RADFORD ARMY AMMUNITION PLANT
RADFORD, VIRGINIA

Solid Waste Management Unit 40
(Nitro Landfill)
Geophysical Investigation Report

DRAFT
MARCH 2007

PREPARED BY:

URS

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cc Tina_Devine@URSCorp.com, jim spencer <james_o_spencer@urscorp.com>

bcc

Subject SWMU 40 Geophysical Investigation Report Comments

EPA and DEQ approve of the well locations for SWMU 40, the Nitro Landfill. Our comments on the report are basically the same as what was discussed at the meeting regarding the well locations. We would just like to have the URS response in writing. This can be done via email. Thanks

COMMENTS

1. Section 5.0, Conclusions and Recommended Monitoring Well Locations, on page 7 indicates that URS is recommending placement of two additional monitoring wells. These recommendations and variations from the conclusions presented in Appendix B, ATS International Resistivity Imaging Survey Report are not explained clearly. Section 6, Recommendations for Additional Monitoring Wells, of Appendix B includes suggested locations on page 7. Examples include, ATS recommended advancing the proposed well 40MW5 to a depth of 100 feet, but URS is proposing only 75 feet. Additionally, ATS recommends placement of a well along study "Line 2," to capture groundwater conditions to the west. URS is not proposing any additional wells along "Line 2." Please provide a detailed discussion on the viability of the wells proposed in light of the recommendations provided in Appendix B.

2. Appendix A, Draft RFI Assessment of Subsurface Conditions includes information from Appendix C.1 - Draft RFI Report. Section C.1.2, page C-1 indicates that Boring Logs are included in Appendix C.2. This information does not appear to have been included as part of Appendix A. Please either revise this statement or include the Boring Log information referenced as Appendix C.2 in the Report.

Similarly, Section C.1.3, also on page C-1, indicates that complete analytical results are included in Appendix C.6. This information does not appear to have been included in the Report either. Please either revise this statement or include the analytical results referenced as Appendix C.6 in the Report.

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ALLIANT TECHSYSTEMS
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April 4, 2007

Mr. William Geiger
RCRA General Operations Branch, Mail Code: 3WC23
Waste and Chemicals Management Division
U. S. Environmental Protection Agency, Region III
1650 Arch Street
Philadelphia, PA 19103-2029

Subject: Solid Waste Management Unit 40 (Nitro Landfill) Geophysical Investigation Report
Draft Document, March 2007
Radford Army Ammunition Plant Installation Action Plan
EPA ID# VA1 210020730

Dear Mr. Geiger:

Enclosed is the certification for the subject document that was sent to you on April 4, 2007.

Please coordinate with and provide any questions or comments to myself at (540) 639-8658, Jerry Redder of my staff (540) 639-7536 or Jim McKenna, ACO Staff (540) 639-8641.

Sincerely,

P.W. Holt, Environmental Manager
Alliant Techsystems Inc.

c: Russell Fish, P.E., EPA Region III, 3WC23

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Draft Document, March 2007
Radford Army Ammunition Plant Installation Action Plan
EPA ID# VA1 210020730

Dear Mr. Geiger:

Enclosed is one copy of the subject document. Your additional four copies and the certification will be sent under separate cover. Also under separate cover, one copy each will be sent to the distribution below.

This document contains proposed well locations so your quick response would be greatly appreciated.

Please coordinate with and provide any questions or comments to myself at (540) 639-8658, Jerry Redder of my staff (540) 639-7536 or Jim McKenna, ACO Staff (540) 639-8641.

Sincerely,

P.W. Holt, Environmental Manager
Alliant Techsystems Inc.

c: Russell Fish, P.E., EPA Region III, 3WC23

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bc: Administrative File
J. McKenna, ACO Staff
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J. J. Redder
Env. File

Coordination: [signature] for
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07-815-75
JMcKenna

SOLID WASTE MANAGEMENT UNIT 40 (NITRO LANDFILL)
GEOPHYSICAL INVESTIGATION REPORT
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LIST OF ABBREVIATIONS AND ACRONYMS

° ....Degree
2D-ERI............Two-Dimensional Electrical Resistivity Imaging
ATS.................ATS International
bgs...................Below Ground Surface
EPIC................Environmental Photographic Interpretation Center
ERI..................Electrical Resistivity Imaging
ft.......................Feet
MMA ....Main Manufacturing Area
PCB.................Polychlorinated Biphenyl
RFAAP............Radford Army Ammunition Plant
RCRA..............Resource Conservation and Recovery Act
RFA.................RCRA Facility Assessment
RFI ....RCRA Facility Investigation
SWMU............Solid Waste Management Unit
USEPA............United States Environmental Protection Agency
VDEQ ....Virginia Department of Environmental Quality
VI ....Verification Investigation

1.0 INTRODUCTION

1.1 SITE DESCRIPTION

Solid Waste Management Unit 40 (SWMU 40) is an inactive landfill (also known as the Nitro landfill) located in south-central portion of the Main Manufacturing Area (MMA) at Radford Army Ammunition Plant (RFAAP), Radford, Virginia (Figure 1). The landfill was not permitted and received paper, office trash, concrete, and rubber tires during the 1970s and early 1980s. Operations ceased and the unit was closed with a clay cap and grass cover. In approximately 1991, an asbestos container storage area was constructed immediately northeast of the landfill area. This area is fenced enclosed gravel covered area that contains a covered roll off container box used to temporary store asbestos containing material in double bags. Figure 2 shows the site layout.

The site is located at an elevation of approximately 1,880 to 1,900 feet (ft) above mean sea level in an upland area characterized by gently to steeply sloping ridges, the presence of landforms indicative of karst topography (e.g., sinkholes) and a general downward slope toward the northwest. The site is topographically lower than areas to the east, south, and west, and topographically higher than areas to the north (Figure 1).

Dense maintained grass covers the site. The land slopes gently to the northeast. The southeastern portion of the area is 4 to 5 ft below the grade of a generally east-west bearing paved road, whereas the southwestern portion of the site is generally level adjacent to this road. The western portion of the site is roughly coincident with a tree line. The northern boundary of the site is characterized by a distinct 10-ft scarp running generally east west and the eastern boundary is roughly coincident with the fenced asbestos storage area and is further defined by a paved road. SWMU 71, the Flash Burn Area, is located on the southwestern corner is identified by a small area surfaced with gravel.

1.2 SITE BACKGROUND AND PREVIOUS INVESTIGATIONS

The Resource Conservation and Recovery Act (RCRA) Facility Assessment (RFA) conducted by the U.S. Environmental Protection Agency (USEPA) in 1987 identified the site as having the potential to release contaminants into the environment (USEPA, 1987).

In 1992, the Environmental Photographic Interpretation Center (EPIC) under the direction of USEPA performed an assessment of multiple SWMUs at RFAAP using selected aerial photographs taken from 1937 to 1986. The study identified features representing a potential groundwater or surface water contamination sources (USEPA, 1992). Activity was first noted at SWMU 40 in a 1971 photograph and was reportedly ongoing through a 1986 photograph. The 1971 photograph reportedly indicated significant filling with three phases interpreted in the site area (USEPA 1992). The 1986 photograph indicated most of the site was re-vegetated with the exception of the northeast corner where recent filling was visible. SWMU 71 activity was first noted in the 1986 photograph. A photo-geologic interpretation was also performed as part of the EPIC study to identify solution features such as fractures and sinkholes south of the south central MMA.

Dames & Moore conducted a Verification Investigation (VI) at the site in 1991 and 1992. Four borings were completed around SWMU 40 to a depth of 49 to 162 ft below ground surface (bgs) for planned monitoring well installations. Groundwater was not encountered during drilling or in the subsequent measurements collected from borings 40MW2 and 40MW4. Bedrock encountered in the borings consisted of argillaceous limestone and dolomite with abundant clay zones. Numerous zones of intense weathering and fracturing were encountered in the borings.

Prior to development of a RCRA Facility Investigation (RFI) work plan for SWMU 40, surface and subsurface geophysical investigations were conducted by Geophex Services, Ltd (Geophex, 2001) and Argonne National Laboratory in 2001 and 2002 (ANL, 2003), respectively. Surface geophysical surveys completed included magnetic, electromagnetic, two-dimensional electrical resistivity imaging (2D-ERI), and seismic refraction tomography. Downhole electrical resistivity logging was conducted in borings

40MW2 and 40MW4 along with borehole velocity measurements for the seismic study. The geophysical surveys focused on delineating the lateral and vertical extent of waste and characterizing shallow subsurface conditions below the landfill.

A RCRA Facility Investigation (RFI) is currently being conducted at the site by URS (URS, 2004). A draft report was submitted to the USEPA and the Virginia Department of Environmental Quality (VDEQ) in December 2004 and based on comments received additional investigations will be conducted at SWMU 40 and adjacent SWMU 71 to fill identified data gaps, including:

- Further characterizing the nature and extent of polychlorinated biphenyls (PCBs) in soil north of the landfill area;
- Investigation of the groundwater migration pathway and characterization of groundwater conditions and quality in the immediate landfill area; and
- Further characterizing the nature and extent of metals and PCBs in soil at SWMU 71.

Appendix C.1 of the Draft 2004 RFI provided an in-depth discussion of site geologic and hydrogeologic conditions. It focused on the extent of the landfill material and presents results of the soil boring and test pit sampling program. A detailed comparative analysis of the various geophysical investigations was also completed. For brevity, the information is not re-presented herein but included as Appendix A. This portion of the RFI study concluded that the landfill was originally cited within a sinkhole, which can be observed in the Radford North USGS 7.5-Minute Topographic Quadrangle. Based on the soil boring and test pit sampling program, depth to bedrock interpretations were also developed and presented.

The site is underlain by the Cambrian age Elbrook Formation. The Elbrook Formation is comprised of laminated to thick-bedded dolomite, thin- to medium-bedded limestone, and dolomitic platy shale and siltstone. The average strike and dip of bedrock in the vicinity of the site is approximately 110°/26° to the southwest (URS, 2004).

Bedrock in the vicinity of SWMU 40 is highly karstified with numerous large sinkholes present. A dye-trace study completed by Parsons Engineering Science, Inc. (Parsons) (ES, 1994; Parsons, 1996) indicated that a stream which sinks approximately 200 ft east of SWMU 40 flows westward to a spring on the New River. The spring was named Parsons Spring 3. The dye traveled a distance of 4,800 ft in approximately 24 hours, indicating the presence of an open-flow karst conduit beneath or in the immediate vicinity of SWMU 40.

1.3 TASK OBJECTIVES

The objectives of this geophysical investigation at SWMU 40 are to use 2D-ERI to:

- Evaluate local bedrock structures influencing groundwater flow and potential leachate migration from the landfill waste area; and
- Identify optimal monitoring well locations and depth intervals for monitoring to intercept any potential leachate plume and to detect releases of hazardous constituents to groundwater.

2.0 INVESTIGATION METHODOLOGY

A 2D-ERI survey was conducted by ATS International (ATS), Christiansburg, Virginia under contract to URS on December 11 and 12, 2006. Survey equipment included a Tigre® 64 resistivity system manufactured by Allied Associates, Ltd in Great Britain. Data from two resistivity lines were collected at the site. Electrode spacing for each resistivity line was 5 meters (16.4 ft), and data was collected using the dipole-dipole and pole-dipole arrays with measurements to n=64. Line 1 was placed trending east to west on the north side of SMWU 40. Line 2 was placed trending north to south on the west side of the landfill area. These orientations were intended to provide optimum imaging of karst features and geologic structures at depth in the vicinity of the site, and intercept the anticipated hydraulic gradient to the north and/or west towards the New River. Figure 2 illustrates the resistivity line locations.

Resistivity measurements are collected by applying an electric current into the ground via two electrodes, and simultaneously measuring the potential at two other electrodes with a multi-meter. The dipole-dipole array provides data of significantly higher resolution than the pole-dipole array, while the pole-dipole array provides data to a greater depth. For the dipole-dipole array, a current is applied between two electrodes (current dipole) positioned a predetermined distance apart. The voltage across two other electrodes (potential dipole) is measured simultaneously with the applied current. In the pole-dipole array, an additional electrode (the remote electrode) is placed a large distance from the line of electrodes. A current is applied between the remote electrode and one within the main line of electrodes. The voltage is measured across two other electrodes in the main line of electrodes. The meter was connected via a multi-conductor cable to electrodes placed in the ground. Measurements were initiated at one end of the line and incrementally moved through the electrodes until readings had been taken at every position along the line. The value of n was then increased to add additional resistivity readings at greater depths in the subsurface. The apparent resistivity measurements collected in the field were corrected using the RES2DINV inversion modeling software (see Appendix B).

Electrode locations were flagged and marked in the field and labeled with a unique identifier for future reference. Where satellite coverage was available out of the tree line, the location of each electrode location was surveyed by URS using a Trimble global positioning system (GPS) unit.

The survey was modified from the approved work plan based on field conditions. A two-phased approach was to be used for the survey, varying the electrode spacing and length of lines. Both phases would use a dipole-dipole array. The first phase was to use two short lines in the vicinity of the landfill using an electrode spacing of 10 meters. A second longer set of resistivity lines would then be placed with electrodes at 5 meter intervals to provide high-resolution images of areas identified in the low-resolution lines. In a practical sense, the site has limited space to increase the lines along the intended orientation. Line 2 also had to be moved just west from the proposed location to maintain a straight line orientation around the fenced metals and drum storage area. It was decided to place a single set of high resolution lines with electrodes spaced at 5 meters, and to extend the lines to the maximum length the site would reasonably allow. This also had the advantage of reducing the survey time by removing the step of removal and repositioning electrodes from the low to high resolution configuration. The additional desired depth imaging was then acquired with a second pole-dipole array. Task objectives were obtained using both the dipole-dipole and pole-dipole electrode arrangements for both lines placed at maximum length. The 2D-ERI survey procedures used were consistent with the RFAAP Master Work Plan Standard Operating Procedure 20.7 (URS 2003).

3.0 INVESTIGATION RESULTS

This section summarizes the results of the resistivity survey. The dipole-dipole pseudo-section images for lines 1 and 2 are presented as Figure 3. For a more detailed presentation of results, the reader is referred to Section 4 of the ATS report (Appendix B).

A shallow zone of low resistivity indicative of landfill materials is observed between electrodes 1-32 and 1-56 (Figure 3). Two zones of abnormally low resistivity values (less than 20 Ohm-meters) are also observed in the central portion of the line below the landfill materials. The shallower of these two anomalies occurs at a depth of approximately 60 feet, and is located beneath the area between electrodes 1-32 and 1-35. The deeper anomaly occurs at a depth of approximately 100 feet, and is located beneath the area between electrodes 1-39 and 1-43. Both zones are likely karst features or fracture zones. Their location and the unusually low resistivity values may also suggest the presence of contamination (leachate) associated with the former disposal area. It is reasonable to interpret that one or both of the anomalies in that portion of Line 1 likely represents karst solutional features related to the known buried sinkhole. This interpretation is supported by previous soil boring investigations conducted by URS in 2004 (see Appendix A), and the known sinkhole feature observed on the USGS topographic map of the site which was prepared prior to placement of fill material.

In the western portion of Line 1, numerous small, relatively shallow low-resistivity features are observed which likely represent soil-filled karst features. These features are at a higher elevation than SWMU-40/71, and therefore would not be suitable locations for the placement of monitoring wells. However, a vertically extensive low-resistivity zone is observed beneath electrodes 1-17 to 1-20 which may represent a fracture zone or a larger and deeper karst feature. The central part of this feature is approximately 100 feet below grade and approximately 60 to 70 feet lower than the buried fill materials in SWMU-40.

The results for Line 2 reveal the complex and highly varied nature of the subsurface beneath the site, bearing characteristics typical of highly fractured and highly karstified terrain (Figure3). Numerous anomalies are observed in the section for Line 2, with possible fracture zones identified beneath the vicinities of electrodes 2-13, 2-23, and 2-48 and possible karst features identified beneath electrodes 2-13, 2-38 and 2-48. The interpreted karst feature beneath electrode 2-38 is at an approximate elevation of 1,830 feet, consistent with the elevation of the anomaly previously described beneath electrode 1-18, and also bears the characteristics of a partially soil- or water-filled karst feature. Due to the similarities in elevation and character of these two anomalies, it is possible that they represent a continuation of a karst conduit between those two locations.

As with the pole-dipole dataset for Line 1, the pole-dipole section for Line 2 revealed similar characteristics as the dipole-dipole data, but provided greater depth.

4.0 DISCUSSION OF GEOLOGIC AND HYDROGEOLOGIC CONDITIONS

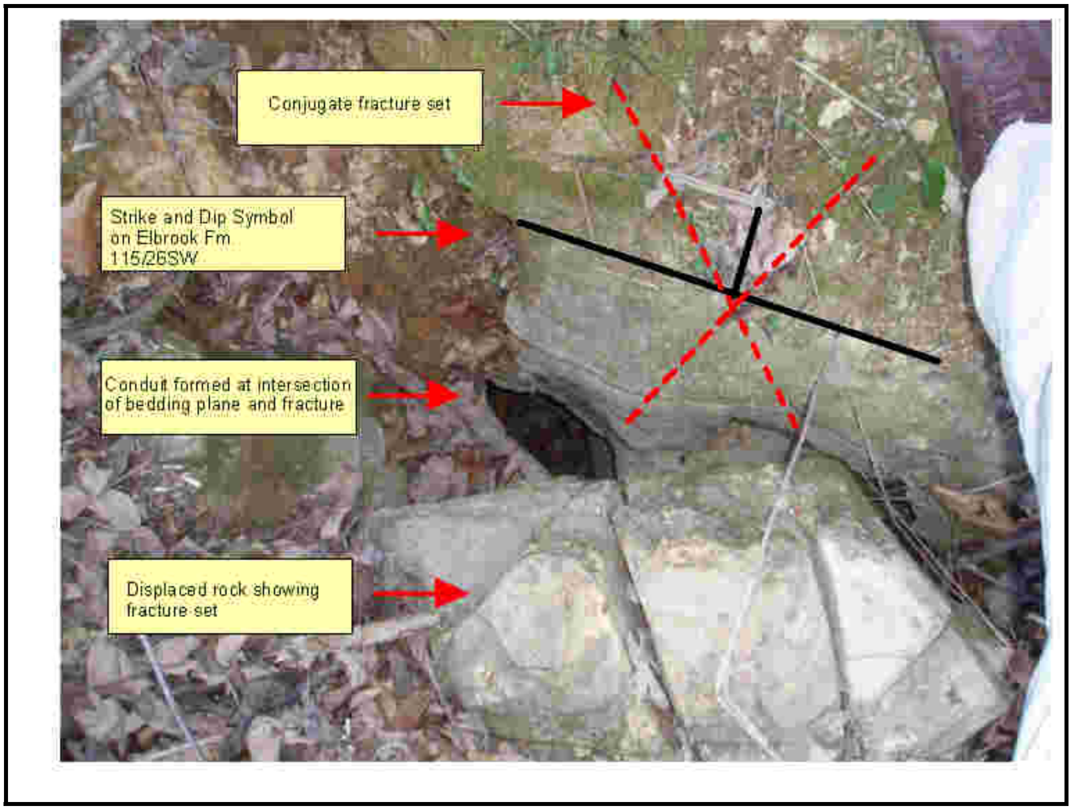
Investigation results identify several low resistivity anomalies that appear to be favorable for monitoring well placement in the immediate vicinity of the landfill. However, a number of considerations must be taken into account to determine optimal well locations, including:

1. The highly variable nature of subsurface conditions and the difficulty in placing wells to intercept preferential groundwater flowpaths developed in karst terrane.
2. Dye from injection point INJ1 at SWMU 17 traveled a minimum straight line distance of 4,800 feet in a day to S136 (Parsons 3 Spring), thus demonstrating the existence of a groundwater conduit(s) beneath the site. The direction of travel appears to be along the predominant average strike of bedrock bedding planes (110°) in the vicinity of the site. Figure 4 provides a close-up of Figure 3-7 prepared by Shaw Environmental, Inc. in the 2005 current conditions report (Shaw, 2005). It illustrates the dye travel path along with various photo-lineament, structural features and sinkhole location interpretations.
3. The Parsons 3 Spring and other springs are located within or in close proximity to the Max Meadows Tectonic Breccia, which outcrops at this location along the New River. The breccia occurs within the fault zone at the base of the Elbrook Formation. The fault in this area is a refolded splay fault structurally above the main décollement for the Pulaski Fault (Schultz, 1986).
4. Low resistivity zones and resistivity contrasts identified at depth at the site can reasonably be assumed to be water saturated karst features indicative of preferential pathways for groundwater flow.

Since geologic and hydrogeologic conditions control groundwater flowpaths, optimal placement of wells is dependent on development of an accurate working hypothesis for selection of well locations and depths.

Results of studies in the Shenandoah Valley indicate caves in the Cambro-Ordovician limestones and dolomites form along the intersections of bedding planes and joints (Harlow et al., 2005; Orndorff and Harlow, 2002). Cave conduits in general form along bedding planes, joints and faults or at the intersection of any two of these (Worthington, 2001). Additionally, sinkholes (and conduits) may preferentially develop along bedding strike with more rapid dissolution of lithologically less resistant rock. This preferential development is more readily expressed as bedding is folded and exposed to weathering. The annotated photograph on the following page illustrates some of these features of sinkhole and conduit formation in the vicinity of SWMU 40.

Conduits typically organize into a structurally controlled dendritic network feeding larger second and third order conduits that outfall to large springs (Worthington, 2001). As the distance from the spring to the perimeter of the recharge area increases, the deeper the groundwater flow, and the larger the spring. Studies in Virginia have shown that even at depths of 100 meters or more, large scale thrust faults in Virginia can be high transmissivity fault zone aquifers (Seaton and Burbey, 2005). These and the other considerations noted above suggest that the groundwater flow underneath SMWU 40 feeding the Parsons 3 Spring area is relatively deep and fed by a conduit(s) developed within or in close proximity to the Pulaski Thrust Fault at the base of the Elbrook Formation. The larger conduit(s) is fed by smaller structurally controlled conduits formed along the intersections of bedding planes and fractures or joints. It is within this context results of the resistivity survey are evaluated and the suitability of low resistivity anomalies assessed as optimal target locations for monitoring wells.



Photograph taken at the bottom of the sinkhole at resistivity line 2, electrode 46. The sinkhole location is noted on Figure 3.

5.0 CONCLUSIONS AND RECOMMENDED MONITORING WELL LOCATIONS

The positive dye trace conducted from the sinkhole at SWMU 17 indicates that an open-flow karst conduit exists beneath or in close proximity to SWMU 40. This information combined with the understanding that SWMU 40 was constructed above a sinkhole suggests groundwater migration from the vicinity of SWMU 40 is likely to be primarily to the west, generally along strike, and primarily through relatively well-developed karst conduits. The resistivity data collected to the north and to the west of SWMU 40 shows bedrock beneath the site is characterized by numerous low-resistivity anomalies which are consistent with bedrock fracture or fault zones and karst-related dissolution features.

A total of seven resistivity anomalies were identified and interpreted by ATS as fracture zones and/or karst features. Two zones of very low resistivity values are observed in the central portion of Line 1 and are interpreted as karst features or fracture zones. The anomalously low resistivity values at these locations may also indicate the presence of contamination associated with the former disposal area. Numerous anomalies are also observed in the section for Line 2, with ATS interpreting possible fracture zones beneath electrodes 2-13, 2-23, and 2-48 and possible karst features identified beneath electrodes 2-13, 2-38 and 2-48. Each of these areas are possible target locations for installation of monitoring wells.

URS recommends placement of two groundwater monitoring wells based on site geologic and hydrogeologic conditions, and the recommendations provided by ATS. Monitoring well 40MW5 is recommended to be placed at electrode 1-34. Monitoring well 40MW6 is recommended to be placed at or in the immediate vicinity of electrode 41. Wells placed at these locations would target the very low resistivity anomalies observed beneath the northern margin of the landfill area, and would likely intercept karst drainage from the probable sinkhole buried beneath SWMU 40. Well 40MW5 and 40MW6 should be completed to minimum depths of 75 and 130 feet, respectively. Figure 5 illustrates the well locations along with other wells in the vicinity of SWMU 40 that would be used during groundwater sampling at the area.

6.0 REFERENCES

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FIGURES

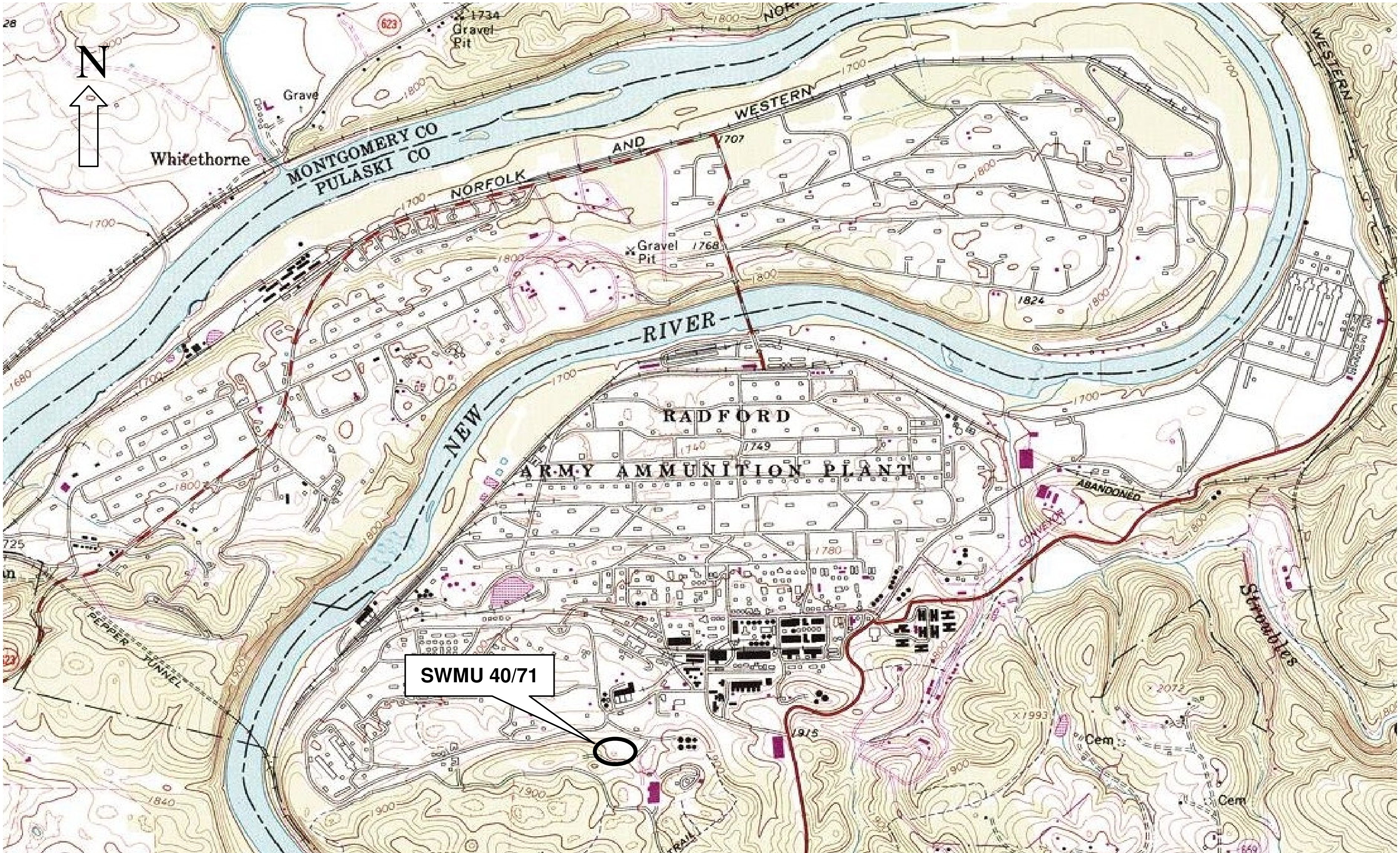


FIGURE 1

Site Location Map

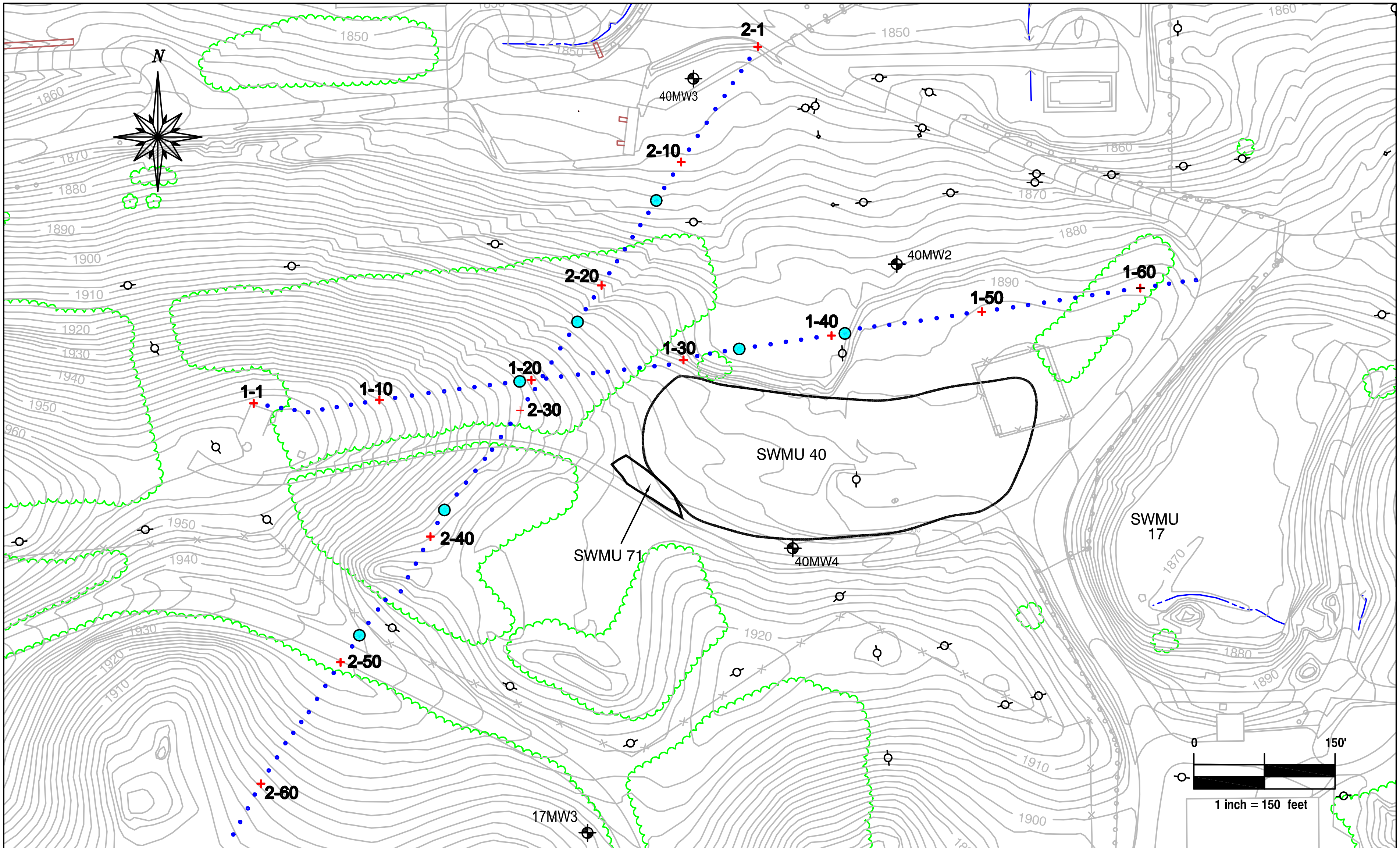
Date: January 2007	URS Project #: 21354880
Prepared by: DBC	Approved by: JOS
Scale: 1" = 2000'	File Name: Figure 1 Site Loc

SWMU 40/71

RCRA Facility Investigation
Radford Army Ammunition Plant
Radford, Virginia

URS

URS Group, Inc.
540 Falmouth Street
Suite 201
Richmond, Virginia 23230



Legend

- SWMU Boundary
- Existing Monitoring Well
- 1-10 Geophysical Resistivity Stations
- Topographic Contour
- Favorable Drilling Target for Proposed Monitoring Well
- Overhead Electric Pole

FIGURE 2

Site Layout with
Geophysical Resistivity Lines

Date: January 2007	URS Project #: 21354880
Prepared by: DBC	Approved by: JOS
Scale: 1 inch = 150 feet	File Name: Fig.2

SWMU 40/71

RCRA Facility Investigation
Radford Army Ammunition Plant
Radford, Virginia

URS Group, Inc.
5540 Falmouth Street
Suite 201
Richmond, Virginia 23230

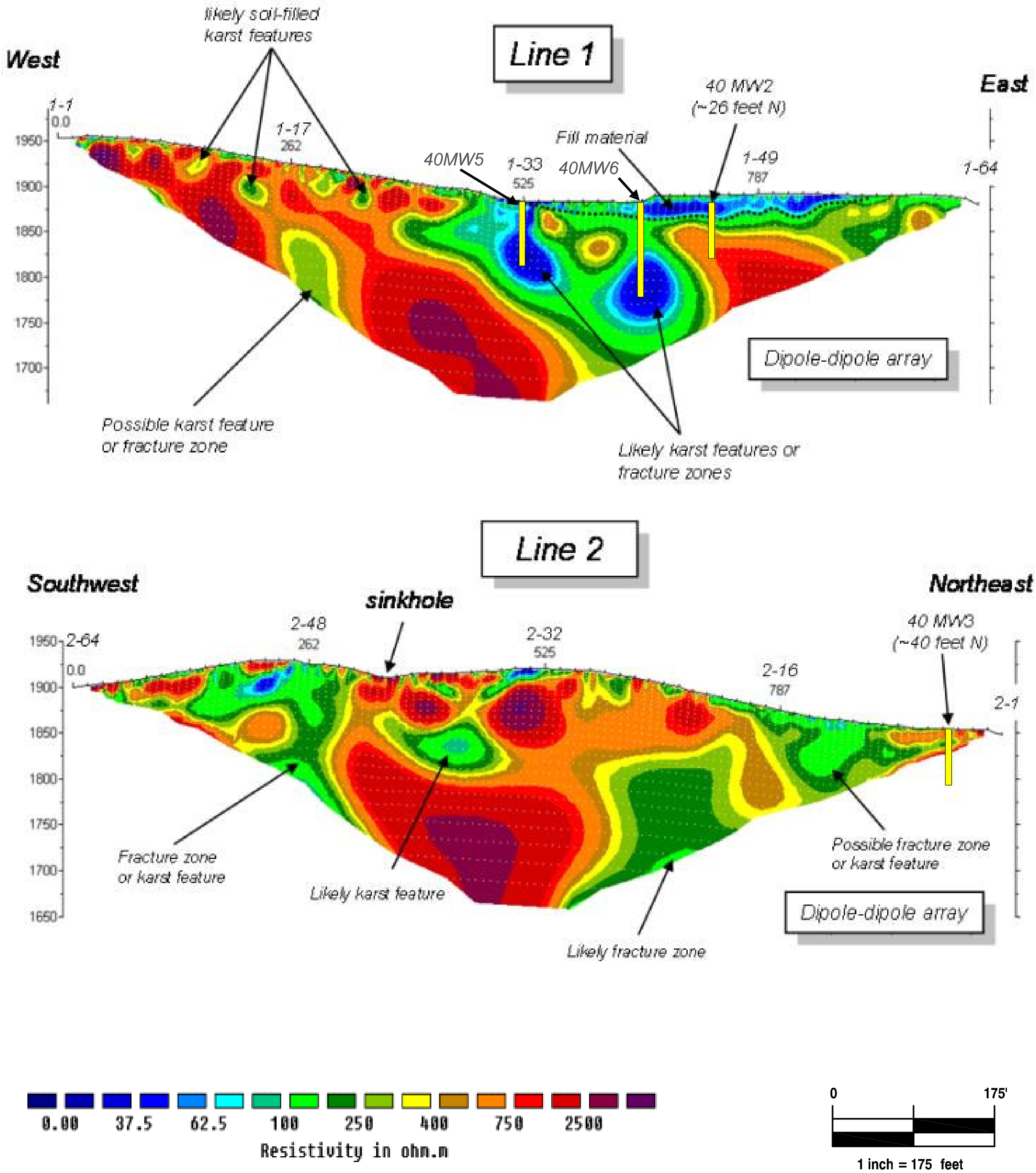
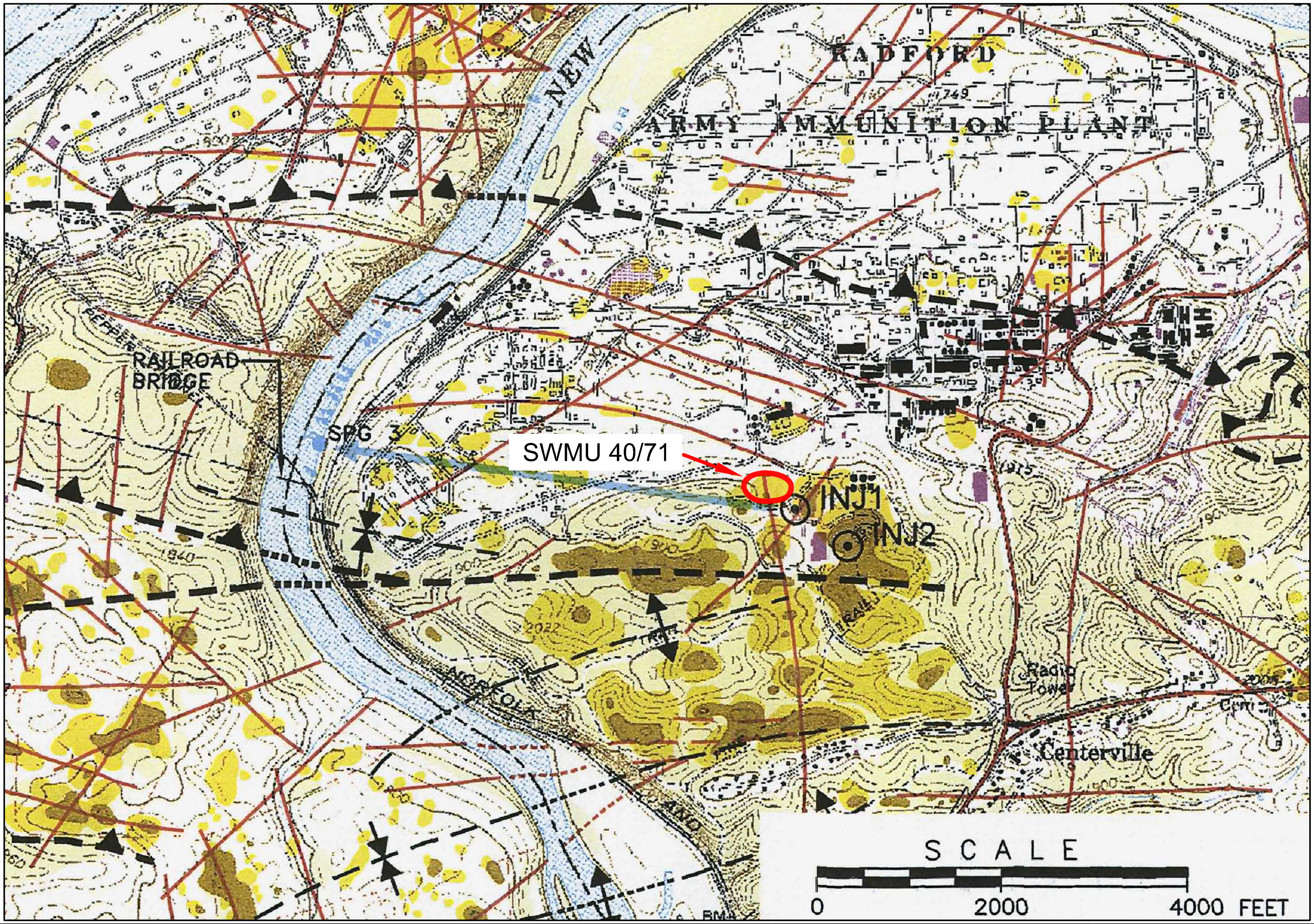


FIGURE 3 Annotated Dipole-Dipole Resistivity Psuedo-Sections		SWMU 40/71 RCRA Facility Investigation Radford Army Ammunition Plant Radford, Virginia
Date: February 2007	URS Project #: 21354880	
Prepared by: DBC	Approved by: JOS	URS URS Group, Inc. 5540 Falmouth Street Suite 201 Richmond, Virginia 23230
Scale: 1 inch = 175 feet	File Name: Fig. 3 Annot.DD Res	



LEGEND:

- PHOTOLINEAMENTS
- USGS SINKHOLES
- ENGINEERING SCIENCE INC. SINKHOLES
- INJ2 DYE INJECTIONS
- SPG 3 SPRING
- DYE TRACE FLOW DIRECTION

STRUCTURES:

- PULASKI THRUST FAULT SPLAY
- ANTIFORM
- SYNFORM

Source: Current Conditions Report, Shaw, 2005

N

FIGURE 4

Interpreted Photo - Lineaments, Sinkholes and Dye Trace Results

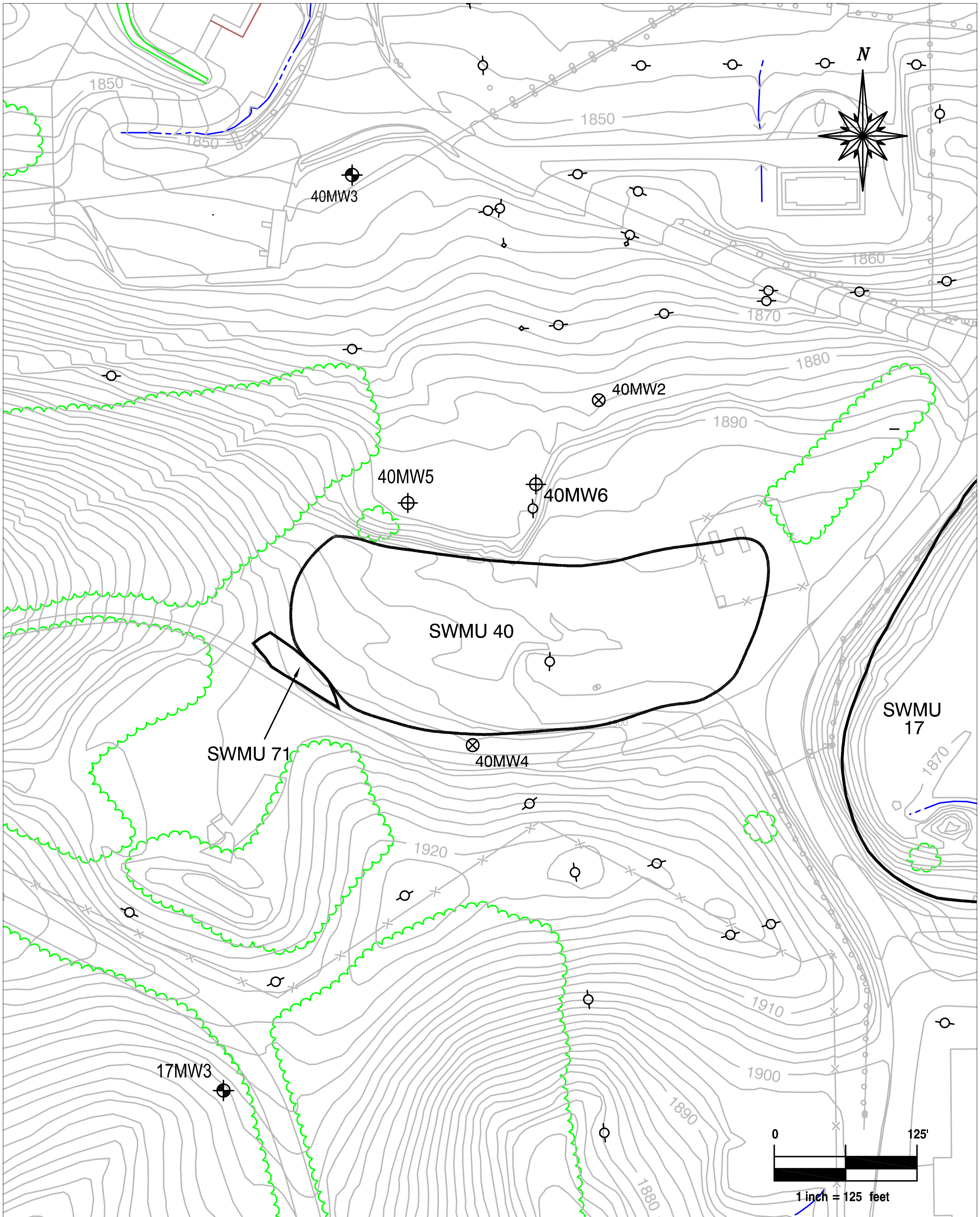
Date: January 2007	URS Project #: 21354880
Prepared by: DBC	Approved by: JOS
Scale: As Shown	File Name: Fig.2

SWMU 40/71

RCRA Facility Investigation
Radford Army Ammunition Plant
Radford, Virginia

URS

URS Group, Inc.
5540 Falmouth Street
Suite 201
Richmond, Virginia 23230



Legend

- SWMU Boundary
- Existing Monitoring Well
- Proposed Monitoring Well Location
- Previous Bedrock Boring Location
- Overhead Electric Pole

FIGURE 5

Proposed Monitoring Well Locations

Date: February 2007	URS Project #: 21354880
Prepared by: DBC	Approved by: JOS
Scale: 1 inch = 125 feet	File Name: Fig. 3 Prop. Well Loc.

SWMU 40/71

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APPENDIX A

DRAFT RFI ASSESSMENT OF SUBSURFACE CONDITIONS
(APPENDIX C.1 – DRAFT RFI REPORT)

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C.0 ASSESSMENT OF SUBSURFACE CONDITIONS

A description of the regional soil, geology, and hydrogeology at RFAAP is presented in Section 3.0 of the MWP (URS, 2003). General information on site-specific conditions, as revealed by previous investigations, is presented in Section 2.0 of this report.

C.1 DATA COLLECTION ACTIVITIES

Historical aerial photographs and previous investigation data were reviewed, and surface and borehole geophysical surveys were conducted by Geophex. These data were used to initially evaluate the potential horizontal and vertical extent of the former Landfill and to locate RFI soil borings, test pits, and follow up geophysical surveys at SWMU 40/71.

Pertinent data points used to evaluate subsurface conditions are shown on Figure C-1. The data points include VI borings and groundwater monitoring wells, RFI soil borings and test pits, and selected bedrock outcrops. Field investigation methods for the RFI data collection activities are discussed in Section 3.4 and RFI field activities are discussed below.

C.1.1 Soil Borings

Sixteen direct-push soil borings were completed to refusal, which presumably occurred on weathered bedrock (see Figure C-1). Boring depths ranged from 6.0 ft bgs (40SB13) to 44.8 ft bgs (40SB4). Summary data for the soil borings completed at SWMU 40/71 are presented in Table C-1. Boring logs are included in Appendix C.2.

C.1.2 Test Pits

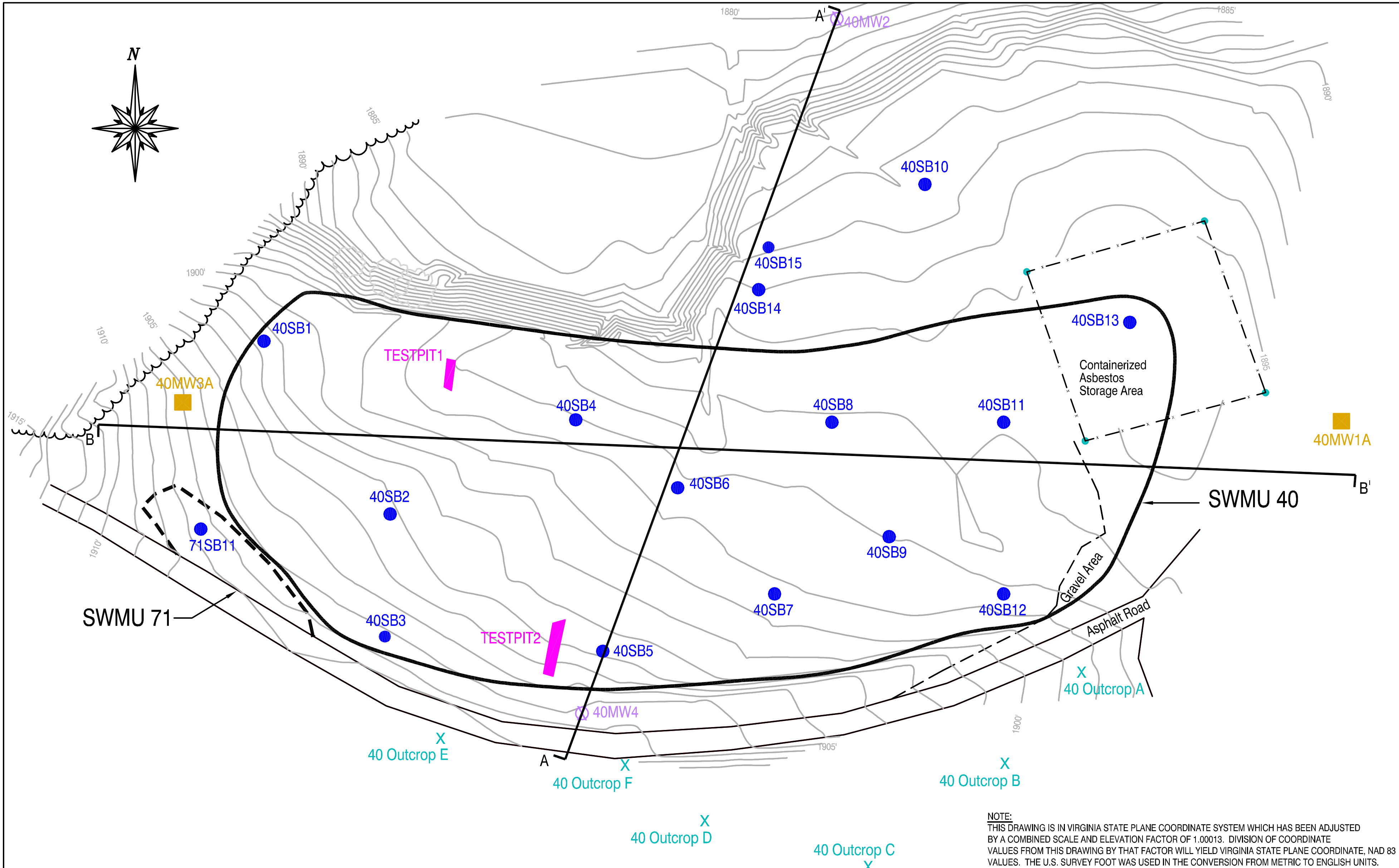
Two backhoe test pits (Test Pit 1 and Test Pit 2) were excavated at areas within SWMU 40 (see Figure C-1). Test pit logs are included in Appendix C.2.

Test Pit 1 was excavated to a depth of 13.7 ft bgs within the northwestern part of SWMU 40 in an area of geophysical anomalies identified by Geophex. Landfill material was encountered in this test pit from a depth of 1 ft bgs to the termination depth. Water seepage from the landfill material into Test Pit 1 was observed at a depth of 11 ft bgs.

Test Pit 2 was excavated to near the southern edge of SWMU 40 to further evaluate the southern extent of landfill material and its nature. This test pit was excavated to refusal on weathered bedrock, which occurred at depths ranging from 4.5 ft bgs (south end) to 13 ft bgs (north end). Approximately 2 ft of landfill material was encountered at the southern end of the test pit, which was underlain by approximately 1 ft of residual soil above weathered bedrock. Approximately 6.5 ft of landfill material was encountered at the northern end of the test pit, which was underlain by 2 ft of residual soil above weathered bedrock. Water seepage was not observed in Test Pit 2.

C.1.3 Physical Soil Testing

Four soil samples from the soil borings were submitted to the URS geotechnical laboratory in Totawa, New Jersey for physical soil testing. Physical testing parameters are described in Table 3-1 and in Section 3.2. Testing results are summarized in Table C-2, with complete analytical results in Appendix C.6.



Legend

1915	Topographic Contour Line
—x—x—	Fence
X 40 Outcrop B	RFI Bedrock Outcrop
TESTPIT1	RFI Test Pit
40SB8	RFI Soil Boring
40MW2	VI Groundwater Monitoring Well
40MW3A	VI Boring
A A'	Geologic Cross-section

0 60'
1 inch = 60 feet

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SWMU 40/71 RFI

FIGURE C-1

RFI Geologic Data Points

Date: *November 2003*	**Prepared By:** *KDC/CL*
Scale: *1" = 60'*	**File Name:** *21354880*

Table C-1
Soil Boring, Test Pit, and Bedrock Outcrop Data
SWMU 40/71 RCRA Facility Investigation Report
Radford Army Ammunition Plant, Radford, Virginia

Data Point ID No.	Date	Elevation				Depth to Bottom			Thickness			Comments
		Ground Surface	Refusal (Top of Bedrock)	Top of Landfill Material	Bottom of Landfill Mat / Top Residual Soil	Soil Fill	Landfill Material	Boring Refusal	Soil Fill	Landfill Material	Residual Soil	
SWMU 40 - Landfill												
40SB1	15-Nov-02	1901.9	1890.9	1898.9	1893.8	3.0	8.1	11.0	3.0	5.1	2.9	Landfill Material
40SB2	15-Nov-02	1902.1	1887.0	1900.8	1888.1	1.3	14.0	15.1	1.3	12.7	1.1	Landfill Material
40SB3	14-Nov-02	1905.3	1896.4		1903.2	2.1		8.9	2.1		6.8	No Landfill Material
40SB4	14-Nov-02	1896.6	1851.8	1893.1	1878.6	3.5	18.0	44.8	3.5	14.5	26.8	Landfill Material
40SB5	14-Nov-02	1901.8	1892.8	1899.3	1893.8	2.5	8.0	9.0	2.5	5.5	1.0	Landfill Material
40SB6	13-Nov-02	1897.9	1881.0	1893.9	1882.0	4.0	15.9	16.9	4.0	11.9	1.0	Landfill Material
40SB7	13-Nov-02	1898.4	1877.4	1891.9	1881.4	6.5	17.0	21.0	6.5	10.5	4.0	Landfill Material
40SB8	13-Nov-02	1896.2	1871.1	1889.7	1878.2	6.5	18.0	25.1	6.5	11.5	7.1	Landfill Material
40SB9	13-Nov-02	1897.0	1877.0	1892.5	1882.0	4.5	15.0	20.0	4.5	10.5	5.0	Landfill Material
40SB10	13-Nov-02	1892.7	1877.8		1889.7	3.0		14.9	3.0		11.9	No Landfill Material
40SB11	12-Nov-02	1895.9	1870.1	1891.9	1882.9	4.0	13.0	25.8	4.0	9.0	12.8	Landfill Material
40SB12	11-Nov-02	1897.2	1870.2		1894.7	2.5		27.0	2.5		24.5	No Landfill Material
40SB13	19-Nov-02	1895.5	1889.3		1890.3	5.2		6.2	5.2		1.0	No Landfill Material
40SB14	18-Nov-02	1893.9	1880.5		1885.9	8.0		13.4	8.0		5.4	No Landfill Material
40SB15	18-Nov-02	1892.9	1861.4		1881.9	11.0		31.5	11.0		20.5	No Landfill Material
40MW1A	21-Oct-91	1892	1890		1892.0			2.0	0.0		2.0	No Landfill Material
40MW2	20-Oct-91	1881	1864		1881.0			17.0	0.0		17.0	No Landfill Material
40MW3A	18-Oct-91	1905	1901		1904.0	1.0		4.5	1.0		3.5	No Landfill Material
40MW4	28-Oct-91	1906	1892		1905.0	1.0		14.0	1.0		13.0	No Landfill Material
TEST PIT 40TP-1	20-Nov-02	1897.3		1896.3	< 1882.6	1.0	> 13.7		1.0	12.7		Refusal not reached *
TEST PIT 40TP-2	20-Nov-02	1903.5	1890.5	1899.0	1892.5	4.5	11.0	13.0	4.5	6.5	2.0	Refusal south edge
40 OUTCROP A		1898.4	1898.4									Strike 110.0 Dip 15.0
40 OUTCROP B		1900.1	1900.1									Strike 111.0 Dip 16.0
40 OUTCROP C		1912.3	1912.3									Strike 112.0 Dip 12.0
40 OUTCROP D		1910.4	1910.4									Strike 114.0 to Dip 12.0
40 OUTCROP E		1908.5	1908.5									Strike 115.0 to Dip 15.0
40 OUTCROP F		1907.3	1907.3									Strike 111.0 to Dip 16.0
SWMU 71 - Flash-Burn Area												
71 SB11	18-Nov-02	1906.6	1899.7		1904.4	2.2		6.9	2.2		4.7	No Landfill Material

Table C-2
Soil Physical Testing Results
SWMU 40/71 RCRA Facility Investigation Report
Radford Army Ammunition Plant, Radford, Virginia

Soil Sample				Physical Analyses															
Location	Depth (feet) bgs	SWMU 40/71 Geologic Unit	USCS Soil Type	Water Content (D2216)	Liquid Limit (D4318)	Plastic Limit (D4318)	Plastic Ind. (D4318)	Sieve Minus No. 200 (D422)	Hydrometer % Minus 2 µm (D422)	pH Distilled Water (D4972)	pH 0.01 M CaCl Solution (D4972)	Organic Content (D2974)	Soil Particle Density (D854)	Total Bulk Density (D2937)	Dry Bulk Density (D2937)	Hydraulic Conductivity (D5084)	Total Soil Porosity (Calculated)	Air-Filled Soil Porosity (Calculated)	Water-Filled Soil Porosity (Calculated)
				%	-	-	-	%	%	--	--	%	--	pcf	pcf	cm/sec	-	-	-
40SB4	**0 - 4**	**Soil Fill**	**CL**	18.1	35	13	22	60.9	27	6.8	6.6	5.5	2.687	129.0	109.2	6.6E-08	0.35	0.02	0.33
40SB4	**30 - 32**	**Residual Soil**	**CH**	41.0	50	23	27	79.9	33	6.5	6.4	3.0	2.691	114.9	81.4	8.5E-08	0.52	0.00	0.52
40SB9	**0 - 4**	**Soil Fill**	**CL**	19.4	30	14	16	nt*	nt*	8.8	7.5	2.8	2.692	131.9	110.5	2.7E-09	0.34	0.00	0.34
71SB11	**3 - 5**	**Residual Soil**	**CH**	32.1	55	23	32	95.1	53	6.6	6.4	4.1	2.685	117.2	88.7	1.1E-07	0.47	0.01	0.46

Notes:
nt* = Not tested because of insufficient sample quantity
bgs = Below ground surface
pcf = Pounds per cubic foot
cm/s = centimeters per second
USCS = Unified Soil Classification System
CL = Low Plasticity Clay
CH = High Plasticity Clay
(D2216) = ASTM Test Method
Unconsol = Unconsolidated
-- = Unitless

Two samples submitted for testing were representative of the surface soil fill material overlying the landfill material at SWMU 40; these samples were collected from borings 40SB4 and 40SB9 at a depth interval of 0 to 4 ft bgs. The remaining two samples submitted for testing were representative of undisturbed naturally occurring subsurface residual soil present below landfill material and above weathered bedrock; these samples were collected from borings 40SB4 (32 to 39 ft bgs) and 71SB11 (3 to 5 ft bgs).

C.1.4 Evaluation of Bedrock Outcrops

Six outcrops of the Cambrian-Age Elbrook Formation were examined during the RFI at locations just south of the asphalt road that runs along the southern boundary of SWMU 40/71 (Figure C-1). Exposed bedrock at the five outcrops was geologically described and the strike and dip of bedding were measured. Outcrop elevation data and strike and dip measurements are summarized in Table C-1 and in Section C.1.4.

C.2 GEOPHYSICAL SURVEYS

Surface geophysical surveys and borehole geophysical logging were performed at SWMU 40/71 by Geophex before preparation of WPA 14. The objectives of the Geophex surveys were to characterize subsurface conditions and develop a preliminary estimate of the extent of the former Landfill.

ANL conducted follow-up geophysical surveys during the RFI, which included both surface and subsurface components. The objectives of the ANL surface survey were to confirm the geophysical models constructed by Geophex, assess the top of weathered bedrock and bedrock, and assist in further definition of the extent of buried material. The objective of the subsurface survey (borehole geophysical logging) was to evaluate subsurface characteristics in two VI monitoring wells to provide control for the surface geophysics.

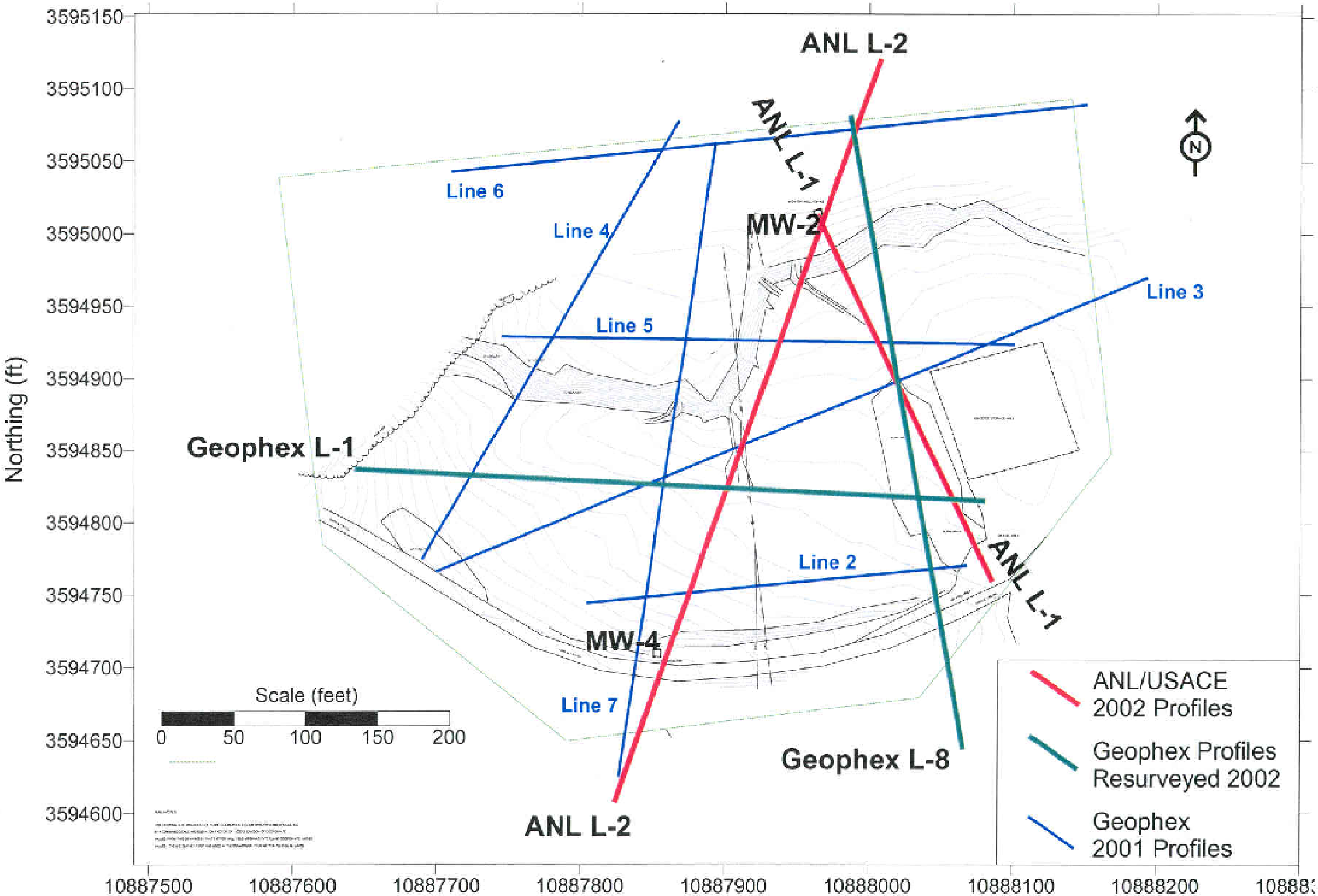
C.2.1 Geophex Survey - 2001

The Geophex geophysical survey used magnetic, EM induction, and DC resistivity methods. Borehole logging of VI monitoring wells 40MW2 and 40MW4 was conducted using natural gamma ray and EM induction methods (conductivity and resistivity). EM and magnetic surveys were conducted on parallel tracklines spaced at intervals of 5 feet. After analysis of the EM and magnetic data, Geophex completed DC resistivity profiles along eight profile tracklines, which included three generally parallel north-south lines (Nos. 4, 7, and 8), and five generally parallel east-west lines (Nos. 1, 2, 3, 5, and 6). The locations of the geophysical tracklines are shown on Figure C-2.

Potential limits of waste disposal at SWMU 40/71 were mapped by the EM survey, as shown on Figures C-3 (1,050-hertz) and C-4 (170-hertz). Additional discussions of the EM survey and other Geophex survey are presented in Section 2.3.4 (previous investigations), in Section C.3.2 as part of the integrated interpretation of subsurface conditions using geophysical, boring, and test pit data, and in the ANL Geophysical Report included in Appendix D.2.

C.2.2 ANL Survey - 2002

The ANL surface geophysical survey used 2D-ERI and seismic refraction profiling/tomography to evaluate changes in the electrical (2D-ERI) and acoustic (seismic) characteristics of subsurface materials. Borehole velocity surveys were conducted in VI monitoring wells 40MW2 to 57 feet bgs and 40MW4 to



Legend

MW-4 □	VI Groundwater Monitoring Well (40MW2 and 40MW4)
ANL	Argonne National Laboratory
Geophex	Geophex Services, Ltd.
*Note:	Modified from Argonne National Laboratory, April 2003.

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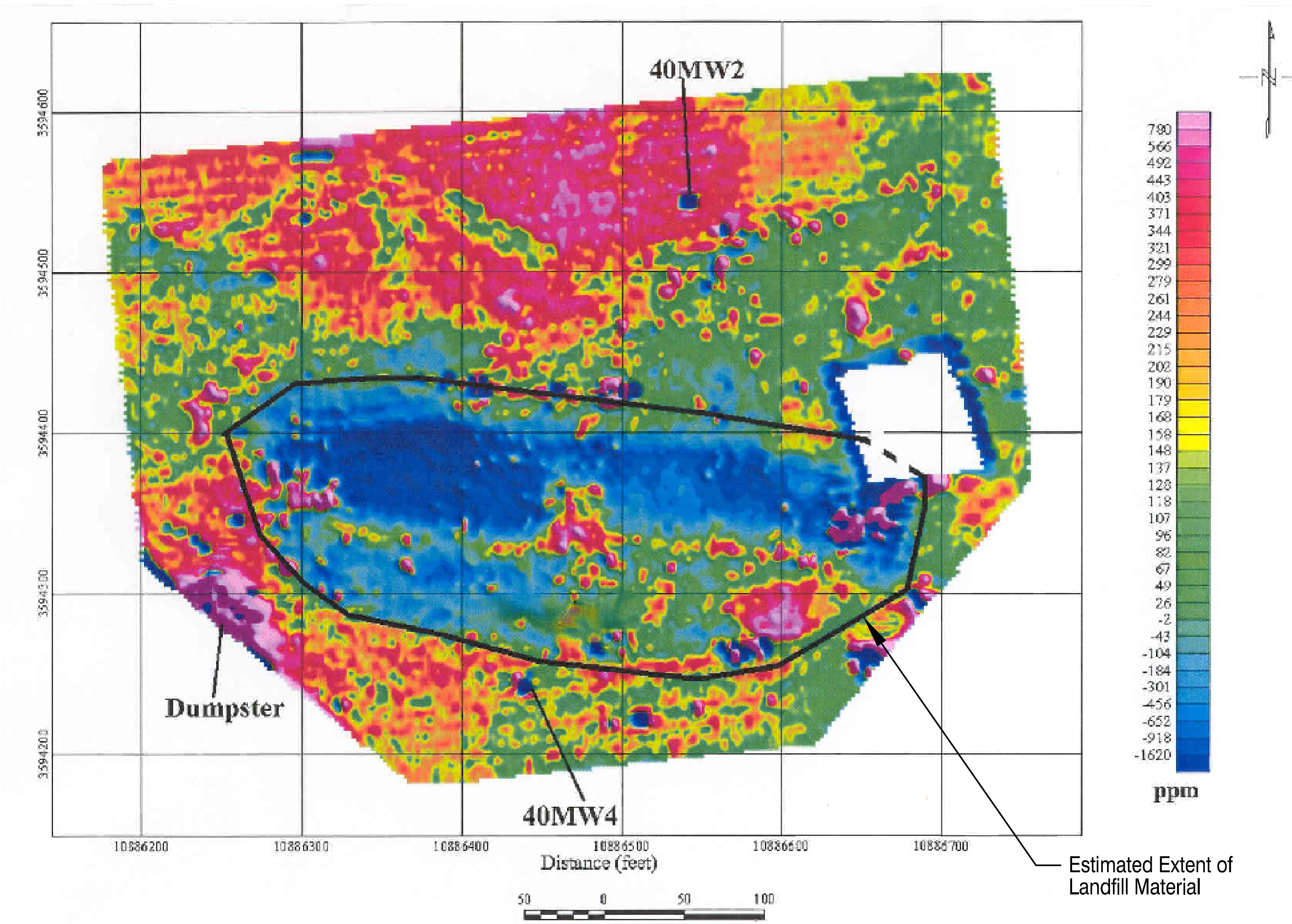
Scale: 1" = 100'	File Name: 21354880

FIGURE C-2

Surface Geophysical Survey Profile Lines



Legend

40MW4 VI Monitoring Well

*Note: Modified from Geophex Services, Ltd., May, 2001.

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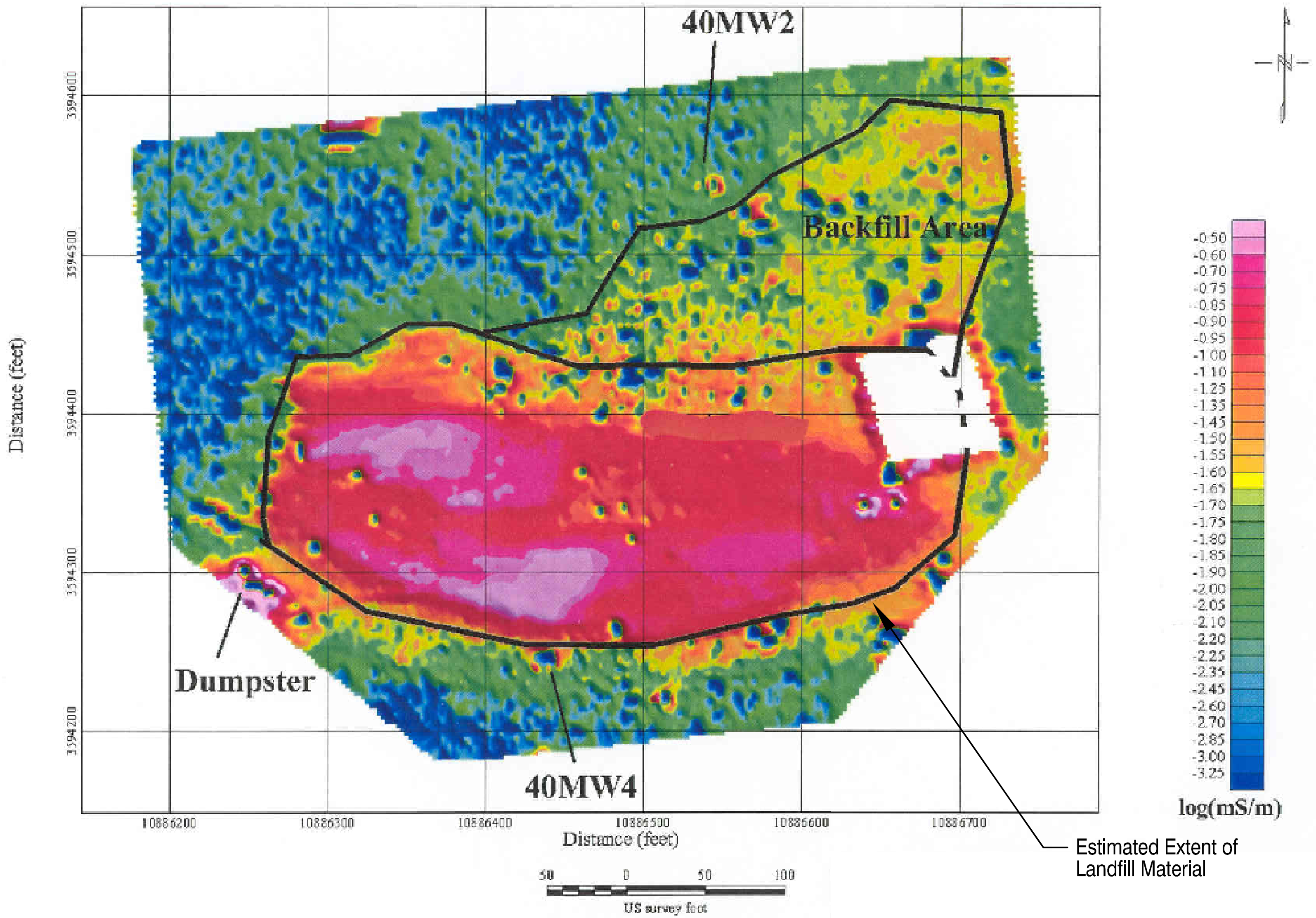
Scale: 1" = 100'	File Name: 21354880

FIGURE C-3

Geophex EM 1,050 Hz. Inphase Survey



Legend

40MW4 VI Monitoring Well

*Note: Modified from Geophex Services, Ltd., May, 2001.

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Scale: 1" = 100'	**File Name:** 21354880

FIGURE C-4

Geophex EM 4, 170 Hz. Apparent Conductuvity

64 feet bgs to provide confirmatory/baseline information concerning the subsurface geologic-material for the seismic refraction models.

The ANL surface geophysical surveys were performed along four profile tracklines at SMWU 40/71 shown on Figure C-2 as described below.

ANL Profile L-2 (see Figure C-5) – Both 2D-ERI and seismic refraction profiling/tomography surveys were performed along this north south profile that connects monitoring wells 40MW2 and 40MW4, which were used as subsurface control points;

ANL Profile L-1 (see Figure C-6) – Both 2D-ERI and seismic refraction profiling/tomography surveys were performed along this north south profile tied to monitoring well 40MW-2;

Geophex Profile L-8 (see Figure C-6) – ANL reprocessed existing Geophex data along this profile and completed a new 2D-ERI survey; and

Geophex Profile L-1 (see Figure C-7) – ANL reprocessed existing Geophex data along this profile and completed a new 2D-ERI survey.

Interpretations of the above profiles and subsurface geophysical data are presented in Sections C.3.1 through C.3.3 as part of the integrated geologic analysis of the geophysical and geotechnical data collected at SWMU 40/71 for the RFI.

C.3 SUBSURFACE CONDITIONS

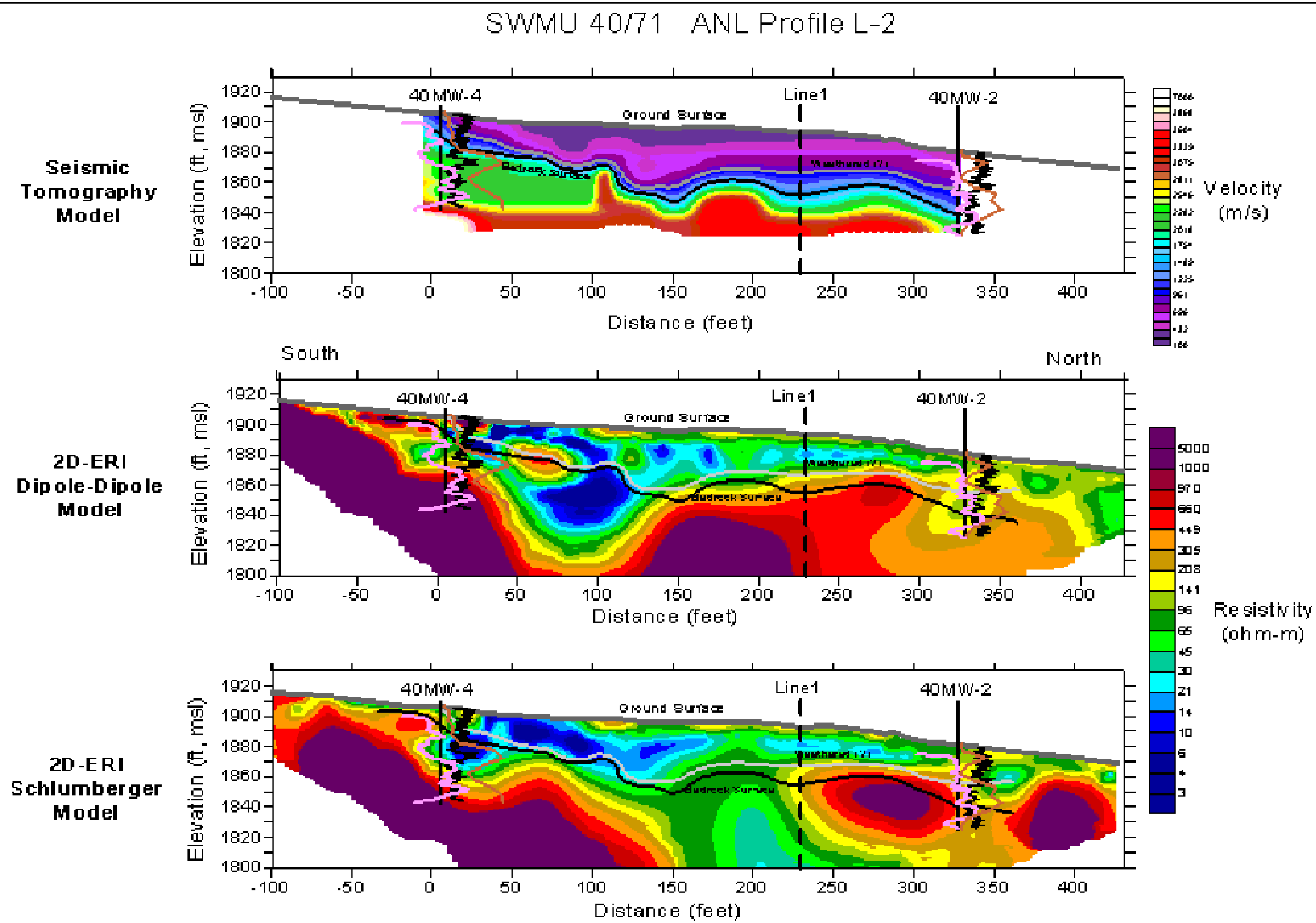
In addition to the geophysical surveys, subsurface conditions at SWMU 40/71 were evaluated for the RFI through the drilling of 16 soil borings and excavation of two backhoe test pits. In addition, six outcrops of the Elbrook Formation were geologically assessed. The locations of the RFI boreholes, test pits, and bedrock outcrops are shown on Figure C-1.

Subsurface investigations have identified four strata underlying the SWMU 40/71, which consist of from top down: soil fill, landfill material, residual soil, and bedrock. The following sections discuss the nature of these strata and present integrated geological interpretations of the geophysical and geotechnical data collected at SWMU 40/71.

Two geological cross-sections (A-A’ and B-B’) have been constructed to show the interpreted geologic conditions in the area of SWMU 40/71. Cross-section A-A’ is oriented along Profile ANL-2, which runs north south across SWMU 40 between monitoring wells 40MW2 and 40MW4 (see Figure C-8). Cross-section B-B’ is oriented along Geophex Profile L-1, which runs east west across the center of SWMU 40 (see Figure C-9).

C.3.1 Soil Fill

Soil fill material is present at the surface and across the area of SWMU 40/71 extending to the base of the scarp located north of SWMU 40. The thickness of fill material encountered at boring and test pit locations ranged from 1 ft at the southern and eastern periphery of SWMU 40 to 11 ft at boring 40SB15 located north of SWMU 40. Within the area of SWMU 40, soil fill material caps underlying landfill material, with a maximum observed thickness of 6.5 ft above the landfill material (see Table C-1). Soil fill material generally consists of dark brown to yellowish brown lean clay (CL) and sandy lean clay (CL) with variable gravel at the surface or near surface. A more extensive area of surface gravel and cinder



Legend

VI Monitoring Well

ANL Profile Line 1

*Note: Source: Argonne National Laboratories (ANL) (2003)

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SWMU 40/71 RFI

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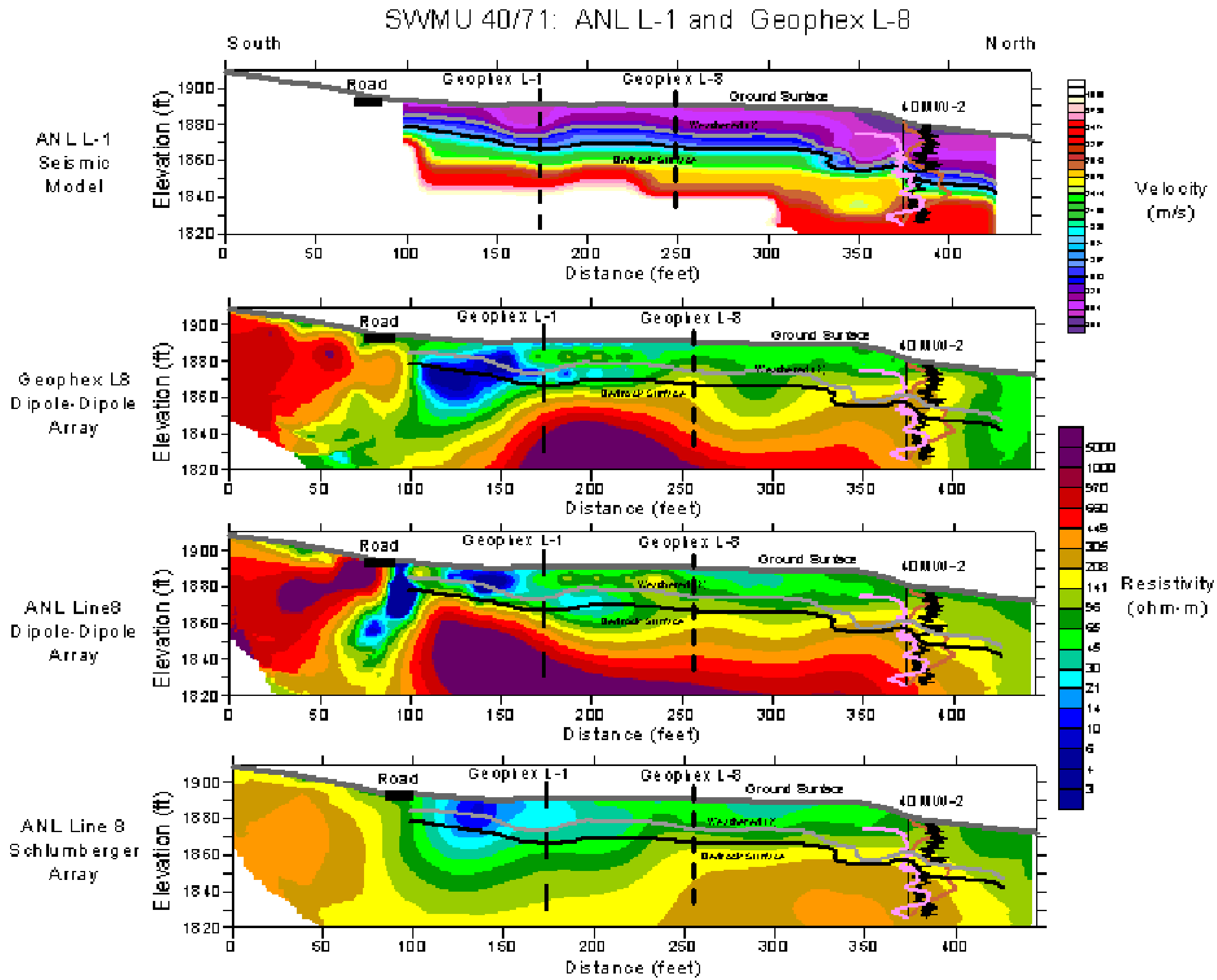
Scale: As Shown

File Name: 21354880

FIGURE C-5

ANL Geophysical Surveys Profile Line ANL L-2



Legend

| VI Monitoring Well

¦ ANL Profile Line 1

*Note: Source: Argonne National Laboratories (ANL) (2003)

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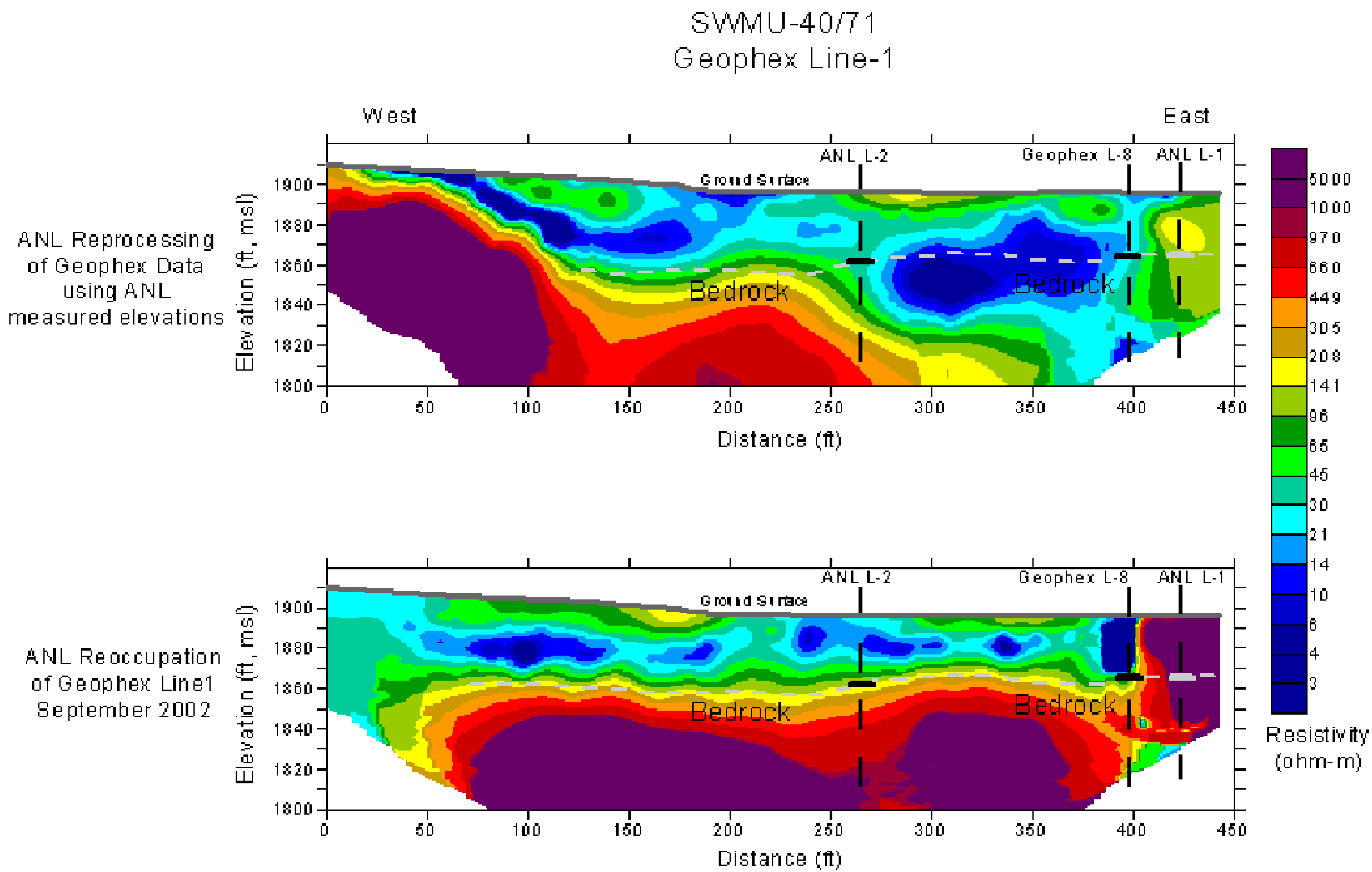
SWMU 40/71 RFI

Date:	Prepared By:
November 2003	*KDC/CL*
Scale:	**File Name:**
As Shown	*21354880*

FIGURE C-6

ANL Geophysical Surveys Profile Line ANL L-1 and Geophex Profile L-8



Legend

VI Monitoring Well

ANL Profile Line 1

*Note: Source: Argonne National Laboratories (ANL) (2003)

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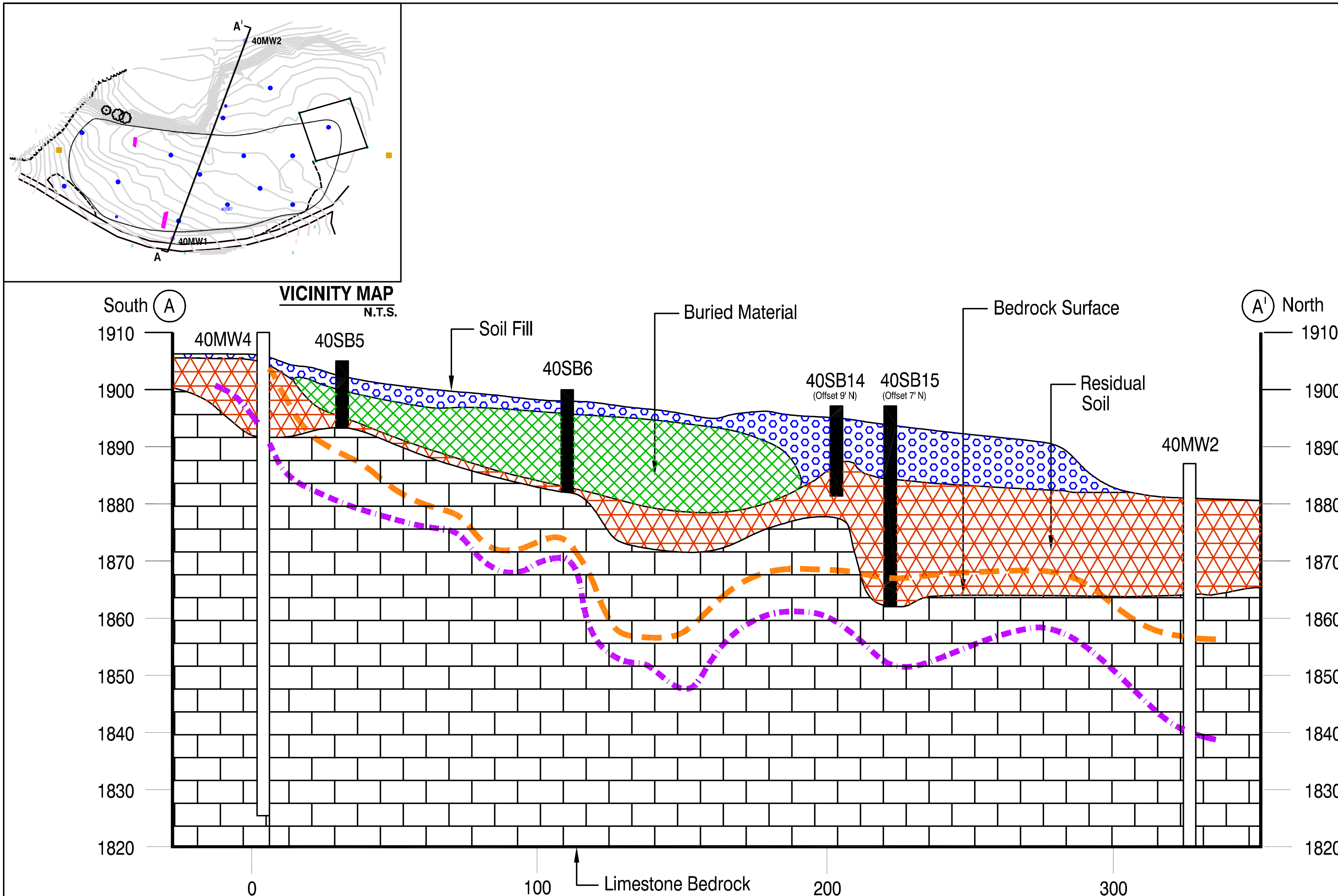
Scale: As Shown	File Name: 21354880

FIGURE C-7

ANL Geophysical Surveys Geophex Profile L-1



Legend

- RFI Soil Boring
- VI Monitoring Well
- Top of Weathered Bedrock - Seismic Tomography Survey - ANL L-2 Profile (ANL 2003)
- Top of Bedrock - Seismic Tomography Survey - ANL L-2 Profile (ANL 2003)

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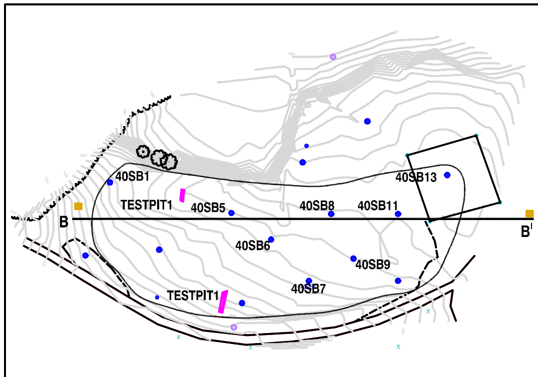
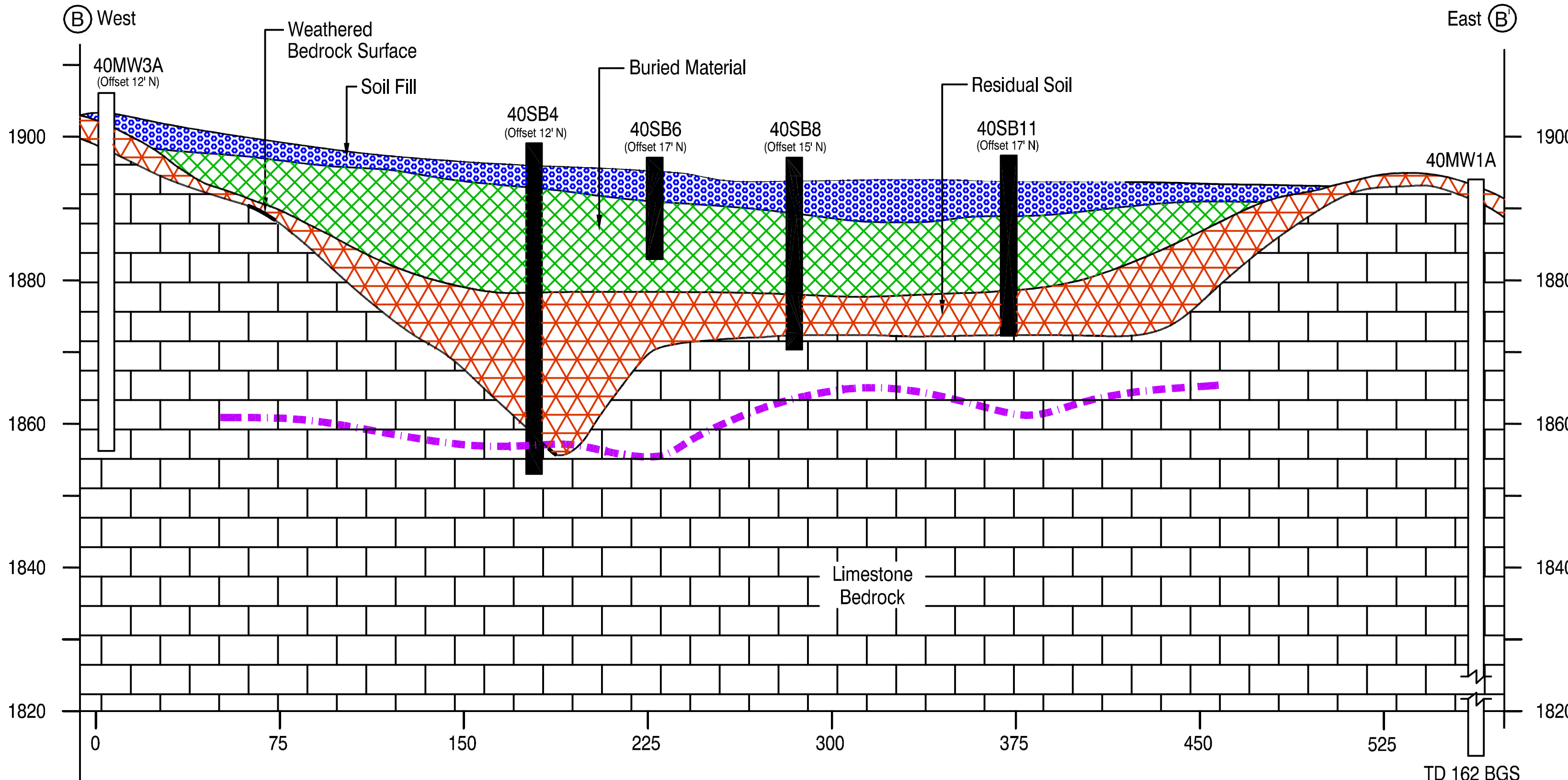
Scale: 1"=50' (Horizontal) 1"=25' (Vertical)	**File Name:** 21354880

FIGURE C-8

Geologic Cross-section A-A'



VICINITY MAP
N.T.S.



Legend

RFI Soil Boring

VI Boring

Top of Bedrock - Tomography Survey - Geophex L-1 Profile (ANL 2003) (Line Inferred From Discreet Survey Points East of 40SB4)

Notes: BGS = Below Ground Surface
TD = Total Depth

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Date:	Prepared By:
November 2003	*KDC/CL*
Scale: *1"=75' (Horizontal)* *1"=25' (Vertical)*	**File Name:** *21354880*

FIGURE C-9

Geologic Cross-section B-B'

material is present in the eastern part of SWMU 40 (Cindered Area and Asbestos Storage Area) and in SWMU 71 (see Figure C-1). Geologic cross-sections A-A' and B-B' show the extent and nature of soil fill material across the SWMU 40/71 area in north-south and east-west directions, respectively.

Two representative samples of soil fill material collected from borings 40SB4 and 40SB9 were submitted for physical testing. Samples 40SB4 and 40SB9 were classified as sandy lean clay (CL) with moisture contents in the range of 18 to 19 %. Both samples had low vertical hydraulic conductivities in the range of 10^{-8} to 10^{-9} centimeters per second (cm/sec). Percent organic content was 5.5 % for sample 40SB4 and 2.8 percent for sample 40SB9. Samples 40SB4 and 40SB9 had slightly acidic and basic pH values, respectively (see Table C-2 and Appendix C.6).

C.3.2 Landfill Material

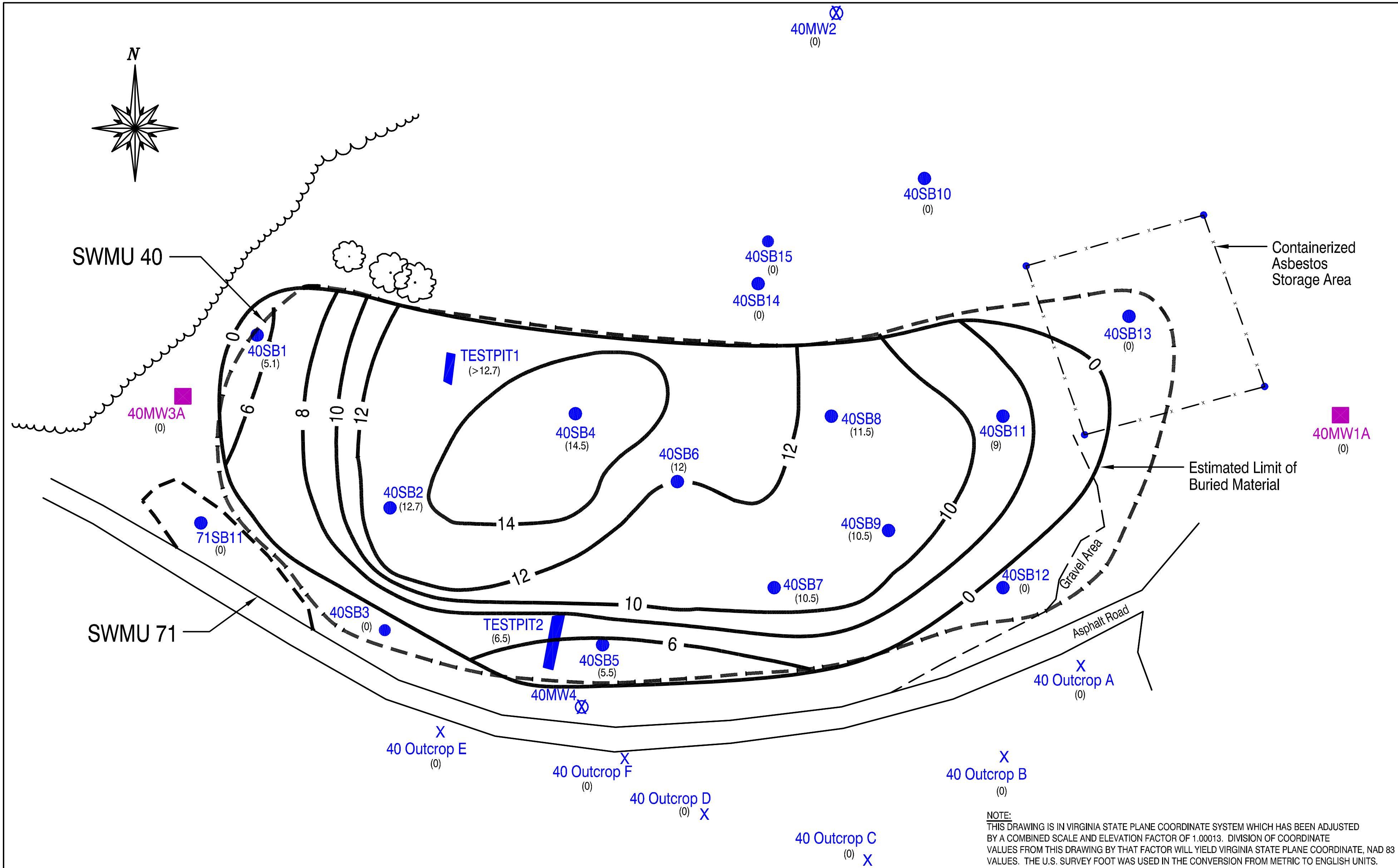
Landfill material underlies soil fill within the area of SWMU 40. In general, this material consists of gray to black clay, sand, gravel, and cinders mixed with abundant paper, glass, plastic, metal, wood chips, rubber, and bagged garbage. Landfill material was described as moist to wet with an odor ranging from sulfurous to strongly acrid and bitter. In some areas, such as boring 40SB6, the landfill material sequence was composed primarily of soil fill with only a minor amount of other types of material. Fluid seepage from landfill material occurred within Test Pit 1, with an accumulation of 2 to 3 ft of water observed in the bottom of the test pit after three hours. Landfill material was described as wet at soil borings 40SB6, 40SB7, 40SB8, and 40SB9 completed near of the center of the landfill area.

Figure C-10 shows the approximately lateral extent and thickness of landfill material as defined by borings and test pits completed at SWMU 40/71. The lateral extent of this material is generally at or within the boundary of SWMU 40. EM surveys conducted by Geophex are in general agreement with the lateral delineation provided by the borings and test pits; the exception being the 170-hertz EM survey, which appears to overestimate the lateral extent of landfill material at the eastern and northern periphery of SWMU 40 compared with the boring data (see Figures C-3 and C-4).

The observed thickness of landfill material ranged from 5.1 ft (boring 40SB1) to 14.5 ft (boring 40SB4). In general, the thickness of landfill material increases from the western, southern, and eastern periphery of SWMU 40 toward the central and northern part of SWMU 40 (see Figure C-10). The top surface of the landfill material generally slopes northeastward across SWMU 40 from an elevation of 1,900 ft msl to 1,890 ft msl; the exception being in the eastern third of SWMU 40 where a slight slope toward the north is apparent (see Figure C-11). Soil boring and test pit investigations confirm that earlier interpretations of 2D-ERI data by Geophex had significantly overestimated the thickness of landfill material; thereby supporting the ANL hypothesis that the presence of broad zones of low-resistivity (< 20 ohm/m) in the 2D-ERI survey were likely related to features in weathered bedrock, such as clay zones (ANL, 2003).

Table C-3 presents volume estimates of landfill material at SWMU 40. Based on the landfill thickness data collected from the borings and test pits, approximately 20,300 cubic yards of landfill material may be present at SWMU 40.

Geologic cross-sections A-A' and B-B' show the extent and nature of landfill material across the SWMU 40/71 area in north-south and east-west directions, respectively.



Legend

—x—x—	Fence	40MW2	VI Groundwater Monitoring Well
X 40 Outcrop B	RFI Bedrock Outcrop	40MW3A	VI Boring
TESTPIT1	RFI Test Pit	—10—	Isopach Contour Line in Feet
40SB8	RFI Soil Boring	C.I.	= 2.0 Feet

0 60'

1 inch = 60 feet

RFAAP

SWMU 40/71 RFI

Date: *November 2003*

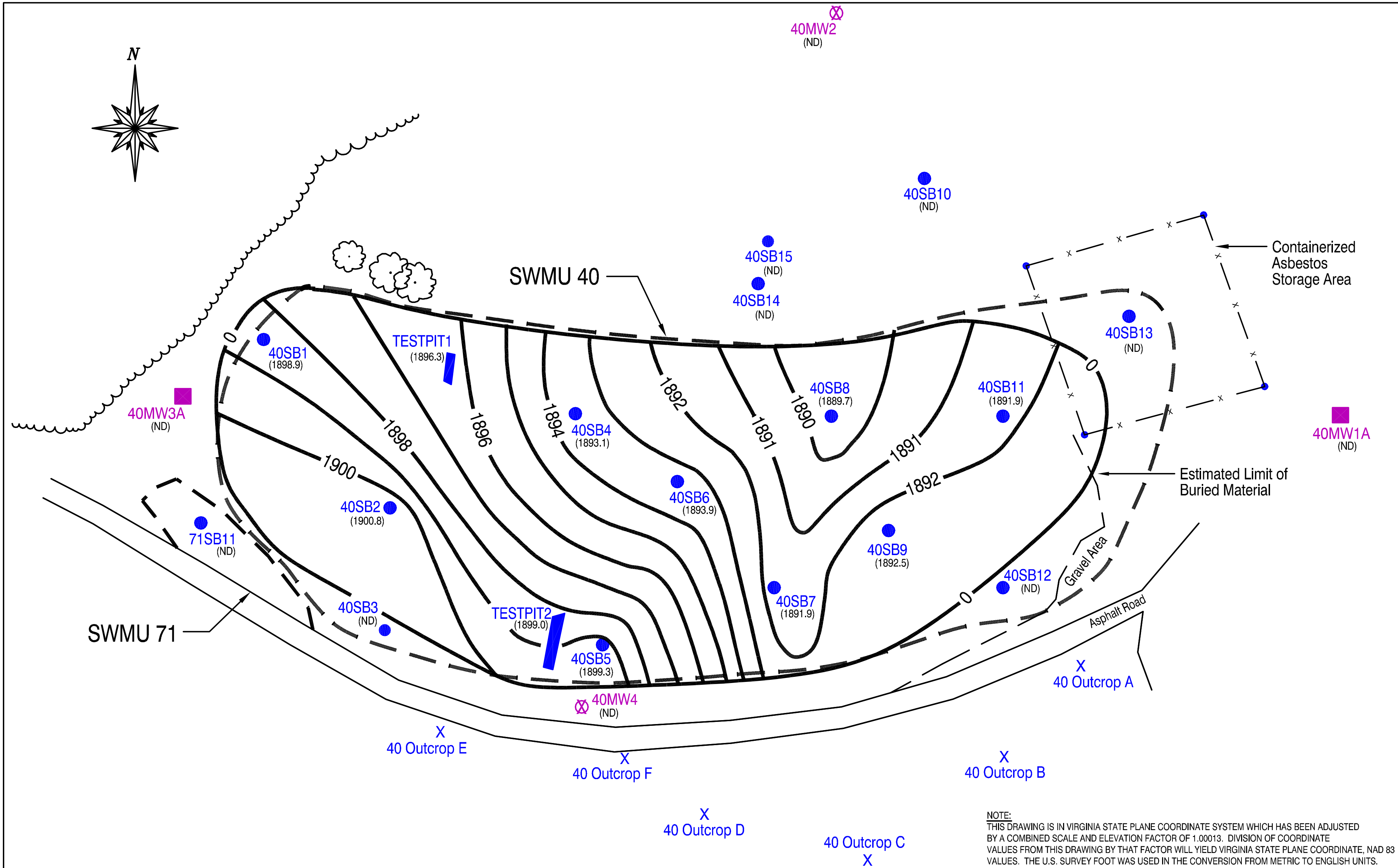
Prepared By: *KDC/CL*

Scale: *1" = 60'*

File Name: *21354880*

FIGURE C-10

Thickness of Buried Material



NOTE:
THIS DRAWING IS IN VIRGINIA STATE PLANE COORDINATE SYSTEM WHICH HAS BEEN ADJUSTED BY A COMBINED SCALE AND ELEVATION FACTOR OF 1.00013. DIVISION OF COORDINATE VALUES FROM THIS DRAWING BY THAT FACTOR WILL YIELD VIRGINIA STATE PLANE COORDINATE, NAD 83 VALUES. THE U.S. SURVEY FOOT WAS USED IN THE CONVERSION FROM METRIC TO ENGLISH UNITS.

Legend

—x—x—	Fence	40MW2	VI Groundwater Monitoring Well
X 40 Outcrop B	RFI Bedrock Outcrop	40MW3A	VI Boring
TESTPIT1	RFI Test Pit	1900	Contour Line in Feet MSL
40SB8	RFI Soil Boring	C.I.	= 1.0 Feet
		ND	No Buried Material Present

0 60'
1 inch = 60 feet

RFAAP
SWMU 40/71 RFI

FIGURE C-11

Structural Contour Map- Top of Buried Material

Date: *November 2003*	**Prepared By:** *KDC/CL*
Scale: *1" = 60'*	**File Name:** *21354880*

Table C-3
Volume of Landfill Material
SWMU 40/71 RCRA Facility Investigation Report
Radford Army Ammunition Plant, Radford, Virginia

Contour Interval			Estimated Area		Estimated Thickness	Volume of Landfill Material		Estimated Weight *	
			(Feet)	(Acres)	(Feet)	(Cu Feet)	(Cu Yards)	(Tons) 28 lbs/ft^3	(Tons) 46 lbs/ft^3
1	> 14	Center	5,292	0.1215	15	79,380	2,940	1,111	1,826
2	12 - 14	Center	12,165	0.279	13	158,145	5,857	2,214	3,637
3	10 - 12	Center	15,598	0.358	11	171,578	6,355	2,402	3,946
4	8 - 10	South	11,046	0.254	9	99,414	3,682	1,392	2,287
5	6 - 8	South	1,263	0.029	7	8,841	327	124	203
6	0 - 6	South	787	0.018	3	2,361	87	33	54
7	8 - 10	West	2,023	0.046	9	18,207	674	255	419
8	6 - 8	West	1,227	0.028	7	8,589	318	120	198
9	0 - 6	West	883	0.020	3	2,649	98	37	61
Totals			50,284	1.15	10.8 **	549,164	20,339	7,688	12,631

Notes:
Cu Feet = Cubic Feet
Cubic Yards
lbs/ft^3 = Pounds Per Cubic Feet
* = Landfill Material Unit Weight Derived from Solid Waste Association of North America,
Manager of Landfill Training and Certification Course, January 1989
** = Average Thickness of Landfill Materials

C.3.3 Residual Soil

Residual soil, which has weathered in place from argillaceous carbonate bedrock, underlies landfill material at SWMU 40/71. Outside of the landfill area, residual soil underlies soil fill material. The contact with overlying fill is sharp and is more gradational with underlying weathered rock. Residual soil generally consists of brown to yellowish red clay (CL or CH) with variable sand content and occasional gravel.

Four physical samples of residual soil (VI and RFI) were laboratory classified as CL or CH (see Table C-2). Both RFI physical samples (40SB4 and 71SB11) had low vertical hydraulic conductivities in the range of 10^{-7} to 10^{-8} cm/sec. The organic content of the RFI samples was 3 to 4%, with a slightly acidic pH.

The observed thickness of residual soil within the SWMU 40/71 area ranged from 1 to 27 ft, with an increase in thickness generally observed toward the northern and eastern boundary of SWMU 40 (see Figure C-12). The isopach map shown as Figure C-12 is considered to represent the minimum thickness of residual soil present at the boring locations investigated; since it is assumed that boring refusal by the direct-push unit represents the top of weathered rock. Bedrock outcrops occur south of SWMU 40, where the residual soil unit is absent.

The top surface of the residual soil generally slopes northward across SWMU 40 toward the north central boundary of SWMU 40 (see Figure C-13). This pattern suggests that a single excavation or fill area existed over the majority of the SWMU rather than separate trenches into natural residual soil as originally thought.

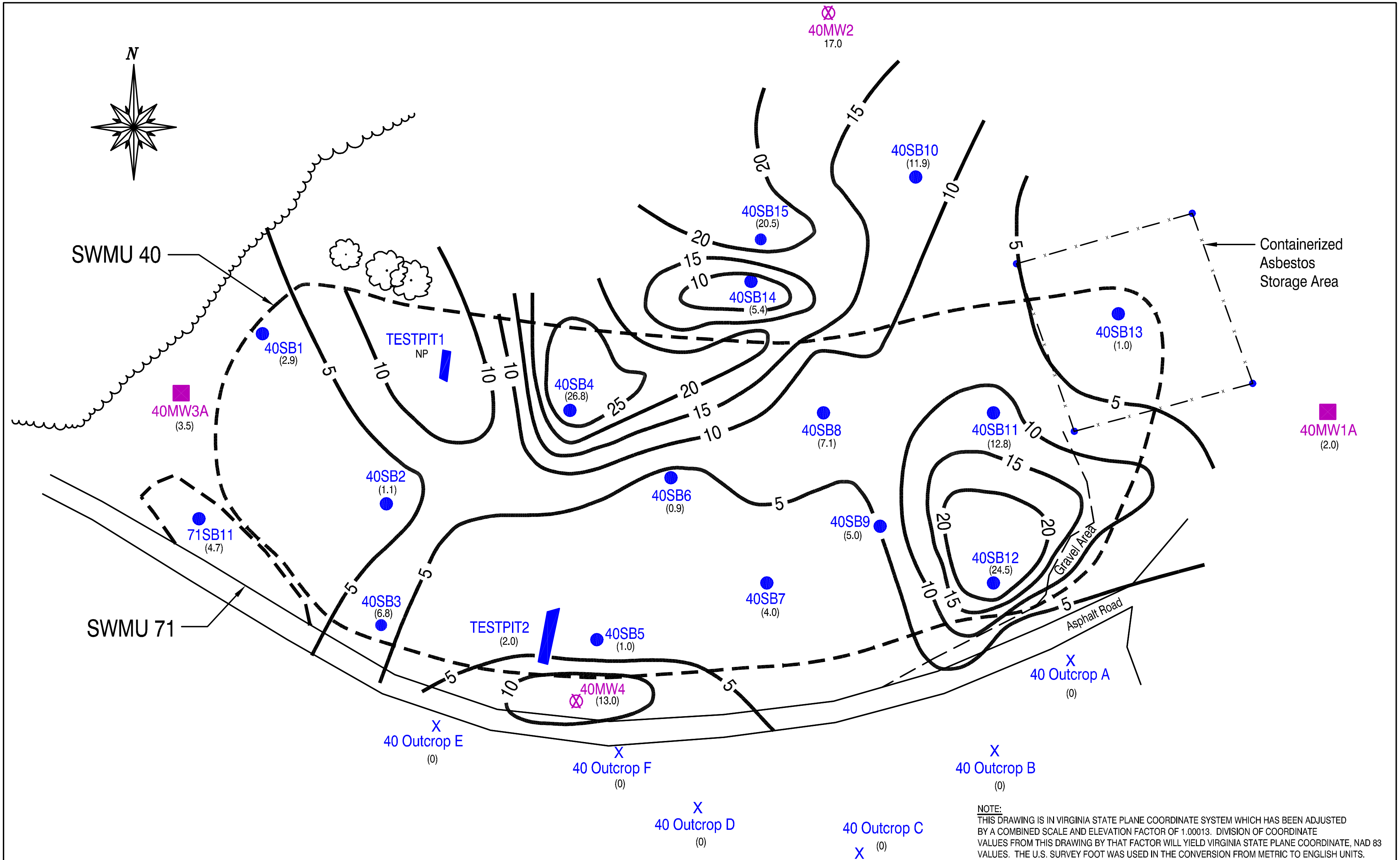
Geologic cross-sections A-A' and B-B' show the extent and nature of residual soil across the SWMU 40/71 area in north-south and east-west directions, respectively.

C.3.4 Bedrock

Previous investigations at SWMU 40/71 indicate that argillaceous carbonate bedrock of the Elbrook Formation underlies the area of SWMU 40/71 (Dames & Moore, 1992). VI borings 40MW1A, 40MW2, 40MW-3, and 40MW4 penetrated 43 to 160 ft of limestone and dolomite bedrock at the periphery of SWMU 40/71 (see Appendix C.1). Bedrock generally consists of light gray to bluish gray limestone or dolomite with some interbedded brown siltstone. Depth to bedrock in the VI borings ranged from 2 to 17 ft bgs (see Table C-1). Several outcrops of bedrock occur immediately south of SWMU 40/71. Strike and dip measurements obtained at five outcrops indicate bedrock strikes in the range of 110 to 115° with bedrock dips ranging from 12 to 16° (see Table C-1).

The consistency of bedrock encountered in the VI borings ranged from soft to hard with numerous zones of intense weathering and fracturing. Clay filled weathered zones and voids were encountered in each of the VI borings, with notable voids and/or weathering at the completion depth of borings 40MW2, 40MW3A, and 40MW4. Zones of more competent bedrock were encountered in boring 40MW1A at depths below the completion depths of the other borings.

In general, weathered bedrock underlies residual soil at SWMU 40/71. The contact between residual soil and weathered bedrock may be abrupt or gradational over several feet, depending on the degree of weathering. For purposes of the RFI intrusive investigation, direct-push boring or test pit refusal was assumed to represent the top of weathered bedrock. However, the upper surface of



NOTE:
THIS DRAWING IS IN VIRGINIA STATE PLANE COORDINATE SYSTEM WHICH HAS BEEN ADJUSTED BY A COMBINED SCALE AND ELEVATION FACTOR OF 1.00013. DIVISION OF COORDINATE VALUES FROM THIS DRAWING BY THAT FACTOR WILL YIELD VIRGINIA STATE PLANE COORDINATE, NAD 83 VALUES. THE U.S. SURVEY FOOT WAS USED IN THE CONVERSION FROM METRIC TO ENGLISH UNITS.

Legend

—x—x—	Fence
X 40 Outcrop B	RFI Bedrock Outcrop
TESTPIT1	RFI Test Pit
40SB8	RFI Soil Boring
40MW2	VI Groundwater Monitoring Well
40MW3A	VI Boring
— 10 —	Isopach Contour Line in Feet
C.I.	= 5.0 Feet
NP	Not Penetrated

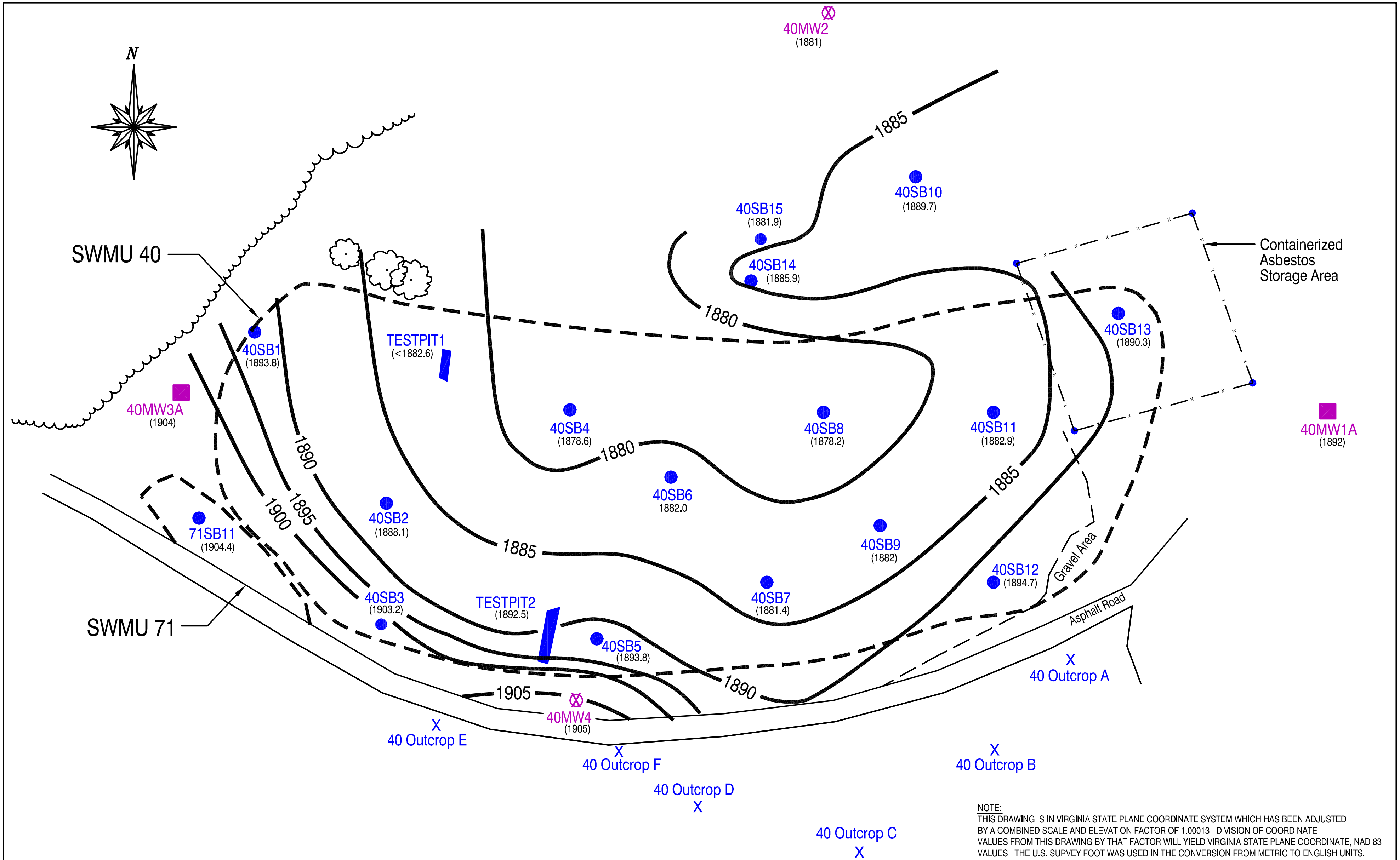
0 — 60'
1 inch = 60 feet

RFAAP
SWMU 40/71 RFI

Date: November 2003
Prepared By: KDC/CL
Scale: 1" = 60'
File Name: 21354880

FIGURE C-12

Thickness of Residual Soil



Legend

—x—x—	Fence	40MW2	VI Groundwater Monitoring Well
X 40 Outcrop B	RFI Bedrock Outcrop	40MW3A	VI Boring
TESTPIT1	RFI Test Pit	1890	Contour Line in Feet MSL
40SB8	RFI Soil Boring	C.I.	= 5.0 Feet

0 60'

1 inch = 60 feet

RFAAP

SWMU 40/71 RFI

Date: *November 2003*

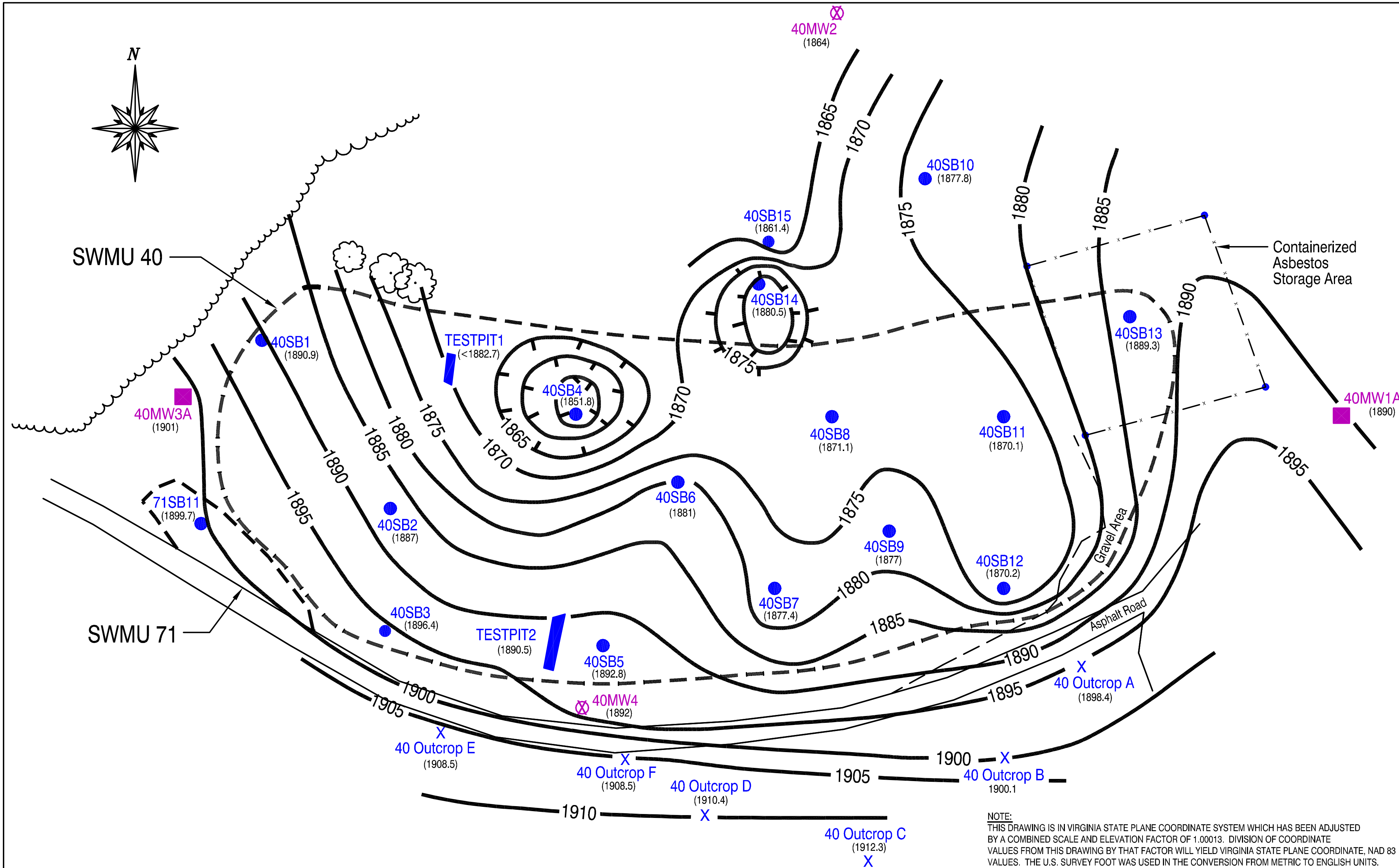
Prepared By: *KDC/CL*

Scale: *1" = 60'*

File Name: *21354880*

FIGURE C-13

Structural Contour Map- Top of Residual Soil



Legend

—x—x—	Fence	40MW2	VI Groundwater Monitoring Well
X 40 Outcrop B	RFI Bedrock Outcrop	40MW3A	VI Boring
TESTPIT1	RFI Test Pit	1900	Contour Line in Feet MSL
40SB8	RFI Soil Boring	C.I.	= 5.0 Feet

0 60'

1 inch = 60 feet

RFAAP

SWMU 40/71 RFI

FIGURE C-14

Structural Contour Map-
Top of Weathered Bedrock

Date: *November 2003*	**Prepared By:** *KDC/CL*
Scale: *1" = 60'*	**File Name:** *21354880*

weathered bedrock may be identified at deeper depths with other drilling techniques or by geophysical surveys such as seismic refraction tomography.

The depth of soil boring refusal ranged from 6.2 ft bgs (boring 40SB13) to 44.8 ft bgs (boring 40SB4). Based on the soil boring and test pit data, the elevation of top of weathered bedrock ranges from 1,912 ft msl at the bedrock outcrop area to less than 1,852 ft msl in the north central part of SWMU 40 (see Figure C-14). In general, the weathered bedrock surface slopes from the western, southern, and eastern periphery of SWMU 40/71 toward the north central border of SWMU 40. An apparent depression in the weathered bedrock surface occurs in the area of boring 40SB4, where approximately 45 feet of overburden overlies bedrock (see Figure C-14).

ANL performed borehole velocity surveys in existing VI monitoring wells 40MW2 and 40MW4 to provide control for the surface tomography surveys. In Well 40MW2, seismic velocities increased from approximately 1,900 feet per second (ft/s) to 5,000 ft/s at a depth of approximately 25 ft bgs indicating a change from residual soil to weathered rock. Seismic velocities did not increase at greater depths indicating that a significant degree of weathering was present in the bedrock sequence at this location. At Well 40MW4, an increase in seismic velocity from 2,500 ft/s to 10,000 ft/s occurred at a depth of approximately 25 feet bgs indicating a change from residual soil/weathered bedrock to competent bedrock.

Geophex performed geophysical logging in wells 40MW2 and 40MW4. Gamma logging in 40MW2 indicated three general zones (0-28, 28-49, and >49 feet bgs) that appear to correspond to residual soil (upper zone), weather bedrock (middle zone), and competent bedrock (lower zone). Increased conductivity was also measured at the transition points of the major zones. In the MW404 logs, two general zones were present, 0-30 and >30 feet bgs, with the upper zone corresponding to residual soil and the lower zone with bedrock containing zones of weathered material through the sequence. Summary borehole geophysical logs are shown on the ANL surface geophysical profiles presented in Figures C-5 and C-6.

Geologic cross-sections A-A' and B-B' show the configuration of the weathered bedrock surface as inferred from the soil borings, monitoring well borings, and test pit data. The top of weathered bedrock and top of bedrock inferred from the ANL seismic survey was plotted on these cross-sections to show the differences in the inferred bedrock surface with the different data platforms.

Cross-Section A-A' (Figure C-8) and ANL Profile L-2 (Figure C-5)

Boring data across this profile within the landfill area generally indicates a 5 to 15 ft shallower depth to weathered bedrock than ANL seismic surveys. The weathered bedrock surface modeled by the seismic survey mimics the surface inferred from the soil boring and test pit data; both platforms indicate that bedrock slopes from south to north across the profile on Figure C-8. The seismic survey models the weathered bedrock surface approximately 5 ft higher than suggested by the boring data at locations north of the landfill area and boring 40SB15, except in the area of 40MW2 where this difference is reversed. At the extreme southern end of the profile, the seismic survey indicates a shallower depth to weathered bedrock than that inferred from the boring data.

The 2D-ERI and seismic surveys model weathered bedrock at similar depths at the northern and southern ends of the profile (see Figure C-5). A discrepancy exists between the 2D-ERI dipole-dipole and seismic models within the landfill area. The dipole-dipole solution suggests a major depression in the weathered bedrock surface to depths of 70 to 80 ft bgs contrasted with the 30 to 40 ft bgs projected by the seismic model (see Figure C-5). In this area, the 2D-ERI Schlumberger and seismic models predict a similar depth to weathered bedrock. The weathered bedrock surface modeled by seismic data and boring data cut through the bedrock low modeled by the dipole-dipole solution. This suggests that clay zones, or other sources of low resistivity present within the bedrock are the cause of the broad zone of low resistivity rather than the presence of landfill material or residual soil.

Cross-Section B-B' (Figure C-9) and Geophex Profile L-1 (Figure C-7)

Boring data across this profile indicate that the surface of weathered bedrock slopes from the eastern and western edges of SWMU 40 toward a bedrock low in the area of soil boring 40SB4. Projected surfaces of weathered bedrock and bedrock are also shown on Figure C-7, as modeled from seismic data along profiles ANL-1/Geophex and ANL-2 where they intersect Geophex L-1. Projections from seismic and boring data are in close agreement from 225X eastward on Figure C-7, with a 3 to 7 ft shallower depth to weathered bedrock indicated by the boring data. Weathered bedrock surfaces projected by seismic and boring data intersect in the area of the bedrock low (165X to 200X). Seismic projections of a level bedrock surface extending to the west of the bedrock low do not correlate with boring data, which indicate an upward sloping weathered bedrock surface from boring 40SB4 to 40MW3A. The bedrock surface modeled by ANL reprocessing of the Geophex 2D-ERI data (dipole-dipole) along L-1 closely correlates with the boring data in this area (see Figure C-7).

Reprocessing of the Geophex 2D-ERI data along L-1 still shows a thick zone of low resistivity in the eastern third of the model. The weathered bedrock surface inferred from the boring data and predicted by the seismic data along this profile cut through the zone of low resistivity. Similar to profile ANL-2, clay zones or other sources of low resistivity present within the bedrock are the likely cause of this broad zone of low resistivity rather than the presence of landfill material or residual soil.

The 2D-ERI data generated by ANL during its reoccupation of Geophex L-1 models bedrock as a high-resistivity zone (>400 ohm-m) with a relatively horizontal top at approximately 1,860 ft msl and slight westward dip of 15 ft over the length of the profile (ANL, 2003). This model is in reasonable agreement with the bedrock surface projected by the seismic data across the profile.

Profiles ANL L-1 and Geophex L-8 (Figure C-6)

The seismic survey along ANL L-1 models a weathered bedrock surface that closely agrees with the elevations and bedrock configuration presented on the structural contour map of weathered bedrock (see Figure C-14). Both data platforms indicate a northward sloping weathered bedrock surface toward Monitoring Well 40MW2.

Reprocessing of the Geophex 2D-ERI data (dipole-dipole) along L-8 indicates that the bedrock surface modeled by resistivity is deeper than that predicted by seismic; the exception being at the northern and southern ends of the profile where the models are in close agreement. There is a larger discrepancy between these models between 100 and 150X, where the resistivity model suggests that landfill material may be present to depths of 40 ft. The weathered bedrock surface modeled by seismic data and boring data cut through this low-resistivity zone; thus, this zone of low-resistivity cannot be attributed to landfill material and is likely related to features of the underlying bedrock.

C.4 Geologic Summary

The shallow geology at SWMU 40/71 generally consists of fill materials overlying natural deposits. SMWU 40, a former landfill, appears to be a laterally contiguous disposal area overlying residual soil, filled with various types of landfill materials, soil, and cinders, and then capped by emplacement of soil fill. The soil fill consists of generally fine-grained materials (sandy clay and clay) that contain lenses of gravel, sand, and cinders. A surface veneer of cinders is present in the eastern portion of SWMU 40. Soil fill at SWMU 71 is mixed with cinders and rests directly upon residual soil.

Residual soil is present beneath the entire landfill and consists of fine-grained material, principally slightly sandy clay, derived from the inplace weathering on the underlying Cambrian-Age Elbrook Formation argillaceous carbonates. The residual soil grades downward into weathered bedrock that, in turn, grades downward into competent carbonate bedrock that contains fractures, cavities, vugs, and other solution features.

A karst depression, potentially a sinkhole or enlarged fracture, in the carbonate bedrock appears to be present in the area of soil boring 40SB4 (see Figures C-9, C-12, and C-14). Relief of at least 15+ ft on the weathered bedrock surface appears to be present in this area; relief is greater (25+ ft) to the northeast where the apparent shallow depth of weathered bedrock at boring 40SB14 may indicate the presence of a karst pinnacle. The depression contains the thickest sequence of residual soil at SWMU 40/71; one of the thinnest natural sequences, i.e. no excavation in the area, is present at boring 40SB14 (Refer to Figure C-12).

The lateral and vertical extent of landfill material in SWMU 40 has been defined through the combination of surface geophysics and subsurface data. Surface geophysics identified the top of weathered bedrock and competent bedrock that varied greatly in depth across the SWMU. Along some profiles, general geophysical trends appear to correspond to elevation configurations projected from soil boring data, but deviations in projected depths of the weathered bedrock surface were present.

APPENDIX B

ATS INTERNATIONAL RESISTIVITY IMAGING SURVEY REPORT

Resistivity Imaging Survey for SWMU-40/71
Radford Army Ammunition Plant (RFAAP)
Radford, Virginia

prepared for

URS Corporation
5540 Falmouth Street, Suite 201
Richmond, VA 23230

by

ATS International, Inc.
107 Lester Street
Christiansburg, Virginia 24073

ATS International Project No. P06-04

January 9, 2007

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List of Figures

Executive Summary

ATS International, Inc. (ATS) was retained by the URS Corporation (URS) to perform a resistivity imaging study at SWMU-40/71, located within the Radford Army Ammunition Plant (RFAAP) near Radford, Virginia. The objective of this study was to identify drilling targets for the installation of additional monitoring wells in the vicinity of SWMU-40/71. The tasks involved in this study included:

(1) Collection and processing of resistivity imaging data.

(2) Integration and synthesis of geologic data from previous studies into interpretation of new resistivity data for most comprehensive interpretation of new data.

(3) Preparation of this document detailing our methods and findings.

The site and immediate surroundings are underlain by the Cambrian-aged Elbrook Formation, which is comprised of laminated to thick-bedded dolomite, thin- to medium-bedded limestone, and dolomitic platy shale and siltstone. The strike of bedrock in the vicinity of the site is approximately 110°. Within a sinkhole located approximately 250 feet southwest of SWMU-40/71, bedrock was observed to dip approximately 10 to 30 degrees to the south-southwest.

The bedrock subsurface in the vicinity of SWMU-40/71 is highly karstified, with numerous large sinkholes and sinking streams present. In 1996, a dye-trace study revealed that a stream which sinks approximately 200 feet east of SWMU-40/71 flows westward to a spring on the New River. In that study, the dye traveled a distance of 4,800 feet in approximately 24 hours, indicating the presence of an open-flow karst conduit beneath the vicinity of SWMU-40/71.

Data from two resistivity lines were collected at the site. Line 1 was located just north of SWMU-40/71 and was oriented in an east-west direction, while Line 2 was located just west of SWMU-40/71 and was oriented in a northeast-southwest direction.

Leachate from leaking landfills typically results in vertically or laterally extensive zones of abnormally low resistivity values extending from the landfill area. Two zones of abnormally low resistivity values (with values as low as 20 Ohm-meters) are observed in the central portion of Line 1 which may suggest the presence of contamination associated with the former disposal area(s). The nature of these anomalies also suggests that they are located within interpreted karst features or fracture zones.

Of additional note is that the Radford North USGS 7.5-minute topographic quadrangle, which illustrates the surface topography prior to the creation of SWMU-40/71, indicates the prior existence of an enclosed depression (i.e. sinkhole) immediately beneath the current location of SWMU-40/71. Based on this information, it is reasonable to interpret that one or both of the anomalies in that portion of Line 1 likely represent(s) karst solutional features related to that buried sinkhole.

Numerous anomalies are observed in the section for Line 2, with possible fracture zones identified beneath the vicinities of electrodes 2-13, 2-23, and 2-48 and possible karst features identified beneath electrodes 2-13, 2-38 and 2-48.

A total of seven resistivity anomalies are identified as interpreted fracture zones and/or karst features. Each of these anomalies may represent possible locations for intercepting groundwater through the installation of a monitoring well. The selection of monitoring well locations should take into account the 3-dimensional heterogeneity of the karst subsurface, with special consideration given to the fact that groundwater migration through potentially open-flow karst from the vicinity of SWMU-40/71 is not likely to follow normally intuitive parameters.

The fact that a positive dye trace was conducted from the sinkhole at SWMU-17 (on the east side of SWMU-40/71) almost due west to the New River reveals that an open-flow karst conduit exists beneath the vicinity of SWMU-40/71. Given this information, combined with the fact that SWMU-40/71 was evidently constructed immediately above a sinkhole, it is reasonable to expect that groundwater migration from the vicinity of SWMU-40/71 would be primarily to the west, generally along strike, and primarily through relatively well-developed karst conduits.

1. Introduction

ATS International, Inc. (ATS) was retained by the URS Corporation (URS) to perform a resistivity imaging study at SWMU-40/71, located within the Radford Army Ammunition Plant (RFAAP) near Radford, Virginia (Figure 1). SWMU-40/71 is located in the southern portion of the RFAAP property, approximately seven tenths of a mile northwest of the RFAAP Main Entrance on VA Route 114 (Figure 2).

Detailed geophysical studies have been conducted previously at SWMU-40/71 by Geophex Services, Ltd. (May 2001) and Argonne National Laboratory (April 2003). The objectives of those investigations were to characterize the subsurface beneath SWMU-40/71 and to identify the lateral and vertical extents of waste.

The objective of this study was to identify drilling targets for the installation of additional monitoring wells in the vicinity of SWMU-40/71. The tasks involved in this study included:

(1) Collection and processing of resistivity imaging data.

(2) Integration and synthesis of geologic data from previous studies into interpretation of new resistivity data for most comprehensive interpretation of new data.

(3) Preparation of this document detailing our methods and findings.

2. Site Geology

The site is located within the Valley and Ridge Province, which consists of elongate parallel mountain ridges and valleys that are underlain by folded and faulted Paleozoic sedimentary bedrock. These parallel ridges and valleys are the result of differential weathering of layered clastic and carbonate rocks.

The site and immediate surroundings are underlain by the Cambrian-aged Elbrook Formation, which is comprised of laminated to thick-bedded dolomite, thin- to medium-bedded limestone, and dolomitic platy shale and siltstone (Figure 3). The strike of bedrock in the vicinity of the site is reported to be approximately 110°. Within a sinkhole located approximately 250 feet southwest of SWMU-40/71, bedrock was observed to dip approximately 10 to 30 degrees to the southwest.

The bedrock subsurface in the vicinity of SWMU-40/71 is highly karstified, with numerous large sinkholes and sinking streams present. With the local abundance of sinking streams, well-developed cave systems should be expected through which groundwater can travel very rapidly, both vertically and laterally.

This condition is evidenced locally in the large sinkhole approximately 200 feet east of SWMU-40/71, in which SWMU-17 is located. A surface stream sinks into the karst subsurface in the southwestern edge of that sinkhole, and its drainage has been positively dye-traced to a spring on the New River approximately 4600 feet to the west of SWMU-40/71 (ES 1994, Parsons 1996). In that study, the dye traveled a distance of 4,800 feet in approximately 24 hours, indicating the presence of an open-flow karst conduit beneath the vicinity of SWMU-40/71. The spatial relationship between the dye injection point and the observed outflow at the river suggests a strike-oriented flow pathway. This is supported by the shape and distribution of local sinkholes, suggesting that local karstification may be strongly influenced by the strike of the lithologic bedding.

3. Resistivity Imaging

Resistivity imaging provides cross-sectional images of the resistance to electric current. Electrical resistivity is a fundamental parameter of the material that describes how easily the material can transmit electrical current. High values of resistivity imply that the material is very resistant to the flow of electricity; low values of resistivity imply that the material transmits electrical current very easily.

The primary factors affecting the resistivity of earth materials are porosity, water saturation, clay content, and ionic strength of the pore water. In general, the minerals making up soils and rock do not readily conduct electric current and thus most of the current flow takes place through the material's pore water. The relatively high levels of pore water in soils and other unconsolidated materials tend to give low resistivity values for the shallow subsurface. Where the levels of pore water in soils and other unconsolidated materials are low, resistivity values tend to be high in the shallow subsurface.

3.1. Principals of Resistivity

Experiments by Gorge Ohm in the early 19^{th} century revealed the empirical relationship between the current flowing through a material and the potential required to drive that current. This relationship is described by

$$V = IR$$

where V is voltage in volts, I is the current in amperes, and R is the proportionality constant. Rearranging the equation to

$$\frac{V}{I} = R$$

gives resistance with the units of volts divided by amperes, or ohms.

The resistance of a material is dependent not only on the property of the material but also the geometry of the material. Specifically, a longer travel path for the current or smaller cross-sectional area would cause the resistance to increase. The geometry-independent property used to quantify the flow of electric current through a material is resistivity, given by

$$\rho = \frac{RA}{L}$$

where ρ is the resistivity, R is the resistance, A is the cross-sectional area through which the current flows, and L is the length of the current flow path. With all length units expressed as meters, the units associated with resistivity are ohm - meters (ohm - m).

3.2. Field Methods

For any two-dimensional resistivity survey, a series of electrodes is placed in the ground in a straight line with a uniform spacing between electrodes. Resistivity measurements are accomplished by applying an electric current into the ground via two electrodes, and simultaneously measuring the potential at two other electrodes. Numerous configurations (or arrays) of electrode placement are commonly employed, each with unique data characteristics. For this study, data were collected using the dipole-dipole array and the pole-dipole array. The dipole-dipole array provides data of significantly higher resolution than the pole-dipole array, while the pole-dipole array provides data to a greater depth.

For the dipole-dipole array, a current is applied between to two electrodes (current dipole) positioned a predetermined distance apart (distance *a*). The voltage across two other electrodes (potential dipole) is measured simultaneously with the applied current. The electrodes in each dipole are always spaced distance *a* apart and the distance between the current dipole and the voltage dipole is always a multiple of *a* ($n \bullet a$). In the pole-dipole array, an additional electrode (the remote electrode) is placed a large distance from the line of electrodes. A current is applied between the remote electrode and one within the main line of electrodes. The latter is called the local current electrode. The voltage is measured across two other electrodes placed a distance *a* apart. The distance between the local current electrode and the voltage electrodes is always a multiple of *a* ($n \bullet a$). To obtain apparent resistivity values, the voltage and current measurements are input into the following formula for dipole-dipole surveys

$$\rho = 2\pi(n+1)\cdot(n+2)\cdot a\cdot\frac{V}{I}$$

and the following formula for the pole-dipole array:

$$\rho = 2\pi a\cdot n(n+1)\frac{V}{I}$$

Resistivity data were collected using a Tigre® 64 computerized resistivity system manufactured by Allied Associates, Ltd in Great Britain. The resistivity meter was connected via a multi-conductor cable to electrodes placed in the ground. Measurements were initiated at one end of the line and incrementally moved through the electrodes until readings had been taken at every position along the line. The value of *n* was then increased to add additional resistivity readings at greater depths in the subsurface.

Data from two resistivity lines were collected at the site. Line 1 was located just north of SWMU-40/71 oriented in an east-west direction, and Line 2 was located just west of SWMU-40/71 oriented in a northeast-southwest direction (Figure 4).

Each resistivity line employed a spacing of five meters (16.4 feet) between electrodes. The electrodes were assigned a unique identifier that consisted of the line number followed by a dash and the electrode number. For example, the first electrode on Line 1 was identified as 1-1, the first electrode on Line 2 as 2-1, etc. The elevation of each electrode was taken from the surface topography data in the site plans provided by URS (CAD file entitled "40-71 area only.dwg") so that the resulting resistivity sections would include the local topographic relief. The elevation information was also used in the inversion modeling process as changes in elevation influence the inversion results.

3.3. Inversion Modeling

The resistivity measurements on a section are called apparent resistivities. They may differ from the actual resistivities because the measured data may be affected by passage through inhomogeneous materials and the distance of travel through the media. Therefore, linear inversion techniques were applied to the data using RES2DINV inversion modeling software. Linear inversion modeling fits the measured data in the resistivity section to an earth model that may represent the actual resistivities in the section. The inversion modeling is completed by calculating apparent resistivity from the earth model for comparison to the measured data. If the comparison is within reasonable limits, the earth model can be accepted as an approximation of subsurface conditions. Details of the inversion process may be found in Lines and Treitel (1984), Loke and Barker (1995), and Loke and Barker (1996).

4. Resistivity Results

Because the dipole-dipole array generates a model of higher resolution than that of the pole-dipole array, results of the dipole-dipole array will be discussed first.

4.1. Line 1

The resulting section for Line 1 illustrates a shallow zone of low resistivity values between electrodes 1-32 and 1-56 (Figure 5). This zone is coincident with the area of backfill observed on the ground surface and in geophysical interpretations from previous studies at the site. Monitoring well 40MW2 is graphically projected onto the section for Line 1, although it is located approximately 26 feet north of Line 1.

Landfill materials and leachate typically exhibit resistivity values that are significantly lower than natural earth materials. Two zones of abnormally low resistivity values are observed in the central portion of the line, with values as low as 20 Ohm-meters. The shallower of these two anomalies occurs at a depth of approximately 60 feet, and is located beneath the area between electrodes 1-32 and 1-35. The deeper anomaly occurs at a depth of approximately 100 feet, and is located beneath the area between electrodes 1-39 and 1-43.

Leachate from leaking landfills typically results in vertically or laterally extensive zones of abnormally low resistivity values extending from the landfill area. The unusually low resistivity values seen in Line 1 may suggest the presence of contamination associated with the former disposal area(s). The shape and distribution of these anomalies also suggest that they may be located within karst features or fracture zones.

Of additional note is that the Radford North USGS 7.5-minute topographic quadrangle presented in Figure 2, which illustrates the surface topography prior to the creation of SWMU-40/71, indicates the prior existence of an enclosed depression (i.e. sinkhole) immediately beneath the current location of SWMU-40/71. Based on this information, it is reasonable to interpret that one or both of the anomalies in that portion of Line 1 likely represent(s) karst solutional features related to that buried sinkhole. This possible interpretation is supported by previous soil boring investigations conducted by URS (2004), which showed a significant increase in depth to bedrock in this area in boring 40SB4. A bedrock pinnacle was also noted nearby in boring 40SB14. These borings are located approximately 60 feet and 20 feet south of Line 1, respectively.

In the western portion of Line 1, numerous small, relatively shallow low-resistivity features are observed which likely represent soil-filled karst features. These features are at a higher elevation than SWMU-40/71, and therefore would not be suitable locations for the placement of monitoring wells. However, a vertically extensive low-resistivity zone is observed beneath electrodes 1-17 to 1-20 which may represent a fracture zone or a larger and deeper karst feature.

The pole-dipole data for Line 1 provided data to a depth of approximately 350 feet. Its characteristics generally mimic those of the dipole-dipole data, with the exception of the anomaly just described. With the added depth of data provided, the resistivity contour values enclose around that anomaly beneath the vicinity of 1-18, rendering it more characteristic of a partially soil- or water-filled karst feature rather than a fracture zone. This anomaly is at an approximate elevation of 1835 feet, approximately 60 to 70 feet lower than the buried fill materials in SWMU-40/71. Two deeper low-resistivity anomalies are observed at the bottom of the section. These occur at an approximate elevation of 1650 feet MSL and are therefore below the level of the New River. As such, they are not considered relevant to this study.

4.2. Line 2

The results for Line 2 reveal the complex and highly varied nature of the subsurface beneath the site, bearing characteristics typical of highly fractured and highly karstified terrain (Figure 6). Numerous anomalies are observed in the section for Line 2, with possible fracture zones identified beneath the vicinities of electrodes 2-13, 2-23, and 2-48 and possible karst features identified beneath electrodes 2-13, 2-38 and 2-48.

The interpreted karst feature beneath electrode 2-38 is at an approximate elevation of 1830 feet, consistent with the elevation of the anomaly previously described beneath electrode 1-18, and also bears the characteristics of a partially soil- or water-filled karst feature. Due to the similarities in elevation and character of these two anomalies, it is possible that they represent a continuation of a karst conduit between those two locations.

As with the pole-dipole dataset for Line 1, the pole-dipole section for Line 2 revealed similar characteristics as the dipole-dipole data, but provided greater depth.

5. Existing Monitoring Wells

The locations of existing monitoring wells in the immediate vicinity of SWMU-40/71 – as indicated in CAD drawings provided to ATS by URS – are presented in Figure 3, and are identified as 40MW2, 40MW3 and 40MW4. Because of their proximity to Lines 1 and 2, monitoring wells 40MW2 and 40MW3 were plotted graphically onto the resistivity sections so that their proximity to resistivity anomalies could be evaluated. It should be noted, however, that the map in Figure 3 indicates that 40MW3 is located between electrodes 2-4 and 2-5, while in the field, 40MW3 is located approximately 40 feet northwest of that location.

6. Recommendations for Additional Monitoring Wells

The resistivity data collected to the north and to the west of SWMU-40/71 reveals that the bedrock subsurface beneath the site is of a highly varied and complex nature, and is characterized by numerous low-resistivity anomalies which are consistent with bedrock fracture or fault zones and karst-related dissolution features. A total of seven resistivity anomalies have been specifically identified in Figures 5 and 6 as interpreted fracture zones and/or karst features. Possible karst features which could be expected beneath the site may include completely soil-filled cavernous voids, laterally extensive open-air cavernous voids (which are at least partially filled with highly conductive soils and/or water), and open-flowing bedrock stream conduits as would be expected to exist in association with the sinking stream located just east of SWMU-40/71 (at the south end of SWMU-17).

Each of these areas may represent possible locations for intercepting groundwater through the installation of a monitoring well. The selection of monitoring well locations should take into account the 3-dimensional heterogeneity of the karst subsurface, with special consideration given to the fact that groundwater migration through potentially open-flow karst from the vicinity of SWMU-40/71 is not likely to follow normally intuitive parameters.

The fact that a positive dye trace was conducted from the sinkhole at SWMU-17 (on the east side of SWMU-40/71) almost due west to the New River reveals that an open-flow karst conduit exists beneath the vicinity of SWMU-40/71. Given this information, combined with the fact that SWMU-40/71 was evidently constructed immediately above a sinkhole, it is reasonable to expect that groundwater migration from the vicinity of SWMU-40/71 would be primarily to the west, generally along strike, and primarily through relatively well-developed karst conduits.

As such, several recommendations for additional monitoring well locations have been provided. The locations are listed in the table below, and refer to the electrode flag numbers which were placed in the field:

Line 1	Line 2
1-18.5	2-13
1-33.5	2-23
1-41	2-38
	2-48

At a minimum, we recommend that a monitoring well be placed along Line 1, either at electrode 1-33.5 (i.e. halfway between 1-33 and 1-34) or at electrode 1-41. If the direction of groundwater migration from SWMU-40/71 were at all to the north, then a monitoring well placed at either of these locations would be likely to intercept karst drainage from the probable sinkhole buried beneath SWMU-40/71, and therefore likely to bear any dissolved constituents associated with the disposed material. If the location at electrode 1-33.5 is drilled, it should be completed to a minimum depth of 100 feet. If the location at 1-41 is drilled, it should be completed to a minimum depth of 130 feet.

Based on the resistivity results and the body of data for the site, monitoring wells drilled on Line 2 at electrodes 2-23, 2-38, and 2-48 would be most likely to intercept westerly groundwater flow from SWMU-40/71. The low-resistivity anomaly beneath 2-13 would likely intercept groundwater, but drilling this location would not be necessary if a monitoring well is placed at 1-41 and/or 1-33.5.

Due to terrain or other site restraints present at some of the suggested drilling targets, it may be desirable to drill targets not listed above, including locations which may not lie directly on the two resistivity lines. Doing so may still intercept groundwater and achieve the desired results; however, this would be at your discretion.

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Figures

Report Title: *Resistivity Imaging Survey for the RAAP SWMU 40-71, Radford, Virginia*

File Name: *RAAP SWMU 40-71 Res ls.ppt*

Date: *12/13/06* Draftsman: *CMP*

ATS Project Number: *P06-05*

Figure 1. Portion of road map illustrating the approximate location of SWMU 40-71 and other local features.

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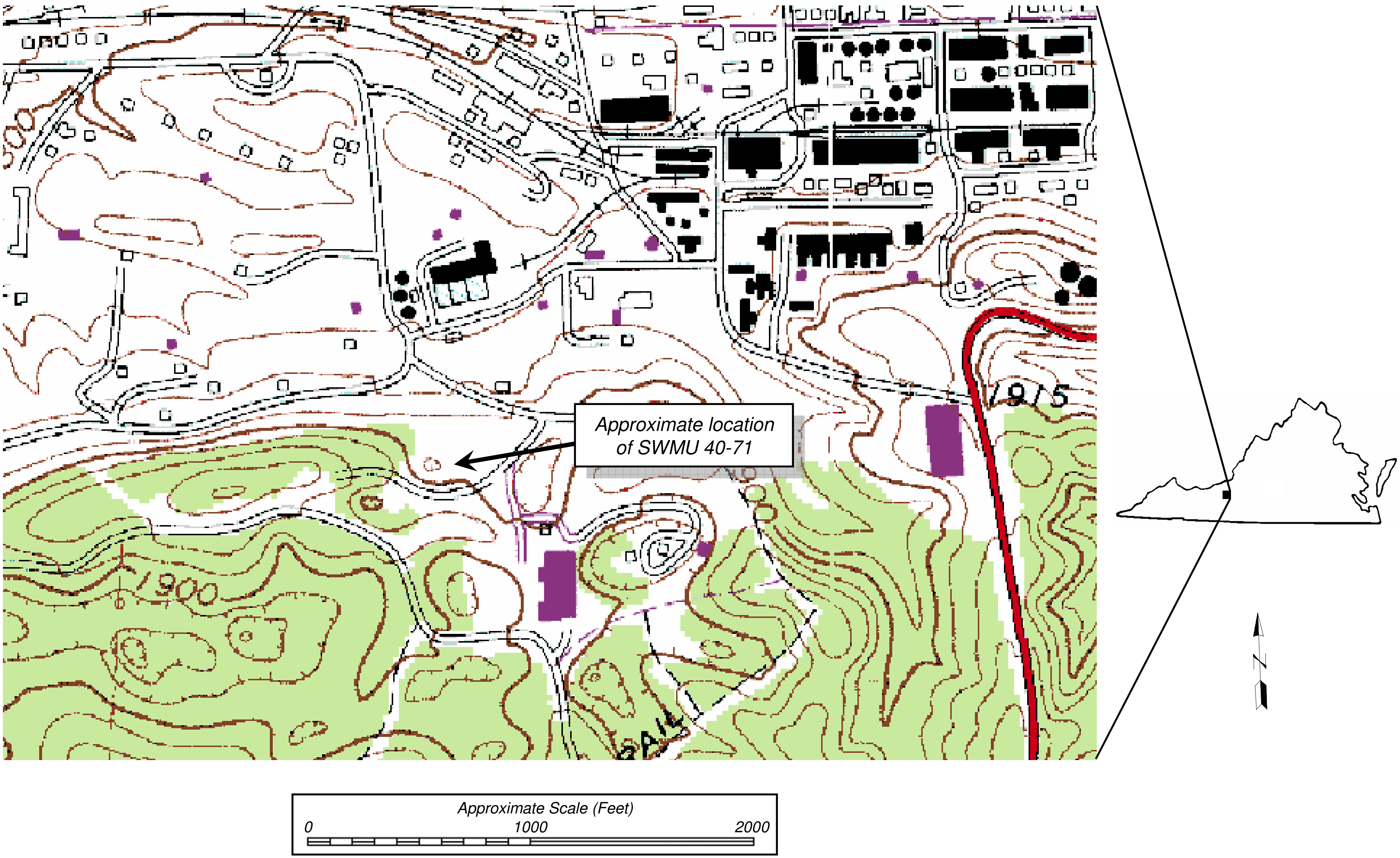

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Figure 2. Portion of the Radford North USGS 7.5-minute topographic quadrangle illustrating the approximate location of SWMU 40-71 and other local features. (Note the sinkhole which evidently existed prior to the creation of SWMU 40-71).

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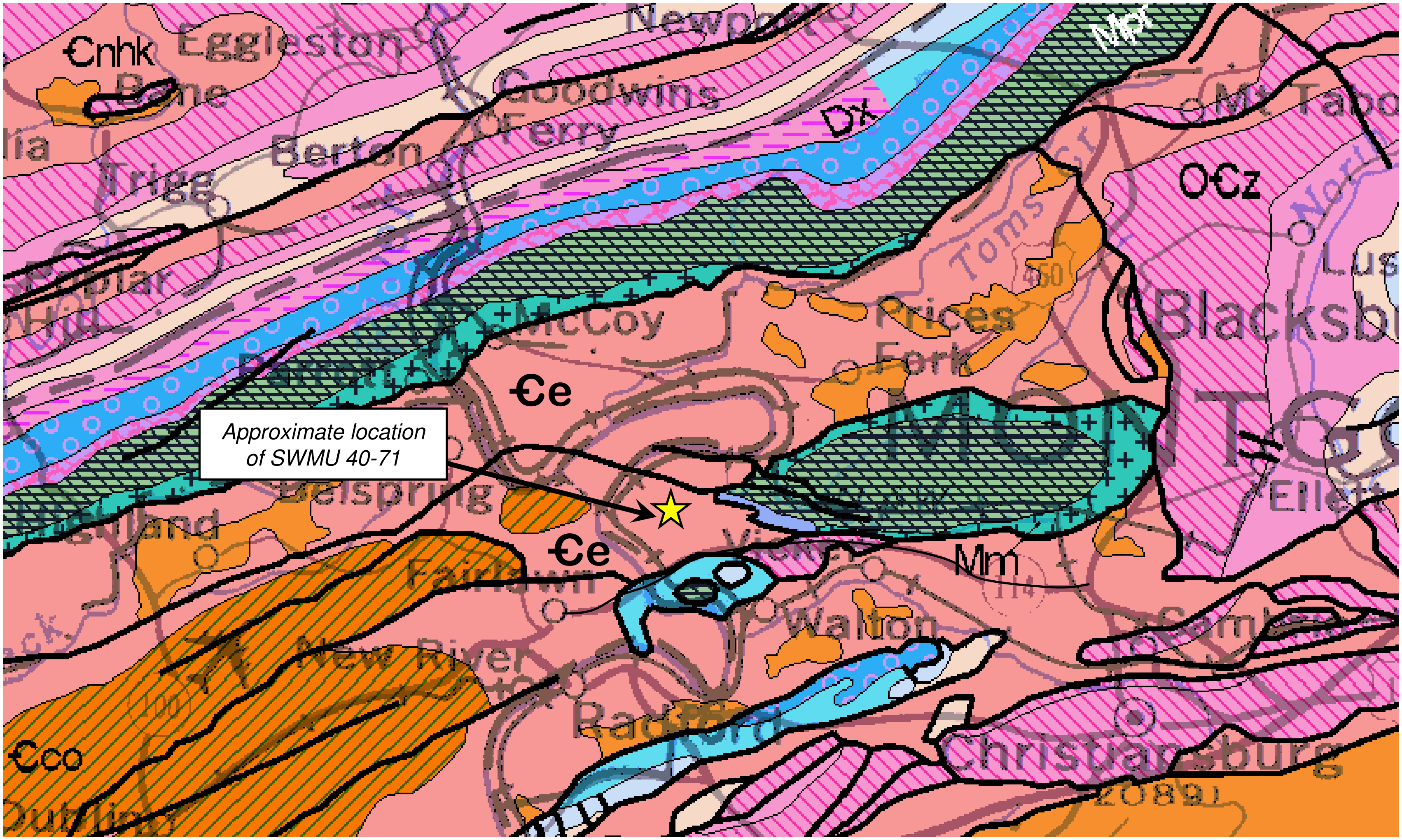

Ꞓe = **Elbrook Formation:** *Dolostone, Limestone, Dolomitic Platy Shale and Siltstone*

Map Scale 1:500,000
1 inch = Approximately 8 miles

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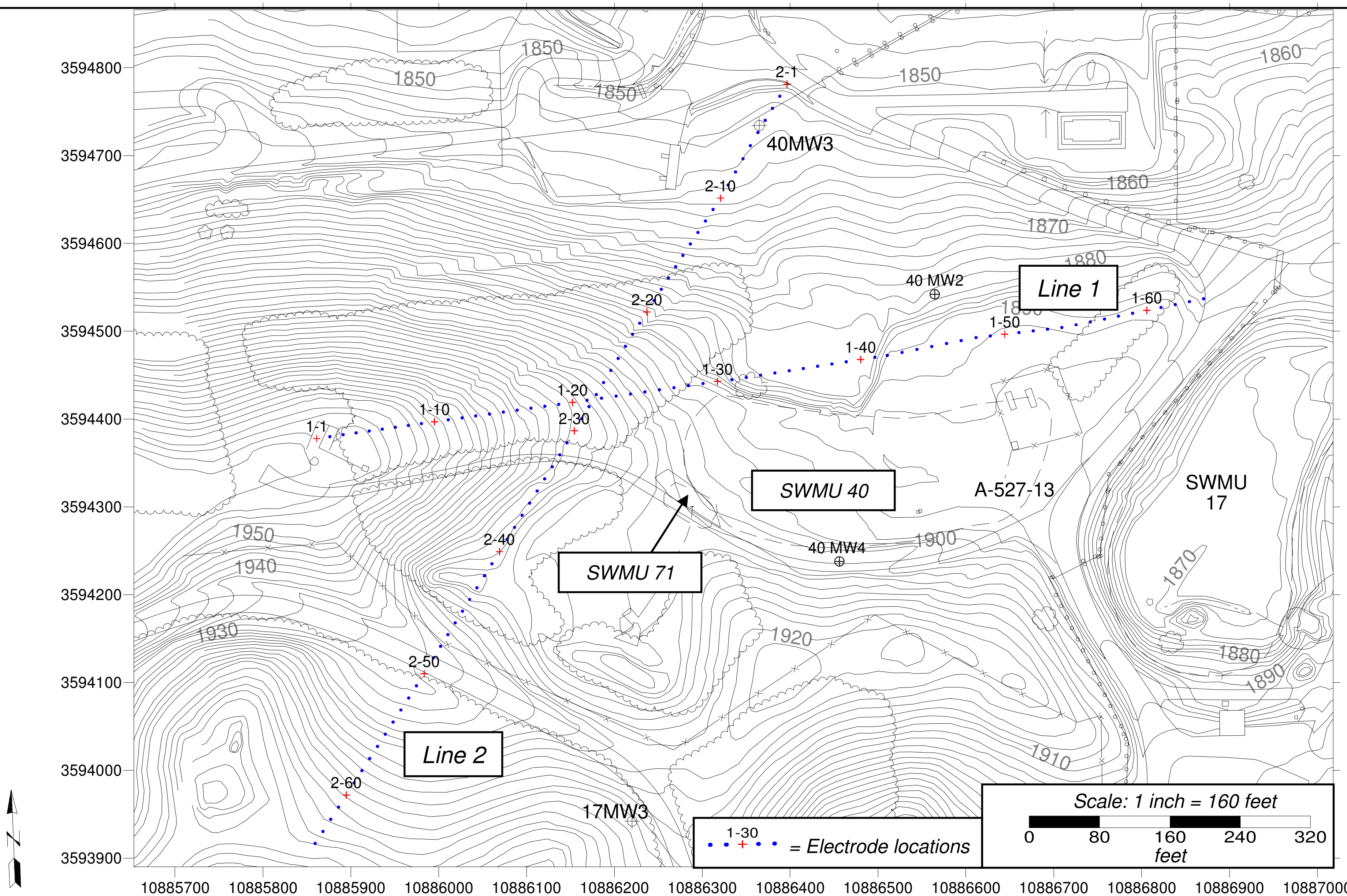

Report Title:
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File Name: *RAAP SWMU 40-71 Res Is.ppt*

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Figure 4. Portion of site layout illustrating the location of SWMU 40-71, the locations of resistivity electrodes and other site features.

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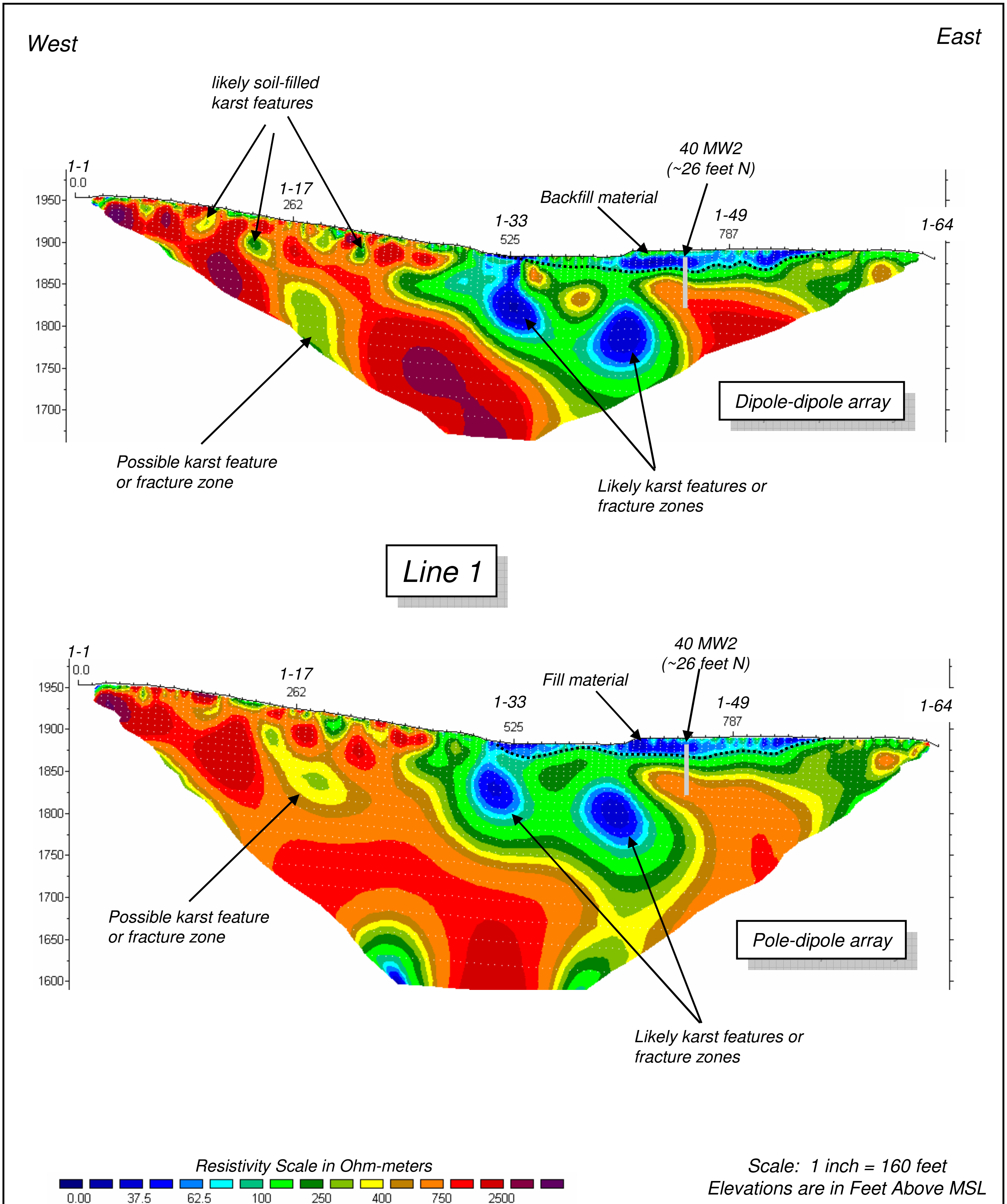

Report Title: *Resistivity Imaging Survey for the RAAP SWMU 40-71, Radford, Virginia*	*Figure 5. Results of Line 1, illustrating data from the pole-dipole array and the dipole-dipole array and recommended monitoring well locations.*	ATS **International** Advanced Technical Services Christiansburg, VA 540-382-8861 *Engineering Geology, Hydrology, and Geophysics* *Computer Modeling and Visualization*
File Name: *RAAP SWMU 40-71 Res pt.ppt*		
Date: *12/14/06* Draftsman: *CMP*		
ATS Project Number: *P06-04*		

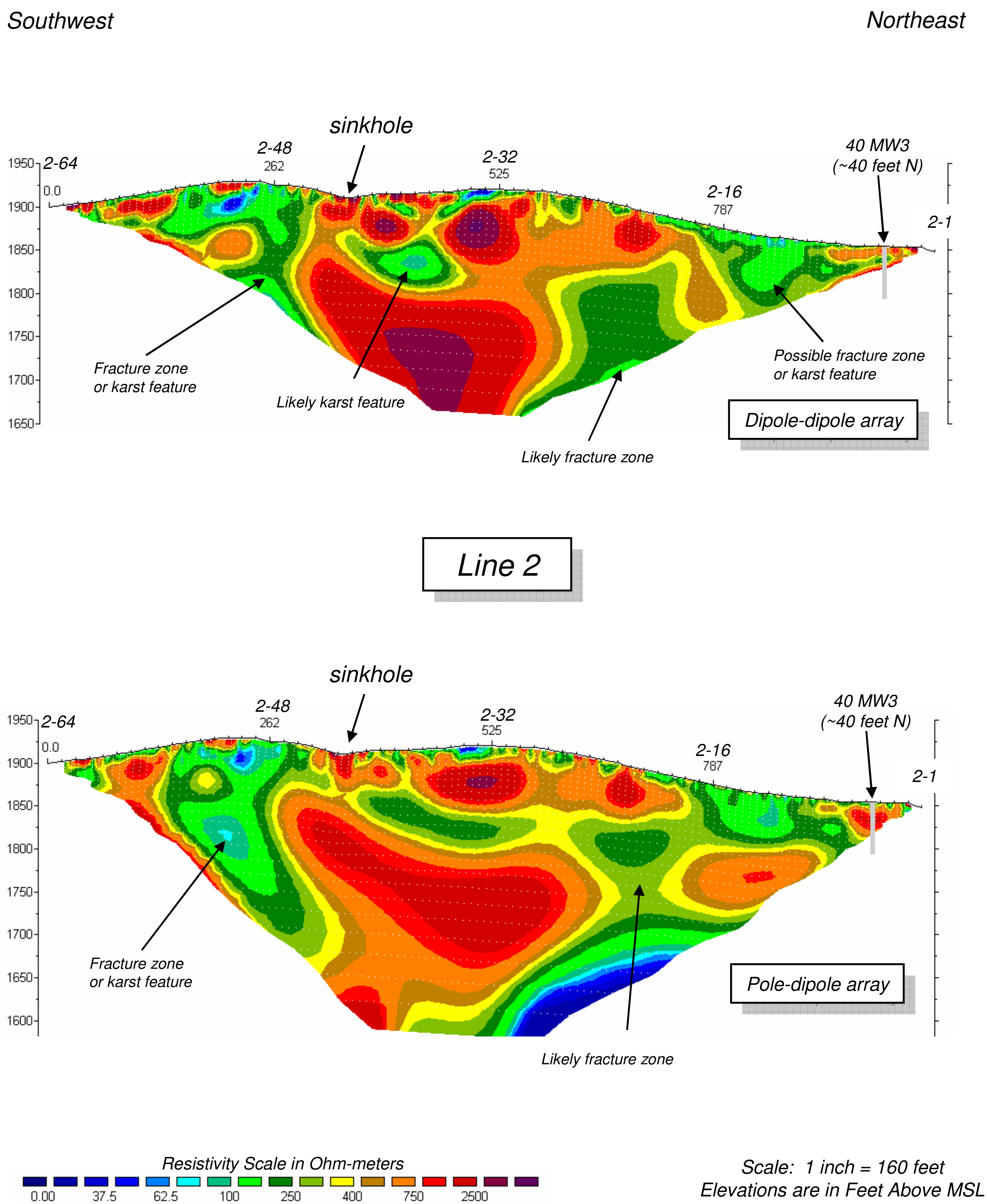

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Figure 6. Results of Line 2, illustrating data from the pole-dipole array and the dipole-dipole array and recommended monitoring well locations.

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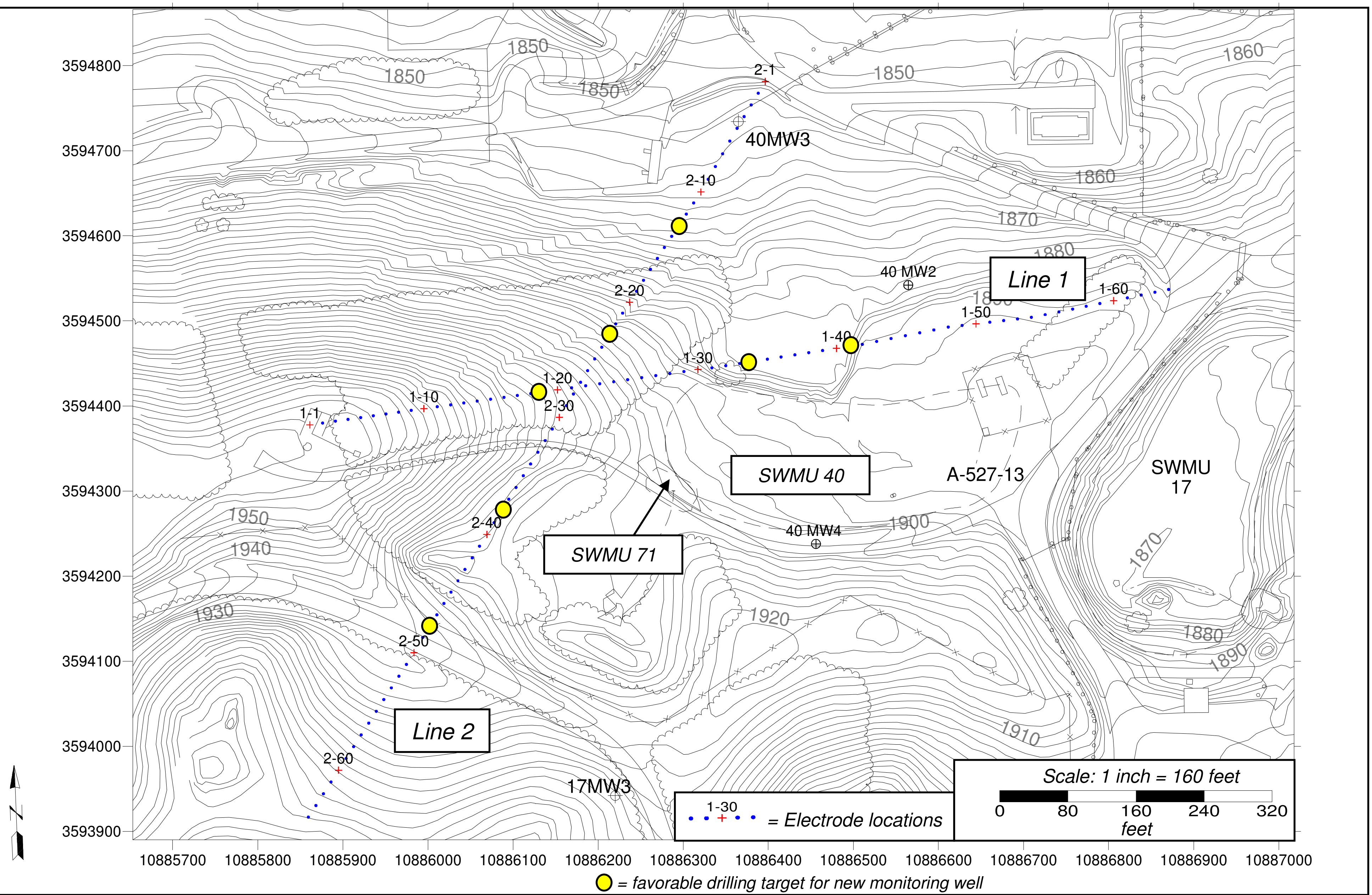

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Figure 7. Portion of site layout illustrating electrode flag locations of all favorable drilling targets for new monitoring wells based on interpretation of the resistivity data.

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