**Investigation on the Combined Use of Ground Penetrating Radar,
Cone Penetrometer and High Resolution Seismic Data for Near
Surface and Vadose Zone Characterization in the A/M Area of the
Savannah River Site, South Carolina**

RECEIVED

JUN 05 1998

OSTI

by

D. E. Wyatt

Westinghouse Savannah River Company
Savannah River Site
Aiken, South Carolina 29808

R. J. Cumbest

R. K. Aadland

F. H. Syms

D. E. Stephenson

J. C. Sherrill

DOE Contract No. **DE-AC09-96SR18500**

This paper was prepared in connection with work done under the above contract number with the U. S. Department of Energy. By acceptance of this paper, the publisher and/or recipient acknowledges the U. S. Government's right to retain a nonexclusive, royalty-free license in and to any copyright covering this paper, along with the right to reproduce and to authorize others to reproduce all or part of the copyrighted paper.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
JS

**Upper Three Runs Watershed
A/M Area Advanced Geological Study
Part 1 of 3**

**Investigation on the Combined Use of Ground
Penetrating Radar, Cone Penetrometer and High
Resolution Seismic Data for Near Surface and
Vadose Zone Characterization in the A/M Area of
the Savannah River Site, South Carolina (U)**

D. E. Wyatt
R. J. Cumbest
R. K. Aadland
F. H. Syms
D. E. Stephenson
J. C. Sherrill

Site Geotechnical Services
Westinghouse Savannah River Company
P. O. Box 616
Aiken, South Carolina 29808

SAVANNAH RIVER SITE

Upper Three Runs Watershed
A/M Area Advanced Geological Study
Part 1 of 3

Investigation on the Combined Use of Ground
Penetrating Radar, Cone Penetrometer and High
Resolution Seismic Data for Near Surface and
Vadose Zone Characterization in the A/M Area of
the Savannah River Site, South Carolina (U)

D. E. Wyatt
R. J. Cumbest
R. K. Aadland
F. H. Syms
D. E. Stephenson
J. C. Sherrill

Site Geotechnical Services
Westinghouse Savannah River Company
P. O. Box 616
Aiken, South Carolina 29808

The A/M Area Advanced Geological Study is comprised of three separate reports as follows:

Part 1

Investigation on the Combined Use of Ground Penetrating Radar, Cone Penetrometer and High Resolution Seismic Data for Near Surface and Vadose Zone Characterization in the A/M Area of the Savannah River Site, South Carolina (U)

Part 2

Interpretation of Geological Correlation Borings 1, 2, 3 in the A/M Area of the Savannah River Site, South Carolina (U)

Part 3

Geological Interpretation of the Structure and Stratigraphy of the A/M Area, Savannah River Site, South Carolina (U)

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (615) 576-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.

DISCLAIMER

**Portions of this document may be illegible
electronic image products. Images are
produced from the best available original
document.**

TABLE OF CONTENTS

Executive Summary	3
Introduction	5
Techniques	7
Borehole Geophysical Data	7
Cone Penetrometer Data	9
High Resolution Seismic Data	10
Ground Penetrating Radar Data	13
Interpretation	13
Geologic Correlation of Data Sources	23
Summary of Geology	27
References	29
Appendices	
Appendix A - CPT Data	
Appendix B - Field GPR Data	

LIST OF FIGURES

Figure 1. Study Area Base Map	6
Figure 2. Geophysical Log Correlation Suite	8
Figure 3. CPT and GCB-1 Correlation Panel	17
Figure 4. HRS and CPT Correlation	19
Figure 5. GPR Z-Plot	20
Figure 6. GCB-1, CPT and GPR Correlation	21
Figure 7. CPT and GPR Correlation	25

This page intentionally left blank.

EXECUTIVE SUMMARY

This study compares data from Cone Penetrometer Tests (CPT), high resolution surface reflection seismic (HRS) data and ground penetrating radar (GPR) data in the upper 120 feet (40 meters) of the A/M Area, Upper Three Runs Watershed at the Savannah River Site in South Carolina. The CPT, GPR and HRS data were obtained along the Silverton Road in the western sector of the A/M Area groundwater plume, and adjacent to Geophysical Correlation Boring #1 (GCB-1). This location allows for multiple correlations to be made between the various data sources, and supports shallow investigations for near surface effects of the Crackerneck Fault, a major structural feature in the area.

Borehole geophysical data from GCB-1 were used to provide subsurface constraints on the CPT, GPR and HRS data. Core data, natural gamma ray, spectral gamma data, multi-level induction resistivity, density and sonic data were utilized to distinguish clays, sands and silts. The CPT data provided tip bearing and sleeve stress, as an indicator of stratigraphy. Reflection seismic data provided continuous subsurface profiles of key marker horizons. Ground Penetrating Radar provided information on shallow subsurface geological features.

Conclusions from this study suggest that there is a high degree of correlation between the CPT and borehole geophysical data, specifically, the Friction Ratio and gamma/spectral gamma curves. The Upland/Tobacco Road, Tobacco Road/Dry Branch, Dry Branch/Santee, Santee/Warley Hill and the Warley Hill/Congaree contacts are discernible. From these contacts it is possible to map structural relationships in the shallow subsurface that are tied to regional data. Because formation contacts are discernible, CPT, HRS, GPR and geophysical log intra-formational anomalies are mappable. These features allow for stratigraphic and facies mapping using the GPR and HRS data for continuity and the CPT and geophysical data for lithofacies analysis. It is possible to use the combination of these tools to map shallow, stratigraphy and structure across the A/M Area.

The following geological interpretations are made for the east-west section along Silverton Road near GCB-1. Sediments below the Santee unconformity, and possibly to the Upland-Tobacco Road contact, are affected by the fault bend folding associated with the Crackerneck Fault. For these sediments, an anticline is present approximately 300 feet (91.4 m) immediately east of GCB-1 with sediments dipping eastward on the hanging wall side of the fault and westward into the footwall synclinal trough. The Upland Formation sediments exhibit bar and sheet sand facies as well as an noticeable channel in the

vicinity of GCB-1. The Tobacco Road and Dry Branch Formations are fairly homogeneous with more thin clay lamina and silts eastward becoming more sandy westward. Within the area of this study, the Tobacco Road and Dry Branch Formations thin adjacent to the Crackerneck Fault. The Santee and Warley Hill Formations show numerous interspersed facies changes throughout their interval. Within these formation the sediments generally become thicker westward and down dip. Additional sands and clays are present down dip from the flexural high adjacent to A-CNF-C07 and C08. These sediments may be related to channel or distributary fill associated with the Crackerneck syncline. The "Green Clay Confining Zone" is traceable as a CPT stratigraphic horizon but exhibits facies changes from a silty clay to a clayey sand. No distinct aquitard is defined by this horizon. No obvious fault offsets are seen in the upper 120 feet (40 m) of sediments evaluated in the area of this study.

INTRODUCTION

Studies of geomorphological processes and environmental characterizations in the unconsolidated sediments of the Atlantic Coastal Plain require a knowledge of near surface geology that may involve paleochannels, facies change, jointing and faulting. Shallow buried channels, while obvious in outcrop, are seldom apparent from surface characterization. Near surface faulting and fracturing in unconsolidated sediments exists in a variety of forms at the SRS and may not be obvious from surface or shallow subsurface mapping. Detecting the presence of shallow features in the alternating sands and clays of the southeastern U.S. coastal plain is important for an understanding of the affects on hydrogeologic properties associated with contaminant transport to areas not predicted in conventional groundwater modeling.

This study compares data from Cone Penetrometer Tests (CPT), high resolution surface reflection seismic (HRS) data and ground penetrating radar (GPR) data in the upper 120 feet (40 meters) of the A/M Area. The CPT, GPR and HRS data were obtained along the Silverton Road in the western sector of the A/M Area groundwater plume, and adjacent to Geophysical Correlation Boring #1 (GCB-1) (reference Figure 1). This location allows for multiple correlations to be made between the various data sources, and supports shallow investigations for near surface affects of the Crackerneck Fault, a major structural feature in the area. The Crackerneck Fault is thought to influence present groundwater flow and historically may have influenced sediment patterns, that may in turn, further affect groundwater flow and contaminant transport.

An example of the shallow geology underlying the study area is shown on Figure 2. These data were combined with that from core descriptions and geophysical lithology cross-plots from GCB-1. This geology consists predominately of unconsolidated fluvial and deltaic sediments with a near shore marine influence. The sediments within the upper 120 feet (40 m) comprise the Upland, Tobacco Road, Dry Branch, Santee and Warley Hill Formations. The surface of the unconfined aquifer (Steed Pond Aquifer or water table) is approximately at the depth of the Warley Hill Formation (110-120 feet (34-37 m) at GCB-1).

The present day surface at the Savannah River Site consists of units varying in age from Holocene to Upper Tertiary. Pleistocene and Holocene drainages incised older sediments and deposited bar sands interbedded with channel sands and clays. These sediments overlie unconformably older units

Figure 1. General location description and relationship between the Penetrating Radar, Cone Penetrometer and High Resolution Seismic data with Geophysical Correlation Boring, GCB-1. The SRS lies within the upper Carolina Coastal Plain of the eastern US.

exposed when sea level fell during the late Tertiary providing the opportunity to see, at or very near the surface, many different facies. The immediate surface area of this study location is comprised of near shore, channel and fluvial sands of the Upland Formation, interbedded with thin silts and clays.

The "Upland Unit" is generally exposed throughout the area and consists of poorly sorted sands and clays interbedded with conglomerates generally thought to have been deposited in a fluvial environment (Fallaw and Price, 1995). Recognizable facies include channels, bars, and numerous crossbedded units. The lower contact is irregular and incises the underlying sediments.

The Tobacco Road and Dry Branch Formations are exposed in valley walls and floors. The Tobacco Road contains poorly sorted sands interbedded with clay lenses. The presence of marine fossils and glauconite indicate a shallow marine environment. In the upper part, clay laminae suggest that this was deposited in a transitional tidal flat to back bay setting (Fallaw and Price, 1995). The Dry Branch Formation consists of sands, clays, calcareous siliciclastics and some carbonates. While all of the various facies indicate a marine unit, the depositional environments range from back bay and lagoonal muds to barrier islands.

The Santee Formation consists primarily of calcareous sands and muds and the underlying Warley Hill Formation consists of clayey sands and sandy clays. The Warley Hill Formation comprises the hydrostratigraphic Green Clay Confining Zone (when present), the first aquitard within the study area.

Underlying the Green Clay Confining Zone is the Steed Pond Aquifer of the Lost Lake Aquifer System, (Aadland et al., 1995). The Steed Pond Aquifer generally consists of shallow marine shelf, near shore to intertidal and subtidal sands and clays of the Congaree Formation. The Steed Pond/Congaree is the deepest horizon considered in the CPT, GPR, HRS correlation.

TECHNIQUES

Borehole Geophysics

Borehole geophysical data from GCB-1 were used to provide subsurface constraints on the CPT, GPR and HRS data. Within the upper 120 feet (40 meters), core data, natural gamma ray, spectral gamma data, multi-level

GCB-1

Figure 2. Shallow geology from core descriptions and geophysical log response in borehole GCB-1, immediately underlying the Silverton Road study area. Stratigraphic horizons were determined from correlations with core data and field descriptions, and from correlations with surrounding borings. Hydrostratigraphy and stratigraphy are from Aadland et al., (1995). Environments of deposition were determined from geophysical log analysis and field core descriptions. Stage ages are from DNAG, 1983.

induction resistivity, density and sonic data were utilized to distinguish clays, sands and silts. Core and gamma ray data provided information on the lithology of the sediments underlying the test area. Induction resistivity data provided information on the conductance and dielectric properties of the sediments possibly corresponding to GPR horizons. Density and sonic data provide information on the bulk properties of the sediments possibly corresponding to CPT information. All borehole geophysical data were calibrated to American Petroleum Institute (API) standards.

Cone Penetrometer

The cone penetrometer used for this investigation was a "shoulder cone" (type 2 piezo-cone) electronic penetrometer equipped to measure excess pore pressure during penetration. The CPT is equipped with load cells to directly measure the tip bearing stress, and sleeve stress, as the probe is advanced. A pressure transducer measures pore pressure changes within a fluid filled cavity and porous stone (piezoelement) located above the cone tip. Penetration rates are generally around 0.5 inches per second. The CPT push rig was rated at a mass of 24 tons (21.8×10^3 kg) with a capacity of up to 30 tons (27.2×10^3 kg). Soundings were pushed until refusal (defined as a measured tip resistance of 1800 psi), usually the Congaree Formation (approximately 125-130 feet (40 m)) in this study, or reaching the capacity rating of the hydraulic push system. CPT testing procedures and equipment are standardized by the American Standard Testing Methods (ASTM) D5778, Standard Test Method for Performing Electronic Friction Cone Piezocone Penetration Testing of Soils. This has resulted in a highly consistent method of profiling the subsurface because test equipment, calibration requirements, testing procedures and data reduction have been standardized.

The standardized testing methods of the CPT yield a consistency (repeatability) of measurements leading to a reliable means of identifying unconsolidated sediment strata. Extensive research has been conducted to estimate relative soil types from CPT measurements for geotechnical purposes. The most common relationships are based on tip resistance and the calculated ratio of the sleeve stress divided by the tip resistance (friction ratio). Because the CPT is measuring physical properties of the soils as the probe is advanced, in-situ conditions can affect these measurements i.e., different conditions in the same lithologic sediments can yield different measurements. These may include moisture content, overburden stress, stress history and various other conditions. CPT data from this study has been plotted with the borehole geophysical curve in Figure 3 to provide a correlation to subsurface strata.

Prior to each sounding the following calibrations of test equipment were performed: (1) pre and post push zero load readings on the cone tip and sleeve load cells and pore pressure transducer, (2) saturation of the piezoelement, (3) disassembly of the probe before and after each sounding to examine for foreign material, (4) verification of tip and sleeve dimensions, and (5) calibration of the string potentiometer for depth control. Appendix A contains sounding plots of the 12 CPT's pushed in the study area.

The Friction Ratio data (sleeve friction divided by the tip resistance) have been evaluated for this study. Tip resistance is a measurement obtained by a conical tip located at the terminal end on the CPT probe usually reported in tons per square foot or megaPascals (tsf or mPa). This measurement is generally interpreted as an indication of the in-situ soil stiffness and/or density. Tightly packed sands generally have relatively high tip resistance as compared with clays which generally have lower resistance. The sandier and denser the soil, the higher the tip resistance. The tip resistance (q_T) is corrected for measured pore pressures within the saturated part of the section (below water table). Sleeve friction is a measurement of stress, or drag, induced along the cylindrical component located above the tip and directly behind the porous element on the Type 2 cone during penetration. The measured sleeve stress is an indication of the relative cohesion of the soils i.e., clay content. High sleeve stress generally indicates a finer grained soil while lower stresses indicate sandier soils. The pore pressure is a measurement of the excess pore pressure generated in the saturated piezoelement directly above the cone tip during the advancement of the probe. The amount of pressure induced is an indication of the openness or drainability of the sediments. Clayey units generally have high pore pressures while sands have lower pressures. The Friction Ratio is the calculated ratio of the sleeve friction divided by the tip resistance and is expressed as a percent. In a sandier soil, tip resistances are high relative to the sleeve friction resulting in lower values. As the sleeve friction increases due to the sediments becoming finer (silty or clayey), tip resistances generally decrease resulting in higher ratio values. Therefore, higher Friction Ratios generally indicate finer grained or clayey sediments.

High Resolution Seismic

Seismic line CNF-1 was obtained in an effort to define the stratigraphy and locate possible faulting and channeling inferred from borehole data, particularly the Crackneck Fault system, along Silverton Road. The line traversed a distance of approximately 14,000 feet (4267 m), along a west to east profile using an acquisition geometry designed to image deeper horizons. The basic seismic theory, acquisition parameters, data and results of the line are discussed below.

Reflection seismic data provides a continuous profile of key subsurface marker horizons and allows for a more uniform mapping in areas without detailed well information. In areas where geology varies abruptly, such as adjacent to shallow faulting or in area of rapid, near shore facies changes, continuous seismic reflection data may be the only method to locate and map these changes. In addition to horizon mapping, attributes of the seismic data may also be used to estimate types of sediments, bulk properties such as porosity and stratigraphic relationships necessary to understand modeling parameters.

The seismic reflection technique is based on the theory of acoustical waves traveling through subsurface media. Under the assumption that subsurface media is heterogeneous and stratified, an acoustical pulse traveling from the surface downward will encounter differing materials with differing physical parameters. If a material has a different physical makeup than material above or below, for example density, bulk or shear modulus, then the acoustical pulse will be partially reflected to the surface and partially transmitted through to the underlying material, according to Snell's Law. Each successive material will partially reflect and partially transmit the acoustic pulse until the initial energy is dissipated. Since sound travels in different materials at different velocities, the reflected pulse will arrive at receiver on the surface according to the velocity and depth of the reflecting material.

If depth is converted to time assuming a velocity, then sequentially and horizontally obtained seismic records will image or map differences in subsurface materials. Further, if the acoustic pulse is known, i.e., the shape, frequency and amplitude of the wavelet, then the deviation of this initial wavelet from a wavelet recorded on the surface, carries information about the nature of the subsurface material that deformed the initial wavelet.

The relationship between the wavelength (λ), velocity (V) and frequency (f) of seismic waves is the equation;

$$\lambda = V / f,$$

or wavelength equals velocity divided by frequency. Because acoustical energy is transmitted as a waveform, certain imaging restrictions apply. Principally, the vertical limit of resolution (the minimum thickness of a subsurface material detectable), depends on the dominant frequency and bandwidth of the wavelet. Routinely, one-quarter of a wavelength is commonly accepted as the limits of resolution (in fact, this is rarely achieved), therefore, if the subsurface wave has a frequency of 120 Hertz (cycles per second) and the average subsurface

velocity equals 4000 feet per second (1219 m/sec) (typical for SRS soils), then the resolvable limit will be $\lambda / 4$ or $(4000 / 120) / 4$ which approximates 8 feet (2.4 m).

The horizontal limits of resolution are commonly accepted to be one quarter of the diameter of the Fresnel Zone, or zone of subsurface illumination of a material by an incident wavefront. The Fresnel Zone may be thought of as a zone in the subsurface being affected by the energy of the incident acoustical wave, and commonly imagined as an inflated balloon pressed on a table. The flat area of contact between the balloon and table diverges spherically, much like a flashlight beam expanding when shown across a longer distance. Therefore, the Fresnel Zone expands in size with increasing depth from the surface, resulting in decreasing horizontal resolution with depth.

The Fresnel Zone may be expressed by the equation;

$$\text{radius of Fresnel Zone (r)} = V/2\sqrt{(T_0/f)},$$

where r = radius of zone, V = seismic velocity, T_0 = time of reflection event (in seconds) and f = dominant frequency of reflection event

Therefore, for a 120 Hz wavelet in a 4000 feet per second (1219 m/s) material at a depth of 60 milliseconds (0.06 seconds), the Fresnel Zone would be 45 feet (13.7 m) and the best horizontal resolution would be approximately 11 feet (3.3 m).

Field data was acquired using an OYO DAS-1 signal enhancement seismograph operating in 96 channel mode. 40 Hz OYO geophones were used in geophone strings having 3 phones per string. The energy source consisted of an IVI MiniVIBE® remotely triggered vibrator.

A simple asymmetric split spread geometry was utilized. Geophone spacing was 20 feet (6 m) with a 20 foot (6 m) near offset. The first 24 geophones were spaced with a 480 foot (146 m) far offset and geophones 25 through 96 had a far offset of 1440 feet (439 m). Shot spacing was 20 feet (6 m) with a linear frequency sweep from 50 to 200 Hz for 6000 milliseconds.

The following processing sequence was applied to the data: reformat SEG-2 field files to SEG-Y format, apply vibroseis whitening, F-K filter, predictive deconvolution, bandpass filter, trace edit, crooked line sort, statics, bulk velocity shift, velocity analysis, residual statics, apply normal moveout, stack, bandpass filter, trace amplitude balance, apply AGC.

Ground Penetrating Radar

Ground Penetrating Radar has been successfully used at the SRS for the detection of subsurface geological features (Wyatt et al, 1993, Wyatt and Temples, 1995). For this study, a multiple antenna frequencies approach (similar to Smith and Jol, 1992) was followed. The seasonal variation of moisture remained steady throughout the study and radar signal variations due to moisture, noted in Roberts and others (1991) are not thought to affect the data. All GPR interpretations in this study assume a single velocity model because the water table depth is below most observable structures.

GPR data was acquired using 100, 50 and 25 MHz center frequency antenna configurations with a Pulse Ekko-100 acquisition system in a common midpoint (CMP) mode. After field testing, the 25 MHz data provided the best depth penetration and was used for subsequent acquisition. Six fold data were acquired along a 400 foot transect using a three foot station interval. The transect extended from A-CNF-C09 to beyond A-CNF-C10. Soil velocities of 3 to 3.5 nanoseconds per foot were utilized using a processing sequence of dewowing, DC shifting, raw data gain application, time shifting, bandpass filtering, velocity analysis, spiking deconvolution, normal moveout correction, data stacking and final filtering. Record lengths were 1024 ns with a sampling rate of 0.25 nanoseconds. The theories of signal interpretation (for example the Fresnel Zone equation and Snell's Law) as described in the HRS discussion also applies to GPR data.

INTERPRETATION

The geological interpretation of each data source is discussed. Specific geological horizons are consistent between the data sources and include principal formational contacts and erosional surfaces as described in Fallaw and Price (1995) and Aadland et al. (1995). Geochron sequence markers that may appear in the study interval, such as the Santee unconformity, are also included and are based on regional correlations, and where available, lithostratigraphic core data.

Specific morphological interpretations include geomorphological features such as channels, bars, joints, and faults. Lithostratigraphic and facies interpretations include sedimentary interval descriptions such as point bar, beach sand and near shore marine as examples. Specific criteria for major features, such as channels and faults, are defined below.

The criteria used to define a channel are discussed in Reineck and Singh (1980) and include: 1) an obvious, incised erosional surface, 2) the presence of cross-bedding, 3) presence of point bar sequences, 4) an apparent thalweg, and 5) alternating sand/clay/gravel bars. Beres and Haeni (1991) also describe ground penetrating radar signatures in channel type deposits, including lap, cross-bedding, hummocky and flaser bedding. Several of these features are usually observable within a channel that incises relatively undisturbed sediments.

The criteria for determining jointing from GPR in unconsolidated sediments are from Wyatt and Temples (1995) and include: 1) a pattern of predominately straight and relatively continuous reflectors trending at intersecting angles to the horizontal, 2) a pattern of predominately straight and relatively continuous zones of disturbed or missing signal trending at intersecting angles to the horizontal, 3) a pattern of vertical or near vertical zones of no signal or chaotic signal return, and 4) traceable horizontal reflectors exhibiting no apparent offset across the above. It should be noted that vertical or nearly vertical jointing, with fill similar to surrounding material and with opening of less than one quarter wavelength were usually not detectable in the GPR data. Jointing with secondary fill material (for example, kaolinite or limonite in a sand formation) were usually observable even if the joint openings are less than one quarter wavelength.

Fault criteria used to interpret the seismic and radar data are those of Sheriff (1982) and Campbell (1965) and include 1) abrupt reflector terminations, 2) direct fault plane reflections, 3) presence of diffractions especially at a termination, 4) visible drag and rollover, 5) correlations of reflectors across a fault plane and possibly 6) loss of coherency beneath a fault plane or distorted dips seen through the fault plane (fault shadow).

Borehole Geophysical Data

The interpreted borehole geophysical and core data used in this comparison, compared with stratigraphic and hydrostratigraphic units, are shown on Figure 2. This figure shows data from the upper 120 feet (40 m) of GCB-1 and near surface lithostratigraphic and time picks are shown. There are only minor core description variations in the data with most observable changes being in color and grain size and shape. Changes in gamma ray values suggest a lithologic change at approximately 48 feet (14.6 m), which, when compared to the field core data, is interpreted to be the contact between the Upland Unit and the Tobacco Road - Dry Branch Formations. The presence of permeable zones and heavy minerals from the core data and geophysical logs, at a depth of 78 to 80 feet (24 m), is interpreted to be the Santee unconformity. The greatest

zones of permeability (40 to 50 millidarcies) appear to be within the Tobacco Road - Dry Branch interval and at the Santee unconformity. In the geophysical data, the most pronounced horizon, the "Green Clay" is at a depth of approximately 125 feet (38.1 m). The elevation of the water table is evident at 105 to 110 feet (32 to 33.5 m) by the change in resistivity data. On the resistivity log scale, minor variations occur within the section that may correspond to GPR horizons. Spectral data suggests that the only clays of significance within the section are associated with the upper portion of the Warley Hill Formation and contained within the "Green Clay", as indicated by both a uranium and thorium peak and the contact between the Dry Branch/Tobacco Road horizon. Field log descriptions indicate that only thin clay lamina (usually less than 6 inches or 0.15 m) are present throughout the Upland to Warley Hill section. Permeability variations, above the water table, are not indicated on other curves and may be due to changes in grain size and angularity, since only minor compositional changes are suggested by other log curves and the core analysis.

Cone Penetrometer Data

Twelve Cone Penetrometer Test soundings (CPT) were pushed along the center part of the seismic reflection line A-CNF-1 as shown on Figure 1. Individual CPT plots (examples are seen on Figure 3) are included in Appendix A. The spacing between soundings is approximately 100 feet (30.5 m) located every tenth shot point of HRS line CNF-1. The purpose of the CPT's was to provide shallow stratigraphic control in the upper portion of the section where the seismic signal is dampened out. It has been shown in other areas of the SRS that the CPT can be directly correlated with the geology and used to map subsurface formations, (Syms, 1997, MS thesis, Van Pelt, 1995). The friction ratio curve from the CPT (defined as the sleeve stress divided by the tip stress) can be interpreted as a relative shift in mud content. In general, low friction ratio values indicate lower mud content while higher values indicate higher mud content. Therefore, the friction ratio curve has been used as the primary curve for making geologic interpretations based on relative changes.

A CPT based shallow stratigraphy has been developed along the A-CNF-1 seismic line using cross correlation methods between the twelve soundings and the geophysical log response from GCB-1. Calibration of the CPT friction ratio curves was established by correlating the geologic picks made for well GCB-1 and CPT A-CNF-C4. The remaining CPT curves were then correlated based on similar friction ratio responses. Vertical gradational changes, interpreted from the CPT friction ratio logs, were used to describe depositional sequences such as fining or coarsening upward sequences, lithologically similar sections, and high or low frequency interbedded sequences.

Ground surface to about 180 feet (54.8 m) depth (150 feet (45.7 m) MSL) has been divided into three CPT units that can be correlated between the soundings and GCB-1. Characteristics and interpretation of these layers are provided in the following discussion beginning with the deepest layer. All CPT soundings terminate at the top of the Congaree Formation (Gordon Aquifer unit) except A-CNF-C08 which met refusal in the Santee Formation. The correlation panel developed from the CPT's and GCB-1 is shown on Figure 3. Unit specific interpretations are described below.

Warley Hill

The Warley Hill interval represents the deepest formation fully penetrated with the CPT and has been divided into two layers. The basal layer is interpreted as having a relatively moderate to high mud content with thin high frequency bedding and is typically referred to as the "Green Clay" (GC) or the "Green Clay Confining Zone". From the GC, the CPT depositional pattern rapidly transitions to thin and alternating fining upwards to coarsening upward sequences defining the upper layer of the Warley Hill. This portion of the Warley Hill can be interpreted as a predominantly near shore sandy facies. The top of this interval is marked by a sharp increase in the friction ratio, correlated between the adjacent CPT soundings and defining a basal clay contact with the Santee.

Santee Formation

The Santee Formation is interpreted as a generally sandy unit with a basal zone marked by a relatively high mud, clay content with high frequency bedding. A middle is interpreted as a dominantly sandy unit with low frequency bedding. The upper most zone of this interval is marked by a sharp increase in the friction ratio varying in thickness from less than five feet to over ten feet thick suggesting a variable clay/silt layer that may be correlative to the Santee unconformity.

Tobacco Road and Dry Branch Formations

The Tobacco Road and Dry Branch Formations are difficult to distinguish in the field and on many CPT logs and are therefore often combined together. These formations are characterized as sandy to silty facies that are a

Figure 3. Cone penetrometer and GCB-1 correlation panel. Panel is hung on a datum of 330 feet MSL, the approximate surface elevation of GCB-1 and A-CNF-C04. Friction Ratio curves are shown for the CPT data and the spectral gamma ray is used for GCB-1. The "Tobacco Road/Dry Branch" horizon is the base of the Upland, top of Tobacco Road contact. "Top Santee" marker is the contact between the Dry Branch and Santee Formations and is the probable horizon of the Santee unconformity. The "Top Warley Hill" is the contact between the Warley Hill and Santee Formations. The Green Clay Aquifer Zone of the Warley Hill Formation is shown. "Top Gordon Aquifer" is the contact between the Warley Hill and Congaree Formation and the top of the Lost Lake Aquifer Zone.

generally homogeneous unit with relatively thin and alternating coarsening and fining upwards sequences. The regularity of the thin and alternating coarsening and fining sequences suggests that these sediments were deposited in a shoaling environment. This sequence generally thins from approximately 40 feet (13 m) to 30 (9.6 m) feet across the Crackerneck Fault system.

High Resolution Seismic Data

Generally, the determination of continuous reflection horizons in the near surface section of CNF-1 is difficult because of the absence of the zones of seismic attenuation (mainly clays) and the lack of lateral continuity of the horizons. Also, line CNF-1 was designed to image deeper horizons associated with the Crackerneck Fault, therefore shallower intervals are more difficult to discern. Seismic data are shown on Figure 4.

The key horizons designed to be imaged by line CNF-1 were the Lang Syne/Sawdust Landing Formations (Crouch Branch Confining Unit, CBCU), within the Cretaceous and Paleozoic (Pzm) crystalline basement and possibly the Green Clay Confining Zone (a portion of the Warley Hill Formation) all deeper than the 120' (40 m) interval in this study (approximately 100 milliseconds). However, the following interpretations may be derived from the data.

Along the seismic line, the Warley Hill, Santee and Tobacco Road/Dry Branch markers are vague and only interpretable because of the corresponding patterns of the seismic data (white lines on Figure 4). These patterns show localized depressions, such as the swale at A-CNF-C10, possibly suggesting structural sag or localized channel. No obvious channel fill is present within the depression so it is not possible to classify the zone as a definitive channel feature. It is interesting to note that the sides of this swale correspond with the anticlinal to synclinal flexure of the Crackerneck Fault bend fold system.

The frequency anticipated and received averaged 100 Hz. Assuming an average near surface interval velocity of 2400 feet per second (731.5 m/s) for sediments above the water table, then wavelengths will average 20 feet (6 m). As a result, resolvable horizons will approximate 5 feet (1.5 m) in thickness. Assuming an average velocity of 5600 feet per second (1707 m/s) below the water table, then wavelengths will average 56 feet (17 m), and horizons less than 13 feet (4 m) thick may not be resolved.

Overall, the dominant feature of the CNF-1 seismic line is the fault bend fold sequence associated with the northward trending Crackerneck Fault System.

Figure 4. Correlation of high resolution seismic and CPT data using land surface as the datum. The Santee and Warley Hill contacts are those from the correlation panel (Figure 3). Overall, the data is marginal to poor in the upper 100 ms although the pattern of the seismic horizons (in white) is similar in shape to the stratigraphic horizons. The differences are probably caused by problems in near surface statics.

Figure 5. Z-Plot of percent mud (clay, numbers on graph corresponding to colors on scale) versus deep induction resistivity versus gamma curve and depth. Z intervals (colored boxes) are arbitrarily selected to zone resistivity values. Low resistivity and low gamma values (yellow box) suggest clean, saturated sands. High resistivity zones (black or pink) may be associated with silty sands or clays which form GPR reflection events. Based on the differences in resistivity zones and changes in mud percent (in colored boxes) and changes between zones that are highlighted on the log plot (corresponding zones in similar colors) then possible GPR reflection events, are shown as red triangles.

Figure 6. CPT-09 and 10 and 25 MHz GPR data overlay. Interpreted horizons from the correlation panel (Figure 3) are shown. Depth scales are in nanoseconds. Datum is set to surface (zero time). The trends of the horizons are similar to those of the correlation panel.

Faulted basement rocks underlies CPT's A-CNF-C12 to C09, with the axis of the fault bend anticline underlying A-CNF-C08 and C07 and near HRS shotpoints 320-50. The effect of the fault is seen to near surface horizons with a trend of eastward dipping reflectors east of the fault plane and flat to westward dipping horizons from the footwall. There is an apparent depression or sag on the footwall block adjacent to the fault plane that may have an increased thickness of sediment. The presence of this sag is seen in the CPT logs (Figure 3) and may be present on the GPR record (Figure 6). It is not apparent that the sag extends to the surface.

Ground Penetrating Radar Data

Geophysical and core data from GCB-1 were used to estimate possible radar and seismic reflective horizons from the surface to an approximate depth of 120 feet (40 m). Using TerraSciences® software, a z-plot, comparing geophysical log derived deep induction resistivity data with calculated gamma ray information and the percentage mud fraction determined from the core analysis, was made. A z-plot compares the magnitude of a variable against two other variables and Figure 5 plots the magnitude of the mud fraction against resistivity and the gamma ray values. On this figure, highlighting clusters of data by relative resistivity values and gamma count allows zones of similarity to be plotted against depth from surface. Low resistivity, low gamma values (yellow) appear to be isolated into specific horizons as do higher resistivity, higher gamma values (black for example). The GPR signal is sensitive to changes in subsurface dielectric values which vary based on resistivity or conductivity. Sediments with higher mud values also have generally higher dielectric values. Because there is distinctive clustering in the data, based on mud percent and resistivity, it should be possible to define specific reflectors on the GPR reflection section.

The GPR profile shown on Figure 6 is aligned with the locations of the CPT's shown as a reference. Probable GPR reflection horizons, determined from comparing deep induction resistivity values to mud/clay percent, are shown. The GPR interpretation assumes a single velocity model because the water table depth is below the effective GPR data. No useable data is apparent below 800 nannoseconds. Fault and channel criteria used to interpret the radar data are the same as those used for the high resolution seismic data. Because lateral changes seen on the 25 MHz data may be caused by soil changes and/or antenna coupling, a conservative approach was taken in interpreting the data and only visibly and laterally coherent events were selected. Changes on the GPR section due to soil changes or antenna motion are expected to be vertical. Additionally, anomalous or disturbed reflection zones may be caused by changes in the dielectric constants and/or subsurface conductivity. These

changes are expected along faulted interfaces due to mineralization, fluids and abrupt geologic contacts.

The wavy character of the reflectors between A-CNF-C10 and C09 may be interpreted as a bedded sand and silt channel following the suggestions of Beres and Haeni (1991) and confirmed by the thickening sand interval in the Dry Branch Formation interpreted from the CPT data. Hummocky reflectors surrounding this feature may indicate discontinuous bedded sands of varying grain character as suggested from the field core description from GCB-1.

The overall character of the GPR data, with a structurally lower set of near surface horizons in the east and shallowing to the west, is consistent with the HRS and CPT data. The hummocky and thickening interval on the GPR between traces 220 and 100 corresponds to the thickening Dry Branch interval on the CPT correlation panel between A-CNF-C06 and A-CNF-C12.

GEOLOGIC CORRELATION OF DATA SOURCES

Correlating the datasets used in this study requires that specific horizons, or markers, be determined that are common to each set of information. Once these common horizons are determined, then the specific attributes of individual stratigraphic units may be determined from the unique measurements each tool provides.

Figure 7 is a synthetic radargram calculated from CPT A-CNF-C04. A reflection coefficient model, calculated from the friction ratio data, generates a normal synthetic radargram that is compared to the actual GPR data. This radargram is calculated using the assumption that changes in the friction ratio correspond to changes in lithology between sand and clay and that there are electrical property changes between the sand and clay. These relationships were established by comparing several dielectric values with friction ratios at a nearby site. This assumption is supported by the relationships seen on the figure. Based on this comparison, it is evident that obvious correlating reflectors are present at depths of 15-20, 50 and 70 feet (4.5, 15 and 21 m). Less obvious correlations are present throughout the section to an approximate time of 800 ns. Because the CPT data are interpretable for stratigraphic horizons, and a correlation exists between the synthetic radargram created from the CPT, with the actual radar section, it is possible to identify reflection events on the GPR data.

The correlation of synthetic radar data, generated from the CPT data, is compared to the GPR data on Figure 6. There is a high amplitude, low

frequency CPT anomaly associated with a high amplitude GPR event at approximately 400 ns in CPT-10. In CPT-9, the same high amplitude, low frequency CPT anomaly is seen at approximately 550 ns. These anomalies are thought to be correlative with the difference in time caused by the higher velocity sands in the GPR channel seen in the shallow subsurface at CPT-9, that is not present in CPT-10 and with the change in subsurface elevation of the strata associated with the channel. A pattern of high frequency, high amplitude anomalies is seen on both CPT sections. The pattern of these anomalies is similar and thought to represent the resistivity changes seen in the GCB-1 z-plot (Figure 5). However, the GPR data below approximately 600 ns is weak and it is not possible to specifically determine the correlations of reflection events to lithology. The possible GPR reflectors on Figure 5 probably correspond to these intervals on the CPT synthetic GPR data.

On Figure 5, a z-plot of percent clay versus resistivity suggests that there are up to three principal GPR events possible within 100 feet (30.5 m) of the surface. The processed GPR section indicates that mappable reflectors below 600 ns (50 feet, (15.2 m)) are not present and that a clear water table horizon is not seen. The section also indicates that there are more GPR event horizons than may be determined from the geophysical log. The first dominant reflector at 260-270 ns corresponds with the approximate base of the Upland Formation. Earlier events on the section are probable due to bedding, facies or erosional changes within the Upland Formation.

Correlating reflection events on the GPR data suggests that there is an undulating or folded bedding surface and channeling in the near surface of the study area (refer to Figure 1). A channel exists between GPR traces 220 and 100 as evidenced by thalweg, scour, point bar infill and a hummocky appearance. The hummocky nature of the fill material in the basal beds of the channel, and the consistent character of the sands in the upper beds, suggests that the channel was formed as a result of erosion possibly associated with sea level regression. This channel incises the entire Upland interval. Sediments adjacent to the channel are gently undulating and maintain a fairly uniform thickness. Changes in the amplitude and frequency character of the reflection events may suggest changes in sediment character or facies but no definitive radar signature exists to correlate specific facies to signal. There are no definitive indications of event offsets that might suggest near surface faulting. Underlying the Upland, the weaker reflectors of the Tobacco Road Formation are defining a gentle syncline with an axis at approximately 130 ns.

Figure 7. Correlation of GCB-1 with synthetic GPR signature calculated from CPT A-CNF-C04. Data are tied to the GCB-1 geophysical log and A-CNF-C04 Friction Ratio log. Calculated curves with synthetic GPR traces, and corresponding GPR synthetic radargram trace are correlated with a portion of the actual field GPR data. This figure establishes a correlation horizon for the CPT and GPR data. There is no useable GPR data below approximately 80 feet (27 m).

The correlation of CPT to HRS data is also shown on Figure 4. Only that portion of CNF-1 that underlies the CPT and GPR data is considered in this study. Similar to the GPR data, the HRS data defines an undulating subsurface with structure influenced by the presence of the Crackerneck Fault System. A fault bend fold system exists associated with the Crackerneck that influences overlying sediments to within approximately 50 ms of the surface. A possible channel morphology is centered along the axis of the syncline. Thicker sediments in the deeper portions of the hanging wall suggest that the fault was active prior to the Late Cretaceous. Visible offset of reflectors is obvious through the Late Cretaceous and fault bend folding is apparent through possibly the Warley Hill, and/or Santee unconformities. There is no apparent faulting to the surface.

In general, the correlation of the high amplitude, low frequency GPR event (Figure 6) matches the undulations seen on the seismic data in the near surface (high in the east and low in the west). The pattern of the high amplitude, high frequency events also mimic the nature of the seismic data but do not correspond to specific reflection events. The general pattern of seismic, CPT and GPR data suggests that there is a fairly uniform thickness of Upland sediments that generally thin to the east. These sediments overlie a Tobacco Road section that thins to the west and east and thickens in an apparent channel between CPT locations A-CNF-C11 and C05. This channel is apparent on the GPR data between shotpoints 220 and 100. The Dry Branch Formation has an undulating thickness variation that thins and possibly shoals in CPT A-CNF-C07 and C06.

The overall character of the sediments changes below the Santee unconformity. There is minimal GPR information below this horizon and the character of the HRS data is non-distinct. In general, remaining Santee sediments are thinner to the east while thickening between CPT A-CNF-C07 and C11, possibly suggesting a channel similar to the Tobacco Road interval. The Warley Hill Formation is undulating across the section while the "Green Clay" interval is fairly uniform in thickness and character, slightly thickening to the west. Strata below the Santee unconformity generally dip to the west from the hanging wall to the footwall of the Crackerneck Fault. As suggested in the GCB-1 geophysical log, specifically the spectral and core data, there are no appreciable clay units in the upper 120 feet (40 m) of the study area, although there are clayey sediments associated with the Upland and Tobacco Road contact.

SUMMARY OF GEOLOGY

Along the line of study, the combination of the HRS and GPR data with stratigraphic horizons tied by the CPT and GCB-1 correlation allow for a continuous geological section to be interpreted. Therefore, it is possible to infer the following geological information from the data generated in this study.

- There is a high degree of correlation between the CPT and borehole geophysical data, specifically, the Friction Ratio and gamma/spectral gamma curves. The major formation contacts, including the Upland/Tobacco Road, Tobacco Road/Dry Branch, Dry Branch/Santee, Santee/Warley Hill and the Warley Hill/Congaree contact are discernible. From these contacts it is possible to map structural and stratigraphic relationships in the shallow subsurface that are tied to regional data.
- Because formation contacts are discernible, CPT, HRS, GPR and geophysical log intra-formational anomalies are mappable. These features allow for stratigraphic and facies mapping using the GPR and HRS data for continuity and the CPT and geophysical data for lithofacies analysis. It is possible to use the combination of these tools to map shallow, vadose zone facies across the A/M Area.
- There is a general agreement between the predicted GPR events from the borehole geophysics and z-plot data and the actual GPR reflection events. Where core and resistivity data are available in a boring, it should be possible to estimate GPR reflection capability, and
- Since the general structural and stratigraphic pattern observed on the HRS data is seen in the CPT, borehole and GPR data, then the capability to infer the affects of shallow features within the A/M Area, particularly those associated with the Crackerneck Fault System, is possible.

The following geological interpretations are made for the east-west section along Silverton Road near GCB-1. Sediments below the Santee unconformity, and possibly to the Upland-Tobacco Road contact, are affected by the fault bend folding associated with the Crackerneck Fault. For these sediments, an anticline is present approximately 300 feet (91.4 m) immediately east of GCB-1 with sediments dipping eastward on the hanging wall side of the fault and westward into the footwall synclinal trough. The Upland Formation sediments exhibit bar and sheet sand facies as well as an noticeable channel in the vicinity of GCB-1. The Tobacco Road and Dry Branch Formations are fairly homogeneous with more thin clay lamina and silts eastward becoming more

sandy westward. Within the area of this study, the Tobacco Road and Dry Branch Formations are essentially flay lying except for intervals possibly affected by the Crackerneck Fault. The Santee and Warley Hill Formations show numerous interspersed facies changes throughout their interval. Within these formation the sediments generally become thicker westward and down dip. Additional sands and clays are present downdip from the flexural high adjacent to A-CNF-C07 and C08. These sediments may be related to channel or distributary fill associated with the Crackerneck syncline. The "Green Clay Confining Zone" is traceable as a stratigraphic horizon but exhibits facies changes from a silty clay to a clayey sand. No distinct aquitard is defined by this horizon. No obvious fault offsets are seen in the upper 120 feet (40 m) of sediments evaluated in the area of this study.

REFERENCES

- Aadland, R. K., J. A. Gellici and P. A. Thayer, 1995, Hydrogeologic framework of West-Central South Carolina, South Carolina Department of Natural Resources, Water Resources Division, Report 5, 200 p.
- Beres, M. and F. P. Haeni, 1991, Application of ground penetrating radar methods in hydrogeological studies. *Groundwater*, Vol. 29, No. 3. pp. 375-386.
- Campbell, F. F., 1965, Fault criteria. *Geophysics*, Vol. 30, No. 6, pp. 976-997.
- Fallaw, W. C. and V. Price, 1995, Stratigraphy of the Savannah River Site and vicinity. *Southeastern Geology*, Vol. 35, No. 1, pp. 21-58.
- Reineck, H. E. and I. B. Singh, 1980, Depositional sedimentary environments, 2nd ed. Springer-Verlag, New York, 549 p.
- Roberts R, J. L. Daniels and M. Vendl, 1991 Seasonal variations and ground penetrating radar data repeatability, In: Expanded Abstracts 61st Annual Meeting. Society of Exploration Geophysicists, Tulsa, Vol. 1, p. 486-489.
- Sheriff, R. E., 1982, Structural interpretation of seismic data, Education Course Series #23, AAPG, Tulsa, 73 p.
- Smith, D. G. and H. M. Jol, 1992, Ground penetrating radar investigation of a Lake Bonneville delta, Provo Level, Brigham City, Utah. *Geology*, Vol. 20, pp. 1083-1086.
- Syms, F. H., 1997, Geologic interpretation of the Electric Piezocone Penetrometer Sounding vertical sequence analysis and lithofacies mapping of Eocene Carolina Coastal Plain Sediments-Savannah River Site, University of South Carolina, unpublished Master's thesis.
- Van Pelt, R. S., 1995, Integration of innovative and traditional investigative technologies in subsurface hydrogeological characterization at the Savannah River Site, SC (abstract), 1995 Geological Society of America Annual Meeting.
- Wyatt, D. E., M. G. Waddell and G. B. Sexton, 1995, Geophysics and shallow faults in unconsolidated sediments. *Groundwater*, Vol. 34, No. 2, March-April 1996, pp. 326-334.

Wyatt, D. E. and T. J. Temples, 1996, Ground-penetrating radar detection of small-scale channels, joints and faults in the unconsolidated sediments of the Atlantic Coastal Plain. *Environmental Geology*, Vol. 27, pp. 219-225.

WSRC-RP-97-0184

Revision 0

June, 1997

Appendix A
Cone Penetrometer Logs

WSRC-RP-97-0184

Revision 0

June, 1997

This page intentionally left blank.

A-CNF-C01

APPLIED RESEARCH ASSOCIATES, INC.

06/27/96

North 99744.4

East 46495.0

Elevation 333.2

A-CNF-C02

APPLIED RESEARCH ASSOCIATES, INC.

06/28/96

North 99702.2

East 46374.0

Elevation 332.3

A-CNF-C03

APPLIED RESEARCH ASSOCIATES, INC.

06/28/96

North 100087.9

East 46222.3

Elevation 334.4

A-CNF-C04

APPLIED RESEARCH ASSOCIATES, INC.

07/02/96

North 100230.3

East 46081.4

Elevation 337.4

A-CNF-C05

APPLIED RESEARCH ASSOCIATES, INC.

07/01/96

North 100319.1

East 45902.5

Elevation 341.4

A-CNF-C06

APPLIED RESEARCH ASSOCIATES, INC.

07/02/96

North 100389.3

East 45715.4

Elevation 347.2

A-CNF-C07

APPLIED RESEARCH ASSOCIATES, INC.

07/03/96

North 100457.4

East 45527.4

Elevation 354.5

A-CNF-C08

APPLIED RESEARCH ASSOCIATES, INC.

07/08/96

North 100526.2

East 45339.7

Elevation 360.0

A-CNF-C09

APPLIED RESEARCH ASSOCIATES, INC.

07/09/96

North 100594.1

East 45151.9

Elevation 362.8

A-CNF-C10

APPLIED RESEARCH ASSOCIATES, INC.

07/09/96

North 100681.7

East 44972.6

Elevation 359.0

A-CNF-C11

APPLIED RESEARCH ASSOCIATES, INC.

07/10/96

North 100797.4

East 44809.7

Elevation 358.5

A-CNF-C12

APPLIED RESEARCH ASSOCIATES, INC.

07/10/96

North 100919.4

East 44650.9

Elevation 359.7

WSRC-RP-97-0184

Revision 0

June, 1997

Appendix B
25 MHz Ground Penetrating Radar Data

WSRC-RP-97-0184

Revision 0

June, 1997

This page intentionally left blank.

Well Cluster Road GPR (@ 3' station interval) = Seismic Line A-5 (@10' station interval)

Start 0' = Sta. #770 on A-5

End 315' = Sta # 801.5 on A-5

Trace #1 on GPR = approx. 770.5 on A-5

Trace #100 on GPR = approx. 785 on A-5

Trace # 200 on GPR = approx. 800 on A-5

GPR traces = 1.5' between stacked traces. Surface movement of source/receiver = 3 feet

Stacked section has 6 fold

Processing sequence:

Dewow

DC shift

Gain raw data

Time shift

Bandpass Filter

Velocity Analysis

Spiking Decon

Normal Move Out

Stack

Alpha Trim Mean/Median Filter

Silverton Road GPR (@ 3' station interval) = Seismic Line CNF-1 (@ 5' station interval)

Start 0' = Sta. #1034 on CNF-1

Intermediate 220' = Sta # 990 on CNF-1

Trace #1 on GPR = approx. 1033 on CNF-1

Trace #100 on GPR = approx. 1014 on CNF-1

Trace # 200 on GPR = approx. 994 on CNF-1

Trace # 250 on GPR = approx. 984 on CNF-1

Trace # 261 on GPR = approx. 982 on CNF-1

GPR traces = 1.5' between stacked traces. Surface movement of source/receiver = 3 feet

Stacked section has 6 fold

Processing sequence:

Dewow

DC shift

Gain raw data

Time shift

Bandpass Filter

Velocity Analysis

Spiking Decon

Normal Move Out

Stack

Alpha Trim Mean/Median Filter

Atta Fault Area GPR (@ 3' station interval) = Old GPR Line shot with GSSI Radar System

GPR traces = 1.5' between stacked traces. Surface movement of source/receiver = 3 feet

Stacked section has 6 fold

Processing sequence:

Dewow

DC shift

Gain raw data

Time shift

Bandpass Filter

Velocity Analysis

Spiking Decon

Normal Move Out

Stack

Alpha Trim Mean/Median Filter

** 0 ns. is approximately the ground surface on all sections. The air wave has been muted out. **

#982 - CNF-1

#1033 CNF-1