Delineation of a produced water plume in Pointe Coupee Parish, Louisiana

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DELINEATION OF A PRODUCED WATER PLUME IN
POINTE COUPEE PARISH, LOUISIANA

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
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Abstract

Three pits were excavated in the 1960’s at the Fordoche Oil Field in Lottie, Louisiana, as evaporation pits for oil well produced brines. The pits were closed and completed in the 1980’s. Previous studies indicate that produced water has leached into the subsurface within the area to the south and southeast of the pits. Ground penetrating radar (GPR) was utilized in an attempt to delineate the present location of the plume as well as test the feasibility of GPR within a clayey soil in south Louisiana. In addition to collection of GPR data, electrical conductivity logs and soil cores (including core sampling for sediment classification and chloride analysis) were collected. Electrical logs confirmed the presence of permeable zones interlaying impermeable zones. Core sampling for chloride confirmed the presence of the produced water within the study area. GPR was unsuccessful in delineating the plume at the site because of the high conductivity of the shallow sediments which inhibited penetration of radar waves. Calibration GPR studies were completed at grave sites in north and south Louisiana which proved successful due to favorable conditions.
Introduction

Ground penetrating radar (GPR) can be used for environmental site assessment (Benson, 1993; Reyes-Lopez et. al., 1998; Cassidy, 2007; Carsione et. al., 2000) provided that suitable conditions exist at the site. The site examined in this paper is located at Long Ranch near Lottie, Louisiana, within the Fordoche Oil Field (Figure 1). GPR was used at this site to test the hypothesis that the radar waves could delineate the front of the waste water plume. High

Figure 1: Pits (blue) and area of investigation (AOI, red). Insert in upper right corner shows location of study area in Pointe Coupee Parish.
conductivity of the waste water plume would cause a zone of attenuation (no signal return, Figure 2) that would contrast with reflectors from sedimentary layers in zones of low salinity pore water.

Goals of this study include: (1) determine whether GPR can be used to delineate a produced waste water plume; (2) test suitability of GPR for characterization of the subsurface in the area of interest (AOI); (3) determine electrical properties of the soil; (4) determine near surface stratigraphy within the AOI; and (5) determine chloride concentration of pore water within the sediments. Two GPR surveys were conducted 10 months apart to determine whether movement of the plume could be observed. In addition, two calibration studies were performed at grave sites in Oak Ridge, Louisiana, and St. Gabriel, Louisiana. The goal of the calibration studies was to verify the suitability of GPR for near surface imaging in other areas of Louisiana with known targets.

Figure 2: GPR transect using 50 MHz antennae showing a contaminant plume, modified from Porsani et. al., 1994. Note zone of attenuation.
Background

Three produced water waste pits were excavated at the study area in the 1960s. Pit No. 1, Pit No. 2, and Pit No. 3, cover an area of approximately 8360, 15980, and 8550 square meters, respectively (Figure 1). Each pit was excavated to a depth of approximately 1.2 m. Closure of the three pits began in 1984 and was completed in 1985 (Site Characterization Study, 1986). Following a lawsuit filed by landowners, a site assessment was conducted in 1986 by Woodward-Clyde Consultants. The assessment included geophysical mapping of the area as well as sediment coring, ground water sampling, core sampling and sediment characterization.

The geophysical conductivity survey was conducted with a Geonics EM 34 Terrain Conductivity Meter with 10 m spacing between coils which allowed for measured values to a depth of 15 m. The majority of the contaminant resides in the upper subsurface above 7.5 m (see Appendix C for figures from previous studies). Subsequent surveys have identified zones of relative high conductivity outside of the Woodward-Clyde surveys (see Appendix C). No terrain conductivity studies were completed after 1993.

Groundwater sampling was conducted from wells and hand auger boreholes to determine pH, alkalinity, chloride, sodium, sulfate and total dissolved solids (TDS) and established 3 known permeable zones within the upper 30 m of the subsurface; the first two are bound from 0-3.7 m, and 11.9-13.4 m, and the third is found at 27.1 m (Site Characterization Study, 1986; Supplemental Terrain Conductivity Survey Verification and Horizontal Delineation of Chlorides Fordoche Field, 1993; Terrain Conductivity Survey and Groundwater Verification Survey Fordoche Field, 1993). The majority of the wells and borings were completed within the shallow and intermediate permeable zones. Groundwater sampling was continued on a semiannual to annual basis after the Site Characterization Study was completed. Groundwater flow is to the
southeast and hydraulic conductivity was estimated to be 0.2 m per day in the shallow permeable zone and 0.026 m per day in the intermediate permeable zone (Revised Risked Evaluation/Corrective Action Program Investigation Report, 2006).
**Geology and Hydrogeology**

The site in Pointe Coupee Parish (Figure 1) consists of Holocene alluvial sediments (Generalized Geologic Map of Louisiana, 2008). The surface geology consists of natural levee and distributary channel deposits of the Mississippi River System. The deposits are composed of irregular beds of fine sands, silts, and clays. These deposits overlay older Quaternary age alluvial sediments, which also consist of irregular sand beds, silts, and clays. The alluvial sediments are underlain by a thick sequence of Cenozoic age alluvial, deltaic, and marine sediments (RECAP Evaluation of the Fordoche Field Site, 1996). The soil at the site largely consists of poorly drained silt loam and silty clay loam with a slope of less than one degree on natural levees of the Mississippi and Atchafalaya rivers and their distributaries (Pointe Coupee Parish Soil Survey, 1982).

Hand auger borings and cores completed using direct push Geoprobe rigs were completed throughout the site for the purpose of collecting soil and groundwater samples. The sediments within these hand auger borings and cores were identified as silts, clays, clayey silts and silty clays with some sands by previous characterization studies (Site Characterization Study, 1986; Terrain Conductivity Survey and Groundwater Verification Survey Fordoche Field, 1993; Hanor, 1997). The log descriptions of these studies are noted as containing orange-red (ferrous) staining and mottling, wood chips, high organics, and iron and calcareous nodules (Hanor, 1997).

According to several of the previous environmental characterization and impact studies (Site Characterization Study, 1986; Terrain Conductivity Survey and Groundwater Verification Survey Fordoche Field, 1993; Supplemental Vertical Migration of Chlorides in the Second and Third Permeable Zones Fordoche Field, 1993) the immediate underlying geology consists of several impermeable and permeable zones. The First Permeable Zone (shallow zone) lies
approximately 0 to 3.7 m below ground surface. The Second Permeable Zone (intermediate zone) lies approximately 11.9 to 13.4 m below ground surface, and a Third Permeable Zone (deep zone) is found at 27.1 m. Confining units lie in between the permeable zones. The average hydraulic conductivities of the First and Second Permeable Zones are $1.2 \times 10^{-3}$ cm/s and $2.6 \times 10^{-4}$ cm/s, respectively, and the average gradients in both the First and Second Permeable Zones are $9 \times 10^{-4}$ m/m to the south-southeast with porosity assumed to be 30 percent (Hanor, 1997). The permeable layers are not lithologically uniform and vary considerably both in composition and thickness over the extent of the study area.

The shallowest aquifers, which underlie the site, are Quaternary age alluvial sediments. These aquifers are in the Mississippi River Valley Alluvial (MRVA) Aquifer system which extends approximately 46 to 90 m below ground surface. Below the MRVA aquifer lie more continuous sand layers of Pleistocene deltaic deposits that are part of the Baton Rouge Aquifer System (RECAP Evaluation of the Fordoche Field Site, 1996).

The calibration site at Oak Ridge consists of Pleistocene terraced braided stream deposits (Generalized Geologic Map of Louisiana, 2008). The Sterlington silt loam is found throughout the site. It is a well-drained silty to sandy loam with a slope of less than one percent on natural levees bordering former channels and distributaries of the Arkansas River (Morehouse Parish Soil Survey, 1985).

The calibration site at St. Gabriel consists of Holocene alluvial sediments (Generalized Geologic Map of Louisiana, 2008). The Sharkey clay is found throughout the site, and is moderately to poorly drained clay with a slope of less than one percent on natural levees of the Mississippi River and its distributaries (Iberville Parish Soil Survey, 1977). Both calibration sites exhibit better drainage than the site in Pointe Coupee Parish.
**Methods**

GPR was used in an attempt to delineate the waste water plume by performing (1) two GPR surveys of an area south of the pits over the course of 10 months (Figure 3), (2) electrical conductive logging of soil at the site, and (3) coring at the site including sampling of the cores for chloride analysis and core sediment classification. GPR was used at the secondary sites in an attempt to verify the location of graves and to assess the performance of GPR in Louisiana soils with known targets.

A literature review was conducted to determine the area to be surveyed with GPR at the Pointe Coupee Parish site. An area southeast of the pits was chosen based on observed flow of the waste water plume in the Terrain Conductivity Survey and Groundwater Verification Survey Fordoch Field, 1993, (Figure 4) and grid lines were created using a well head as a reference. 50 MHz and 100 MHz GPR data were collected as continuous reflection surveys using instrumental default step size (the distance between traces) with regards to antenna frequency (0.5 m for 100 MHz and 1 m for 50 MHz), default distance between antennas (1 m for 100 MHz and 2 m for 50 MHz), a system stack of 4, AUTO Gain and DEWOW correction. Electrical logs were
completed to a depth of 12 m and cores were completed to a depth of 6 m. Electrical logs and cores were completed with a Geoprobe Model 6610DT direct push rig. Electrical logs were taken using a Geoprobe SC5000 electrical logging tool (Figure 5). The tool has sensors arranged in a Wenner array: 4 evenly spaced electrodes which produce an alternating current and measure current and voltage across the subsurface as the probe is pushed through the sediments (Gibson and George, 2003). Figure 6 shows locations of electric logs and core samples in the study area. Samples from cores were sedimentologically classified using ASTM 151H hydrometers and

![Isopach map showing chloride concentrations](image)
1000 mL graduated cylinders. Sediment samples from the cores were sent to Gulf Coast Analytical Laboratory for chloride analysis using EPA method 9251.

Figure 5: Diagram of the SC5000 tool. The sensors on the tool are arranged in a Wenner Array which consists of 4 evenly spaced electrodes. Modified from www.geoprobe.com.

Figure 6: Electrical log and core locations at the Pointe Coupee site.
GPR Processing

Data collected at the site in Pointe Coupee Parish were processed using Sensors and Software Ekko_View and Ekko_View Deluxe software. Data collected at the secondary sites were not processed as the raw data displayed on the digital video logger (DVL) were sufficient to determine the presence or absence of graves (See Appendix A for GPR parameters and transects).

A DEWOW filter was automatically applied to the data during collection. According to Sensors and Software (Ekko_View Enhanced and Ekko_View Deluxe User’s Guide, 2003), the DEWOW filter is applied in order to remove a slowly decaying low frequency “wow” trace, which would be superimposed upon and obscure high frequency reflections. AUTO Gain was also applied during data collection in order to boost weaker signals returning at later times. The next process applied to the data was background subtraction in order to remove the airwave. The final process applied to the data was a bandpass filter. Figures 7, 8, and 9 show a single trace before processing (Figure 7), after application of background subtraction (Figure 8), and after application of bandpass filtering (Figure 9). Raw data (Figure 10) are then processed using background subtraction, a filter which creates a moving average along the traverse using each trace and X traces on either side of the trace being averaged (Figure 11). This process tends to cancel out horizontal traces and emphasize dipping traces. In data from the Pointe Coupee Parish site background subtraction was used to eliminate the airwave (direct transmission from transmitter to receiver). Average as well as moving average background subtraction is used to eliminate clutter, including airwaves, surface and subsurface reflections (Olga Lopera et. al., 2007). The number of traces used for the background subtraction filter was determined by applying an interval of 5% of the total number of traces in the transverse to the filter, starting at
0% (minimum 3 traces) and then adding 5% at each increment (0%, 5%, 10%, etc.). If an increment resulted in a fraction or even number of traces, the increment was rounded to the nearest whole odd number. A background subtraction filter of 10% of the total number of traces of the transverse was found to most effectively remove the airwaves from each transverse (compare figures 7 and 8 and figures 10 and 11). However, the airwave is not completely removed by the process.

Next a bandpass filter was applied in order to filter out noise that masks returning signals (Figure 12). This is accomplished by aliasing noise outside of the frequency band (Vaughn, 1991). The bandpass filter operates by using a Fast Fourier Transform algorithm. A set of four frequencies is chosen to set the range included in the pass: F1, F2, F3, and F4. Above F4 and below F1 all frequencies have an amplitude of 0. Between F1 and F2 the frequency ranges from 0 and transitions along a cosine curve to the frequency defined for F2. Between F2 and F3 the filter has unit amplitude. The transition between F3 and F4 occurs from the frequency defined for F3 and transition to 0 along a cosine curve. A bandpass filter of 0-10-50-100 returned the best results for transects completed with the 50 MHz antennae and a bandpass filter of 0-25-100-200 returned the best results for transverses completed with the 100 MHz antennae. A frequency of 37 had the greatest amplitude for transects completed with the 50 MHz antennas and a frequency of 74 had the greatest amplitude for transects completed with the 100 MHz antennae (Figure 13).

Each method was tested on a GPR transect created using 50 MHz antennae and 100 MHz antennae. Once suitable standards for each filter/process were chosen, all transects were then filtered/processed with the following criteria: (1) DEWOW filter was applied during data collection; (2) automatic Gain was applied during data collection; (3) background subtraction
Figure 7: Single trace, raw data. Airwave is represented by large peaks of the graph reaching both a minimum and maximum of -50.0 and 50.0 mv. Reflections from the subsurface are represented by smaller peaks seen after the airwave. Signal fully attenuates at approximately 70 ns.

Figure 8: Single trace, background subtraction filter applied. Airwave peaks reduced but not removed. Changes in peaks of the subsurface have occurred but maximum and minimum mv values remain essentially the same.

Figure 9: Single trace, bandpass filter applied. The trace has been smoothed out, relative mv values remain the same. Signal fully attenuates at approximately 70 ns.
Figure 10: Transect 50-37C, raw data. 50 MHz antennae used.

Figure 11: Transect 50-37C, background subtraction applied. 50 MHz antennae used. Note airwave has not been fully eliminated and dipping reflectors have been enhanced between 0 and 1 m.

Figure 12: Transect 50-37C, bandpass filter applied. 50 MHz antennae used. Depth of penetration has not been significantly improved if at all.
filter was applied using 10% of the total number of traces for each transect; and (4) bandpass filter was applied using frequencies of 0-10-50-100 for transects completed with 50 MHz antennae, and frequencies of 0-25-100-200 for transects completed with 100 MHz antennae.

Figure 13: Average Amplitude Spectrum plot for transects 37 and 44. The 50 MHz antennae were used in transect 37 and the 100 MHz antennae were used in transect 44. Majority of signal return is 37 MHz for the 50 MHz antennae and 74 MHz for the 100 MHz antennae.
Pointe Coupee Parish Site Investigation

A total of 15 GPR transects with 50 MHz antennae and 14 GPR transects with 100 MHz antennae were completed. All GPR transects run east-west, perpendicular to the direction of flow of the waste water plume shown in previous studies (Site Characterization Study, 1986; Terrain Conductivity Survey and Groundwater Verification Survey Fordoch Field, 1993). All 50 MHz GPR transects show a depth of penetration to 2 to 2.5 m below ground surface (bgs) and all 100 MHz GPR transects show a depth of penetration 1 to 1.25 m bgs. All transects show only the shallow permeable zone. Depth of penetration is dependent on the frequency of the transmitter. Low frequency waves have greater penetration but less resolution (Benson, 1995). The assumed radar velocity when estimating depth was 0.06 m/ns. Transects were not corrected for terrain due to the relative flat topography of the study area. Small, local changes in topography (e.g., ditches) occur at the site, which may cause artificial dipping of units. It was determined that elevation correction was not needed in order to delineate the brine plume.

No transects show consistent evidence for the brine plume. The depth of penetration is more or less uniform across each transect except for transect 50-35A (see Appendix A for all transects). Raw data show possible signal attenuation between 340 and 400 m across the transect. However, after application of the background subtraction and bandpass filters the section of attenuated signal is removed from the transect. Transect 50-35A and 50-36A both display point source reflections at 2.5, 5, 8, and 9 m bgs (Figure 14). These were determined to be due to airwave reflections from point sources, namely a tree line along a road parallel to the transect (deeper point sources) and a well head (shallow point source), see Figure 3. High conductivity of the subsurface and high moisture content of the sediments caused attenuation of the radar signal in all transects.
A total of 9 vertical electrical conductivity logs were completed at the site. A SC500 probe with 4 sensors arranged in a Wenner array was used in conjunction with a Geoprobe Model 6610DT direct push rig. Eight of the nine logs were completed to a depth of 12 m. Log 34 was completed to a depth of 9.5 m and then logging was aborted due to equipment problems. All logs show a marked increase in conductivity between 2 to 4 m bgs (Figure 15). Conductivity then decreases from 8 to 10 m bgs. This would indicate a zone of relative high conductivity from 2 to 10 m below the surface. In unconsolidated sediments, primary controls on conductivity include moisture content, pore water composition and clay mineralogy (Harrington and Hendry, 2006). This zone likely possesses a higher percentage of clays than the surrounding material, as clay has electrical conductivity values ranging from 2-1000 mS/m and

Figure 14: Raw transects 50-35A and 50-36A combined using EKKO View Delux software.
silt has values ranging from 1-100 mS/m (Annan, 2005). Lower conductivity values (100 mS/m or less) are likely to indicate silt within the area. Conductivity logs 47 and 54 show higher conductivity values than other logs taken at the site (Figure 16 and Figure 17). Both logs were completed within the area where previous studies indicate the presence of the waste water plume and it is likely that the high conductivity seen in both logs is a result of the waste water plume.

A total of 4 cores were taken at the site to a depth of 6 m in 1.5 m sections. Visual and tactile descriptions of the cores were completed and core samples were then sent to a lab for chloride analysis (see Appendices C and D for additional information). Samples were taken for chloride analysis from core sections based on depth. For all cores, one sample was taken from the 0-1.5 and 1.5-3 m depth sections. Two samples each were taken from the 3-4.5 and 4.5-6 m depth sections for a total of 22 samples from all core sections. Cores 1 and 2 were completed south of the pits within areas where the brine plume was found by previous studies. Cores 3 and

Figure 15: Overlay of electrical conductivity versus depth logs taken at the site.
4 were completed outside known areas of the brine plume. Chloride concentrations are greatest in Core 1 and Core 2, with increasing chloride concentrations to a depth of 4 m and then decreasing concentrations as the bottom of the core is reached. The highest concentrations of chloride found in Cores 1 and 2 at 4 m were 2550 and 2810 mg/kg, respectively (Figure 18).

Figure 16: Cross section of conductivity versus depth from logs 31 to 39 (west to east).

Figure 17: Cross section of conductivity versus depth from logs 47 to 55 (northwest to southeast).
Chloride concentrations found in Cores 3 and 4 are at least one order of magnitude less than chloride concentrations found in cores 1 and 2 with the highest concentration 161 mg/kg between 3-4.5 m in Core 3. Core 4 possessed the least concentration of chlorides with 2 of the 6 samples returning from Gulf Coast Analytical Labs as “non-detect” (chloride concentrations below a value of 0.25 mg/kg cannot be detected) which would be expected given the flow path of the plume and distance of Core 4 from the pits.

Sediment type was classified using 151H hydrometers in 1000mL graduated cylinders. The hydrometers were calibrated according to Lewis and McConchie (1994). Samples were not sieved due to estimated low sand content after visual and tactile inspection. At least 2 samples were taken from each 1.5 m section. The majority of samples were comprised of clays and silts. Some sand was noted at a consistent depth of 1-2 m throughout all cores. Of note were iron and calcareous nodules within the samples (less than 1% by weight), the largest of which was 3 mm in diameter. Also present in the cores was red-orange staining and mottling, wood debris, and

![Figure 18: Concentration of chloride versus depth from samples taken from cores. Note highest concentrations occur at 4 m bgs. Background chloride concentrations are negligible, see Core 4.](image)
other plant debris. Sediments found within the cores are silts, clayey silts, silty clays, and sands. Cores 1 through 4 as well as 4 cores collected in a previous study by consultants (Terrain Conductivity Survey and Groundwater Verification Survey Fordoch Field, 1993) were used to complete a cross section across the site (Figure 19 and 20).

Sand was found at a consistent depth within the cores that were collected during the site investigation. The study area is very heterogeneous in sedimentary composition. Silty clays and clayey silt predominate the area through the cross section. Silty clays underlie the pits and the area southeast of the pits. Clayey silts underlie the area further southeast of the pits. The only sand of note is a thin layer (less than 0.2 m thick) that extends from Core 1 to Core 4. Sand is seen in other locations of the cores but is marginal compared to the amount of clayey silts, silty clays, and silts.

Figure 19: Map of site showing cross section of A–A’.
Figure 20: Cross section A – A’. SB-9, SB-7, SB-4 and SB-5 are cores collected by consultants at the site (Terrain Conductivity Survey and Groundwater Verification Survey Fordoch Field, 1993). C1, C2, C3, and C4 are cores collected during this study.
GPR Calibration Studies

Secondary field investigations were completed at a cemetery in Oak Ridge and 3 graves in St. Gabriel, Louisiana. The initial goal of each investigation was to verify the location of graves marked with headstones. The other goal was to determine the suitability of GPR for such an application in Louisiana given the poor results from the Pointe Coupee Parish study area. All GPR transects completed in Oak Ridge and St. Gabriel used the Sensor’s and Software SmartCart with 200 MHz antennae. The only processing applied to the transects was AUTO Gain and DEWOW while data were collected. In order to determine the presence or absence of graves no post-processing was completed as transects were analyzed real-time in the field using the digital video logger (DVL). Grids were created along rows of headstones (Figure 21) in order to determine if headstones would interfere with radar signal return as well to verify that a grave was associated with each headstone.

Transects completed at Oak Ridge (Figure 22) show that recent burials are identified as strong, shallow reflectors while older burials are identified as deeper, weaker reflections if at all (Figure 23). Recent burials also provided strong point sources with reflectors being identified both at the top and bottom of the coffin. One unmarked burial was found on the west side of the

Figure 21: Typical arrangement of 3 transects used when imaging graves.
graveyard. A buried broken cement block (Figures 24 and 25) was determined to be marking the grave. Orientation of the GPR transect over the excavated marker in Figure 25 is from right to left of the photograph. An unburied cement block was found within the graveyard indicating that the buried cement block was likely used as a grave marker (Figure 26).

Figure 22: Recent burials from 1956 – 1983. Note narrow, well defined reflectors indicated by arrows. North LA.

Figure 23: Older burials from 1863 – 1892. Note reflectors are broader than recent burials indicated by arrows. North LA.
Figure 24: Reflection of buried grave marker (arrow). The broad reflector indicates the buried grave marker. North LA.

Figure 25: Excavated grave marker imaged in Figure 24. North LA.
GPR transects completed in St. Gabriel, Louisiana, show a distinct, disturbed space underneath the headstones where the graves are presumed to be located (Figure 27).

Another area at the site was a shallow depression that the land owner identified as a possible location of the graves. The shallow depression was surveyed (Figure 28) and although disturbed

Figure 26: Unburied cement block used to mark a grave. This indicates that the excavated grave cement block in Figure 24 and 25 was used as a grave marker. North LA.

Figure 27: Transect across marked grave location. Arrows represent probable grave locations. South LA.
sediment was identified there was no clear indication that burial shafts were present. Some reflectors present in the GPR transects are interference from a large oak tree near the graves.

The graves at the site in St. Gabriel were determined to be in the same location as the headstones.

Figure 28: Transect across the shallow depression. Dipping airwave reflection from tree indicated by red arrow. South LA.
Discussion

Field studies, including GPR reflection surveys and analysis, electrical logs, and sediment core samples were completed near Lottie, Louisiana, to delineate a produced waste water plume. Severe signal attenuation was expected within the plume which would provide substantial contrast with reflectors from the surrounding sediment.

GPR transects were completed east to west, perpendicular to the brine plume. 50 MHz GPR transects penetrate to a depth of 2 to 2.5 m and 100 MHz GPR transects penetrate to a depth of 1 to 1.5 m. All GPR profiles show significant signal loss, no contrast, and similar subsurface structure throughout the site surveyed. GPR transect 50-36A completed to the west of the main

Figure 29: Abnormal signal attenuation seen in center of transect 50-36A. Presence of waste water plume cannot be confirmed in this location at this depth due to lack of data within this section of this transect. Fordoche Field.
grid is directly south of the pits (Figure 29) shows an area between 78 and 145 m that has significant attenuation of signal when compared to the rest of the data in the transect. The cause of the attenuation is unknown as no further data were collected over this section so the cause of the signal loss cannot be identified and is removed when a bandpass filter is applied. High attenuation seen in all transects is likely due to high clay content of the subsurface and high pore water content. As clays are more conductive than silts and sands, more signal would be attenuated and is enhanced by the pore water content. Sufficient penetration was expected in GPR transects which would allow for delineation of the waste water plume but this was not the case as for previously mentioned reasons.

GPR transects completed at the calibration sites used 200 MHz antennae. Depth of penetration was 1 m at the St. Gabriel site and 2 m at the Oak Ridge site. This is equivalent to what was seen in depth of penetration at the Pointe Coupee site although lower frequency antennae frequencies were used. Targets at the calibration sites were shallow, less than 2 m bgs. The graves appear as strong reflectors within the data. Younger burials appear as narrow reflectors near the surface whereas older burials appear as broad, deeper reflectors. Modern grave shafts at Oak Ridge appeared shallow compared to older grave shafts. This was not expected considering that older burials tend to be shallow compared to recent burials given ease of excavation with modern equipment. The reflectors from the older burials are likely the result from settling of sediments and degradation of the casket making the apparent depth of the burial deeper (only the base of the burial is imaged). Subsurface penetration was sufficient to image shallow subsurface targets at the calibration sites. This is due to better drainage and lower clay content at the respective calibrations sites. Of the sites studied, the best location is the Oak Ridge site. Depth of penetration was equivalent to what was seen at the Pointe Coupee site even
though a higher frequency antennae was used (higher frequencies generally have less depth of penetration).

Chloride is considered conservative in soils (Bastviken et al., 2006) and is used as a tracer in shallow groundwater studies (Cox et al., 2007; Bertin and Bourg, 1994). This is possible because the negative charge on the surface of the clay minerals repel anions (Thomas and Swoboda, 1970). Measurements of high chloride concentrations at the site are indicators of the presence or absence of the brine plume. The Annual 2006 Groundwater Monitoring Report (2006) indicates that high levels of chloride were present during the last sampling event (sample concentrations range from 34 mg/L to 23,000 mg/L with a mean concentration of 5400 mg/L). For comparison, seawater generally has chloride concentrations of 19200 mg/L (Thurman and Trujillo, 2004). The result of the 2006 sampling event and previous sampling events can be seen in Figure 30. High concentrations of pore water exist within the area due to poor drainage of the site and pore water retains high chloride concentrations from the plume. Chloride concentration measurements of pore water from core samples indicate that the majority of waste water resides at a depth of approximately 4 m over the study area. Highest concentrations are seen within Core 1 and 2 which is expected given the location of both cores within the brine plume. Lowest concentrations are seen in Core 4 which is the most distant core from the brine plume. This indicates that chloride is not found naturally at the site and the chloride seen in the sediment samples is a result of chloride concentrations in groundwater from the brine plume.

All electrical logs show a general increase of electrical conductivity from 0 to between 2 and 4 m and then a decrease in conductivity from 8 to 10 m to the bottom of the log. This correlates well with the general hydrologic units of the area for the depth to which the electrical logs are completed. The shallow zone, first clay layer and the top of the intermediate zone are
reflected by the moderate (100 mS/m, shallow zone), high (200 mS/m, first clay layer) and then moderate conductivity readings (intermediate zone) viewed in all the logs. Electrical conductivity measurements of soil cores from the Terrain Conductivity Survey and Groundwater Verification Survey Fordoch Field (1993, Figure 31) completed near the pits show similar values.

Figure 30: Groundwater chloride concentrations in the shallow zone taken from annual and semi-annual ground water sampling reports.

Figure 31: Soil electrical conductivity with depth from the Site Characterization Study (1986).
of electrical conductivity at the site in this study. Electrical logs 47 and 54 show the same general profile as the other logs. Both logs indicate a marked increase in conductivity to 400 mS/m, approximately 200 mS/m higher than the maximum conductivity values of all the other logs at similar depths. Figure 4 shows that logs 47 and 54 were completed in a lobe of the waste water plume extending to the southeast along a possible pipeline.

Cores completed at the site in Pointe Coupee Parish indicate sediments are composed largely of silt and clay. Some sands were seen in the cores, in particular at 1 to 2 m depth in each core. The sediments across the site are not lithologically uniform. The silts, clays, and sands seen at the site would be expected considering the depositional environment of the area (over bank deposits from rivers and distributaries). High clay content of the sediments as well as the relatively flat topography of the site itself is a possible reason for water retention and poor drainage of the site (and resulting high GPR attenuation).
Conclusions

GPR was not successful at delineating a waste water plume the site in Pointe Coupee Parish due to attenuation of radar signal within the first 2.5 m of the subsurface. Results consistent with zones of high attenuation caused by the waste water were not seen in multiple transects across the study area as the waste water plume was below the depth of penetration of the GPR and could not be imaged. High attenuation is seen throughout the site which is primarily due to high clay content of sediments and high pore moisture content of the sediments. GPR at the calibration sites was successful in delineating subsurface targets within the subsurface in other locations in Louisiana. Conditions at the calibration sites are better suited to GPR use due to lower content of clays as well as better drainage at the sites. Though 200 MHz antennae were used at the calibration sites, the depth of penetration seen was equivalent to the depth of penetration seen at the Pointe Coupee site using lower frequency antennae (100 MHz and 50 MHz). As per the Louisiana GPR Suitability Map, The Pointe Coupee site is located within a low potential area, whereas the St. Gabriel and Oak Ridge sites are located within areas of moderate and high potential, respectively (Figure 32).

Horizontal movement of the plume is relatively small given the size of the plume, approximately 80 m to the southeast along the possible pipeline from 1986 to 2006 (estimated using chloride isopach maps the Site Characterization Study, 1986, and Revised Risk Evaluation/Corrective Action Program Investigation Report, 2006). Pore water of the sediments possess high chloride concentrations compared to background levels (essentially 0) as seen in Core 4 suggesting that high concentrations of waste water are retained within sediment pores. Through chloride sampling of the soil cores it was determined that the majority of the waste water within the sampling area resides at a depth of 4 m (near the interface of the shallow
zone and first confining clay unit), approximately 1.5 m below the depth to which the brine pits were excavated. High concentrations of chloride are seen from samples taken from areas of the waste water plume and show a decrease in concentration of chloride moving away from the plume as expected.

Electrical conductivity logs 47 and 54 show relatively high conductivity values in comparison to other electrical conductivity logs suggesting the presence of the waste water

Figure 32: GPR suitability map of Louisiana, modified from Ground-Penetrating Radar Soil Suitability Map of Louisiana, 2008. The Pointe Coupee Site is located in a low potential area while the St. Gabriel and Oak Ridge sites are located in moderate and high potential areas, respectively.
plume. The electrical logs confirmed the presence of the shallow and intermediate zones as well as the confining clay unit between the zones. These are illustrated as low conductivity intervals (<100 mS/m, shallow and intermediate zones) and high conductivity intervals (100 to 200 mS/m, confining clay zones).

With regards to GPR use in Louisiana, suitable sites require adequate water drainage, low pore water saturation and relatively low clay content as well as shallow targets for successful acquisition. As a whole, Louisiana is poorly suited to GPR studies unless targets are very shallow.
References


Bastviken, David; Sanden, Per; Svensson, Teresia; Stahlberg, Carina; Magounakis, Malin; and Oberg, Gunilla.  2006.  Environmental Science Technology.  V40, pp2977-2982.


Carcione, Jose M.; Marcak, Henryk; Seriani, Geza; and Padoan, Giorgio.  2000.  GPR modeling study in a contaminated area of Krzywa Air Base (Poland).  Geophysics.  V65 No.2, pp521-525


http://edms.deq.louisiana.gov/


Appendix A: GPR Parameters and Transects

The following transects are raw (unprocessed, pages 38 through 52).

Figure A1: 50-08A

Figure A2: 50-07B
Figure A3: 50-06C

Figure A4: 50-05D
Figure A5: 50-04E

Figure A6: 50-03F
Figure A9: 100-67B

Figure A10: 100-66C
Figure A11: 100-65D

Figure A12: 100-64E
Figure A13: 100-63F

Figure A14: 100-62G
Figure A15: 50-35A

Figure A16: 50-36A
Figure A19: 50-39D

Figure A20: 50-40E
Figure A21: 50-41F

Figure A22: 50-42G
Figure A23: 100-43A

Figure A24: 100-44B
Figure A25: 100-45C

Figure A26: 100-46D
Figure A27: 100-47E

Figure A28: 100-48F
Figure A29: 100-49G

Processed Transects (pages 52 through 66)

Figure A30: 50-08A
Figure A31: 50-07B

Figure A32: 50-06C
Figure A33: 50-05D

Figure A34: 50-04E
Figure A35: 50-03F

Figure A36: 50-02G
Figure A37: 100-68A

Figure A38: 100-67B
Figure A39: 100-66C

Figure A40: 100-65D
Figure A41: 100-64E

Figure A42: 100-63F
Figure A43: 100-62G

Figure A44: 50-35A
Figure A47: 50-38C

Figure A48: 50-39D
Figure A49: 50-40E

Figure A50: 50-41F
Figure A51: 50-42G

Figure A52: 100-43A
Figure A53: 100-44B

Figure A54: 100-45C
Figure A55: 100-46D

Figure A56: 100-47E
Figure A57: 100-48F

Figure A58: 100-49G
<table>
<thead>
<tr>
<th>Site</th>
<th>Operating Mode</th>
<th>Survey Type</th>
<th>Antenna Frequency (MHz)</th>
<th>Number of Stacks</th>
<th>Step Size (m)</th>
<th>Antenna Separation (m)</th>
<th>GAIN Type</th>
<th>Pulsar Voltage (V)</th>
<th>Correction</th>
<th>Velocity (m/ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fordoche Field Livonia, LA¹</td>
<td>Continuous</td>
<td>Reflection</td>
<td>100</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>AUTO</td>
<td>1000</td>
<td>DEWOW</td>
<td>0.06</td>
</tr>
<tr>
<td>Fordoche Field Livonia, LA¹</td>
<td>Continuous</td>
<td>Reflection</td>
<td>50</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>AUTO</td>
<td>1000</td>
<td>DEWOW</td>
<td>0.06</td>
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<tr>
<td>Fordoche Field Livonia, LA²</td>
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<td>Reflection</td>
<td>100</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>AUTO</td>
<td>1000</td>
<td>DEWOW</td>
<td>0.06</td>
</tr>
<tr>
<td>Fordoche Field Livonia, LA²</td>
<td>Continuous</td>
<td>Reflection</td>
<td>50</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>AUTO</td>
<td>1000</td>
<td>DEWOW</td>
<td>0.06</td>
</tr>
<tr>
<td>Cemetery Oak Ridge, LA</td>
<td>Continuous</td>
<td>Reflection</td>
<td>200</td>
<td>4</td>
<td>0.5</td>
<td>0.5</td>
<td>AUTO</td>
<td>1000</td>
<td>DEWOW</td>
<td>0.06</td>
</tr>
<tr>
<td>Graves St. Gabriel, LA</td>
<td>Continuous</td>
<td>Reflection</td>
<td>200</td>
<td>4</td>
<td>0.5</td>
<td>0.5</td>
<td>AUTO</td>
<td>1000</td>
<td>DEWOW</td>
<td>0.06</td>
</tr>
</tbody>
</table>

¹Initial GPR survey
²Secondary GPR survey
Table A2: The GPR Transects are identified as such: GPR antenna frequency - file number and transect. For example, 100-40A would be completed on transect A with 100 MHz antenna and the file number of the transect is 40. All transects are aligned from west to east.

<table>
<thead>
<tr>
<th>Initial Survey</th>
<th>Secondary Survey</th>
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</thead>
<tbody>
<tr>
<td>50-08A</td>
<td>50-35A</td>
</tr>
<tr>
<td>50-07B</td>
<td>50-36A</td>
</tr>
<tr>
<td>50-06C</td>
<td>50-37B</td>
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<td>50-05D</td>
<td>50-38C</td>
</tr>
<tr>
<td>50-05E</td>
<td>50-39D</td>
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<tr>
<td>50-04F</td>
<td>50-40E</td>
</tr>
<tr>
<td>50-04G</td>
<td>50-41F</td>
</tr>
<tr>
<td>100-68A</td>
<td>50-42G</td>
</tr>
<tr>
<td>100-67B</td>
<td>100-43A</td>
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<td>100-65D</td>
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<td>100-62G</td>
<td>100-48F</td>
</tr>
<tr>
<td></td>
<td>100-49G</td>
</tr>
</tbody>
</table>
Appendix B: GPR Calibration Studies

The following survey took place in a cemetery in Oak Ridge, Louisiana. All transects are separated by one meter. All transects run from north to south. In almost all graves, burial is east of headstone, some older graves have burial west of headstone. When a possible grave location was detected, a marker was placed to the side of the GPR unit. All transects were completed with a Sensors and Software SmartCart using 200 MHz antennae.

Transects 00, 01, 02
- 1 large headstone, 5 footstones
- Transect 00 east of headstone
- Transect 01 east of footstones
- Transect 02 three feet east of Line 01
- Photo 0001, 0002 facing south (left of Photo east, right of Photo west)
- Photo 0003 facing west
- Burials between 1956 and 1983

Transects 03, 04, 05
- 10 large headstones
- Transect 03 east of headstones (over grave)
- Transect 04 three feet east of line 03
- Transect 05 west of headstones (no graves)
- Photo 0004 facing south
- Photo 0005 facing west
- Photo 0006 facing southwest
- Burials between 1919 and 1925

Transects 06 and 07
- Transect 06 east of wooden post marker
- Transect 07 three feet east of line 06
- Photo 0007 facing south
- Photo 0008 facing west
- Unsure of year of burial

Transects 08 and 09
- Transect 08 west, near where headstone should be
- Transect 09 three feet east of line 08
- Photo 0009 facing south
- Photo 0010 facing west
- Photo 0011 facing northeast
• Very large cypress w/in 8 feet of northeast corner of grave
• Burial year uncertain

Transects 10, 11, and 12
• Four headstones, one of a child
• Transect 10 east of headstone
• Transect 11 three feet east of Line 10
• Transect 12 west of headstones
• Photo 0014 facing east
• Burials between 1863 and 1892

Transects 13, 14, 15, and 22
• Transect 13 east of marker
• Transect 14 three feet east if line 13
• Transect 15 west of marker
• Transect 22 directly over marked (sediment disturbed due to unearthing of marker)
• Marker was buried cinder block, broken, not all pieces unearthed
• Marker was found when putting flag into ground (flag encountered marker)
• Mr. Earl said it was likely a grave, probably a child’s
• Marker buried w/long axis N-S, same orientation of almost all headstones
• Photo 0016 facing south
• Photo 0017 facing west
• Photo 0020 is roughly half of the cinder block marker
• Photo 0021 another cinder block being used as a marker

Transects 16, 17, and 18 (3 old graves, 2 children ages 11 and 5)
• Transect 16 east of headstones
• Transect 17 three feet east of line 16
• Transect 18 west of headstone
• Large stump near beginning of line 17
• Photo 0022 facing south
• Photo 0024 facing southwest
• Photo 0025 stump
• Burials between 1847 and 1856

Transects 19, 20, and 21 (empty lot, no graves marked on map, no markers, probably will not put graves in area in future)
• Transect 19 most westerly line
• Transect 20 three feet east of line 19
• Transect 21 three feet east of line 20
• Photo 0026 facing south
Transects:

Figure B1: Transect 00

Figure B2: Transect 01
Figure B3: Transect 02

Figure B4: Transect 04
Figure B7: Transect 07

Figure B8: Transect 08
Figure B9: Transect 09

Figure B10: Transect 10
Figure B11: Transect 11

Figure B12: Transect 12
Figure B13: Transect 13

Figure B14: Transect 14
Figure B15: Transect 15

Figure B16: Transect 22
Figure B17: Transect 17

Figure B18: Transect 18
Figure B19: Transect 19

Figure B20: Transect 20
Figure B21: Transect 21

Site Photographs

Figure B22: Photo 0001

Figure B23: Photo 0002
Figure B26: Photo 0005

Figure B27: Photo 0006
Figure B30: Photo 0009

Figure B31: Photo 0010
Figure B32: Photo 0011

Figure B33: Photo 0014
Figure B34: Photo 0016

Figure B35: Photo 0017
Figure B38: Photo 0022

Figure B39: Photo 0024
Figure B40: Photo 0025

Figure B41: Photo 0026
The following survey took place on private property in St. Gabriel, Louisiana. All transects are separated by one meter. Eight transects were completed east-west and three transects were completed north-south. All transects were completed with a Sensors and Software SmartCar using 200 MHz antennae.

**Transects 01, 02, 03, 012**
- 3 headstones
- Crate myrtle is growing within one foot of easternmost headstone
- Large oak tree to west of headstones
- Transect 01 south of headstones
- Transect 02 south of headstones
- Transect 03 south of headstones
- Transect 012 north of headstones
- Photo 0001 transects over graves, facing west
- Photo 0002 transects over graves, facing north

**Transects 04, 05, 06, 07, 08, 09, 010**
- Grid created over depression
- Transects 04, 05, 06, and 07 run east-west
- Transects 08, 09, and 010 run north-south
- Photo 0003 transects over depression, facing west
- Photo 0004 transects over depression and graves, facing north

**Transects:**

![Image of Transect 01](C:\Documents and Settings\marr105\Desktop\runs\DATAZLINE01.DT1)

**Figure B42: Transect 01**
Figure B43: Transect 02

Figure B44: Transect 03
Figure B45: Transect 04

Figure B46: Transect 05
Figure B47: Transect 06

Figure B48: Transect 07
Figure B49: Transect 08

Figure B50: Transect 09
Figure B51: Transect 10

Figure B52: Transect 11
Figure B53: Transect 12

Photos

Figure B54: Photo 0001
Figure B55: Photo 0002

Figure B56: Photo 0003
Figure B57: Photo 0004
Appendix C: Figures from Previous Studies

Figure C1: Subsurface Conductivity Map (1986)
Figure C2: Subsurface Conductivity Map (1986)
Figure C3: Electrical Conductivity Survey (1986)
Figure C4: Electrical Conductivity Survey (1993)
Figure C5: Chloride Isopach Map (1993)
Figure C6: Chloride Isopach Map (1999)
Vita

Matthew Smith was born in Tulsa, Oklahoma, in 1983. He has since live in Bakersfield, California; El Dorado, Arkansas; Mandeville, Louisiana; and currently resides in Baton Rouge, Louisiana. He attended and graduated from Fontainebleau High School in 2001. He attended and graduated with a Bachelor of Science in geology from Louisiana Tech University in 2005. In 2006 he began to pursue a Master of Science in geology at Louisiana State University. Matthew is currently interning with Environmental Resources Management and will likely work full time with the company after graduation. He enjoys the outdoors, rock collecting, and riding bikes with friends.