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Geophysical Investigation at the Mouth of the St. Joseph River Valley and Adjacent Lake Michigan Shoreline in St. Joseph and Benton Harbor, Michigan

David L. Seng

GEOPHYSICAL INVESTIGATION AT THE MOUTH OF THE ST. JOSEPH RIVER VALLEY AND ADJACENT LAKE MICHIGAN SHORELINE IN ST. JOSEPH AND BENTON HARBOR, MICHIGAN

by

David L. Seng

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David. L. Seng, M.S.

Western Michigan University, 1995

A combination of geophysical methods were employed in an attempt to characterize a small section of the shoreline of the St. Joseph, Michigan, region of the Lake Michigan shoreline. Electrical resistivity and Ground Penetrating Radar profiles conducted along the shoreline and within the nearshore environment reveal a buried valley of the ancestral St. Joseph river. This valley represents incision of the channel during lowered lake levels at the end of the Pleistocene.

Lakeward dipping radar reflectors are identified throughout the study site. Within the buried valley the reflectors are not glacial till as is the case outside the inferred valley boundaries. Thick sand sequences, channel fill, channel forms and bedding structures as identified by reflection terminations support the presence of a buried valley. Electrical resistivity measurements indicate a valley width of greater than 3.5 km and a depth of approximately 30 meters.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

At St. Joseph, the Lake Michigan shoreline is oriented northeast-southwest, with prevailing winds from the northwest and a net longshore drift from north to south. Higher wind velocities and longer fetch distances from the northwest produce larger northwest waves and a southerly transport direction resulting in a net drift rate of 110,000 cubic yards per year (USACE, 1983).

In 1903 the U.S. Army Corps of Engineers (USACE) installed a pair of navigational jetties on the mouth of the St. Joseph river. The influence of these structures on the coastal processes resulted in accumulation of sediment on the north side and erosion of sediment on the south side of the jetties. A net horizontal accumulation of 8.10 feet, 0.23 feet/year, along approximately 2000 feet of shoreline extending north of the jetties was substantial enough to require extension of the jetties three times. Conversely, the southern 29,500 feet of shoreline receded at a rate of 2.71 feet/year during the same period (Raphael and Kureth, 1984). In 1976 the USACE, in response to the high erosion rate on the south, implemented a Section 111 plan calling for the placement of material to act as beach nourishment. Previously, sand dredged from the harbor as part of harbor maintenance had been placed on the beach. In 1976 the Section 111 plan provided additional material that was trucked in and used for nourishment. Since 1970 2,177,333 cubic yards of sand have been used to nourish the beach (USACE unpublished data, 1994). Subsequently, the USACE has initiated a study to provide a better understanding of the geologic setting of the ancient St. Joseph river valley and the nearshore area in St. Joseph and Benton Harbor area, enlisting the Western Michigan University Institute for Water Sciences to measure the sand thickness and lateral extent of cohesive substrate in the study area. The results of this study can then be used to determine if the sand is acting as an abrasive agent causing scouring and downcutting of the cohesive layer or whether it acts as a protective cover inhibiting downcutting of the substrate (Anglin et al, 1993).

LOCATION

The study area is located in the St. Joseph, MI, area along the southeast border of Lake Michigan, as shown on Figure 1.

Physiographical features within the area include the Lake Border Moraine on the south and eolian sand dunes on the north. The area includes the mouth of the buried ancient St. Joseph River Valley in the north as well as the modern St. Joseph river (Benton and Passero, 1990). The study area is defined as the region within 500 meters north of the northern boundary of Jean Klock park and 1.7 kilometers south of Shoreham, MI. The easternmost boundary of the study area is the base of the bluff or berm (whichever is closest) and extends to approximately 10 meters of water depth. Shore-normal profiles were conducted offshore along previously established USACE Section 111 study lines.

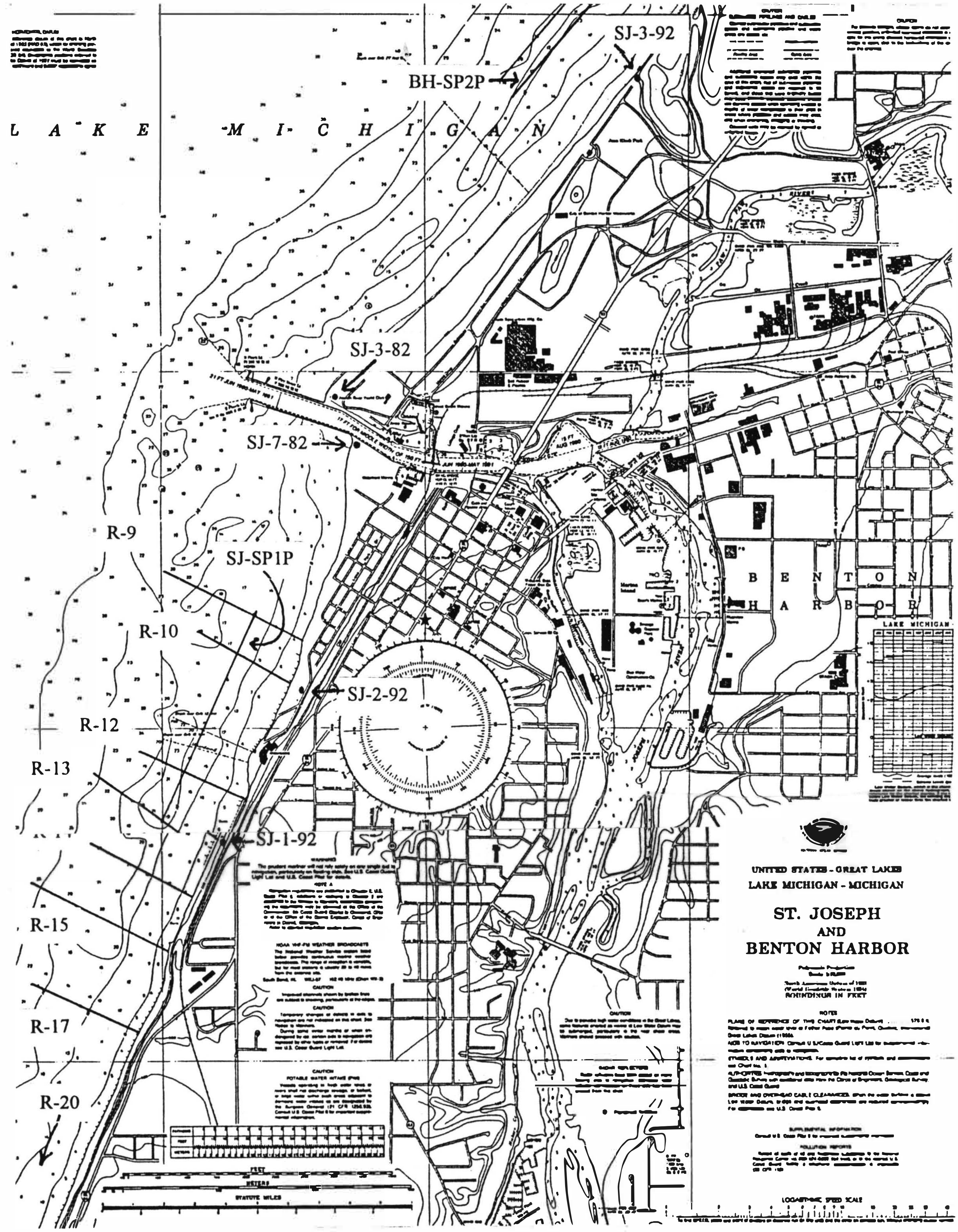

Figure 1. Profile, Well Location Map of the St. Joseph, Benton Harbor Shoreline.

PROBLEM

The USACE's desire to model the shoreline evolved a three-fold problem. Delineation of the lateral extent of the cohesive substrate and overlying volumetric sand determinations ultimately required mapping of the ancestral St. Joseph river valley. Because the ancestral river had cut a broad channel into glacial till, (the cohesive substrate), the location of the ancestral valley is key to marking the lateral extent of the substrate. Shallow geophysical methods have long been recognized as a means of mapping the subsurface. However, these methods have not previously been employed in nearshore coastal regions for the purpose of mapping buried channels and volumetric sediment determinations. Two shallow geophysical techniques, electrical resistivity and ground penetrating radar, were tested in this environment. Sediment samples collected at various locations along the coastline were used to provide geological control for the geophysical data.

GEOLOGY

As the Lake Michigan Lobe of the Laurentide Ice Sheet retreated for the last time it deposited and reworked the coastal sediments into their current form. These modern sediments are underlain in the St. Joseph area by the Late Devonian Ellsworth Shale.

The study site, for the most part, is composed of sand and fluvial sediments. However, the shoreline north of the study area and south of line R-13 is composed of till. To the immediate north of Klock Park there is a high till bluff with a narrow sand beach in front of it. The bluff is non-sorted glacial debris generally lacking stratification. It is composed of gray silts and clay loams with occasional boulders and gravels. Extending from this point south, low sand dunes have accumulated in response to jetty installation. The shoreline south of the jetty, trending NE, is a low sandy terrace that converges to a bluff south of line R-13. The bluff is composed of coarser materials than the bluff to the north, containing well compacted sands and fine gravel lenses (Raphael & Kureth, 1988). To the south of R-13 there is little or no beach in front of the bluff. North of line R-13 the bluff trend becomes ENE. The city of St. Joseph is constructed on the bluff top.

The ancestral St. Joseph River valley was formed during a period of glacial retreat about 10,000 years ago. A combination of isostatically depressed basins and the opening of the North Bay outlet initiated increased northeast drainage, contributing to a greatly reduced lake level. Known as the Chippewa phase, this low stand lasted approximately 4000 years (Hough, 1955). During this phase the lake level initially dropped 80 meters below the historical mean lake level of 176 meters (Coleman, 1992) generating large scale stream incision. Peck and Reed (1954) document paleochannels incised between 6 and 24 meters by streams and rivers along the Chicago and western Indiana shorelines. Continually rising lake level caused infilling of these newly incised channels.

THEORY

Resistivity

Surface resistivity measurements most commonly use an in-line four-electrode array. The two most common arrays use a pair of electrodes to introduce current (I) into the surface and two potential electrodes positioned linearly between the current electrodes. The potential electrodes measure the potential difference or voltage (V) between them. The field determinations of I and V are combined with the array geometry to calculate the resistivity of the material. Because the equation is derived based on the assumption of a homogenous isotropic earth, the resistivity value obtained is termed the apparent resistivity (ρ_a).

Vertical Electric Sounding (VES) is a technique that produces a geoelectric section (variation of resistivity with depth). This method requires a number of resistivity measurements from an electrode array expanded about a central point. This allows the current (I) to penetrate deeper, increasing the sampling depth. Two common arrays used in surface resistivity measurements are the Wenner and the Schlumberger arrays.

This study incorporated the Schlumberger array, requiring a limited number of field assistants. For this array the expression for apparent resistivity is:

$$\rho_a = \pi/4 \left[((AB)^2 - (MN)^2)/(MN)\right](V/I)$$

More importantly, this method is not as susceptible to lateral changes in resistivity as the Wenner array. During a sounding the current (AB) electrodes are expanded for 3-5 readings while the potential electrodes remain fixed. The potential (MN) electrode separation is increased only when the voltage falls below a minimum level. The Wenner array requires that all the electrodes be moved during each expansion, increasing the chances for the potential electrodes to encounter a lateral change in resistivity that could mask the vertical change. For a complete treatment of resistivity theory refer to Telford, et al (1990), Keller and Frischknecht (1966), or Grant and West (1965).

Radar

Radar is an echo-location system that uses the reflection time from a short burst of energy (radio energy) to determine position and range of an object. It was from these principles or more specifically, RAdio Detection And Ranging, that radar got its name. The most common type of radar, pulse radar, emits short pulses of energy through a directional radiator. Immediately after each pulse the transmit antenna is switched to a receiver mode. If a reflective object is in the path of the pulse the energy of the pulse will be reflected in many directions including back to the receiver. Knowing the time it took for the pulse to travel to the object and back (two way travel time) and the speed of the wave in a given medium, 300,000,000 meters/second in air for example, it is possible to calculate its range. For example, if the two way travel time to a target is one ten thousandth of a second it would be at a range of 30,000 meters divided by 2, or 15,000 meters. Knowing the range of the object and the position (azimuth) of the radiator or antenna, the object's position can be located on an oscilloscopic display, such as that of an air traffic controller (Kock, 1973).

Pointing a radar antenna at the ground introduces many more variables and difficulties. Inhomogeneities within the subsurface scatter the radar signal. Moreover, as the water content varies so does the wave velocity. Described as a lossy medium, the subsurface has appreciable and variable conductivity. Because the earth may contain variable amounts of magnetite, magnetic permeability μ will also affect wave propagations.

The range of an object (depth in this case) is determined from the equation

$$Z= (V*t)/2$$

When Z= depth (in meters), t= two way travel time (in seconds), and V= velocity through the host material (in meters / second). An air traffic control radar uses V= $3x10^8$ meters/ second or the velocity of light in air. The velocity of the radar wave in the earth changes based upon the ϵ_r or relative electrical permittivity of the material. Velocity calculations on a GPR profile use the equation:

$$V=(v_0) /(\sqrt{\epsilon_r})$$

Where v_0 = velocity of light in air
= $3x10^8$ m/s
ϵ_r = 81 for water

= 1 for air
= 6 for unsaturated sand (approximate)
= 20-25 for saturated sand

Radio wave velocities can change by almost an order of magnitude depending upon the material they are moving through. This complicates the determination of burial depths of objects, and with the addition of multiple layers and/or variable moisture contents of those layers, depth calculations can be perplexing. Water having a relative permittivity of 81 has the greatest effect on the relative permittivity of a material.

Depth of penetration of electromagnetic waves is a function of the conductivity of the material and the frequency of the waves. The skin depth (Telford et al, 1990) of an electromagnetic wave is a common way to express this. It is defined as the depth at which the signal is reduced to $1/e$, or 37% of its original value. It is given by the formula

$$z_s \approx 503.3(\rho/f)^{1/2}$$

Where ρ=resistivity in Ohm-meter
f=frequency in Hz
z_s=skin depth in meters

The skin depth of a 145×10^6 Hz signal in a 155 ohm meter (a typical surface resistivity in the study site) sediment is 0.52 meters, the skin depth of a 4 Hz signal in the same sediment would be 3112 meters. As can be seen, GPR depth penetration is greatly affected by the resistivity of the material and the frequency of the wave

(Telford et al, 1990). Because of the high dynamic range of modern digital systems, and because of their stacking capabilities, usable signals from depths on the order of 10 skin depths can be extracted.

Radar reflections result from contrasts in electrical impedance across a boundary and are a complex function of conductivity, relative permittivity and magnetic permeability. The reflection coefficient (R.C.) can be expressed as:

$$R.C. = (z_2 - z_1) / (z_2 + z_1)$$

where z_1 = impedance of layer 1
z_2 = impedance of layer 2.

The GSSI SIR 10 is a pulse type georadar that features digital data collection and storage. For a more complete treatment of the subject refer to the manual (GSSI, 1993). It can use an assortment of different antennae operating at different frequencies in either bistatic, (a separate transmit and receive antenna), or monostatic, (a single antenna that transmits and receives) modes. The antennae are usually identified by their approximate center-band frequency (e.g. 100 MHz, 500 MHz, 145 MHz). In general, a high frequency antenna has a higher resolution and a lower depth penetration than a low frequency antenna.

A scan is the record of a single pulse and its reflections plotted as a function of time and amplitude. GPR operates in the nanosecond (ns, where 1 ns=10^{-9} s) range, with typical scan lengths from 10 to 1000 ns. GPR data is displayed much the same way seismic data is displayed, horizontal distance on the X axis and time on the Y axis. Each scan is represented as a vertical line of colors on the screen, with each color corresponding to the amplitude of the received wave at a given time. What appears on the GPR screen is a representation of the differences in electrical properties of the subsurface material as the antenna system is moved along the surface. Those differences are based on the ϵ_r of the materials, which is a combination of the ϵ_r of the matrix and the water content of the pore space. Plagioclase feldspar has a relative permittivity of 5.4 to 7.1, quartz 4.2 to 5, clays 7 to 43, and water 81. By mixing these and other components, as is the case in soils and sands, there is a large range of possible relative permittivities for those materials (Telford et al, 1990). For more comprehensive treatment of GPR theory and interpretation, refer to Daniels (1989), or Ulriksen (1982).

PREVIOUS WORK

Geological

Coastal monitoring studies originated in the St. Joseph area with Davis and Fox when they began measuring beach and nearshore profile changes. Their earliest studies focused on the response of sand bars to storm events (Davis and Fox, 1972). Since then, numerous studies have measured bluff and shoreline erosion rates. Birkemeier (1980) and Raphael and Kureth (1988) used air photos to measure erosion rates. Buckler and Winters (1975 and 1983) and Buckler (1981) used historical maps in conjunction with air photos to determine erosion rates. Focusing mainly on determination of erosion rates, these reports did not address geologic controls of these rates. Shabica and Pranschkle (1994) measured sand thickness above the clay along the Illinois and Indiana shoreline of Lake Michigan using a hydraulic probe.

Geophysical

Most GPR work in water involved either floating the antenna on the surface to produce profiles or by conducting profiles on ice. Gorin and Haeni (1989) compared data from GPR, a black & white fathometer, a color fathometer and a tuned sonar transducer to evaluate river bed scour at piers supporting bridges in Connecticut. They used floating 80 MHZ bistatic antennae and a GSSI SIR 8 system. They noted that the water depth must be less than 20 feet and that multiple reflections may obscure data. They also noted that GPR proved to be a more accurate method of defining subbottom stratigraphy and was especially useful for work involving organic and gaseous materials where fathometers don't work.

Mellet (1993) used a GSSI SIR 3 and 100 MHZ bistatic antennae to successfully guide sediment sampling, using data from summer floating GPR profiles and winter ice profiles. He found that depth of penetration increased in the winter due to decreased water conductivity associated with decreased turbidity and amount of suspended clay particles. Beres and Hanei (1991) conducted profiles, floating a GPR antenna, to determine the thickness and distribution of sediments in shallow lakes.

The U.S. Geological Survey, in conjunction with NOAA, began a pilot study in 1991 designed to map the bathymetry and stratigraphy between Benton Harbor, Mi. and Gary, IN. of coastal Lake Michigan bottom sediments using seismic and sidescan sonar profiles. These methods restricted data collection abilities to water depths of 5 meters or greater, excluding the nearshore sand concentration from their survey. Western Michigan University was contracted to test the GPR method in the nearshore environment to augment their data and investigate the sand wedge thickness between the 5 meter depth contour and the bluff line. This contract was continued with the USACE participation for closely spaced lines in the St. Joseph area, which provided the database for this thesis.

METHODS

Geophysical methods, including Electrical Resistivity and GPR, were employed in this study because they would best define the parameters being sought, sand thickness and the lateral extent of the cohesive substrate in the nearshore region of the St. Joseph area. Resistivity soundings techniques were employed to determine the location of the buried ancestral St. Joseph river valley along the present shoreline. Soundings can be done along a profile line and have the potential for depth penetration to many tens of meters, which was needed for the valley investigation.

Having the potential for up to 5 meters of depth penetration in sandy environments and high resolution, GPR provided a way to define the modern sand-substrate interface outside the valley. This technique is also versatile enough to be functional in the high energy near shore environment. Off shore, shore-perpendicular profiles were made using a submersible GPR antenna to determine the sand thickness.

Electrical Resistivity

A Bison 2390 resistivity meter and nonpolarizing potential electrodes were used to conduct vertical electric soundings (VES) along approximately 4000 m of shoreline within the study area. A Schlumberger array was typically expanded in a logarithmic sequence to a maximum AB/2 spacing of 100 meters, allowing for the detection of geoelectric layers to a depth of about 40 meters at this particular site.

Data was collected to provide 6 data points per decade of AB/2 spacing for three decades, enabling the data to be reduced with a modeling or inversion program. In the field the V/I was recorded for a given AB/2 spacing and a value for the apparent resistivity (ρ_a) was calculated. Once this was determined the array was expanded. When the V reading became less than 3 significant digits the MN spacing was increased, giving two values of apparent resistivity for the same AB spacing. The AB spacing was not increased until the two values were similar. If the ΔV fell below 1 mV, duplicate readings were taken with potential electrode lead wires reversed. The two values of ρ_a were then averaged to arrive at the apparent resistivity for that AB/2 spacing.

The center of the first array was established at the north boundary of Jean Klock Park (Fig.1). All of the arrays were set up along the shore in the saturated sands, eliminating the dry sand/saturated sand boundary. The next array was centered 100 m south of the first VES, and so on. VES measurements were conducted from the north boundary of Jean Klock Park to a point 4000 meters south, where the beach ended at a steel revetment. Vertical Electrical Soundings (VES) were conducted from June 2 to July 17, 1992 in the saturated sands at the water line. This location was selected to eliminate any problem caused by a dry highly resistive sand over a less resistive saturated sand. Soundings K-3 and K-4 were only expanded to maximum AB/2 spacings of 31.62 and 68.13 meters respectively. To resolve greater depths, soundings K-5 through K-41 were all expanded to an AB/2 spacing of 100 meters. Standard copper potential electrodes were used for soundings K-3 through K-13. When it was suspected that electrode polarizations might be influencing the data, $CuSO_4$ non-polarizing electrodes were used for the remaining soundings to eliminate the effects (Telford et al, 1990). The curve was plotted in the field to check data consistency and later smoothed.

Each time the potential electrodes were expanded an apparent resistivity was calculated for the same AB/2 spacing having two different MN spacings. Generally, these data points are not the same and result in an offset of the sounding curve. Adjusting the data set up or down at this point produced a smooth curve. For a more complete explanation see Zohdy, 1974. The data from the smoothed curve were interpreted with the SCHLINV.BAS program (Mooney, 1980; Davis, 1979 and Merrick, 1977). Figure 2 is model output from VES k-5, 200 meters south of the north boundary of Klock Park.

Ground Penetrating Radar

The digital GSSI System 10 GPR, with 16-bit technology and EGA color field monitor was used to collect data both on and offshore. On the beach, profiles were run using a 500 MHZ and a 100 MHZ antenna in both mono and bistatic configurations. The data collected at those locations was compared to soil boring data for determination of the value of ϵ_r of the saturated sands. That value was subsequently used throughout the study area.

Using conventional methods, the antenna was initially floated on the lake surface. Ringing and attenuation of the radar signal in the water column limited depth

VES ID.= L. Mich; K-5

0
RESIST.= 196 THICK.= .89
.89
RESIST.= 233 THICK.= 1.15
2.04
RESIST.= 177 THICK.= 5.2
7.24
RESIST.= 80 THICK.= 11.9
19.14
RESIST.= 37

%RMS ERROR = 0.579
FOR ITERATION No. 10

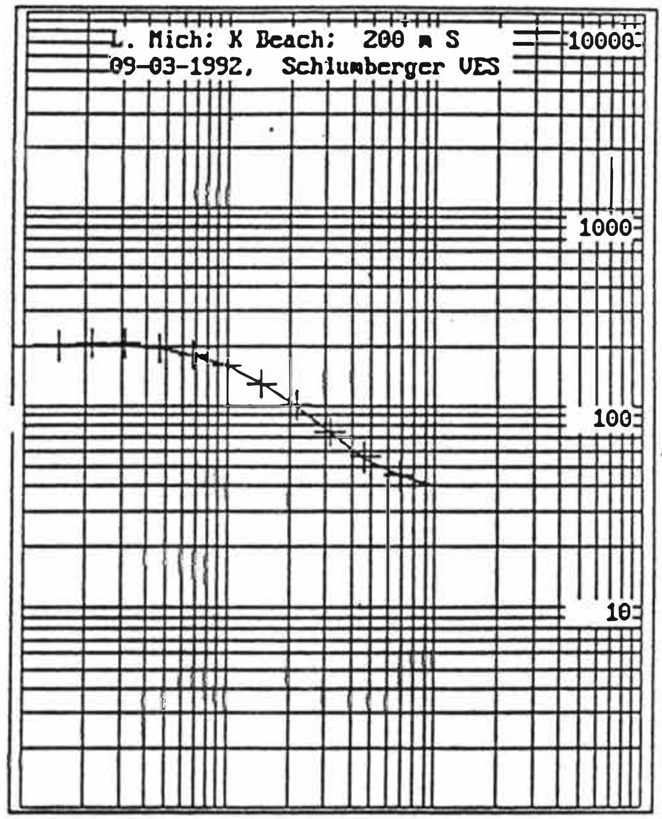

Figure 2. VES Model K-5.

of penetration and produced poor quality sub-bottom data. Abandoning the conventional methods, a new approach was devised for GPR data collection. A 500 MHZ antenna was encased in a plexiglass box which was mounted on a sled that could be pulled along the lake bottom. The sled had to be ballasted with 200 pounds of beach sand, which became very cumbersome. While the technique worked, depth was limited by the 500 MHZ frequency of the antenna and the awkward size of the sled made surveying operations slow and difficult. The sled could only be deployed in areas where a beach existed and where there was a source of ballast material. Further difficulties arose in data interpretation. Running the antenna over the irregular surface of the lakebottom introduced irregularities into the reflectors, as they were themselves referenced to the lake bottom. This was overcome by referencing the records to the surface of the water, producing a profile that depicted the lakebottom topography. Sonar data collected from a transducer mounted on the boat was merged with the GPR profile obtained from the sled being towed 30 meters behind the boat, which again introduced interpretation difficulties. The sled was abandoned and a new compact model was designed, fitted with an upward looking sonar transducer, and a new compact 55 cm dipole GPR antenna.

For offshore GPR work the R.V. SANDSEEKER, a 21 foot Monark aluminum work boat with a cabin was utilized. The GSSI SIR 10 was mounted in the boat as was a Lowrance X-16 paper recording SONAR. The 145 MHz dipole antenna was fabricated and sealed in a PVC bottom sled. An upward looking 192 KHz SONAR transducer was also affixed to the sled. A 35 meter Tescorp cable was used to tow the sled and for GPR data transmission. A coaxial cable connecting the sonar transducer to the sonar console was also affixed to the Tescorp cable.

To conduct the offshore profiles the SANDSEEKER was beached (on lines where a beach existed) so that the antenna sled could be deployed at the waterline. In areas without a beach the SANDSEEKER maneuvered to the revetment or rocks. The antenna was deployed off the back of the boat. The GPR scan length, scan averaging, and the gains were set based on the electrical properties of the sediments at the starting point. In each case a field assistant set up backsight and foresight markers onshore. The backsights used were previously described and surveyed USACE section 111 profile locations. The foresight was determined using either a Brunton compass or a transit aligned with the pre-determined azimuth of the line or by turning an angle between the north channel marker, the backsight, and the line as described by the USACE documents. Separation between the foresight and backsight markers was maximized to increase accuracy of navigation. The foresight, backsight technique is based on the theory that two points determine a line (if the points are very small). In practice the points (traffic cones and bright pink rain coats) are not small but this can be overcome by separating them the maximum possible distance therefore minimizing the angular error. A string distancing device accurate to 0.1 m (Chainman II) was tied to a stake at the water line and used to measure the distance from shore. When all systems were ready the SEEKER was turned and brought on line with the markers and the cable then pulled tight. The sonar and the radar were turned on and the profile was begun. Distance measurements were marked by simultaneous pushbutton event markers on the sonar and radar records in 50 meter increments as indicated by the Chainman II.

Offshore GPR profiles were conducted over three seasons, but the most complete data set was collected during the summer of 1993. During that field season ten shore perpendicular profiles and 4 shore-parallel files were conducted from the R.V. SANDSEEKER. Shore parallel data (on the beach) was collected in Klock Park, from approximately 100 meters north to 500 meters south of the north boundary. The profiles were run adjacent to the boring SJ-3-92. Three shore-parallel lines were conducted offshore north of the jetties in the Klock Park area approximately 140, 250 and 350 meters offshore. Distance marks were recorded based upon structures on the beach and other landmarks. These lines have somewhat less precision in positioning than the shore-perpendicular lines. The profile from 140 meters offshore is the only one included here. One shore parallel profile was conducted south of the jetties 350 meters offshore, crossing lines R-9, 10, 11 and 12 over a length of 1000 meters. On all of these profiles sonar data was collected concurrently (both the GPR and the SONAR transducer on the sled) and digitized at 10 meter intervals, allowing the GPR profile to be draped beneath the sonar profile using Radan III software (GSSI, 1993). This produced a GPR profile that positioned the sub-bottom reflectors in the correct relationship to bottom topography. Undulating reflectors in the original profile flattened out, revealing a single prominent planar reflector overlain by interbedded reflectors.

Sampling Techniques

The USACE has contracted a large number of borings in the St. Joseph area over the years, many of which were done in conjunction with jetty construction and repairs. Figure 1 shows the locations of the borings used. Three borings were logged in an attempt to locate the ancient valley boundaries. They are located at the north boundary of Jean Klock Park, the landward end of line R-10 and on the beach at line R-13. A small track mounted drill rig was used to perform the borings, incorporating a 6 inch hollow stem auger and taking continuous split spoon samples. CTI and Associates Inc. performed the borings; geologist James Surhigh described the samples on site (See figure 3 for geotechnical logs). On July 14, 1993 the USACE performed bulk sampling of the lake bottom cohesive substrate using a 3 cubic yard clam shell bucket suspended from a 100 foot tall crane mounted on a 120 foot barge. Sampling locations were selected based on GPR interpretations of minimal sand thickness. They selected line R-14 at approximately 370 meters from the shore and line R-17 at approximately 330 meters from the shore. The bulk samples extracted offshore outside of the inferred boundary of the ancestral valley confirm the presence of glacial till.

Five test borings, located within the boundary of the ancient river valley, were all too shallow to reach the bottom of the valley and do not contain any glacial till (Figure 3). All but one contain sands with interlayered silt or clay which are not correlatable. These silts and clays show no lateral continuity. The thick clays found in SJ-2-82 and SJ-3-92 could be interpreted as abandoned channel meanders.

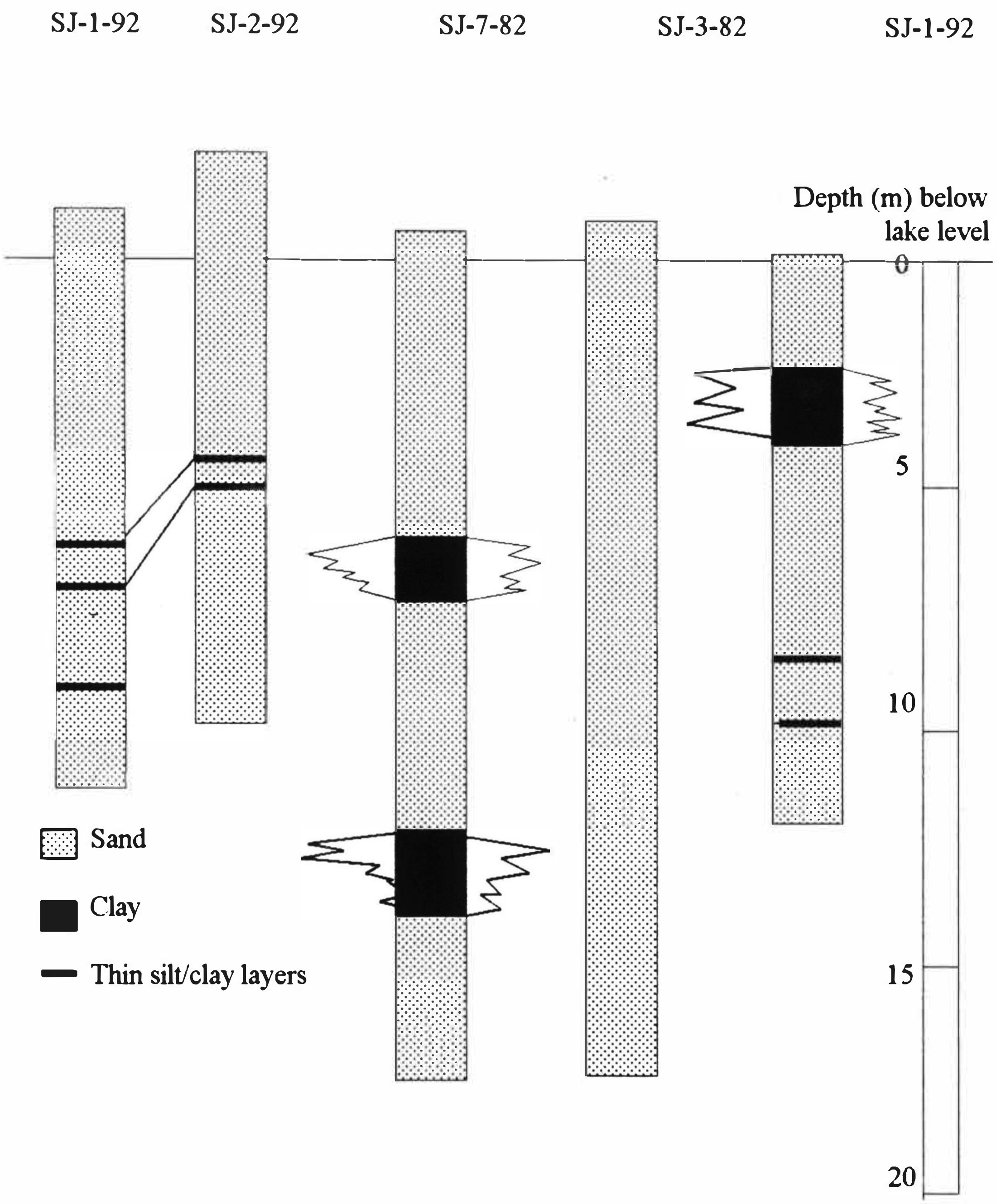

Figure 3. Simplified Geotechnical Logs From the St. Joseph River Valley.

DISCUSSION

This study was designed to define the ancestral St. Joseph river valley, locate the cohesive substrate outside the bounds of this valley and determine the overlying sand volume. Electrical resistivity was used to first define the valley position and GPR was later adapted to determine the depth and lateral extent of the cohesive substrate.

Composite electrical resistivity profiles were produced using the ρ_a from 3 different AB/2 spacings at each of the 41 VES sites. This profile shows the lateral change in apparent resistivity for those given AB/2 spacings (Figure 4). There is a general trend of decreasing resistivity to the south in all of the profiles which may be a function of groundwater stagnation movement and fining of clastic sediments in that direction. The fines may be derived from the river. VES inversions do not support shallowing of basal glacial till or Mississippian shale, which would also result in decreased resistivity values to the south. The smaller AB/2 spacings show a rise in resistivity near the location of the modern St. Joseph River, (gap in profile (figure 4)) indicating cleaner or coarser sands near the river. The higher resistivity values to the north may result from winnowing and removal by longshore currents of fine grained sediments. Increased permeability would decrease both the residence time of pore water and dissolved solid content, resulting in increased resistivity values. Resistivity values decrease with depth, possibly a result of increased fines and/or higher

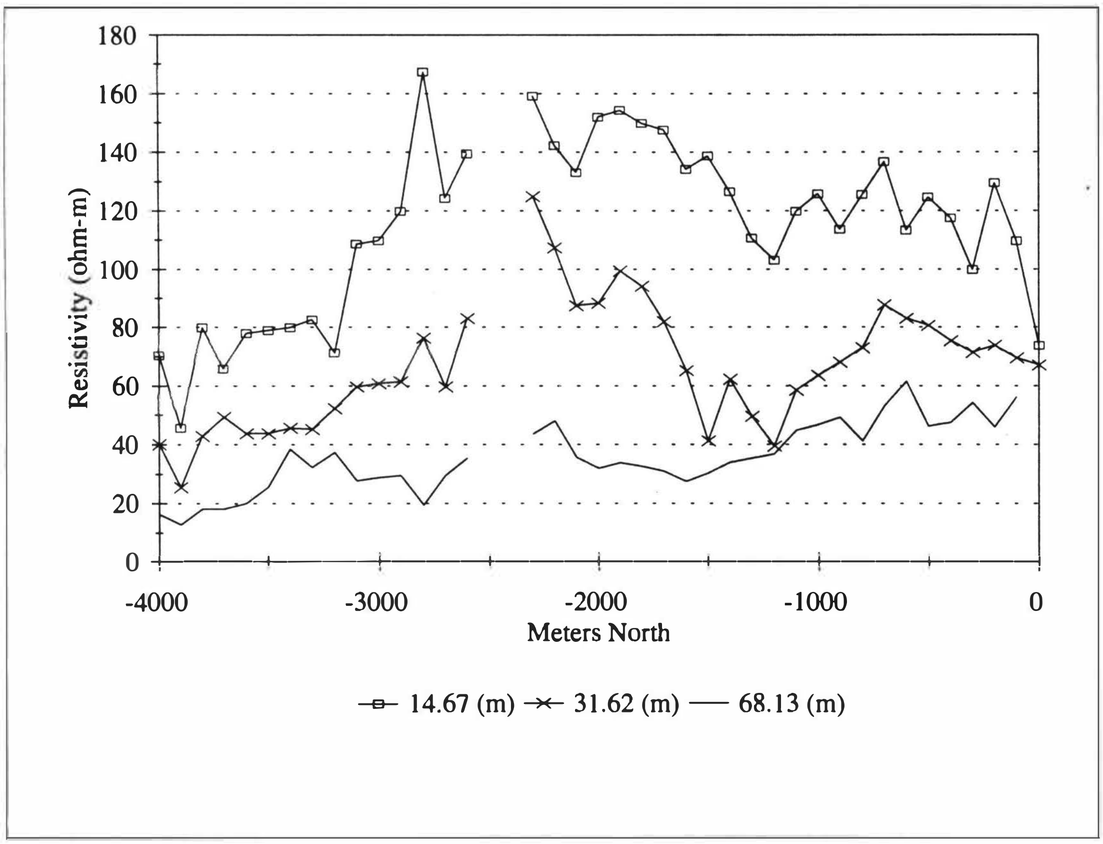

Figure 4. St. Joseph - Benton Harbor, MI, Electrical Resistivity Profile.

dissolved solids in pore waters associated with poorly sorted sediments.

A cross section of the river valley was generated using individual 1-D VES interpretations (see figure 5). This reconstruction suggests that the channel encompasses the area from the north boundary of Jean Klock Park south to a point between line R-12 and R-13. A number of different models were calculated from the sounding curves using 3-6 layers and the best model was selected based on a working knowledge of the area. The individual VES interpretations indicate a somewhat irregular valley depth, caused by lack of more data at larger AB/2 spacings and larger uncertainties associated with interpreting depth to the deepest resistivity boundary. Averaging the interpreted depth for the deepest interface results in a depth of 30 meters, which supports the observations of Peck and Reed (1954) which are 6 to 24 meters. The southernmost boundary of the geoelectric section is not meant to represent the termination of the paleovalley, but the end of the profile data. At this point there was no beach present to continue the survey, only a steel revetment emplaced as an erosion control device. While it is not possible to infer the southern boundary from resistivity data, it should be noted that clayey till was retrieved offshore on line R-14. This would indicate that the south valley wall boundary lies somewhere between line R-12 and R-13.

The GPR profiles suggest the presence of an offshore reflector that may be laterally continuous across the study site. However, boring logs from onshore indicate that north of line R-13 multiple reflectors are thin silt deposits. Within the

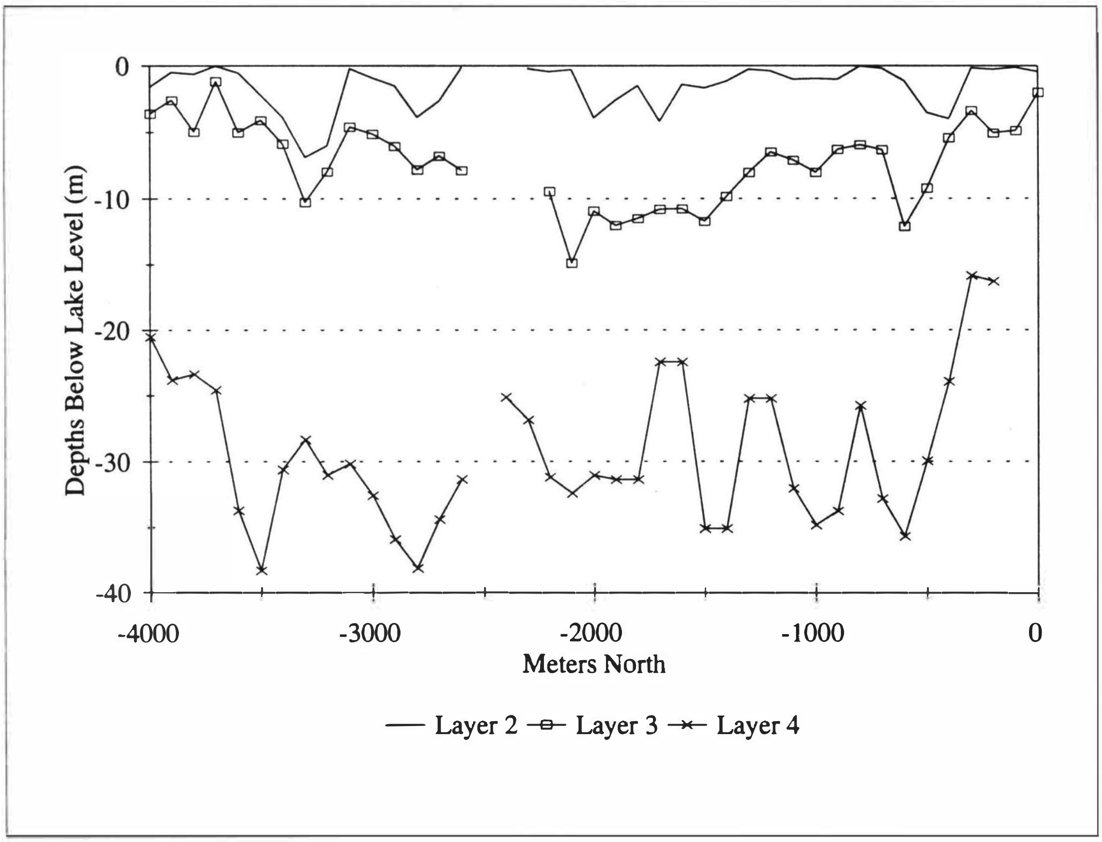

Figure 5. St. Joseph - Benton Harbor, MI, Geoelectric Section.

profile they appear to converge and diverge across the lake bed and to be contained within the ancient valley structure, similar to layer 2 illustrated on the geoelectric section. It is not likely that the second layer illustrated on the geoelectric section is a thin silt deposit. The resistivity values for a layer 3 inches thick would be averaged with the surrounding sediments and it would not be detected as a discrete layer. There were no clearcut lithologic changes in the borings which correlated with the geoelectric section or the GPR profile. Furthermore, soil borings and GPR traverses were not done at coincident locations. It is possible that the layers represented on the geoelectric section are caused by changes in pore water conductivity and not physical parameters. All of the radar profiles, both shore-parallel and shore-perpendicular, show a continuous reflector, ranging from 2 to 11 meters below lake level in the shore-perpendicular profiles, systematically increasing lakeward. Within the shore-parallel profiles there are multiple high amplitude reflectors. Well log data suggests that these reflectors are thin silt layers. Interpreting the thicker clay layers found in SJ-3-92 and SJ-7-82 as oxbow deposits would limit their lateral extent and decrease the likelihood that they would appear as regional reflectors. It is the nature of the reflection terminations that define stratigraphic sequences (Mitchum et al, 1977). The concordant GPR reflection termination patterns within GPR Profile BH-SP2P (Figure 6,map pocket), located approximately 140 meters offshore north of the jetties, suggests a stacked sequence that is interpreted to represent a buried channel structure. The shallowing nature of the reflectors indicated by onlap termination at the northernmost edge of the profile most likely represents the north wall of the ancestral valley. The parallel to subparallel configuration of the reflectors indicate uniform deposition. South of the jetties on GPR Profile SJ-SP1P (shore-parallel approximately 350 meters offshore (Figure 7,map pocket)) the high amplitude reflector is overlain by low amplitude reflectors. These shallower reflections can be described as having basal downlap terminations and parallel prograding clinoforms indicating a net southward movement consistent with known longshore transport direction. The nature of this low amplitude reflector has not been defined, but may be the result of small scale grain size changes or grading. Both of these GPR profiles lie within the ancestral valley. However, neither profile provides a complete record of the valley fill as the penetration maximum is approximately 12 meters below lake level on profile SJ-SP1P.

Profile SJ-SP1P crosses several shore-perpendicular profiles, including R-9,10,11 and 12. The GPR Profile on line R-9 (Figure 8, map pocket) is a good example of typical field data. It is riddled with extraneous noise and reflections from the top of the water surface incurred in shallow water. Because radar wave velocity is so low in water, the scan length is long enough to capture this unwanted reflection only in shallow water. This profile also displays the same prominent concordant high amplitude reflection seen on shore-parallel lines and can be directly correlated with the reflections seen on SJ-SP1P where they intersect. This profile lies within the boundary of the ancestral valley. The reflector appears to dip gently lakeward, a feature that is supported by all other shore-perpendicular lines in this area.

GPR Profile R-13 (Figure 9, map pocket) is inferred to be located on the edge of the ancestral valley and does not cross any shore parallel-profiles. This profile displays a lakeward dipping high amplitude reflector, however the overall relief of this reflector is greater than on other lines. Onlap reflection terminations between 500 and 600 meters off shore suggest landward migration of ridge sands overlying the reflector. Interspersed reflectors within this sediment suggest an increased amount of fine material, most likely due to depth and associated energy levels. The organized nature of the reflection pattern suggests it is a depositional structure indicating its movement onshore. GPR Profile R-14 (Figure 10, map pocket) is located south of the south wall of the ancestral valley. It displays a high amplitude reflector with variable topography. Sampling on this line indicates the reflector is glacial till rather than silt. The overlying sand ridges on profile R-14, between 175 and 550 meters offshore, show low amplitude onlap reflection terminations indicative of onshore translation of offshore bars. Beneath the high amplitude reflector the reflection configuration becomes chaotic as is commonly seen in clayey deposits. Random noise may also be explained as a system artifact which occurs when there is no penetration into clay. In this manner, the GPR record can be used to infer the presence of unstratified till.

The GPR profiles on lines R-9, R-13, SJSP-SP1 and BH-SP2P all lie within the ancestral valley and all display laterally continuous horizontal reflectors. The reflectors within the shore-perpendicular profile on line R-9 can be directly correlated to the shore-parallel profile. Because of the lack of laterally continuous clays or silts within the valley, as seen in the well logs, it is highly doubtful that a continuous reflector within the valley is the physical expression of a lithologic horizon. It has already been suggested earlier in this thesis that resistivity data may reflect variations in pore water conductivity at this site. It is further suggested that this reflector may in certain locations be of a similar origin, such as the contact between higher resistivity sands saturated with lake waters (40 ohm-m) and low resistivity silts and sands containing lower ρ (20 ohm-m) groundwater. Coring techniques used at this study site were not adequate for defining this interface, as a continuous core is necessary for establishing the physical/chemical properties of this contact. Vibracoring techniques were attempted without success onshore and offshore.

Determining the volume of "mobile" sand overlying the till became a questionable task when till was found to be absent north of line R-13. Instead, sand volumes are calculated for that sand which overlies the continuous reflector. Due to the distance between profiles, volumetric determinations are made only for the profile line and not meant to designate any spatial distribution. See Figures 11,12, and 13 for sand thickness interpretation. Figure 14 shows sand volumes normalized to 600 meters above the upper most continuous reflector. The sand volume between the profiles is variable, and shows no obvious difference between sand volumes inside or outside the valley. This would seem to indicate that the continuous reflector in the valley is analogous to the till. This continuous reflector appears to separate modern sands (in that they saturated with the higher resistivity lake water), from older fluvial sands in the valley. South of the valley the reflector separates modern sands from the till. While this reflector does not represent a regional lithological interface, it is a laterally continuous radar reflector. This same reflector has been seen in other work south of St. Joseph all the way to Burns Harbor, Indiana (personal communication Sauck, 1995) and as such can be considered a regional reflector. The nature of this unconformity suggests the possibility of a relationship to lake level rise and may represent an unconformity similar to a transgressive lag surface associated with coastal sealevel rise. While there appears to be no correlation between profiles, it may be useful to track sand volume over time to see if a pattern emerges between the lines, between lines inside and outside the valley, and how individual profiles change. The shore-parallel lines used to correlate multiple shore-perpendicular lines lacked accurate positioning, limiting their usefulness in volumetric determinations.

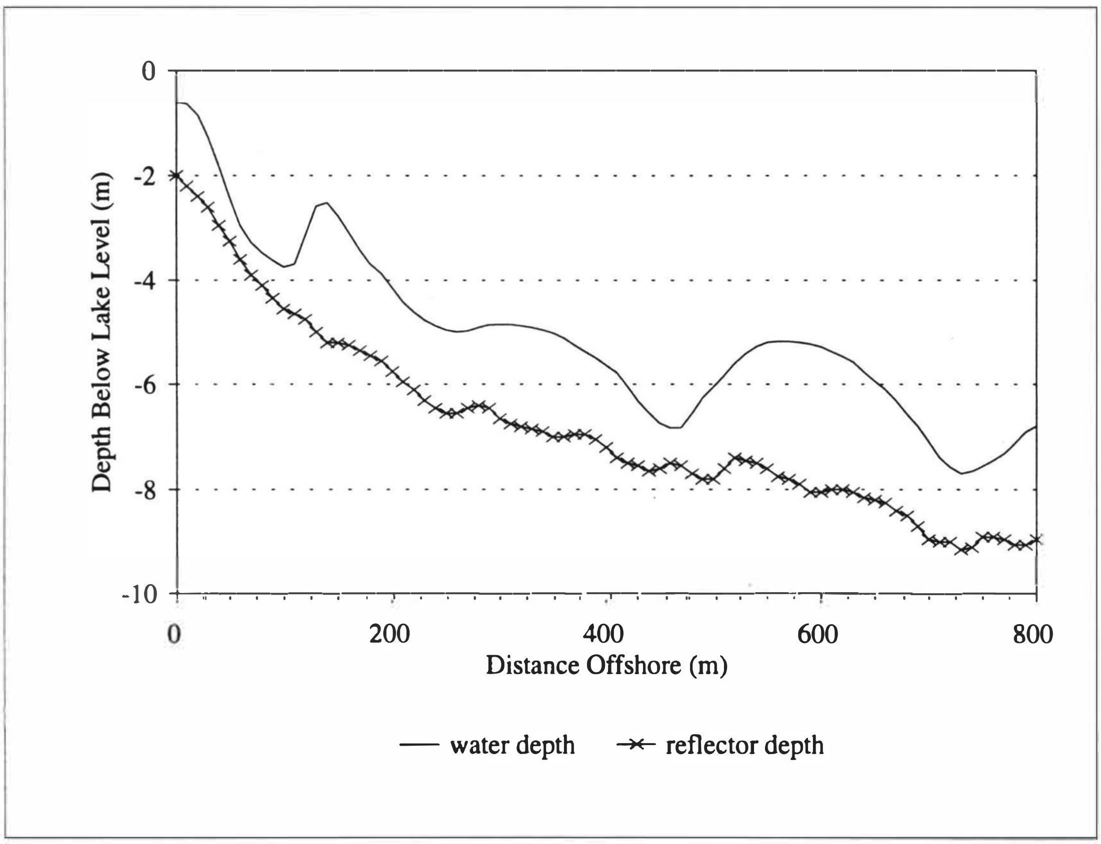

Figure 11. Profile R-9, Sand Thickness Plot.

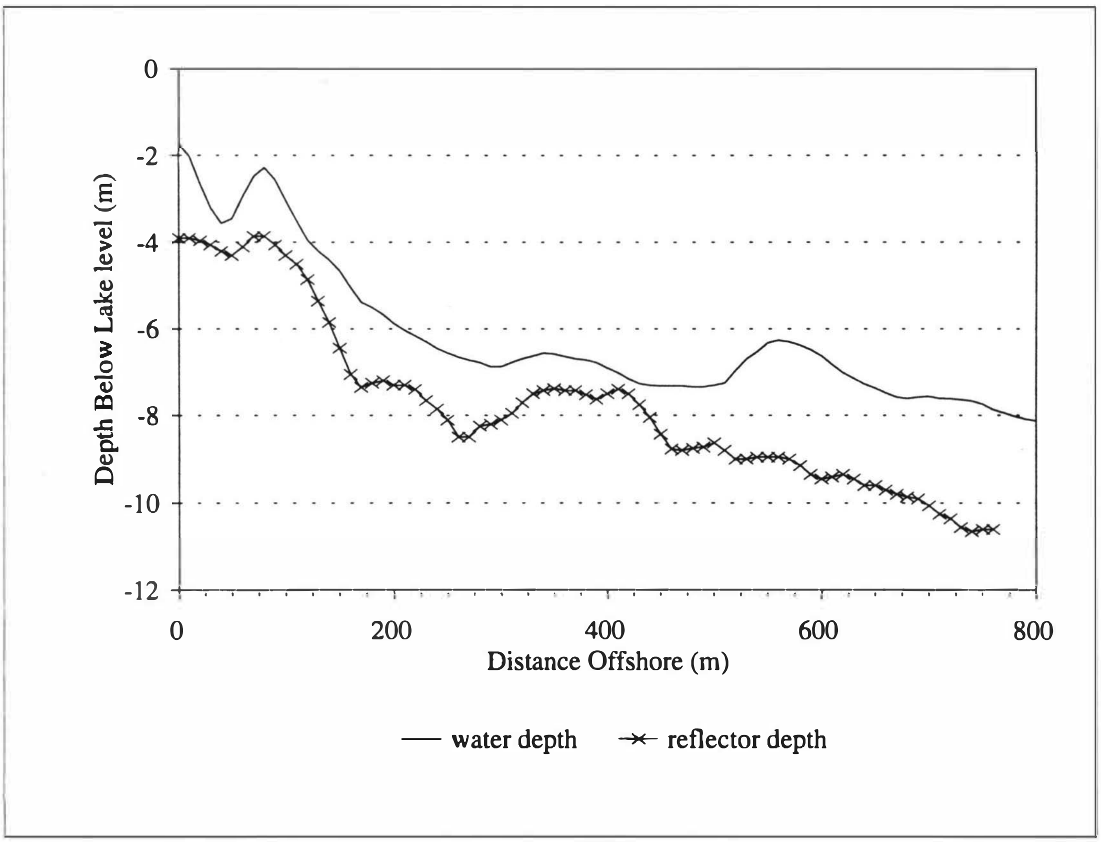

Figure 12. Profile R-13, Sand Thickness Plot.

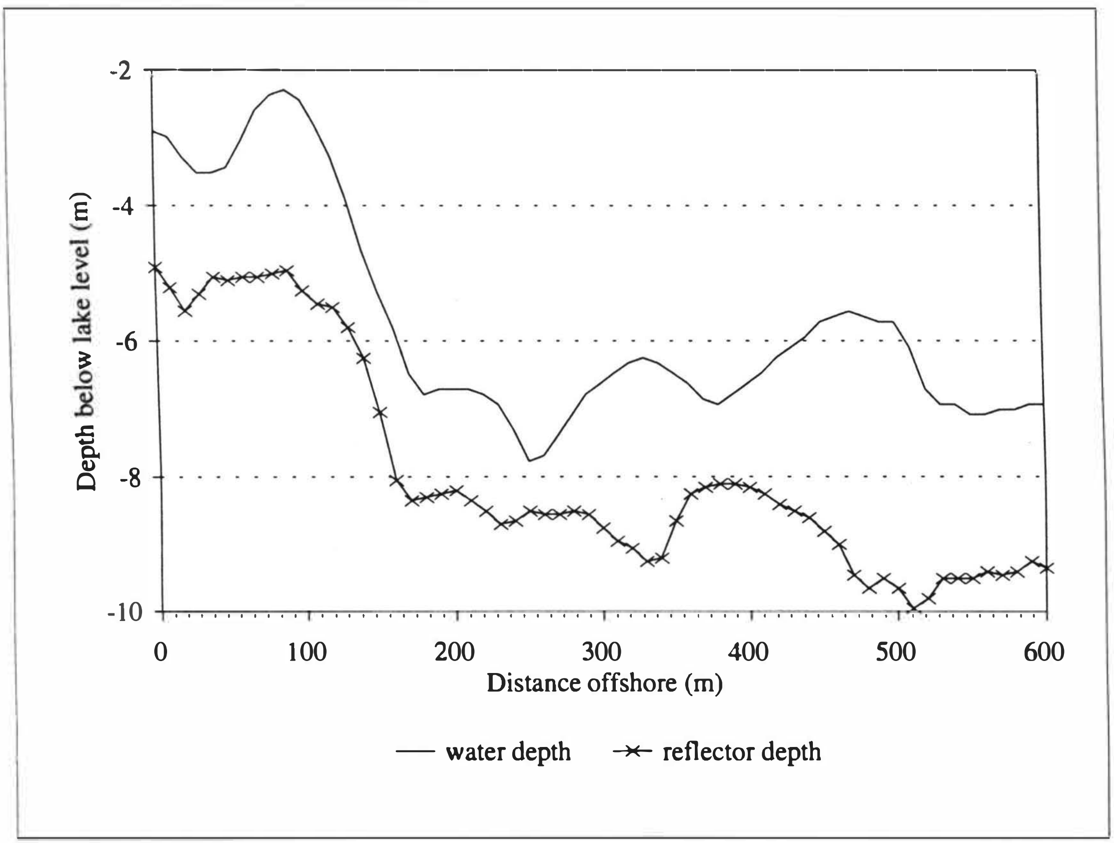

Figure 13. Profile R-14, Sand Thickness Plot.

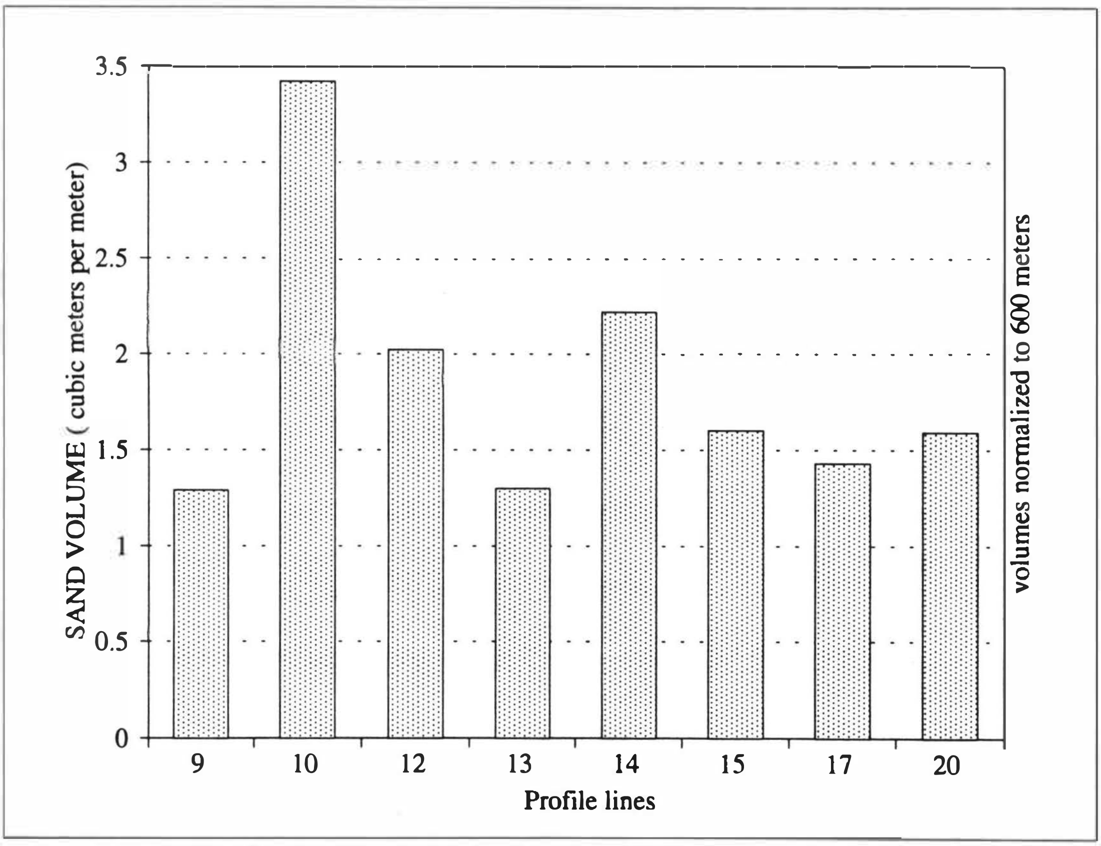

Figure 14. Profile Line Sand Volumes.

CONCLUSIONS

Ground Penetrating Radar and electrical resistivity soundings are viable geophysical methods in the nearshore region of Lake Michigan. Resistivity soundings defined the lateral limits and approximated the depth of the ancestral St. Joseph River valley.

GPR profiles supported resistivity data, identified a lakeward dipping regional reflector, and established sand thickness along the profiles. Aerially inclusive volumetric sand calculations could be made if profile lines were more closely spaced and positioning was more precise. VES data could be interpreted more accurately for the deepest interface if AB/2 spacings were increased beyond the 100 meter maximum used, allowing more accurate calculation of resistivity values and depth determinations of lower layers. While accurate ground truthing would be helpful for establishing the physical/chemical nature of the reflectors, the GPR technique was an overall success. This GPR technique has great potential use in the measurement of modern sand thickness/volume in fresh water lakes. This method would allow for very accurate sand budget calculations which would enable engineers and planners to make more informed decisions.

An innovative method for submerged radar applications in high energy coastal environments was developed and successfully implemented. This dipole antenna mounted on a bottom sled was deployable by two persons on any type of shoreline and was retrievable in deep water.

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