layer). The change in observed reflector travel times can be used to derive a composite velocity estimate for that region of the subsurface. These methods are valid provided the electrical properties of the subsurface across the rest of the site are approximately the same as at the 'calibration' locations. Unfortunately, assumptions regarding homogeneous subsurface conditions are not always valid or known ahead of time, particularly at many urban and industrial sites with complex subsurface conditions. Consequently, some GPR practitioners only convert GPR records to a depth scale when favorable conditions or prior knowledge of subsurface electrical properties are available. Alternatively, it is possible to derive a plausible range of target depths using reasonable estimates of permittivity or pulse velocity through materials known or suspected to be present at a site.

Table A.1 summarizes estimated two-way travel times for GPR signals using very general estimates of velocity and permittivity for materials similar to those that may be present on site. Table A.1 indicates that a reflector buried in a till (silt and clay) at 6-ft would appear at approximately 40 ns, while the same reflector in dry sand would appear at 30 ns.

			Depth (ft)				
Earth Material	Relative Dielectric Permittivity	2-way Pulse Velocity (ns/ft)	2	4	6	8	10
Clay - wet	27	10.5	21	42	63	84	105
Clay - dry	4	4	8	16	24	32	48
Till (clay and silt)	11	6.7	13	27	40	54	67
Sand – wet	25	10	20	40	60	80	100
Sand – dry	6	5	10	20	30	40	50
Fresh water	81	18	36	72	108	144	180

Table A.1 – Estimated two-way travel times (ns) for targets buried at various depths within various earth materials – material values are very generalized and are based on a table available from *Geophysical Survey Systems, Inc.*

A.6 Antenna Frequency and Resolution

The depth of exploration and target resolution of GPR systems is determined by the frequency of the signal used. Typical dipole antennas used for GPR operate in the 50 MHz to 1,000 MHz frequency range. These antennas transmit an impulse consisting of a broad range of frequencies and the antennas are usually identified by their approximate highest power frequency of operation (e.g., 400 MHz, 200 MHz). The trade-off between depth of exploration and vertical resolution is related by the frequency. In general, lower frequency signals (longer wavelength, larger antenna size) penetrate deeper into the subsurface but result in lower resolution (poorer detection of small targets). Conversely, higher target resolution is achieved using a higher frequency antenna although with reduced signal penetration. One rule of thumb regarding vertical resolution and target detectability is that the size of a target must be on the order of one-half the wavelength of the signal within the subsurface. The choice of antenna is site- and target-specific. In general, lower frequency antennas provide only minimal additional depth penetration at sites where unfavorable, conductive near surface conditions are present, and they have the added disadvantage of poorer vertical resolution.

Lateral (horizontal) resolution is controlled by the trace and line spacing, with the in-line resolution usually being considerably higher than the cross-line resolution. As a rule of thumb, the horizontal resolution is approximately two times the trace or line spacing (e.g., 1-ft line spacing => ~2-ft cross-line resolution, 1-inch trace spacing => ~2-inch in-line resolution). This asymmetry in lateral resolution emphasizes the importance of conducting perpendicular crossing scans when possible.

A.7 Data Analysis and Interpretation

The advent of powerful and affordable GPR recording systems, computers and software has led to the increased use of advanced digital data processing of GPR data. Many GPR data analysis procedures were borrowed from the fields of petroleum exploration (seismic) and electrical engineering. The objectives of these methods in general are to improve the appearance of targets or features of interest while simultaneously suppressing undesirable aspects within the data such as noise and clutter. The use and application of various data analysis tools depends on factors including applicability, effectiveness, complexity, software availability, cost, turn-around time, and interpreter experience. Commonly applied data processing routines include: bandpass frequency filtering, spatial filtering, time-variable amplitude gain adjustment, average trace subtraction, and trace averaging. A wide variety of other more advanced processing algorithms may also be appropriate under favorable circumstances. Undesirable interference sources include ambient microwave noise, internal system noise and antenna-ground coupling artifacts (e.g., ringing).

GPR records are usually displayed using various shading or color assignments to correspond to different signal amplitudes. The top, horizontal axis of a GPR record typically corresponds to distance along the ground surface while the vertical axis corresponds to two-way travel time or depth if the appropriate depth conversion is made.

GPR data analysis is highly interpretive and depends on the quality of the field data, data processing methods and interpreter knowledge and experience.

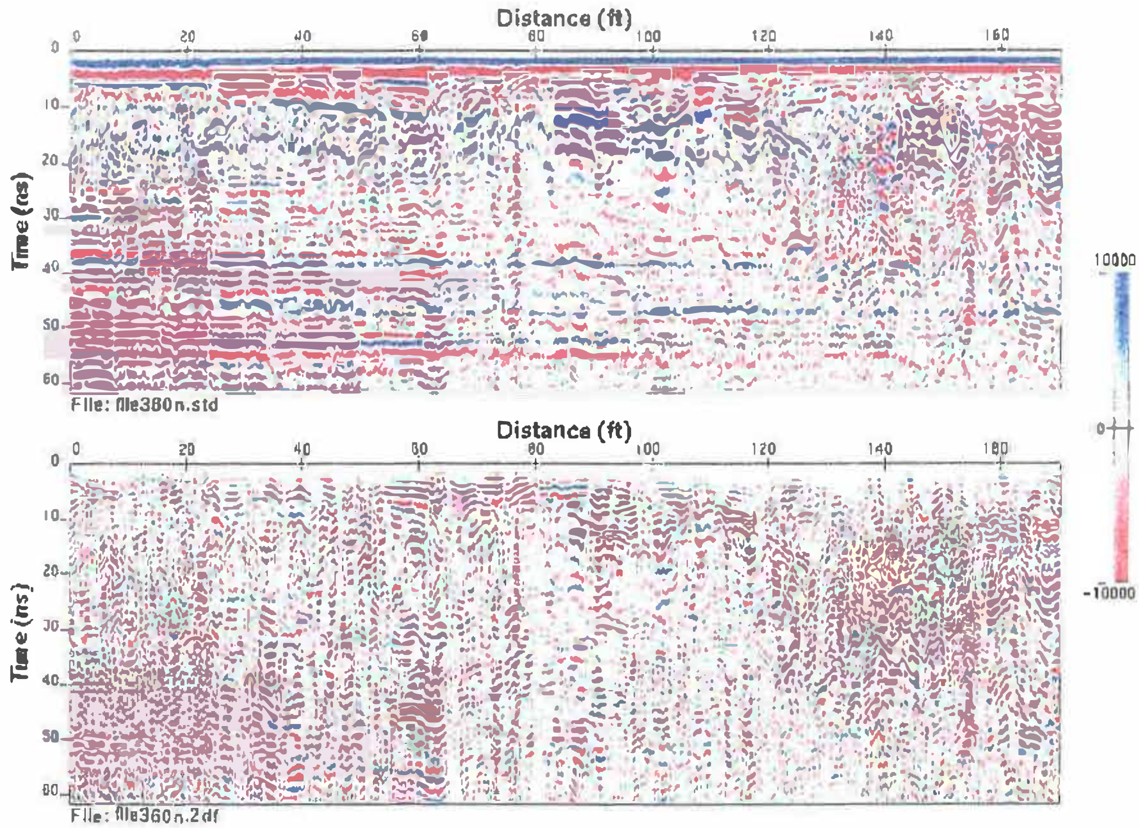


Figure A.1 - Example of raw [top] and processed [bottom] GPR record from the Demonstration-Test Area - Line 45-ft West. The processing included time-variant amplitude-gain adjustment, bandpass and spatial filtering.

APPENDIX B

B.0 3-D GPR – Standard Operating Procedures
***Grumman Exploration, Inc.*, Columbus, Ohio -1998**

B.1 Objectives

These Standard Operating Procedures (SOP) describe the 3-D Ground-Penetrating Radar (3-D GPR) procedures developed and used by *Grumman Exploration, Inc.* This SOP describes the specific equipment requirements, and generalized field, data analysis and 3-D visualization procedures. These procedures do not discuss technical issues related to the operation and application of GPR at specific sites to explore for specific targets, interpretation techniques and criteria, appropriateness of use, survey expectations and objectives, site conditions, cost, scheduling, turnaround, etc. This SOP is a general summary of the procedures used at this time. 3-D GPR is relatively new and constantly evolving to take advantage of recent innovations in computer and software technologies. Consequently, changes in equipment, procedures, computers and software used for 3-D GPR as described in this SOP may occur without notice.

B.2 Requirements

Tables B.1 and B.2 summarize the field equipment and computer technology requirements for performing a 3-D GPR survey following the *Grumman Exploration, Inc.* survey approach. Other instruments, computer and software can be substituted as appropriate and feasible. Figure B.1 shows the basic elements of the system hardware.

Item	Manufacturer/ Source	Model	Dimensions and Weight	Description
GPR System Control Unit	*GSSI*	SIR-2	11.4"x10.6"x5.5" 14 lbs.	Field ruggedized, *Intel* 486 DX2 PC, Color VGA Display, 0.5 GB Hard disk, Standard I/O Ports
GPR Antenna (400 MHz)	*GSSI*	#5103	12"x12x6.5" 12 lbs.	Bistatic dipole antenna, shielded
GPR Antenna (200 MHz)	*GSSI*	#5106	24"x24"x24" 42 lbs.	Bistatic dipole antenna, shielded
Control Cables and Accessories	*GSSI*	---	---	GPR-antenna cables + misc.
Survey Wheel	Custom built	---	---	
Field Data Download/Archive	*Iomega* (Computer Store)	*Zip Drive*	---	Archive/download field data
Power	(Automotive/ Hardware store)	---	~8"x3"x7" ~ 10 lbs.	12-v Lead Acid Battery

Table B.1 Field Survey Instrumentation for 3-D GPR

Grumman Exploration, Inc.
2076 Iuka Avenue, Columbus, Ohio 43201
(614) 421-7944 tel, (614) 421-2688 fax

Hardware	Platform	Operating System	Description
GPR System Control Unit	Customized Intel 486DX2 PC (*GSSI*)	Dos 6.2	Field data acquisition instrumentation
3-D Graphics Visualization Workstation	*Silicon Graphics. Inc. Indy R-5000* Workstation	Irix 6.2 (Unix)	Data processing, image analysis and interpretation, 3-D visualization
Field Laptop/ Desktop Personal Computers (PC)	Standard *Intel Pentium* PCs	Win 95/98/NT	Data interpretation, figure and report preparation, data management, networked to workstation & PCs

Software	Manufacturer/ Author	Platform/ Opr. System	Description (cost/availability)
BOB (Brick-of-Bytes)	*AHPCRC*	*SGI Irix 4.0-6.2*	3-D Data visualization program, Freely available on Internet
Radacal	D. Grumman	*SGI Irix 4.0-6.2*	Processing, display, image acquisition, data management program. Freely available from *The Ohio State University*
Word 97	*Microsoft Corp.*	PC Win 95/98/NT	Report Preparation (<$400)
Corel Draw 8	*Corel Corp.*	PC Win 95/98/NT	Report figure preparation (<$400)

Table B.2 Computer Platforms and Software Programs for 3-D GPR

Field Crew Size: 1-3 Persons

Site Conditions: Open, clear of obstructions, or interfering traffic or electrical noise sources

Weather: Fair weather conditions in all seasons, not during heavy precipitation, through standing water or over accumulated snow

Productivity Approximately ½ - 1 acre per day: depends on site conditions and survey objectives, number and type of antennas used, field personnel number and experience, survey line and trace density

B.3 Field Procedures

B.3.1 Initial Site Reconnaissance

Observe and walk site, meet with persons responsible for site and review project objectives and performance. Note potential problem areas and consider survey objectives, grid design and operational parameters. Identify potential calibration locations (if available).

B.3.2 Survey Design

Designate survey area, line and trace spacing and grid layout line directions and reference points. Specify GPR parameters such as antenna type, range, line density, cross-line density, detail areas.

B.3.3 GPR System Set-up, Check out and Initial Testing

Set up GPR system, check for damaged components, battery/power source integrity. Perform operational checks. Power up and observe boot-up for system problems. Observe ambient and system noise levels. Adjust range, amplitude gain curve, filters, trace averaging, acquisition mode, survey wheel triggering density, sample size, trace size, sample rate, display format and color amplitude assignments.

Run several test lines over selected test areas that may encompass a representative range of conditions anticipated at the site. Adjust the parameters noted above, and repeat test lines noted above. Note potential problems in survey surface or area. Change antennas and repeat process if appropriate.

B.3.4 Calibrations

Run depth/velocity calibrations or walk-away tests at designated location(s) if available. Perform depth velocity calculations if possible using field results.

Perform survey wheel calibration using known, marked distance interval.

B.3.5 Survey Grid Lay-out

Identify approximate limits of area(s) to be surveyed. Establish survey grids across areas. Keep survey line lengths to 100-200 ft maximum or break up survey lines into shorter segments. Reference survey grid to fixed or previously identified points. Establish a survey grid baseline and extend grid out. Use tape measures and triangulation, GPS, or other appropriate measuring tools to lay out grid. Clearly mark and annotate line designations on ground using chalk, tape, flags, traffic cones, etc. Record the general survey grid layout, coordinate system and origin, and line numbering for reference.

B.3.6 Field Survey Log

Prepare field survey log or record. Describe GPR system parameters, site conditions, survey grid and coordinate system notes, weather and other survey parameters in field log. During the GPR survey record all survey line numbers, starting and ending coordinates, data files numbers and other relevant data/observations regarding survey line. System parameters to record include: antenna make/model, center frequency, system make/model, range, zero-position, amplitude gain curve points, filters (types and cut-offs) trace averaging, acquisition mode, survey wheel triggering density, sample size, trace size, sample rate, display format and color amplitude assignments.

B.3.7 Field Survey

Initiate data acquisition and recording for each survey line. Move the antenna over designated survey lines, being careful to stay as close to directly over the line as possible. Keep antenna in close and steady contact with the ground surface as possible. Move antenna by walking, towing or driving with antenna in tow at a rate that does not exceed the data acquisition capabilities. Be careful not to snag or extend beyond the length of the antenna control cable. Stop movement at the end of each survey line and terminate recording. Set up on next line and repeat survey line traverse and data recording procedure. Continue process until survey is complete. During survey performance, periodically observe and check recorded data. If necessary, readjust system parameters and begin survey anew. Review series of lines and check for integrity, line-lengths within error limits, consistency and other problems. Perform preliminary field interpretations and determine whether to increase or decrease line or trace spacing in certain target or focus areas. Perform perpendicular cross-lines.

If a lengthy system shutdown occurs, rerun one or more lines for reference in case of electronic drift or changed field conditions. Monitor power/battery levels during survey to avoid untimely system shutdown. Do not unnecessarily shut down GPR system during survey. Upon completion of survey check line lengths/file sizes and review field data files. Repeat any missing, erroneous or other problem lines as needed. Update field log. Shut down GPR system and demobilize.

Download data to *Zip* drive, hard disk or other digital storage medium as soon after completion of fieldwork as possible. Check that all files are present and match the field log designations and sizes.

B.4 Data Analysis and 3-D Visualization

B.4.1 Preliminary/Set-up

Many of the procedures used in the 3-D GPR processing are summarized in more detail in Daniels and Grumman (1995) which contains a written guide for using the *Radacal BOB* 3-D volume rendering program (*BOB* 1992). *Radacal* is used to process and view the data and prepare the data for 3-D visualization. The *AHPCRC* program *BOB* (brick-of-bytes) performs the 3-D volume rendering. Both programs run on a *Silicon Graphics, Inc.* workstation (*SGI*) running *IRIX 4.0* through *6.2*. Recent developments allow the *BOB* program to run on a standard *Intel*-based PC using the *Linux* operating system.

Transfer data to the SGI and set up directory and file structure to manage the data and image files. Adjust available storage space and adjust as needed – processing can require from three to five times the amount of storage space as the size of the raw data set. Break up the data set into smaller, more manageable units as appropriate. Edit/delete file names and files. Edit file names to indicate line directionality. Create list file for each data group. Use text editor, spreadsheet or word processor to create a list containing the data files in the correct geometric sequence and assign the starting and ending grid line coordinates based on the field log. Check the list file for accuracy and omissions and correct.

B.4.2 Preliminary Processing

Run the *Radacal* program and set up any default parameters such as trace spacing, trace sizes, directories, etc. Perform byte-swapping using the raw data list file. Perform line standardization step to adjust the survey line lengths (number of traces per line) to correspond to actual line lengths (number of traces that should be present) using the known starting and ending coordinates and designated trace acquisition density. Specify the error threshold levels and line reversal designations. View selected 2-D GPR records and observe the raw standardized data. Note aspects such as noise, ringing, amplifications, etc. for possible use in subsequent processing steps. Observe 1-D individual traces to observe amplification levels and frequency spectrum.

B.4.3 Basic Processing Sequences

The three minimum steps that are required include: byte-swapping, line standardization and 3-D volume generation. All other processing steps, such as filtering, gain adjustments, trace averaging, etc., may occur between the line standardization and 3-D volume generation steps. A similar set of procedures occurs with each selected processing step. The generalized processing sequence using *Radacal* is as follows:

- Select processing step
- Modify the parameters
- Run the processing on one or more test files
- View the processed GPR record and selected 1-D traces
- Readjust the processing parameters and repeat until processed data meet interpretation requirements
- Run optimal processing on entire group of data (in batch)
- Move on to next processing step in sequence and repeat steps above (as required)
- Create 3-D data volume and view using *BOB* and *ICOL* program
- View 2-D GPR records, view and save images using *Radacal*
- Modify selected processing parameters and rerun above steps (as required)

There is no fixed sequence of processing steps that are should be used or are even recommended. Any processing steps are at the discretion of the interpreter and should be performed with the objective of preparing a useful 3-D data volume and processed GPR record. These will be what are used to interpret the data. The simplest and most commonly used processing sequence used by *Grumman Exploration, Inc.* includes: amplitude gain modification, bandpass filtering and spatial filtering to suppress the lowest order wave-numbers (removes most horizontal banding in GPR records).

B.4.4 3-D Volume Rendering Using the *BOB* Program

When using the *BOB* program, viewing and manipulating 3-D GPR data on the computer involves using the computer mouse to select, move, rotate and scale the 3-D image as well as change color amplitude assignments. Rendering, viewing and interpreting each 3-D image is highly interactive. Creating each 3-D image requires as little time as a few seconds to a few minutes. The entire volume of data or any sub-volume or data slice may be scaled and viewed from any angle using any color amplitude assignment. One popular approach is to observe thin slices of the data set in plan-view at different time (or depth) intervals, termed 'timeslices'. Proper scaling of the 3-D volume should be determined to maintain the same relative spatial relationships as are present in the survey area. Interpretation usually involves observing and recognizing the spatial position(s) and type(s) of reflection responses.

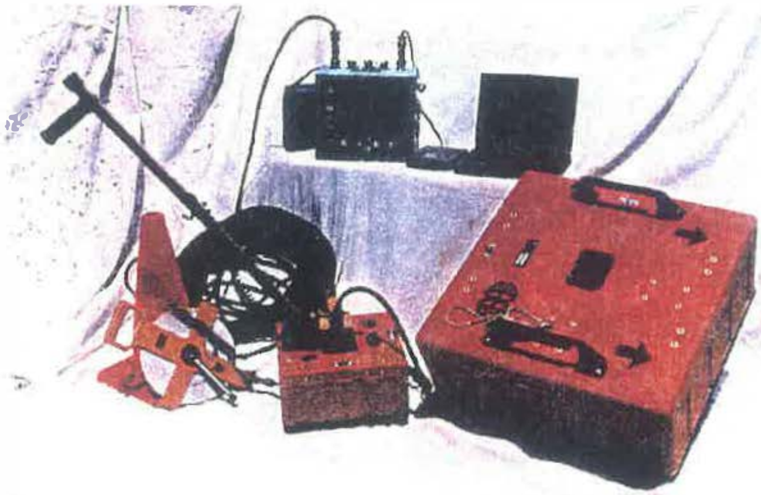
B.5 Figure and Report Preparation

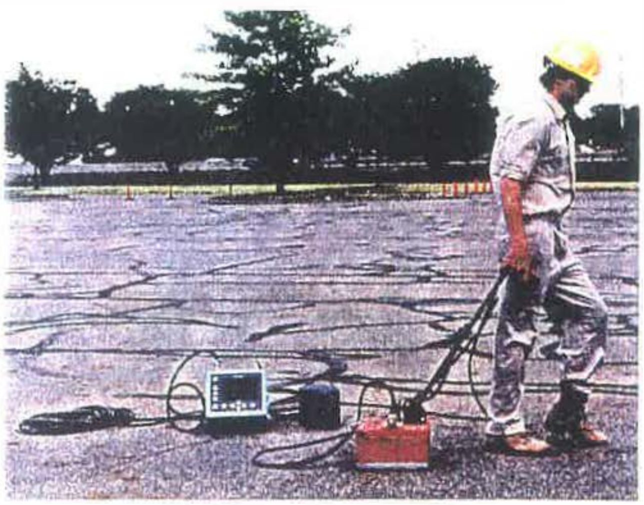
All data images created in *Radacal* and *BOB* are saved in a compressed TIFF file format. These images are portable and can be viewed in most word processing, drawing and image processing programs. The TIFF images are imported into the one or more of these types of programs and may be further interpreted or prepared for inclusion in the final report.

B.6 Data Management

Following each day of fieldwork, the GPR data should be downloaded and archived onto a *Zip* drive or other digital storage medium and checked for errors and consistency. Following the fieldwork all data are usually returned to *Grumman Exploration, Inc.*'s offices for further processing and analysis. After completion of the data processing and analysis, all raw, intermediate and final processed GPR data, including 3-D data volumes, and images, figures, list files, gain curves, and reports are archived on CD-ROM disks.

[Right] The GPR system used on the MGP Demonstration Project included the main GPR system unit (blue box in top center), 400 MHz and 200 MHz antennae (orange boxes, left and right respectively), cables and other field accessories. A *Zip* drive may be used to download the data. A standard laptop or desktop computer or the system unit itself may be used to review and manage the data.





[Left] Conducting a GPR survey using the 400 MHz antenna. While moving the antenna across the ground surface, the data are displayed and recorded in real time on the GPR system unit. The system may be set-up on a mobile platform or at a fixed location. The system requires a 12 volt power source, such as the battery shown in the photo.

[Right] Laptop computer (left) and *Silicon Graphics, Inc.* workstation (right) used for data management, processing and 3-D image analysis. The raw field data are transferred from a standard laptop or desktop PC to the workstation. A few minutes to a few hours are required to create and view 3-D images on the workstation. Recent developments now allow the 3-D imaging system to operate on a standard Intel-based PC under the *Linux* operating system.

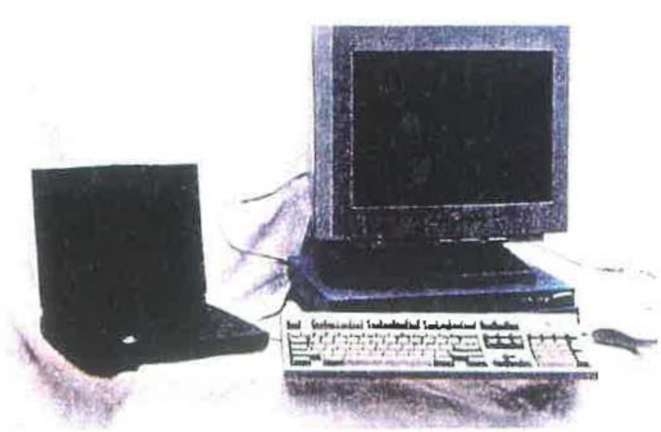


Figure B.1: Photographs of the GPR system, field procedures, and 3-D imaging computer workstation

APPENDIX C

C.0 3-D GPR – Project Cost Analysis

The Court Street MGP site generally appears to be representative of the conditions found at many MGP sites. A 3-D GPR survey performed at this site was conducted in a manner generally similar to the 3-D GPR surveys conducted by *Grumman Exploration, Inc.* at similar urban and industrial environmental sites in the Midwest. The 3-D GPR survey conducted at the Court Street MGP Demonstration site included five main components:

- Mobilization
- Set-up, Site Gridding
- Field Survey
- Data Analysis and Interpretation
- Report Preparation

The productivity and costs associated with these tasks depend on a wide range of variables including but not limited to: mobilization distance and expenses, exploration objectives and target type(s), survey line spacing (grid density) and line orientation(s), number and size of field survey crew, number of GPR system(s), number and type of antennas used, site conditions (subsurface, obstructions, topography, interference), weather conditions, complexity of data processing and analysis, level of documentation and reporting, etc.

Table C.1 summarizes the estimated full project cost and time requirements relating to various 3-D GPR survey scenarios at the Court Street Site. The first scenario is the work actually performed for the Demonstration Project in November 1998. The estimated costs associated with the hypothetical scenarios were based on an analysis of the level of effort and costs incurred during the 3-D GPR demonstration at the Court Street site. The scenario costs can be broadly broken down into a mobilization cost and a per-day onsite cost. Mobilization costs range from $2,300 to $2,400 per field crew and is based on an Ohio to New York mobilization. The daily survey rate ranges from approximately $3,300 to 3,400 per field day for each field crew and GPR system. The per day field survey cost includes all data analysis and reporting. A hybrid and possibly more realistic approach would be to use a flexible combination of these scenarios, as was used during the November demonstration. For example, one could use different survey line densities, antennas, analysis procedures, reporting protocols, etc. for different areas on site depending on the project objectives, constraints, site conditions and target(s) of interest.

3-D GPR Survey Scenario	General Survey Specifications	Survey coverage	Time requirements	Estimated Project Cost
Court Street MGP Site Survey Demonstration Project November 1998	1-ft to 2-ft line spacing, two antennas - partial site coverage, some cross-lines, on site demonstrations and partial in-field data analysis, higher level reporting	2.5 acres	4.5 days	$17,850
Court Street MGP Site Survey* No Demonstration, Same Coverage	1-ft to 2-ft line spacing, two antennas - partial site coverage, some cross-lines, standard reporting	2.5 acres	~3 days	$14,500-$15,000
Complete Site Survey* Standard Density	2-ft line spacing, single antenna 5-ft cross-lines, standard reporting	~3.5 acres	~4.5 days	$16,500-17,500
Complete Site Survey* High Density	1-ft line spacing, single antenna 5-ft cross-lines, standard reporting	~3.5 acres	~6.5 days	$24,000-$25,000

* Estimated level of effort, coverage and cost

Table C.1 Estimated Project Cost Comparison for Various 3-D GPR Survey Scenarios - All scenarios assume a single two-person field crew and GPR system