UNIVERSITY OF CALGARY

Electrical Resistivity Ground Imaging (ERGI): Field Experiments to Develop Methods for Investigating Fluvial Sediments

by

Christopher David Baines

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOGRAPHY

CALGARY, ALBERTA

AUGUST, 2001

0-612-65086-3

Abstract

This research tested a new geophysical tool, electrical resistivity ground imaging (ERGI), to map lithology and geometry of buried fluvial deposits. ERGI uses measurements of the resistance of the ground to an electrical current to develop a 2D model of the shallow subsurface (<100 m).

Research was conducted in spring 2001 on an anastomosing reach of the upper Columbia River, in southeastern B.C., Canada and in late summer 2001 on the Rhine-Meuse Delta, the Netherlands.

ERGI surveys from 2 channel-fills and 2 crevasse-splays are presented and compared to lithostratigraphic profiles from sediment cores. Depth, width and lithology of sand channel-fills, crevasse-splays, and adjacent sediments can be accurately detected and delineated from the ERGI profiles, even when buried beneath 1-20 m of silt/clay.

Methodology experiments examined combined open water and dry land ERGI surveys, assessed electrode arrays, and identified a previously unreported methodological problem: 'cumulative electrode charge-up'.

Table of Contents

List of Tables

List of Figures

CHAPTER 1. INTRODUCTION

This research tested a new geophysical tool, electrical resistivity ground imaging (ERGI), to map lithology and geometry of buried deposits of fluvial sediments. The research included imaging field experiments to determine if ERGI can detect and delimit fluvial sediments and methodology field experiments to determine procedures for obtaining ERGI profiles under typical fluvial research field conditions.

Investigations of fluvial deposits, such as buried mud-encased sand channel-fills and crevasse-splay sheet-sands, are restricted because of our limited ability to obtain information about the shallow subsurface. Until recently, drill cores were the only method available.

Lithostratigraphic logs from boreholes are extremely detailed and have excellent vertical resolution, but only provide data from one dimension. A series of boreholes can provide a weak representation of two or three dimensions, but interpretation is often flawed because the borehole program may not effectively locate all features, define the lateral extent of features, or discover gradual changes that occur between boreholes. Borehole programs must balance the spatial density of the coring program against the time, effort, and cost of each borehole. If ancillary information about a site was available, coring could be much more representative and efficient.

Recently, shallow geophysics has offered new methods to obtain information about the subsurface. Data obtained from shallow seismic and ground penetrating radar (GPR) have been used to produce two-dimensional profiles of the subsurface and as a guide for subsequent coring programs. In many situations, shallow seismic equipment is considered too bulky, heavy, and expensive for fluvial field work, particularly when travel to and from study sites is by small water craft or when the equipment must be back-packed over one kilometer into the survey site. GPR has been used successfully to investigate fluvial deposits, but requires clean (free of silt and clay) sand and gravel. Clay and silt attenuate the signal by absorbing the electromagnetic (EM) energy, which makes GPR mostly ineffective in many fluvial settings such as anastomosing river deposits (Moorman, 1990) and some sand-bed meandering rivers (e.g. the Red Deer and Milk rivers of southern Alberta, D. Smith, pers. comm., 2001).

ERGI is a recent addition to shallow geophysics that may be able to produce effective 2D profiles of buried fluvial deposits in almost all fluvial settings. ERGI uses measurements of the electrical resistivity of the subsurface to produce a two dimensional model of the subsurface called an ERGI profile. ERGI works effectively in clean sand and gravel and in fine sediments such as silt and clay. This is the first research to use ERGI to investigate buried mud-encased sand channel-fills and crevasse-splay sheet-sands.

CHAPTER 2. PREVIOUS RESEARCH

2.1.1. Electrical Resistivity Ground Imaging

ERGI is a recent evolution of an old technique. DC-Resistivity, the precursor to ERGI, uses four electrodes to make a single electrical resistivity measurement. Subsequent measurements require moving the electrodes to a new location for each measurement. A set of resistivity measurements is combined into a plot of either the vertical or the horizontal distribution of resistivity in the subsurface, and then curve matching is used to interpret the data (Broughton Edge and Laby, 1931; Kunetz, 1966). Although both data collection and interpretation are slow and difficult, the method is still in use (e.g. El-Hussain, et al, 2000; Maillol et al, 2000).

ERGI has evolved due to significant improvements to data collection and interpretation. New computer-controlled multi-electrode systems automatically collect large data sets without the need to move electrodes (Griffiths et al, 1990). New software packages use 2D finite difference or finite element inversion routines to produce 2D models of the subsurface (ERGI profiles) (Edwards, 1977; Dey and Morrison, 1979; Barker, 1992; Beard et al, 1996; Loke and Barker, 1996). Lastly, modern high-speed Pentium computers allow for rapid data processing and manipulation (e.g. topographic corrections, Tong and Yang, 2000). Data collection and processing is now quick, simple, and inexpensive, while interpretation is straightforward and reliable (Loke, 2000a and 2000b).

Although ERGI is increasingly popular for geohydrology, geotechnical engineering, and environmental consulting (e.g. Dahlin, 1996; Dahlin and Owen, 1998; Maillol et al., 1999; Daily and Ramirez, 2000; Abdul Nassir et al, 2000; El-Behiry and Hanafy, 2000; Gilsom et al., 2000; Maillol et al., 2000; Wolfe et al., 2000), it is virtually unknown among fluvial geomorphologists and sedimentologists. Previously, no published research has used ERGI to investigate fluvial sediments such as channel-fills and crevasse-splays.

2.1.2. Anastomosing River Deposits

This research project does not investigate anastomosing river deposits *per se*, instead it uses anastomosing river deposits (buried mud-encased sand channel-fills and crevasse-splays) as a means to investigate and evaluate ERGI. Nevertheless, a brief discussion of anastomosing rivers is provided.

Since the early 1970s, 'anastomosing rivers' have been accepted by many researchers as a fourth member of the formerly tripartite river classification of 'straight', 'meandering', or 'braided' rivers (Rust, 1978). Under the tripartite river classification, all multiple channel rivers fell into the braided category. Although 'braiding' implies shallow rapidly evolving channels, some of the rivers grouped into the braided category had deep stable channels. A new category, anastomosing, soon became a 'catch-all' for all non-braided multiple-channel systems. Researchers continue to investigate anastomosing rivers in diverse continental, climatological, and sedimentological settings to learn more about their characteristic processes and deposits. An extensive, but not comprehensive, sample of anastomosing research includes: Leopold et al, 1964; Smith, 1972; Rust, 1978; Smith and Putnam, 1980; Smith and Smith, 1980; Quinn, 1982; Locking, 1983; Smith, 1983a and 1986; Moorman, 1990; van Dijk et al, 1991; Harwood and Brown, 1993; Knighton and Nanson, 1993; Törnqvist, 1993; Miall, 1996; Schumm et al, 1996; Weerts, 1996; Berendsen, 1998; Heritage and Broadhurst, 1998; Makaske, 1998; Abbado and Filgueira-Rivera, 2000; Berendsen and Stouthamer, 2000; Gilvear et al, 2000.

This research loosely follows Smith's (1986) definition of anastomosing. For this research, an anastomosing river reach has low-energy, multiple, interconnected, laterally stable, deep sand-bed channels confined by prominent silty levees. The levees surround extensive wetlands, marshes, and ephemeral and permanent lakes. The multiple channels and wetlands usually cover the entire width of a slowly aggrading floodplain. Typical deposits include buried mud-encased sand channel-fills and crevasse-splay sheet-sands. Silt and clay account for 80-90% of the valley-fill in the upper Columbia valley (D. Smith, pers. comm., 2001).

CHAPTER 3. STUDY SITES

The two study areas for this research project were the anastomosing reach of the upper Columbia River, British Columbia and the Rhine-Meuse Delta, the Netherlands (Figure 1). The original selection criterion for study sites was sites that contained previously studied buried mud-encased sand channel-fills and crevasse splays. As the project progressed, it became necessary to alter the criterion and several of the study sites for the project were selected based on their proximity to sites already in use by the project.

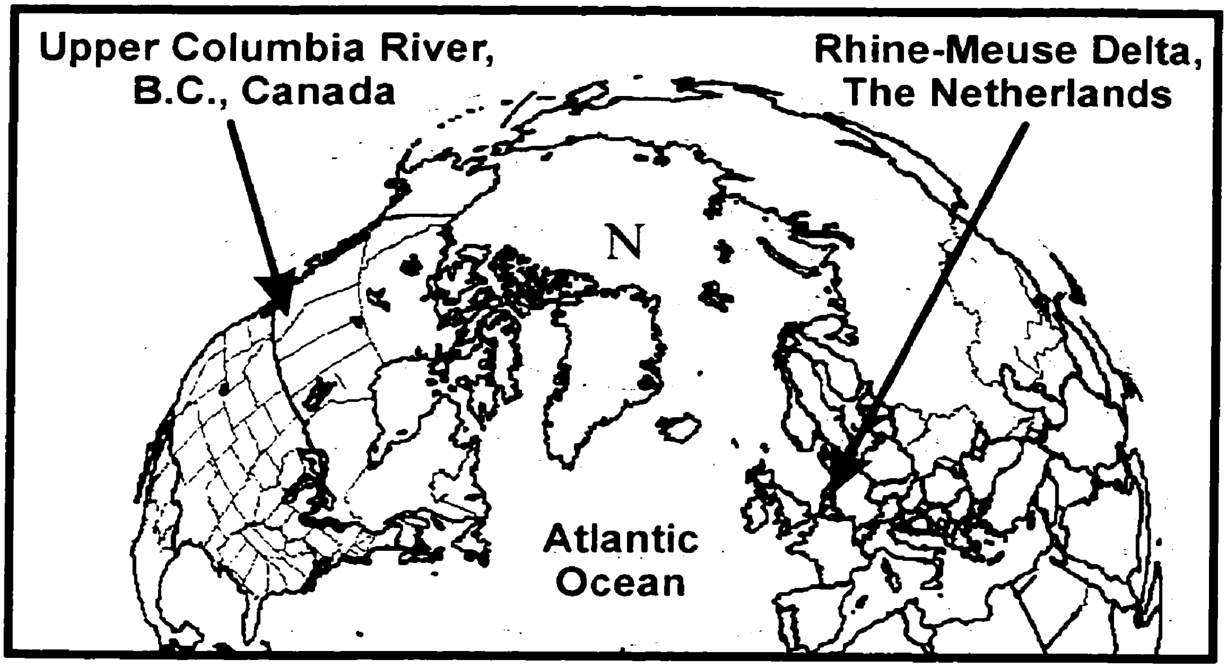


Figure 1 A global view of the ERGI study sites on the upper Columbia River, British Columbia and on the Rhine-Meuse Delta, the Netherlands.

Study sites on previously studied channel-fills were selected from both study areas. Although previous research has examined buried crevasse-splays on the upper Columbia River (e.g. Quinn, 1982), these sites were found to be difficult to examine with ERGI (see Chapter 6 section 2 for more details about the difficulties). Crevasse-splay study sites with no prior subsurface information were selected within the anastomosing reach of the upper Columbia River that were in the vicinity of the channel-fill study site previously selected.

3.1. Upper Columbia River, British Columbia

3.1.1. Regional Setting and Character

The upper Columbia River flows northwestward through a 100 km anastomosing reach from Radium Hotsprings, to the confluence with the Kicking Horse River in the town of Golden, British Columbia. In this reach, the river valley occupies a portion of the Rocky Mountain Trench (Geological Survey of Canada 1972, 1979a, 1979b, 1980). The Beaverfoot and Brisco Ranges of the Rocky Mountains (summits up to 2700 m above sea level: asl) border the valley to the northeast and the Purcell Mountains (summits up to 3000 m asl) border the southwest. The valley floor is ca. 790 m (asl), less than 3 km wide, and has an average gradient of only 12.5 cm/km (Abbado and Filgueira-Rivera, 2000). Clague (1975) provides an excellent Quaternary history of the region.

The planform of the Columbia River is very complex. Any valley cross-section typically contains: up to five active channels; numerous buried channels; a multitude of small lakes, marshes, and mud flats; and a number of active and abandoned crevasse-splays. Lateral facies changes from sand to mud or vice versa are abrupt and numerous. Deposits vary from coarse sand in the channels often with a thin fine-grained (granules and pebbles) gravel lag at the base, silty fine sand in the crevasse-splays, sandy silt in the levees, silty clay in the marshes, organic-rich clays in the lakes, to occasional pockets of peat.

Floods inundate the entire anastomosing reach (topping the levees) for about 45 days per summer (Locking, 1983). The Columbia River has no engineered water control structures upstream of the anastomosing reach. The reach is within the Columbia Valley Wetlands Wildlife Management Area and the Columbia National Wildlife Area, which protects it from development and precludes shallow seismic surveys.

When we arrived at the upper Columbia River (April 1, 2000), the ground water level was approximately 80 cm below the ground surface in the abandoned Beavertail channel. Research at the study site was terminated (May, 24, 2001) when the river rose high enough to pass over low points in the levees and flood all of the practical ERGI survey sites.

3.1.2. Survey Locations

Three ERGI study sites from within the upper Columbia River study area are included in this thesis (Figure 2): the Beavertail channel-fill, the Beavertail crevasse-splay, and the Herron Meadow crevasse-splay. The Beavertail channel and crevasse-splay are located within several hundred meters of the Beavertail Lodge (532210 5651970 UTM), a trapper's cabin on the main channel of the

Columbia River approximately 7.5 km northwest of the town of Harrogate. The Herron Meadow crevasse-splay (532414 5651604 UTM) is located on an inter-channel island between the Baldy Channel and an unnamed channel flowing along the west valley wall approximately 5.5 km northwest of the town of Harrogate. The coordinates for all of the ERGI survey lines and lithostratigraphic logs from the upper Columbia River presented in this thesis are included in Appendix D.

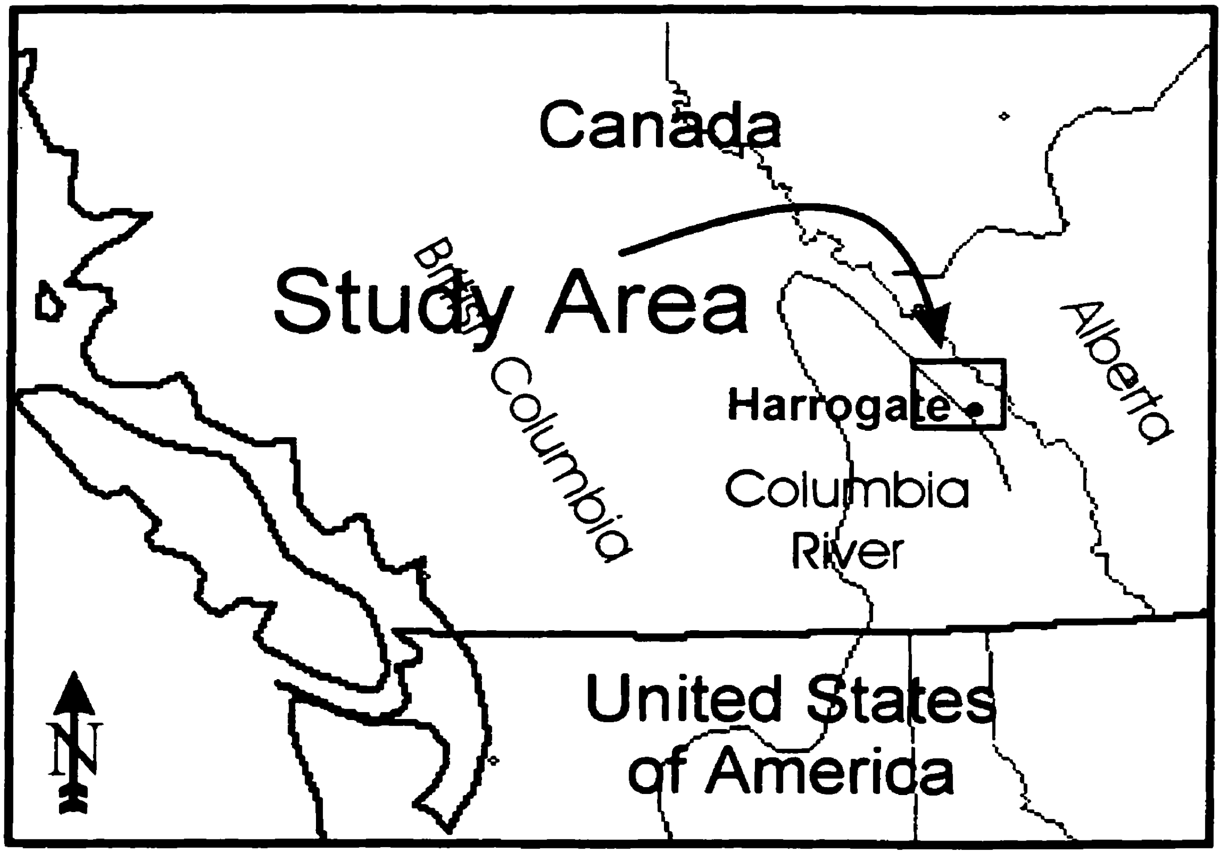


Figure 2 Location of the ERGI study area on the upper Columbia River, British Columbia. The exact locations of all the ERGI surveys and lithostratigraphic logs on the upper Columbia River are provided in Appendix D.

3.2. The Rhine-Meuse Delta, the Netherlands

3.2.1. Regional Setting and Character

The buried mud-encased sand channel-fills and crevasse-splay sheet-sands in the Rhine-Meuse Delta formed as delta distributary features with anastomosing character that is attributed to slow continuous sea level rise throughout the late Weichselian (Wisconsinan) and Holocene (i.e. over the last 18,000 years, Berendsen, 1998). The delta is 130 km long, extending westward from the German border, where it is 20 km wide, to the North Sea, where it is 60 km wide (H.J.A. Berendsen, pers. comm., 2000). The delta is slowly filling a valley bounded by glacial ice-pushed ridges to the north and outcropping Pleistocene sediments to the south (van Dijk et al., 1991). Under the Holocene delta is a continuous Pleistocene sand and gravel braid-plain approximately 6 m below the surface in the east and 22 m below the surface in the west.

The planform of the Rhine-Meuse Delta is very complex, but well known. Berendsen and Stouthamer (2000) have produced spatially and chronologically detailed maps of the Paleogeography of the Rhine-Meuse Delta. Through time, the number of coexistent channels has varied from four to ten (Törnqvist, 1993). Vast interchannel 'islands' separated the channels, which typically contained lakes, marshes, mud flats, and peat bogs. Crevasse-splays were infrequent, but when they did occur, they often formed the basis for a channel avulsion. Because of the extremely low gradient, many of the distal channels show tidal influence.

Lateral facies changes throughout the delta are frequent and sharp. Deposits vary from coarse sand in the channels with a thin gravel lag at the base, through silty fine sand in the crevasse-splays, clayey silt in the levees, silty clay in the mud flats, to vast areas of peat.

The present Rhine-Meuse Delta is, in essence, one large engineered water control structure. Humankind has been directly involved with the hydrologic behavior of the system since AD 1100 (Berendsen and Stouthamer, 2000). Nearly all of the delta is developed and has been in use for settlement and agriculture for many centuries.

All ERGI surveys in the Rhine-Meuse Delta occurred on low relief (< 40 cm) grass-covered fields used as pastures for dairy cattle. Fields are approximately 300 m long by 50 m wide, below sea level, and surrounded by 2 to 5 m wide drainage ditches containing 1 to 2 m of water. Pump systems on the ditches maintain the ground water level approximately 80 cm below the surface.

3.2.2. Survey Locations

Two ERGI study sites from within the Rhine-Meuse Delta study area are included in this thesis (Figure 3): the Schoonrewoerd paleochannel and a collection of unnamed paleochannels next to the Lek River. The Schoonrewoerd paleochannel study site (116950 431200 NLRD) is located in a farm field approximately 1 km south of the town of Molenaarsgraaf and approximately 21 km east of Rotterdam. The study site on the unnamed paleochannels

(110200 436000 NLRD) is located in a farm field on the north bank of the Lek River approximately 3 km east of the town of Lekkerkerk and 14 km east of Rotterdam. The coordinates for all of the ERGI survey lines from the Rhine-Meuse Delta presented in this thesis are included in Appendix D.

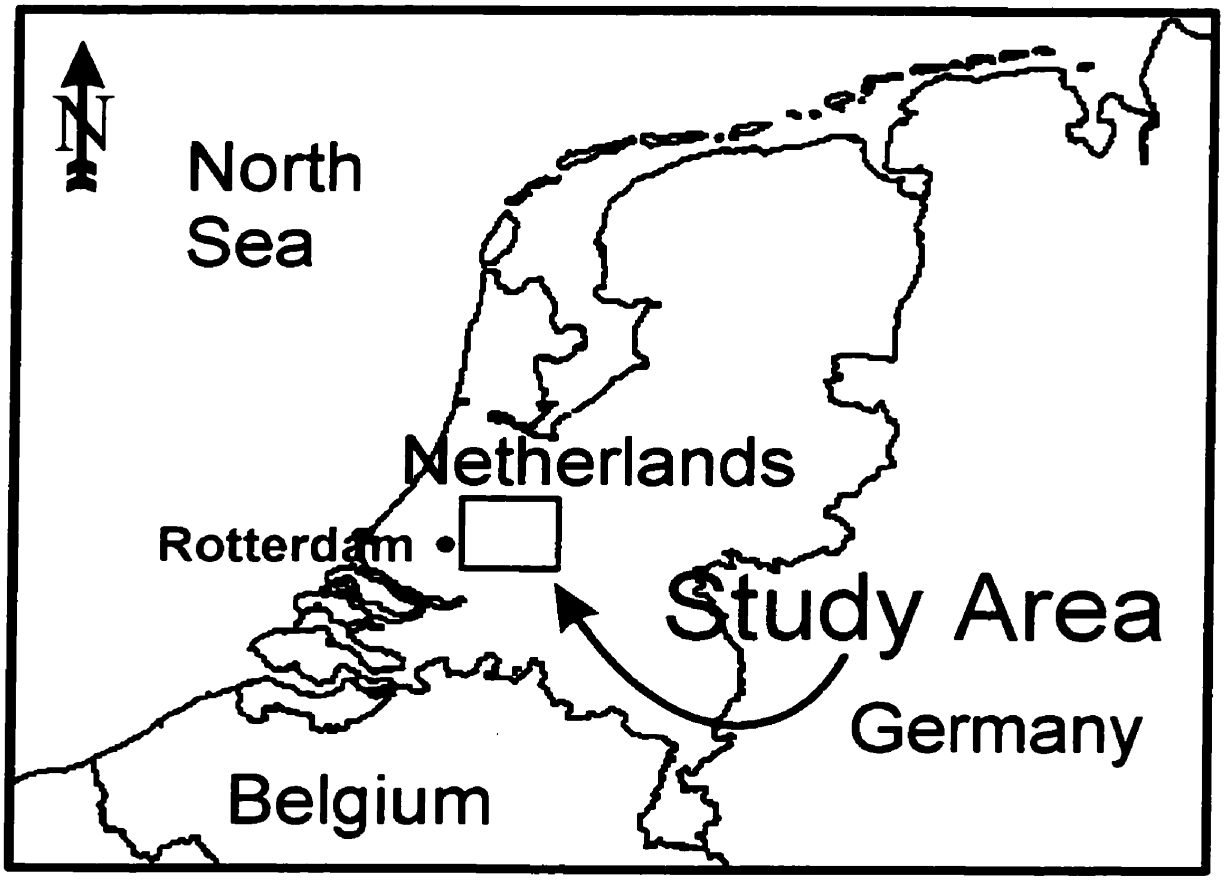


Figure 3 Location of the ERGI study area in the Rhine-Meuse Delta, the Netherlands. The exact locations for all the surveys in the Rhine-Meuse Delta are included in Appendix D.

CHAPTER 4. ERGI THEORY

Although ERGI theory and methodology are amply explained elsewhere (Telford et al, 1990; Ward, 1990; Burger, 1992; Reynolds, 1997; Loke, 1999 and 2000), this section provides a summary of the concepts underlying ERGI data collection and processing. Practical information about where, when, and how to conduct ERGI surveys has been included in appendixes A, B, and C. This includes 'rules of thumb' regarding the depth and resolution of ERGI surveys.

4.1. Electrical Resistivity

Electrical resistivity, measured in Ω m (Ohm· meters) and represented by the Greek letter ρ (rho) is a bulk physical property of materials that describes how difficult it is to pass an electrical current through a block of the material with a given length and cross-sectional area (Figure 4: Gettys et al, 1989; Hazen, 1990). The resistivity of a block of material can be calculated by combining the electrical resistance (R) produced by the entire block, the length (L) of the block, and the area (A) using Equation 1 (Reynolds, 1997):

Equation 1 $$\rho = R\,(A/L)$$

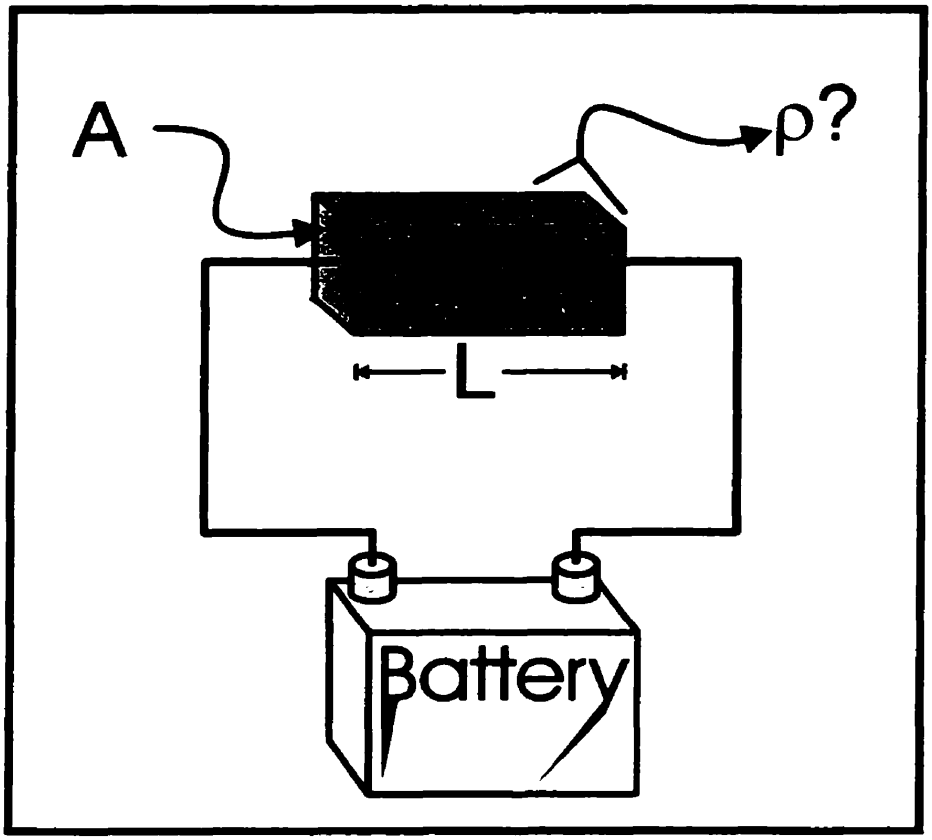


Figure 4 A block of homogenous material (shown in blue) with a given length (L) and area (A) will resist an electrical current (as provided by a direct current source such as a battery) in direct proportion to the electrical resistivity (ρ) of the material.

The resistance of a block of material can be calculated by combining the voltage drop (ΔV) across the block and the current (I) through the block using Ohm's Law:

Equation 2 $$R = \Delta V / I$$

By substituting for R in Equation 1 with the result of Equation 2, resistivity can be equated to four easily measurable quantities:

Equation 3 $$\rho = (\Delta V / I)\ (A/L)$$

Although the resistivity of a block of material is easy to determine, the resistivity is not enough information to identify the material for two main reasons. Firstly, materials do not have a unique resistivity 'signature', and many materials can have the same resistivity (Reynolds, 1997; Loke, 1999). Secondly, the resistivity of a heterogeneous block of materials is dependant on the resistivity, proportion, and arrangement of the component materials that make up the block. In extreme cases, the orientation of the current to the block of material varies the resistivity measurement obtained from the block. This property, anisotropy, is common in layered or interbedded sediments (Christensen, 2000).

Resistivity measurements collected as part of an ERGI survey always involve heterogeneous conditions, because each measurement is a combination of the material itself and whatever is within the pores within that material. Electrolytic conduction (electrical current carried by ions in solution) through pore water within the pore space in common sedimentary materials dominates their resistivity measurement. If the groundwater has consistent ionic content, resistivity measurements are primarily an indicator of formation porosity, permeability, and saturation (Archie, 1942). Recognizing the importance of pore fluids can not be emphasized enough.

4.2. Measuring Electrical Resistivity

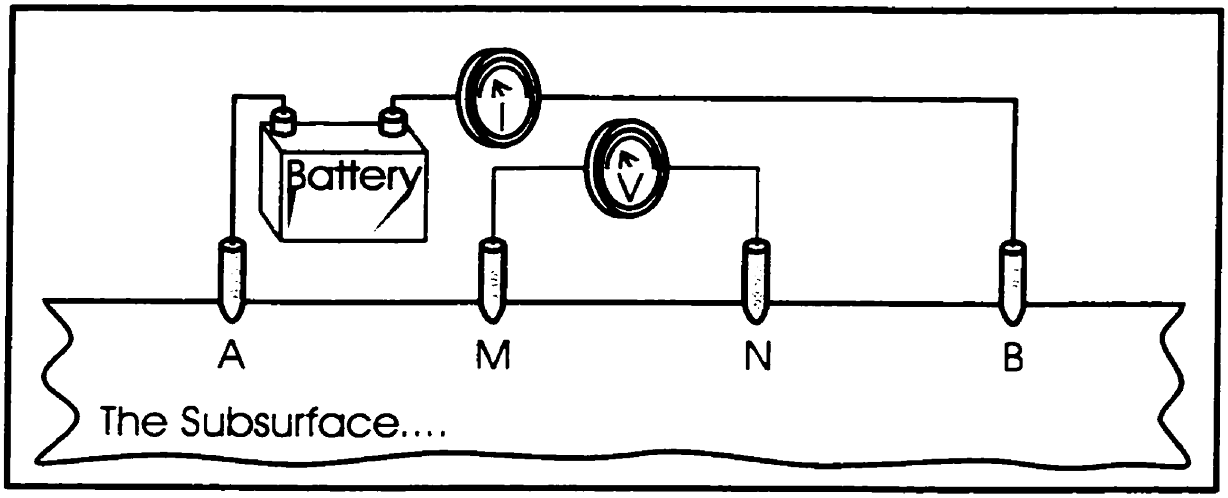


Figure 5 Electrical resistivity measurements in the field use four electrodes inserted into the ground. Two of the electrodes, A and B, inject current into the ground. The other two electrodes, M and N, are used to measure voltage drop across the surface of the ground.

Electrical resistivity measurements in the field use four point electrodes at the ground surface (Figure 5). Two of the electrodes, traditionally called A and B, introduce a current into the ground, while the other two electrodes, traditionally called M and N, measure voltage drop. Electrodes A and B are frequently called the current electrodes, while electrodes M and N are known as the potential electrodes. Field measurements of current and voltage drop are combined into a resistivity measurement using a modified version of Equation 3:

Equation 4 $$\rho = (\Delta V/I)\, K$$

K in Equation 4 is a geometric factor that replaces the simple spatial component of area divided by length in Equation 3. K incorporates the distance from each current electrode to each measurement electrode and a 'half-space' term. The half-space term is included to accurately model the flow of electricity downward and outward from each of the four point sources of electrical contact with the ground.

$$\textit{Equation 5} \qquad K = 2\pi\,(AM^{-1} - MB^{-1} - AN^{-1} + NB^{-1})^{-1}$$

Equation 4 and Equation 5 only hold true when the earth behaves as a homogeneous half-space. Since the earth is rarely a true half-space (topographic undulations) and almost never homogeneous, field measurements are considered apparent resistivity data (ρ_a).

Although Equation 5 works with any arrangement of electrodes, symmetrical linear arrays are typically used. The arrangement of the four electrodes used to make an individual resistivity measurement, called an array, affects the depth of investigation, sensitivity, resolution, and response to noise of an apparent resistivity measurement. Reynolds (1997) provides an excellent description of the strengths and weaknesses of the three most commonly used arrays for ERGI (Wenner, Wenner-Schlumberger, and dipole-dipole). Appendix B provides more information about electrode arrays.

The region of investigation for an apparent resistivity measurement is difficult to define. The shape of the region of investigation is dependant on two things; 1) the array used for the measurement, which is easy to define, and 2) the distribution and character of the sediments in the subsurface, which is very difficult to define without extensive prior knowledge. The region of investigation does not have a sharp boundary because as the electrical field created by the current circuit extends outward and downward from the array it decreases in strength, but never reaches zero.

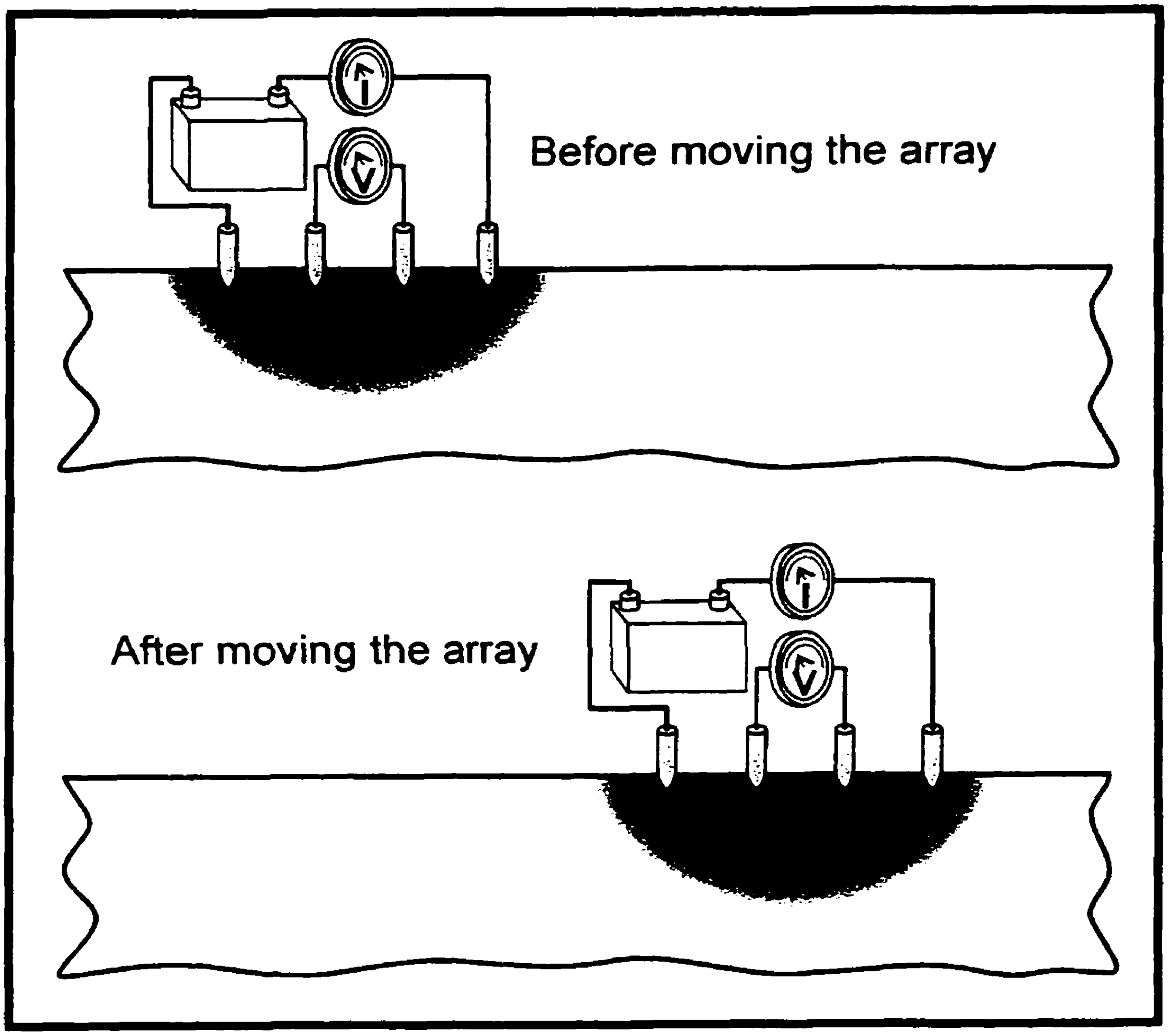


Figure 6 Changing the location of an electrode array, without changing the distance between the electrodes, changes the location of the region of investigation for the resistivity measurement. The depth of the region of investigation does not change. The region of investigation is represented here as an over-simplified sharp-edged round two-dimensional area. In reality, the region of investigation is diffuse, amorphous, and three dimensional.

Although the region of investigation for an apparent resistivity measurement is difficult to define, there are some simple rules for altering its location and depth. The location of the region of investigation is simple to move because its center coincides with the center of the array used to make the measurement. Thus moving the array without changing the distance between the electrodes (electrode spacing) moves the region of investigation (Figure 6).

The size of the region of investigation, and therefore the depth, is directly related to the size of the array. The size of the array is controlled by the electrode spacing. Thus increasing the electrode spacing without changing the center point of the array increases the size, and coincidentally the depth, of the region of investigation (Figure 7).

Appendix B, 'Understanding Electrode Arrays' discusses how multi-electrode ERGI systems alter the depth and location of the region of investigation for apparent resistivity measurements. Appendix A section 2, 'ERGI Resolution and Depth of Investigation' discusses guidelines to assess the depth of ERGI measurements.

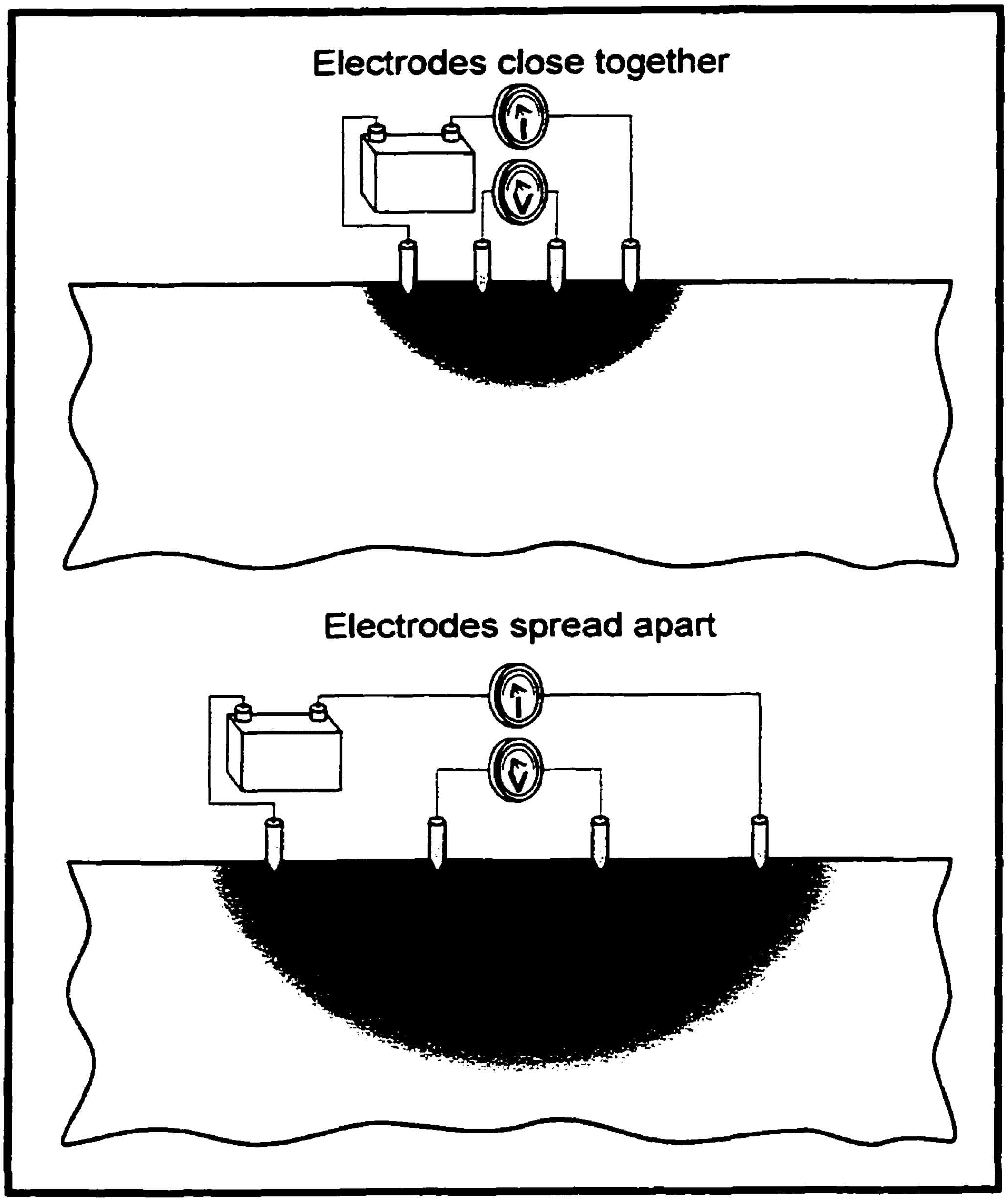


Figure 7 Changing the distance between the electrodes in an electrode array, without changing the location of the center of the array, changes the depth of the region of investigation for the resistivity measurement. The horizontal location of the region of investigation does not change. Note that increasing the distance between the electrodes increases the size of the region of investigation in all directions. This increase in size vastly increases the volume of material contributing to the resistivity measurement.

4.3. Ground Imaging with Electrical Resistivity

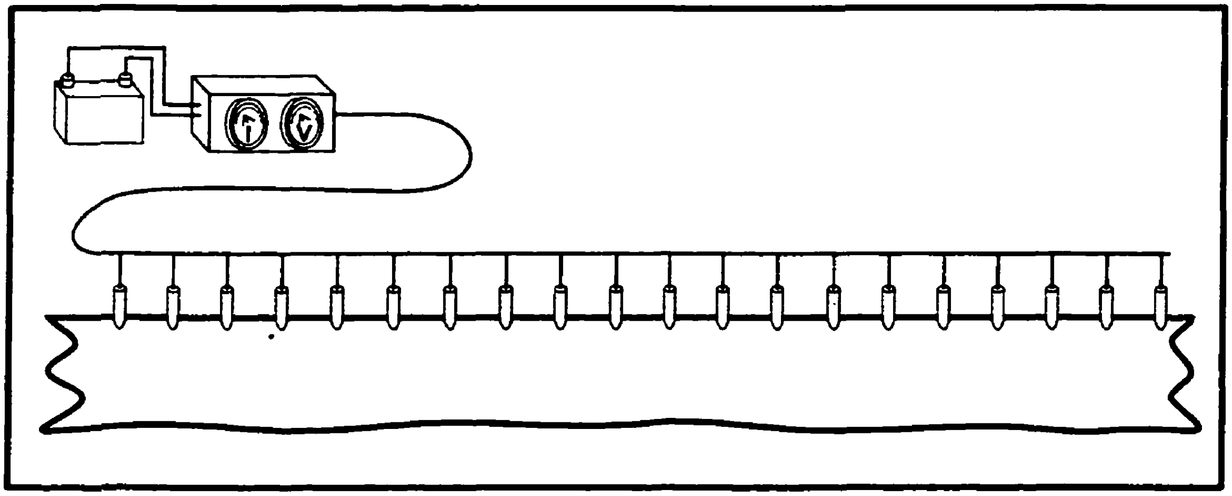


Figure 8 A diagrammatic representation of a multi-electrode resistivity system used for ERGI surveys.

ERGI involves using a multi-electrode resistivity system (Figure 8) to collect many apparent resistivity measurements and then processing the data to produce a two-dimensional profile that shows the variation and distribution of the true resistivity of the subsurface. A multi-electrode resistivity system uses 56 or more electrodes and a computer controlled switching unit to collect data from many different locations and depths by switching which of the electrodes is acting as the A, the B, the M, and the N electrode for each measurement. Once data is collected from all depths and locations possible from a single system layout, a modeling process called 'inversion' is used to convert the apparent resistivity data into a two-dimensional cross-section image representing an approximation of the true resistivity distribution in the subsurface.

Inversion is an iterative least-squares process that searches for the smoothest possible resistivity distribution that would produce the same apparent resistivity measurements as the field data. Commercially available software packages, such as RES2DINV (Loke, 2000), use the diffuse amorphous three dimensional apparent resistivity measurements to generate true resistivity values assigned to two dimensional model blocks. The value assigned to a two dimensional model block is only representative of materials at that depth (z) and horizontal location (x) if there are no resistivity changes to either side of the survey line (y - the third dimension). For ease of interpretation, ERGI profiles are a contoured version of the block model (Figure 9).

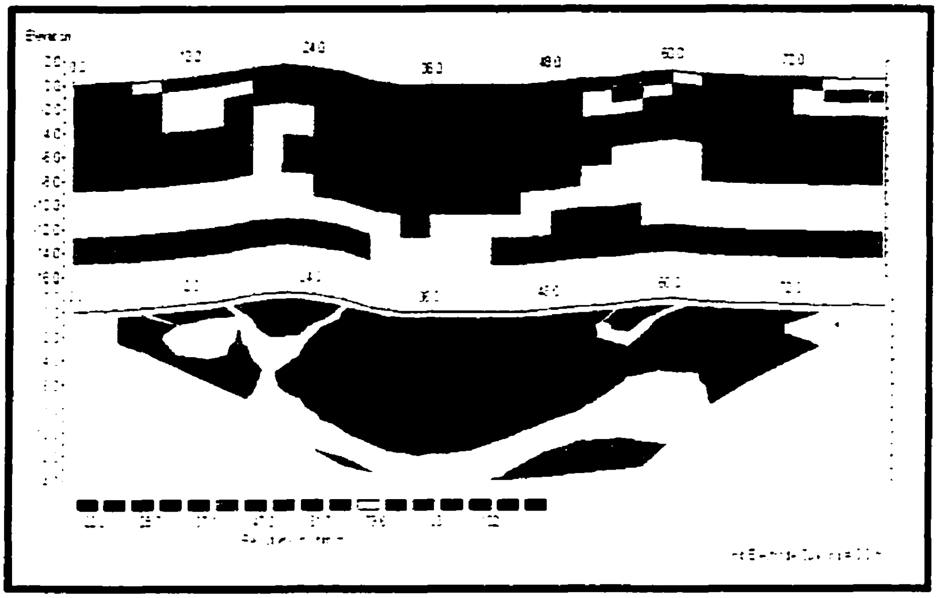


Figure 9 Comparison between an inverted resistivity block model and a contoured model. The block model more closely represents the mathematical output of the inversion process, while the contoured model is easier to interpret.

4.4. ERGI Profile Confirmation and Ancillary Data

ERGI, like other geophysical techniques, can not stand alone. ERGI profiles should be 'ground-truthed' by qualitative comparison with existing subsurface information (e.g. drill core, electric logs, GPR, shallow seismic, exposures) whenever possible (Loke, 1999).

Topographic correction improves the quality of ERGI profiles, because K (from Equation 5) requires the ground to be flat and the real world is rarely flat. This flat/not flat problem introduces errors that can mask features or generate artificial features in an ERGI profile unless corrected (Tong and Yang, 1990; Loke 1999).

CHAPTER 5. METHODOLOGY

Field experiments performed for this research project were conducted between April and May 2000 at the study area on the upper Columbia River, British Columbia, and from late August through September 2000 at the study area on the Rhine-Meuse Delta, the Netherlands. Each of the field experiments utilized special methods to address the particular conditions and goals of each field experiment. The specific methods for each field experiment are discussed with the field experiment. This section outlines the equipment and general techniques used for all the field experiments.

To date, no paper outlines ERGI field procedures. This research project developed its own procedures through extensive field-testing. These guidelines, which cover most aspects of ERGI surveying from site selection to data processing, are included in Appendix A. Appendix C breaks ERGI surveying into 12 easy to follow steps.

5.1. ERGI Data Acquisition

This research project used a 56 electrode AGI Sting/Swift R1 Earth Resistivity Meter to collect the apparent resistivity data. The 56 electrodes are on four inter-connectable electrode cables with 14 electrodes each. The electrodes are separated by 12 meters of cable to allow for ERGI surveys with a 10 meter electrode spacing across irregular terrain (2 m of excess cable to surmount obstacles). For ERGI surveys with smaller spacings, the excess cable is simply laid out to one side of the survey line.

The AGI system uses 'smart' electrodes. Each 'smart' electrode can be passive or act as the A, B, M, or N, electrode for a resistivity measurement. The 'smart' electrodes are controlled by a user modifiable command file on the Sting. See appendix A section 8 for details about creating command files.

The electrodes make electrical contact with the ground by being connected to a metal spike that has been driven into the ground. Laying the electrode on a 'shelf', a 10 cm length of angle iron welded across the stake, provides the electrical connection between the electrode and the stake. The electrode is held on the 'shelf' by an elastic band.

Sometimes the compromise between depth of investigation and resolution produced an overall electrode line length that was shorter than the horizontal extent of the intended survey. Conducting 'roll-along' surveys extended the length of these surveys. A 'roll-along' survey begins by collecting a standard data set. A number of electrodes, for example 14, are then moved from the beginning of the survey line to the end of the survey line without moving any of the other electrodes. Data is again collected in what would be a spatially overlapping data set; however, a special command file avoids collecting redundant data. This 'hop scotching' of electrodes from the front of the survey line to the end can be repeated any number of times and therefore extend a survey line to any length. Appendix A section 9 provides more details about roll-along surveying for ERGI.

5.2. ERGI Data Inversion

This research project used RES2DINV (Loke, 2000) to invert the apparent resistivity data. RES2DINV is a large and complex program with many user modifiable inversion parameters. The software manual provides a detailed explanation of each parameter and its influence on the inversion process.

While in the field, this research project used a Dell laptop computer (Pentium II 266 MHz processor) to invert apparent resistivity data using RES2DINV's default inversion parameter settings. For all but the largest data sets, inversions took less than 90 seconds. In the computer lab, a variety of faster computers was used for further data processing. Appendix A section 7 provides guidelines for ERGI data processing that were developed during this project.

5.3. ERGI Profile Confirmation/Assessment

This research project relied on lithostratigraphic log profiles and individual lithostratigraphic logs for confirmation and qualitative assessment of the ERGI profiles. Most of the profiles were compared to lithostratigraphic profiles from previous research at the study sites. Lithostratigraphic profiles from the upper Columbia River were based on vibracore data, while those from the Rhine-Meuse Delta were based on cores retrieved with hand tools; the Van der Staay Suction Corer and the gouge corer. The University of Utrecht has a collection of 200,000 lithostratigraphic logs collected in this way. These logs include 13 different characteristics, including 28 different sediment texture classes, recorded every ten centimeters (Berendsen, 1994).

No lithostratigraphic data was available for several sites on the upper Columbia River. Vibracores (Smith 1983b, 1992, and 1998) were obtained to provide lithostratigraphic logs for confirmation of the ERGI profiles at these sites. The vibracores were logged to the nearest 10 cm into five sedimentary categories: 1) gravel 2) sand 3) mud 4) organic soil 5) intermixed or inter-bedded (layers less than 10 cm thick) sand and mud.

5.4. Locational Data Acquisition

This research project used a hand-held GPS receiver to obtain coordinates for the ends of all the ERGI surveys and for all of the coring locations. UTM coordinates were used on the upper Columbia River. NLRD coordinates were used on the Rhine-Meuse Delta. No corrections were applied to the GPS positions, and a ± 6 m positional error is assumed (Federal Geodetic Control Subcommittee and GPS Interagency Advisory Council, 2000). All the locations for the surveys presented in this document are included in Appendix D.

5.5. Topographic Data Acquisition

This research project used a David White laser auto-leveler to collect topographic profiles of the ERGI survey lines. The topographic data was collected at 'nick-points' in the terrain, as described in the RES2DINV manual (Loke, 2000).

CHAPTER 6. IMAGING FIELD EXPERIMENTS

The goal of the imaging field experiments was to determine if ERGI can detect and delimit fluvial sediments. This section describes field experiments to image buried mud-encased sand channel-fills and to image crevasse-splay sheet sands.

6.1. Channel-Fill Imaging Field Experiment

The goal of this field experiment was to determine if buried mud-encased sand channel-fills could be imaged with ERGI. Many channel-fills were investigated on the upper Columbia River, B.C., and the Rhine-Meuse Delta, the Netherlands. One representative case from each of these areas is presented: survey line BML101 from the Beavertail Channel and survey line NL9309201 from the Schoonrewoerd channel-fill and braid-plain.

6.1.1. Methods for this Field Experiment

The data for the ERGI profile for the Beavertail Channel was collected using a Wenner array on a 56 electrode survey with a 2 m electrode spacing. Three 14 electrode 'roll-along's extended the survey line to 194 m in length. The command files were designed to measure information from up to 18 m depth.

The Beavertail Channel-fill presented several data collection challenges. The 14 m stretch of open sand in the remnant Beavertail Channel (meter 103 to meter 117) made achieving sufficiently low electrical contact resistance difficult.

Low contact resistance was maintained by flooding a 30 cm wide by 10 cm deep trench with saline solution. For more information on electrical contact resistance, see appendix A section 4.

The heavy brush and deadfall on the levees made travel along the survey corridor and placement of the electrodes difficult. To alleviate this, a 2.5 m wide survey corridor was cleared through the brush on the levees. Large deadfall was removed from the survey corridor when it blocked travel along the survey line and when it was directly in the way of an electrode stake.

The data for the ERGI profile for the Schoonrewoerd channel-fill was collected using a Wenner array on a 56 electrode survey line with a 2 m electrode spacing. The survey line was 110 m long and designed to collect information from up to 18 m deep. There were no electrical contact resistance problems, topographic issues, or challenging ground cover types encountered in the Netherlands.

6.1.2. Results/Discussion

Beavertail Channel-Fill, British Columbia

The Beavertail channel-fill (Figure 10) is a partially abandoned anabranch of an anastomosing river depositional system of the upper Columbia River, British Columbia The channel-fill is located mid-valley 6 km northwest of the hamlet of Harrogate. The Columbia River only flows through the channel during flood discharge, usually from June 1 to July 30. Four vibracores indicate the sand-filled channel varies between 6 and 7 m thick by 45 m wide. The 45 m width was inferred from topography and vegetation changes at the suspected channel margins (D. Smith, pers. comm., 2001). The channel-fill is almost encased in clayey-silt except for 14 m of open sand at the surface (channel 4 in Makaske, 1998).

The ERGI profile at this site nearly duplicates the lithology and geometry of the channel-fill as interpreted from vibracores. In the ERGI profile, the channel-fill has a thickness between 6 and 7 m and a width of 46 m. While vibracores provide excellent vertical resolution (direct measurement of core barrel penetration), ERGI provides better lateral resolution (~1 m), which is far superior to any coring method. This latter point is important for precise delineation of channel-fill margins in anastomosing and deltaic distributary systems where lateral accretion is limited. In this case, the ERGI-based channel width is likely more reliable than the inference based on topography and vegetation. Had the channel-fill had been more deeply buried, the 45 m width could not have been inferred from topography and vegetation, but ERGI would still have provided an accurate estimate.

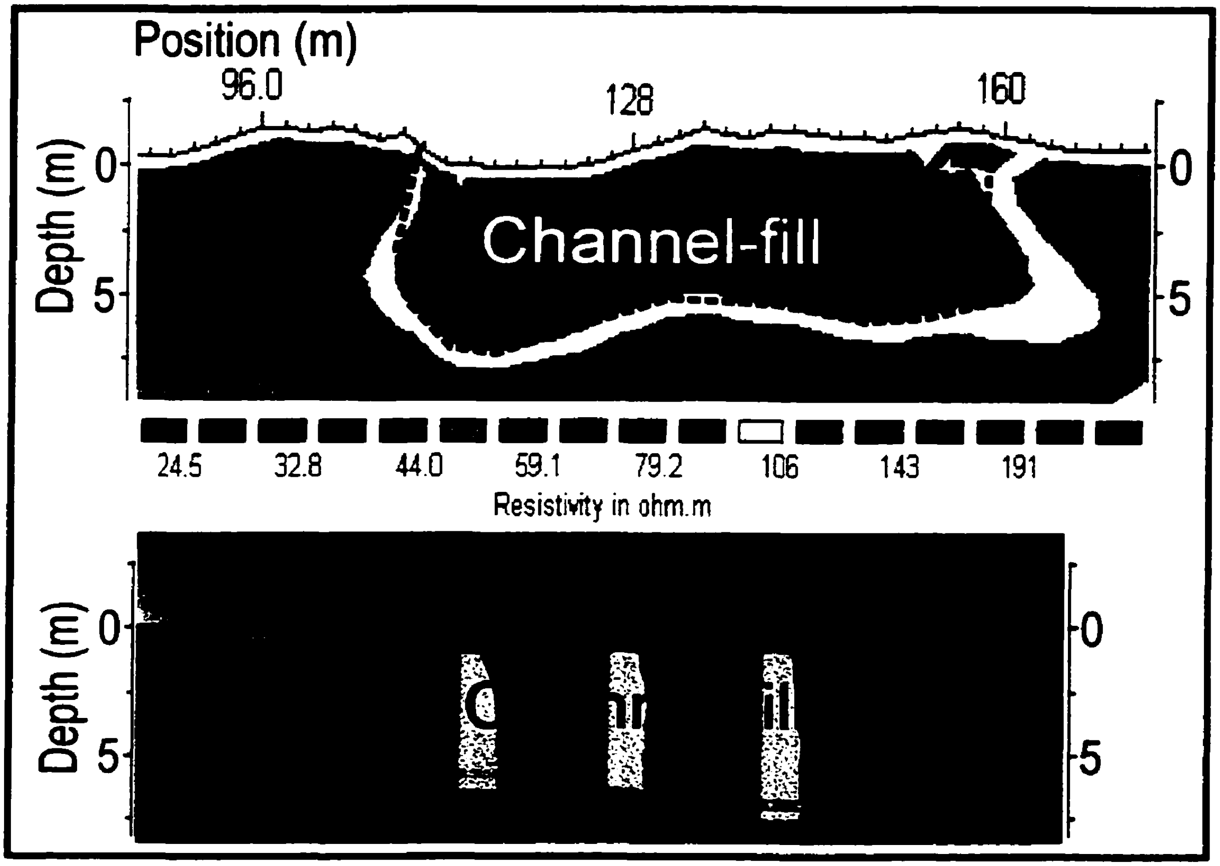


Figure 10 Comparison of an ERGI profile with a lithostratigraphic profile based on vibracores from the sand-filled Beavertail channel in the anastomosing reach of the upper Columbia River, 6 km northwest of Harrogate, B.C., Canada. Data acquisition time for ERGI was 2 hours and for the four vibracores, logging and drafting took 14 hours.

Schoonrewoerd Channel-Fill and Underlying Braid-Plain, the Netherlands

The Schoonrewoerd channel-fill (Figure 11) is a buried delta distributary channel in the Holocene Rhine-Meuse Delta, the Netherlands (Makaske, 1998; Berendsen and Stouthamer, 2000). The channel-fill is located 21 km east of Rotterdam and 1 km south of the town of Molenaarsgraaf. Twenty gouge cores along a 400 m survey-line indicate that the sand-filled channel is approximately

65 m wide by 8.5 m thick. Its top is 1.5 m below the surface and its base is 2 m above the Pleistocene braidplain. There are no topographic or vegetation changes to suggest the locations of the channel margins. The channel-fill is encased in clay and peat with silty/sandy-clay levee 'wings' (Makaske, 1998). The lithoarchitecture of this site, as indicated by the lithostratigraphic profile, is perfect for testing ERGI.

The ERGI profile at this site approximately duplicates the lithology and geometry of the channel-fill as interpreted from the cores. The ERGI profile also detects the basal Pleistocene braidplain sand and gravel. The profile does not show the left side of the channel-fill because a water-filled ditch and adjacent road prevented further data collection. In the ERGI profile, the channel-fill is 9 m thick by 68 m wide and the braidplain sand and gravel is 12 m below the surface. Again, there is remarkable correspondence between the ERGI profile and the interpreted lithology and geometry of the Schoonrewoerd channel-fill. It is important to note that the ERGI data was collected and processed in less than 10% of the time taken for coring.

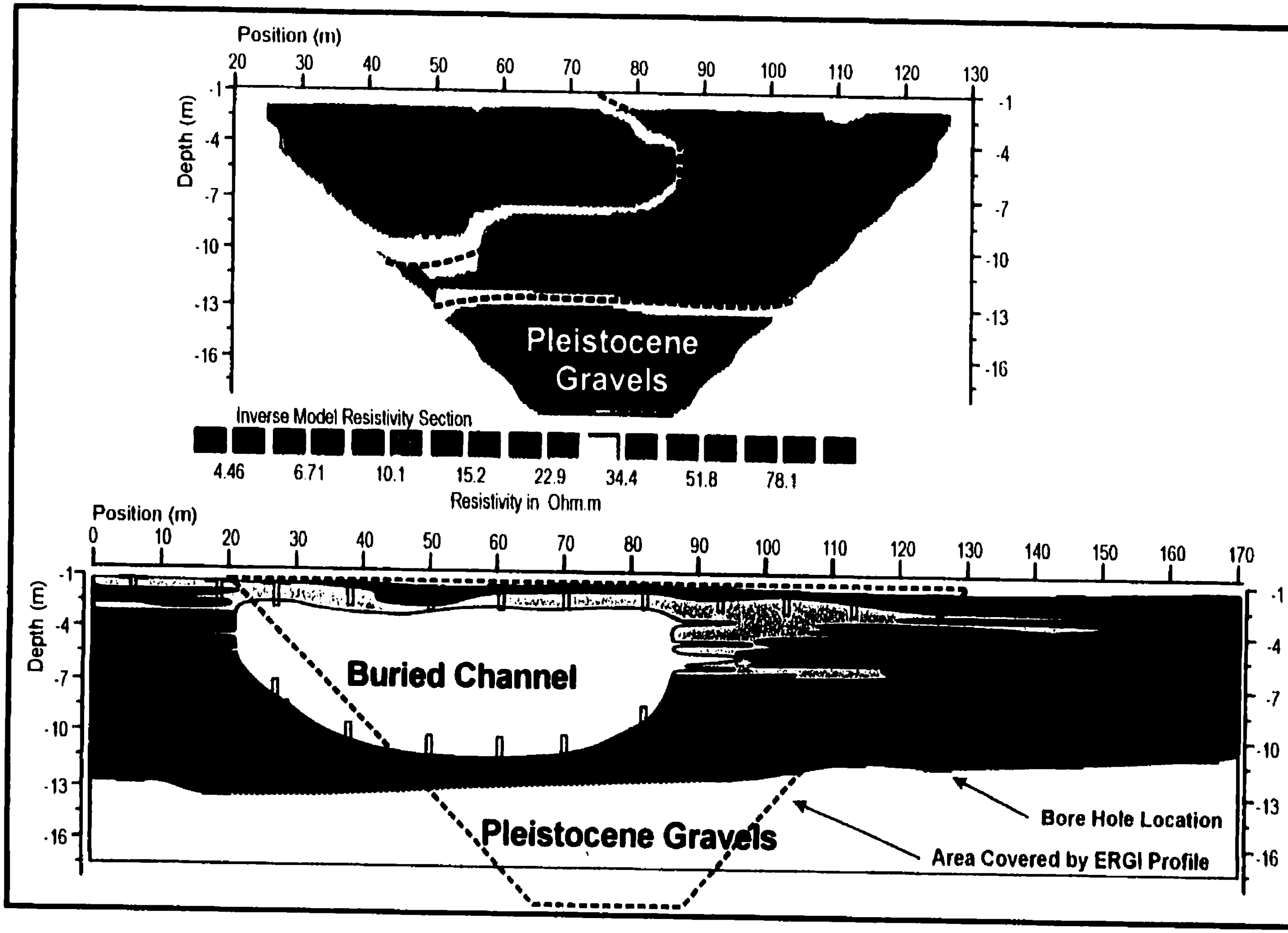


Figure 11 Comparison of an ERGI profile with a lithostratigraphic profile based on core data from the Schoonrewoerd channel-fill and underlying Pleistocene braidplain, Rhine-Meuse Delta. The lithostratigraphic profile is adapted from Makaske (1998).

6.2. Crevasse-Splay Imaging Field Experiment

Our understanding of buried mud-encased crevasse-splay sheet-sands and their possible interconnections with channel sands is limited because they are so hard to study. In anastomosing settings, crevasse-splays buried under more than a meter of clay and silt have almost no surface expression and are extremely difficult to locate. If ERGI can image deeply buried crevasse splays, it could be used as a prospecting tool to locate and then study these deposits. However, preliminary investigations to assess the ability of ERGI to image crevasse-splays is necessary before carrying out an extensive prospecting campaign.

Shallow buried crevasse-splays can be located because they have visually apparent topographic expression and they are typically heavily wooded due to their drainage advantage over the mudflats. Although near-surface buried crevasse-splays are simple to locate, they are a poor choice for ERGI investigations because ERGI is extremely difficult in thick wood cover. Before clearing vast stretches of woody vegetation for a study of shallow buried crevasse-splays, preliminary investigations to assess the ability of ERGI to image surface crevasse-splays was in order.

The goal of this field experiment was to determine if surface crevasse-splay sheet-sands overlying organic-rich muds could be imaged with ERGI. Two crevasse-splays in the upper Columbia River, B.C., were investigated with nine ERGI surveys and 15 vibracores. Two ERGI profiles from the Beavertail crevasse-splay (BTS201 and BTS401) and the two ERGI profiles from the Herron Meadow crevasse-splay (HMS101 and HMS201) are presented.

6.2.1. Methods for this Field Experiment

The ERGI surveys for this field experiment intersect each other at 90° and provide a certain amount of collateral interpretation support. A lithostratigraphic log obtained at the intersection point of the paired surveys is included to assist with qualitative assessment of the ERGI profiles.

For the stretches of open sand, sufficiently low electrical contact resistance was maintained by flooding a 30 cm wide by 10 cm deep trench with 10 L/m of saline solution the day before data was collected. Touch ups with 1 to 2 L of saline solution per electrode were often necessary on the day of data collection. For more information on electrical contact resistance, see appendix A section 4.

On the Beavertail crevasse-splay, the data for survey line BTS201 was collected using a Wenner array on a 54 electrode survey with a 2 m electrode spacing. The survey was designed to be 106 m in length and to measure information from up to 16 m in depth.

BTS201 extends outward from the levee breach past the toe of the crevasse-splay and abuts a small lake. BTS401 crosses a wide mudflat before passing over the crevasse-splay perpendicularly to BTS201. The intersection between survey line BTS201 and BTS401 is at meter 73 on BTS201 and at meter 105.5 on BTS401.

The data for survey line BTS401 was collected using a Wenner array on a 56 electrode survey with a 2 m electrode spacing. One 14 electrode 'roll-along' extended the survey to 138 m in length. The command file for the survey was designed to measure information from up to 18 m in depth.

On the Herron Meadow crevasse-splay, the data for survey line HMS101 was collected using a Wenner array on a 51 electrode survey with a 2 m electrode spacing. The survey was designed to be 100 m in length and to measure information from up to 16 m in depth.

HMS101 extends outward from the levee breach past the toe of the crevasse-splay and abuts the levee on the far side of the island. HMS201 straddles the crevasse-splay perpendicularly to BTS201 and extends into the mudflats on either side. The intersection between survey line HMS101 and HMS201 is at meter 23.3 on HMS101 and at meter 55 on HMS201.

The data for survey line HMS201 was collected using a Wenner array on a 56 electrode survey with a 2 m electrode spacing. The survey was designed to be 110 m in length and to measure information from up to 18 m in depth.

6.2.2. Results/Discussion

The crevasse-splays show up very well in the ERGI profiles. The horizontal extent of the crevasse-splays is portrayed very accurately. The vertical extent of the crevasse-splays is exaggerated, but explainable. Explained and unexplained high resistivity anomalies also appear in the ERGI profiles.

The horizontal accuracy of the ERGI profiles is exceptional. Surficial geology changes indicate that the Beavertail crevasse-splay is 89 m long by 47 m wide, which is the same as what is shown in the ERGI profiles (Figure 12). Similarly, the Herron Meadow crevasse-splay is shown by surficial geology changes to be 43 m long by 45 m wide, while the ERGI profiles indicate that the splay is 44 m long by 45 m wide (Figure 13). This correspondence between ERGI profiles and the surficial geology reinforces the findings of the channel-fill field experiments that ERGI has an untapped potential for delineating the horizontal extent of fluvial deposits.

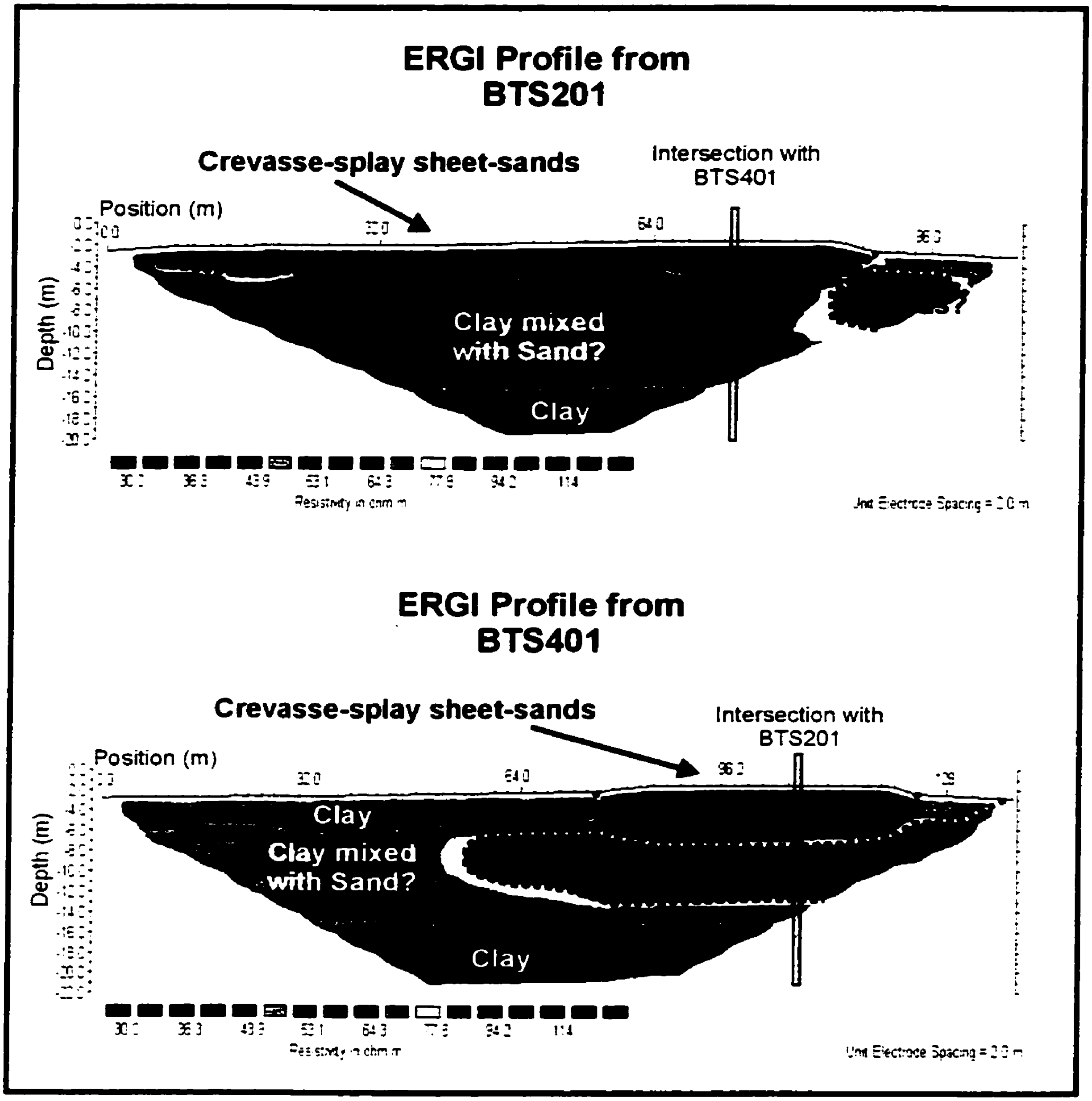


Figure 12 Comparison of two perpendicularly intersecting ERGI profiles on the Beavertail crevasse-splay, upper Columbia River, B.C.. The grey rectangle shows the point of intersection between the two profiles. A comparison between the ERGI profiles and a lithostratigraphic log from a vibracore at the point of intersection is shown in Figure 14. The discrepancy between these two profiles is explained in the discussion.

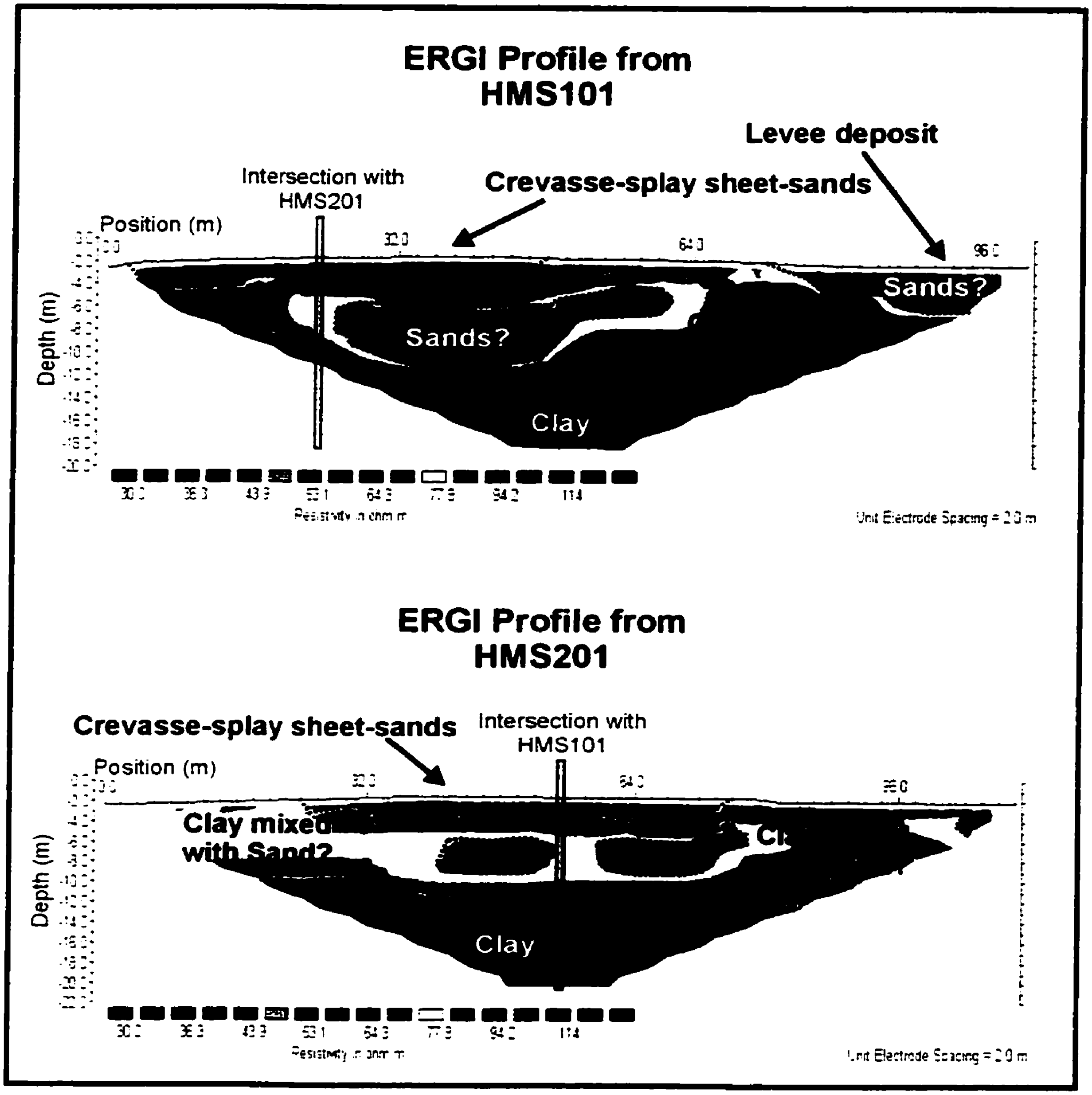


Figure 13 Comparison of two perpendicularly intersecting ERGI profiles on the Herron Meadow crevasse-splay, upper Columbia River, B.C.. The grey rectangle shows the point of intersection between the two profiles. A comparison between the ERGI profiles and a lithostratigraphic log from a vibracore at the point of intersection is shown in Figure 15.

In this case, the crevasse-splay vertical extent (thickness) estimates based on the ERGI profiles are exaggerated. Although a lithostratigraphic log shows the Beavertail crevasse-splay to be 1.4 m thick (Figure 14), the ERGI profiles show it to be either 2.5 m thick (BTS401) or 3.0 m thick (BTS201). Similarly, a lithostratigraphic log shows the Herron Meadow crevasse-splay to be 0.7 m thick (Figure 15), while both the ERGI profiles show it to be 1.5 m thick.

The thickness discrepancy between the lithostratigraphic logs and the ERGI profiles is attributable to the extremely high resistivity of the dry sand within the crevasse-splay and the choice of electrode spacing. The resistivity for the dry sand within the crevasse-splays was modeled as high as 2237 Ω m on the Beavertail crevasse-splay and 1192 Ω m on the Herron Meadow crevasse-splay. This is from 30 to 55 times higher than the clay found below the crevasse-splay (typically < 40 Ω m). Such extreme resistivity contrasts produce 'shadowing' below high resistivity zones within an ERGI profile, which increases their apparent thickness. In this case the 'shadowing' may have doubled the apparent thickness of the crevasse-splay in the ERGI profiles. However, because shadowing is a consistent phenomenon, the lithostratigraphic logs could be used to produce a much more vertically accurate interpretation of the ERGI profiles.

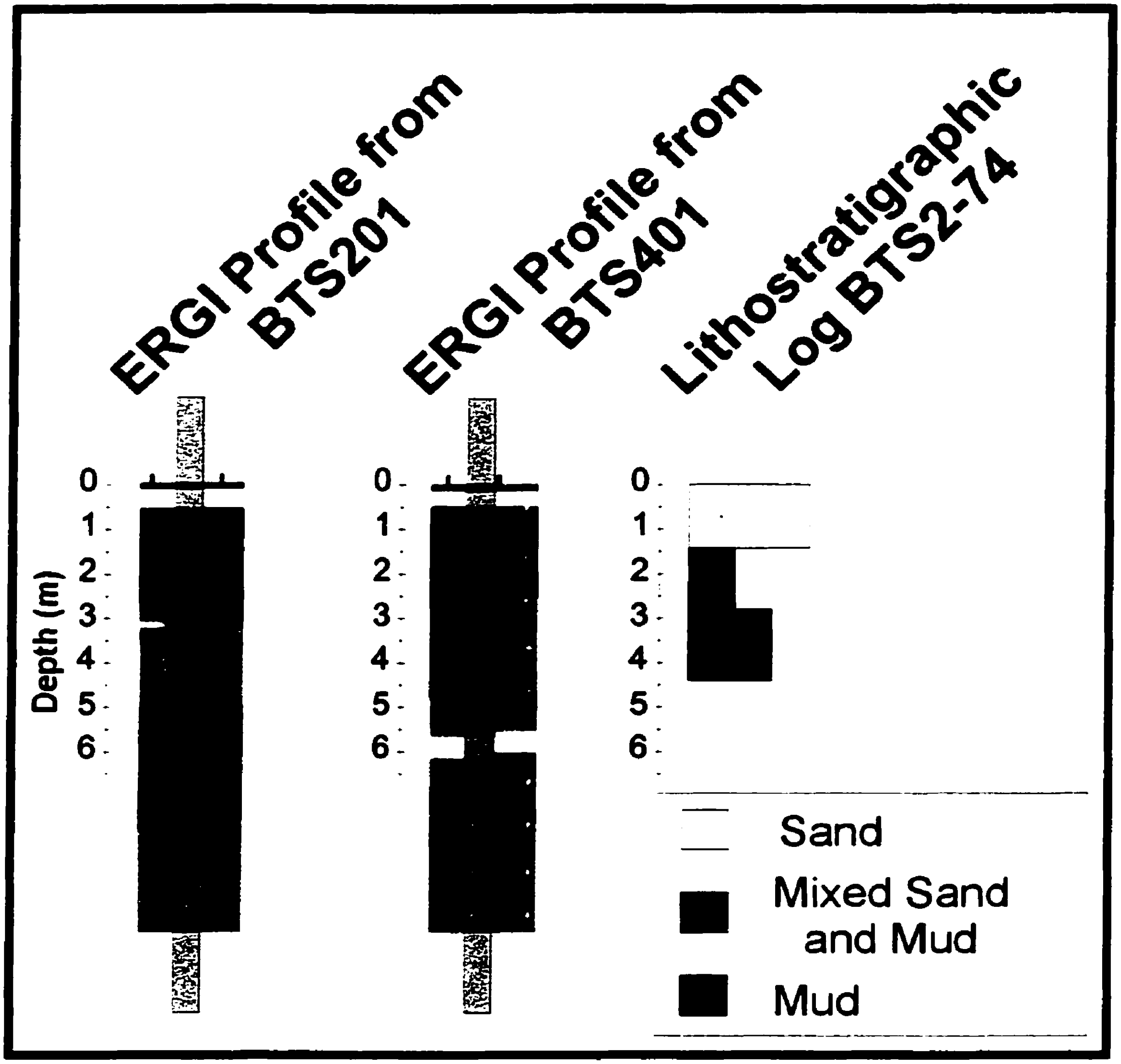


Figure 14 Comparison of the point of intersection between ERGI profiles BTS201, BTS401, and a simple lithostratigraphic log from the same location. The vibracore at this site only penetrated 4.5 m. The ERGI profiles have been arbitrarily cut of at around 12 m. See Figure 12 for the full ERGI profiles.

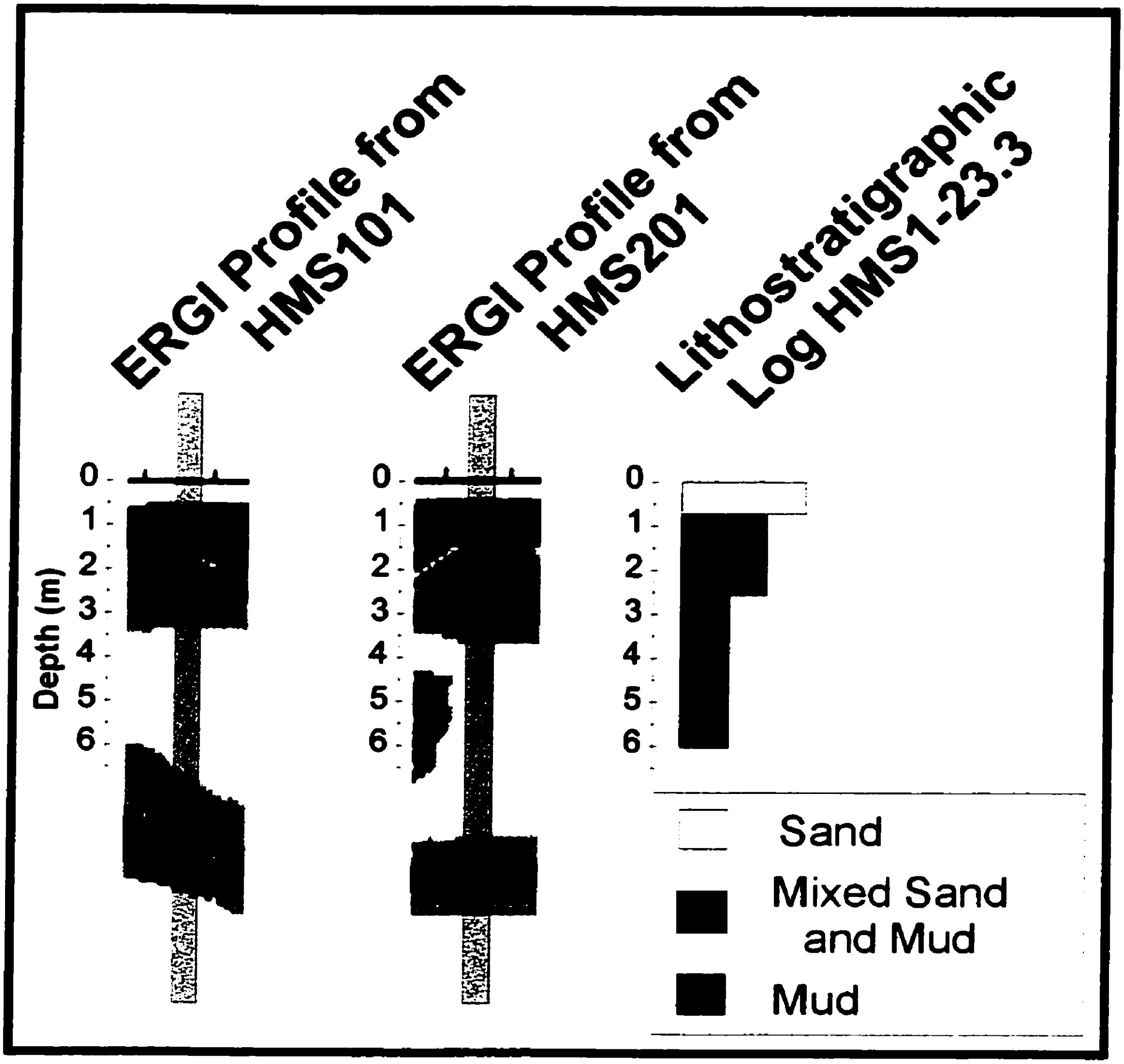


Figure 15 Comparison of the point of intersection between ERGI profiles HMS101, HMS201, and a simple lithostratigraphic log from the same location. The vibracore at this site only penetrated 6 m. The ERGI profiles have been arbitrarily cut of at around 12 m. See Figure 13 for the full ERGI profiles.

The ERGI surveys for the crevasse-splay imaging field experiment were collected with a 2 m electrode spacing. As discussed in appendix A section 2, a 2 m electrode spacing survey produces an ERGI profile with a resolution of approximately ± 1 m. Generally, to define an object within an ERGI profile, it should be at least 2 or 3 times larger than the resolution. The crevasse-splays surveyed for this field experiment were only 0.7 to 1.4 times larger than the resolution of the electrode spacing used. These surveys were conducted before the full impact of electrode spacing was understood. Repeating these surveys with a smaller electrode spacing would produce much better vertical thickness estimates.

The ERGI profiles for the crevasse-splay imaging field experiment contain several high resistivity anomalies that are indicative of sand or gravel other than the crevasse-splays themselves. Some of these anomalies are explained here while others have been left to future researchers for exploration and explanation.

A simple to explain anomaly is the high resistivity zone extending into HMS101 (Figure 13) from the right. This anomaly is under a slight topographic rise leading to the heavily vegetated levee adjacent to the Baldy Channel of the Columbia River. The location of the anomaly suggests that it is a 'levee wing' deposit (Makaske, 1989).

A more complex explanation is required for the high resistivity anomalies centered 4.5 m below meter 93 on BTS201 and 8 m below the surface from meter 54 to the end of BTS 401 (Figure 12), which are most likely caused by the same sedimentary feature. This explanation relies on the inability of ERGI to correctly represent lithology changes that occur to either side of a survey line. A sedimentary feature, such as a sand or gravel body, located parallel to a survey line is incorporated into the resulting ERGI profile as a high resistivity anomaly at a depth proportional to the distance from the survey line to the feature. Lithostratigraphic log BTS2-92 confirms that survey line BTS201 crosses a near-surface buried sand and gravel body which is most likely a small channel-fill at meter 93. Given that this feature is to one side of BTS401, it was included as the deeper anomaly in that profile.

Three dimensional dilemmas, such as the one discussed here, can be solved by comparing intersecting surveys with support from lithostratigraphic logs. For a more intensive solution to this type of dilemma, ERGI can be collected and processed fully in three dimensions.

The high resistivity anomaly centered at approximately 6 m depth below the Herron Meadow splay in profiles HMS101 and HMS201 (Figure 13) is most likely a buried crevasse-splay, but has not been confirmed. Future researchers could use a deeper coring tool than was used for this research project to explore and explain these anomalies.

CHAPTER 7. METHODOLOGY FIELD EXPERIMENTS

The goal of the methodology field experiments was to determine procedures for obtaining ERGI profiles under typical fluvial research field conditions. This section describes field experiments to combine land and water within an ERGI survey, to determine the best electrode array for imaging fluvial sediments, and to assess long-term cumulative electrode charge-up effects on repeated ERGI surveys on the same survey line.

Although informal and anecdotal field experiments to determine procedures for obtaining ERGI profiles under typical fluvial research field conditions are not reported, the resultant improvements to ERGI procedures from said experiments have been included in Appendixes A, B, and C.

7.1. Combination Land and Water ERGI Survey Field Experiment

The landscape encompassing an anastomosing river reach contains so many river channels, lakes, and marshes that any lengthy straight line, such as an ERGI survey line, crosses both dry land and open water. Although techniques exist for ERGI surveys on dry land or under water, there are no techniques for surveying a combination of land and water. The main challenge facing combination land and water ERGI surveys lines is the special equipment and data processing required for underwater surveys. Underwater electrodes are rugged and watertight with sealed connections to robust heavily-insulated cables.

Data inversion of the underwater apparent resistivity measurements requires a correction for the depth and resistivity of the water above each electrode. This correction remedies the false assumption in equation 5 that above the survey line is an infinite hemisphere with infinite resistivity, in other words: air.

This field experiment tested the use of modified land surveying techniques and equipment to obtain an ERGI profile from a survey line that combined both dry land and open water. Survey line BTC301, located on the Beavertail channel and adjacent wetlands, ran ENE from the edge of the main channel of the Columbia River, across a mudflat (the bottom of an ephemeral lake), an abandoned channel and its levees, a lake and a marsh (<1.7 m deep), a small (10 m wide by 50 cm deep) channel and its levees, and eventually abutted the Hogranch Channel of the Columbia river.

7.1.1. Methods for this Field Experiment

The combined land and water ERGI profile data was collected using a Wenner array on a 56 electrode survey line with a 5 m electrode spacing. Two 28 electrode 'roll-along's extended the survey line to 555 m in length. The command files were designed to measure to 20 m depth. The survey line preparation and data collection occurred over a two week period starting April 9, 2000.

For the portion of the survey line crossing land, the experiment used standard ERGI surveying techniques. A 2.5 m wide survey corridor was cleared through the brush on the levees. Large deadfall was removed from the survey corridor when it blocked travel along the survey line and when it was directly in the way of an electrode stake.

For the portion of the survey line crossing water, researchers in chest-waders deployed the stakes and cables from a small boat. Experimental 2 m long aluminum electrode stakes held the electrodes above the surface of the water (Figure 16).

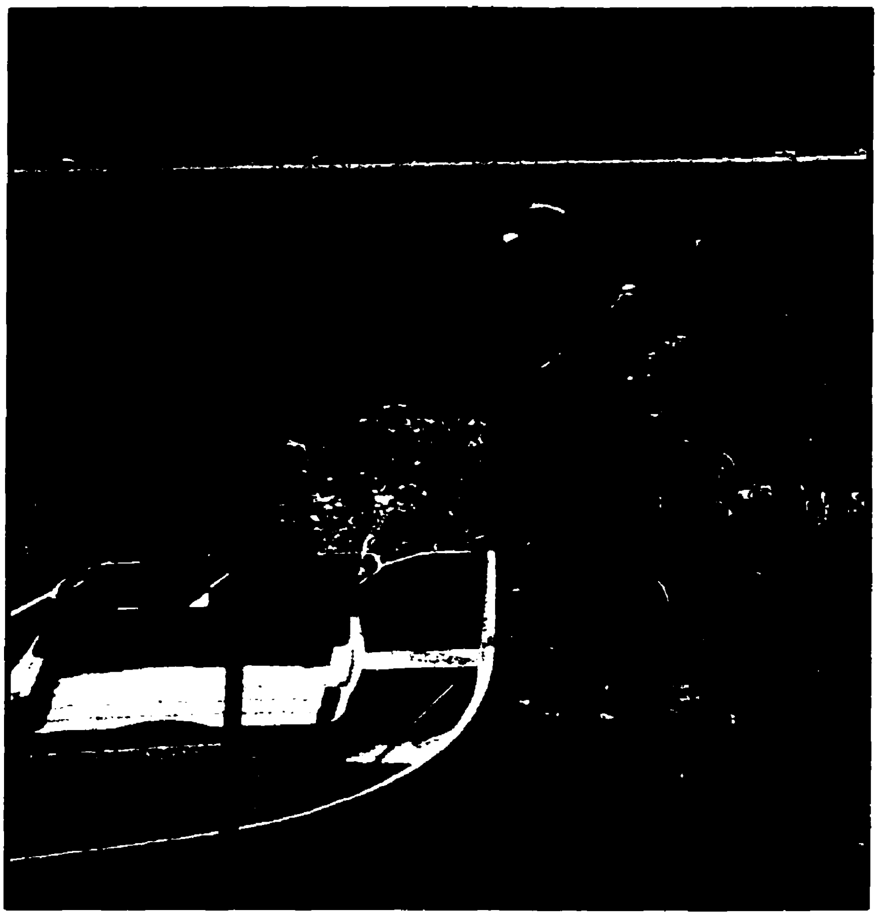


Figure 16 Photograph of a researcher in chest waders deploying ERGI equipment from a small boat for the portion of survey line BTC301 that crosses water. Custom-made 2 m long electrode stakes held the sensitive 'smart' electrodes above the surface of the water.

Standard data processing techniques were used to produce the combined land and water ERGI profile. No compensation was made to account for the portions of the survey crossing open water. The water layer (<1.7 m thick) was thinner than the resolution of the survey (~2.5 m) and was not expected to appear in the profile.

Four vibracores from the Beavertail channel-fill and several sporadically spaced hand cores from Makaske's (1998) study of the same survey line were used to qualitatively 'ground truth' the profile.

7.1.2. Results/Discussion

Although the Beavertail channel-fill is fairly well represented in the combined land and water ERGI profile (BTC301), the rest of the image is difficult to interpret (Figure 17).

The combined land and water ERGI profile failed to produce a well 'ground-truthed' clear profile for two main reasons. Firstly, the 'ground-truthing' information lacked density and depth. Secondly, the field conditions and the equipment used for the resistivity measurements lead to unreliable noisy data that the data inversion was unable to correctly process.

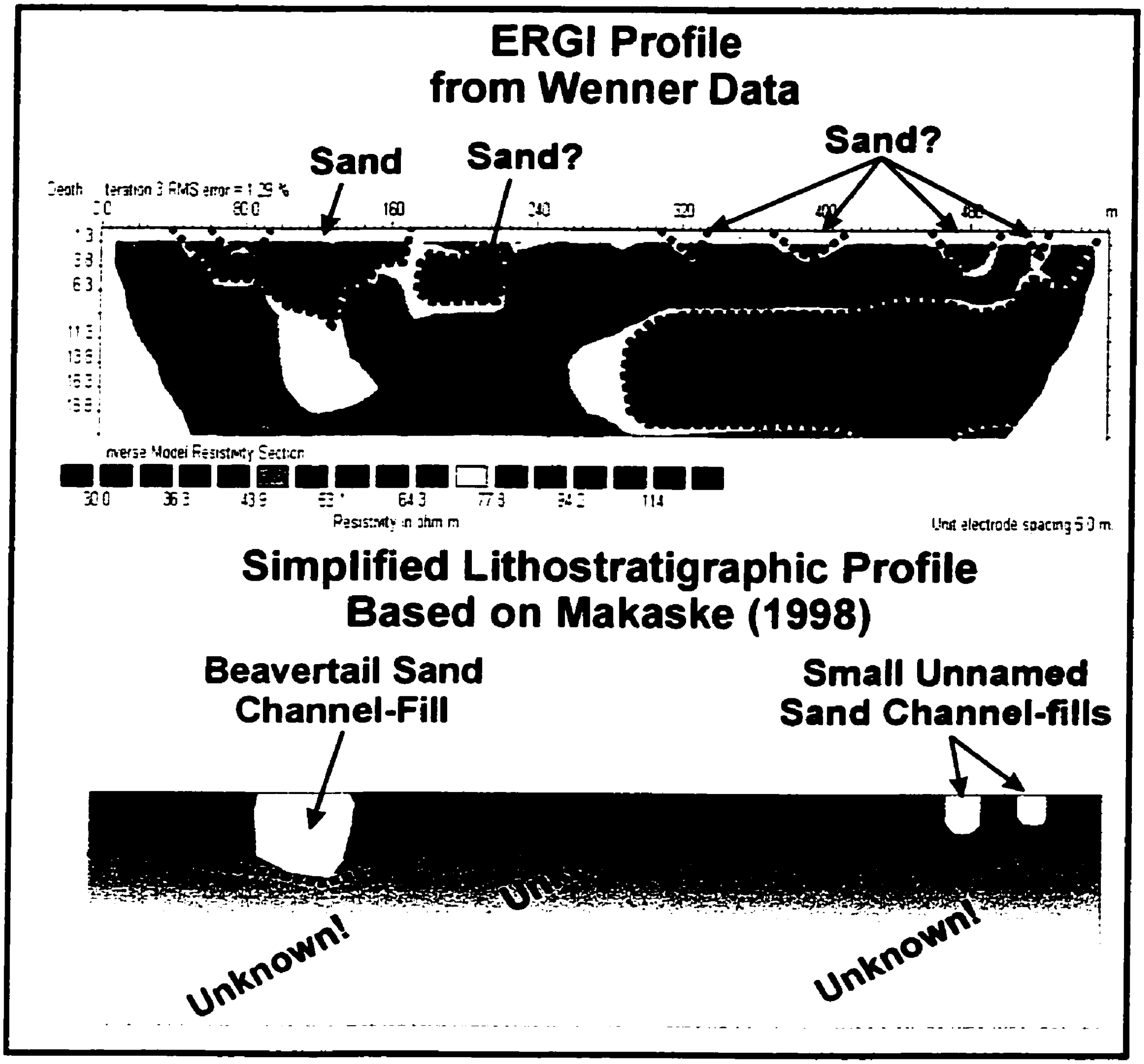


Figure 17 ERGI profile BTC301 compared to a simplified lithostratigraphic profile. The Beavertail sand channel-fill, which is 6.5 to 7 m thick and extends from meter 88 to 135, shows up quite well in this image. Two unnamed channel-fills discovered by Makaske (1998) also are imaged. Many other possible sand bodies appear that are unknown and unverified. The portion of the survey covered by water extends from meter 147 to 462. Heavy brush was encountered at three locations; meter 64 to 87, 125 to 139, and 482 to 517 (see Figure 18).

'Ground-Truthing' Problems

The 'ground-truthing' problems faced by the combined land and water ERGI profile stem from problems with the coring strategy and techniques. The coring strategy of the pre-existing core data led to poor lateral data density. Limitations to the coring technique pre-empted improving some of the data density problems. Limitations to the coring technique also prevent core data from providing good vertical coverage.

Coring strategies based on even spacing, or on specific targets suggested by surficial morphology (such as topography or vegetation changes), frequently miss sub-surface features or poorly assess their horizontal extent. ERGI profiles have very high lateral resolution and effectively delineate all features under the survey line. Coring at the density of an ERGI profile would be prohibitively expensive and time consuming. A targeted coring program based on an ERGI profile would be a much better 'ground-truthing' approach than using pre-existing low-lateral-density core data. This is an important concept, which is contrary to most geomorphic studies, but is commonly employed in the oil industry where seismic surveys are conducted to determine the most suitable location for drilling.

The coring strategy for a combined land and water survey line is constrained by limitations to the coring technique used. Vibracoring and hand coring are the only suitable coring techniques for remote sites such as the Beavertail channel-fill, but neither technique works in deep open water. This explains the lack of core data from approximately meter 150 to meter 390 in the pre-existing core data and why no cores were collected in this region as a part of this field experiment. However, this also leaves less than one half of the lateral extent of the survey line 'ground-truthed'.

Vibracoring through deep water is possible from an ice-covered surface. ERGI, on the other hand, works much better before freeze-up. A two-season field campaign could provide a combined land and water ERGI profile with 'ground-truthing' that has sufficiently high lateral density and coverage. However, 'quick and dirty' studies are currently not possible.

A second limitation to the coring techniques used to ground-truth the ERGI profiles is the maximum penetration depth of cores. A common working depth for both hand cores and vibracores is around 6 meters. Cores up to 18 m deep are possible, but are time and labor intensive (D. Smith, pers. comm., 2001). ERGI profiles can easily image down to 90 m. Much of the information presented in an ERGI profile is too deep to be ground-truthed with hand cores or vibracores.

The combined land and water ERGI profile provides information that is up to 20 m deep, but the pre-existing core data is all less than 8 m deep, and much of it is less than 4 m deep. Consequently, far less than one half of the vertical extent of the profile is 'ground-truthed'.

Overall, problems with the coring strategy and technique left the combined land and water ERGI profile with poor ground-truthing that covered less than one sixth of its area. A post-freeze-up targeted vibracoring program that would have the vastly improved the quality and extent of the ground truthing was not attempted. The extra effort would have been wasted because the profile was critically flawed by poor data caused by data collection problems.

Data Collection Problems

The data collection problems faced by the combined land and water ERGI profile stem from specific field conditions and from the apparent resistivity measurement equipment. The problematic field conditions encountered on land included frost and thick beds of matted vegetation; in the water the loosely compacted organic-rich silts on the lake bottom created problems. The main equipment problem stemmed from the experimental 2 m long aluminum electrode stakes.

The combined land and water field experiment was collected very early in the summer and thick frost was encountered in the shade of the vegetation on the levees. Particularly solid patches of frost were discovered under any of the deadfall removed from the survey corridor. There is very little electrical contact between frozen ground and an electrode stake. If the contact resistance can be lowered enough to allow data collection, the resultant ERGI profile will include the highly resistive frost layer. Patchy frost shows up in ERGI profiles as near surface odd shaped high resistivity blobs that can distort the entire image (Ritz et al, 1999).

The frost problems on the combined land and water survey were compounded by the combination of the increasingly warm weather and the removal of vegetation and deadfall from the survey corridor. Not only was the frost discontinuous, but also its extent was shrinking day-to-day and hour-by-hour. The melting of the frozen zones led to variable electrical contact resistance, unstable currents during the measurement process, and smaller and smaller resistive zones affecting each subsequent apparent resistivity measurement. See appendix A section 4 for more about contact resistance and appendix A section 5 for more instrument errors caused by fluctuating currents.

Contact resistance problems were also caused by repeating layers of overbank mud, leaf matter, woody debris, roots, and stems covering the levees. The woody debris and roots made inserting the electrode stakes difficult. The combination of roots, stems, woody debris, and leaf matter provided an excellent insulator which lead to high apparent resistivity measurements and high electrical contact resistance. When the top layer of matter was removed in the hopes of exposing the 'ground surface', more layers of insulating material were discovered. Occasionally, the 2 m long aluminum electrode stakes were used in an attempt to penetrate through to the sediments beneath the electrically insulating ground cover. These efforts met with limited success mostly due to problems with the 2 m long aluminum electrode stakes, which will be discussed shortly.

The resistivity of the water layer varied over short time periods due to the passage of the researchers along the survey line stirring up the organic-rich silt on the lake bottom. Stirring up the bottom sediments lowers the resistivity of the water because suspended sediments can carry electrical current through water.

As the sediments settle out, the resistivity of the water drops. Thus, the passage of a researcher along the survey line to set up equipment, to troubleshoot equipment, or to retrieve equipment alters the data collected. Presumably, a limited number of field tests could determine a suitable settling interval to wait between stirring up the bottom and collecting data. Underwater ERGI surveys in deep water are not affected by this problem because all the equipment is deployed and retrieved from a boat and there is minimal disturbance of bottom sediments.

Although the experimental 2 m long aluminum electrode stakes were light, inexpensive, and successfully held the electrodes above the water, they had two main problems. The aluminum corroded rapidly which created many errors and erroneous apparent resistivity measurements. The length of electrical contact available on the 2 m long stakes produced non-point source electrical contact that lead to erroneous measurements and incorrect modeling of the data.

The 2 m long electrode stakes were made out of aluminum, which is an excellent conductor. The problem with aluminum arises because it reacts with air or water to form aluminum oxide, which is a very poor conductor. Passing an electrical current through aluminum, such as for an apparent resistivity measurement, encourages the formation of aluminum oxide. The aluminum oxide coating on the stakes rapidly formed a barrier to current flow that generated erroneous measurements, lead to poor electrical contact resistance, and produced many system errors.

Transporting the electrode stakes to an ERGI survey site jostled and bounced the stakes against each other, removing some of the aluminum oxide coating. Inserting the electrode stakes into the ground scraped more of the aluminum oxide off the stakes. Thus, the preliminary electrical contact resistance test on an ERGI survey line usually had reasonable electrical contact resistance. However, the electrical current used to perform the contact tests triggered the formation of aluminum oxide. Any subsequent use of the electrode stakes faced higher and higher contact resistance and system errors when contact became so poor as to prohibit any electrical flow. Simply pushing the problem electrode stakes 5 cm further into the ground cleaned them enough to re-establish electrical contact, but often only enough for one contact test, then it would fail again. This proved very frustrating because every electrical contact troubleshooting effort led to more contact problems.

Recording apparent resistivity data with the 'ghosty' recurring contact problems produced data sets that were noisy and in all likelihood erroneous. The data sets often were missing up to 50 percent of the data due to system errors when the contact proved too poor to allow measurement. Eventually the field protocol evolved to record two or three repeat surveys separated by long bouts of contact problem troubleshooting in the hopes that the holes in the data sets were at different locations. Combining data sets in this way often achieved 95 percent coverage. In one 'worst case scenario', a data set was recorded with the AB circuit on the Sting reversed. Because of the corrosion problem, the combined land and water survey line, BTC301, was not simply a combination of three data sets (the main line and two roll-alongs); it consists of the best data from 6 data sets. Even so, BTC301 was not complete and consists of data that was most likely erroneous to an unknown degree.

A further problem associated with the electrode materials used on the combined land and water survey was the development of spontaneous potential (SP). SP occurs when a combination of natural or introduced conditions generates a difference in charge between two regions in the subsurface. A sensitive volt meter, such as the one in a resistivity measuring device, can directly measure SP. Strong SP will effect the potential (voltage) measurement made during apparent resistivity measurements and result in noisy data.

The combined land and water ERGI survey used both stainless steel and aluminum electrode stakes. Stainless steel and aluminum have different standard reduction potentials (Chang, 1991). A circuit that uses metals with different reduction potentials commonly generates SP, even in a homogenous electrolyte. The stakes for the combined land and water ERGI survey were in contact with ground water and lake water, which are chemically different electrolytes. A circuit that contains two electrolytes commonly generates SP, even if the electrode stakes are uniform. There is every reason to believe that the combined land and water ERGI survey experienced SP effects, but there was no way to test for it. The Sting was not configured to make simple potential measurements that would indicate the presence and magnitude of SP. AGI may be including this ability in future firmware for the Sting (M. Langmanson, pers. comm., 2000).

The length of the 2m long aluminum electrode stakes caused other problems. Equation 5 represents a resistivity measurement made with electrodes that act as point sources of electrical contact with the ground. Widely separated short electrode stakes (penetration < 10 % separation) behave essentially as point sources of electrical contact. The 2 m long electrode stakes used for the combined land and water ERGI survey were often in contact with as much as 1.9 m of electrically conductive material: 1.7 m of lake water and 0.2 m of bottom sediments. At 5 m spacing the separation to penetration ratio climbs to 38 % and the electrodes no longer behave as point sources of electrical contact. With equation 5 violated, the apparent resistivity measurements for the combined land and water ERGI survey are likely erroneous.

Accurate apparent resistivity measurements can be made with land style electrodes and cables in open water so long as the electrodes are provided with a point source of electrical contact. Data processing is simplified if the contact is made either with the surface of the water or with the bottom sediments.

Electrical contact with the surface of the water could be made without making contact with the entire water column or the bottom sediments by using a non-conductive support, such as a wooden pole, to hold a standard length (30 cm) stainless steel electrode stake in contact with the top 20 cm of water. This data could be handled by a standard data inversion and the water would appear as a layer in the ERGI profile. The topographic correction for such a data set would need to follow the water surface elevation. Depths to features in the ERGI profile would be referenced from the surface of either the ground or the water.

Electrical contact with the bottom sediments could be made without making any contact with the water column by heavily insulating all but the bottom 20 cm of a long (>2 m) electrode stake. This method would produce the same effect as laying waterproof electrodes directly on the bottom sediments. A data set that was collected across water with this technique could be processed with a standard underwater data inversion. A data set that incorporated data collected from lake bottom sediments and data collected from dry land would require a 'special' data inversion. At the time of data collection for the combined land and water ERGI survey, no such inversion routines existed that could handle both land and underwater data. After being made aware of this field experiment, Dr Loke released a version of RES2DINV that can process combined land and underwater data. This inversion requires a topographical correction that follows the contours of the bottom of the water body, the resistivity of the lake water, and an elevation value to constrain the location and depth of the water body.

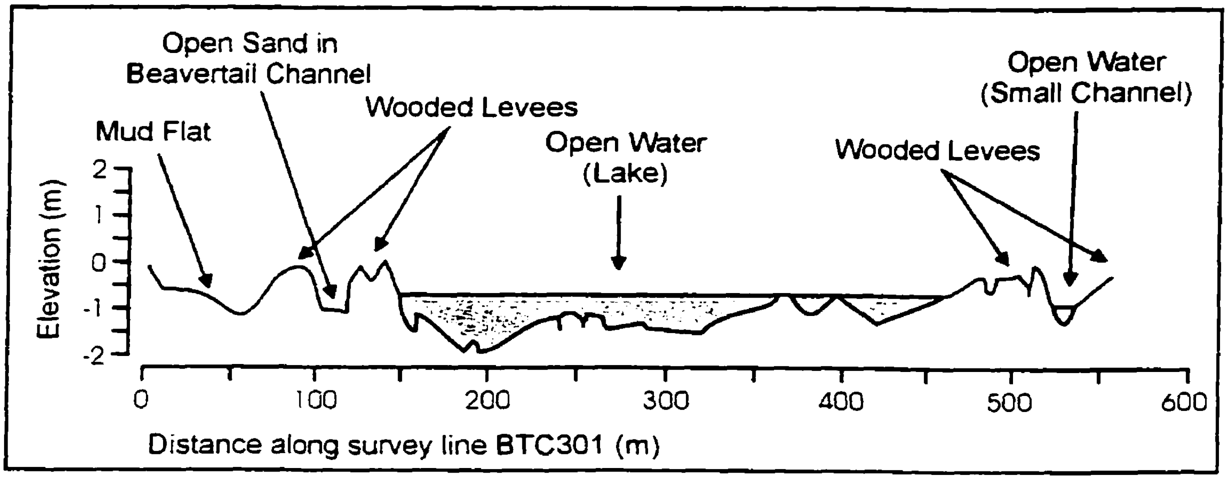


Figure 18 Topographic profile of ERGI survey BTC301. The water surface in the wetland is higher than the surface of the abandoned Beavertail Channel. Elevation in this figure is relative to an arbitrary datum.

Even if all the data collection problems with the combined land and water ERGI survey were corrected, the data set could not be processed with the new combined land and water data inversion. Survey line BTC301 includes two water bodies with different surface elevations and water character (resistivity). Survey line BTC301 also includes several locations that are lower than the water surface that are not underwater (Figure 18). Dr. Loke intends to incorporate horizontal constraints for the location of water bodies in a future release of RES2DINV (pers. comm., 2000).

7.2. Electrode Array Field Experiment

Although a great deal of literature exists that describes the sensitivity, depth of investigation, resolution, and susceptibility to noise of the three commonly used electrode arrays for ERGI (Wenner, Wenner-Schlumberger, and dipole-dipole), each researcher appears to have their own favorite (Ward, 1990; Reynolds, 1997; Dahlin and Loke, 1998; Loke, 1999).

The goal of this field experiment was to determine the best array for imaging buried mud-encased sand channel-fills and crevasse-splay sheet sands. Because this experiment was carried out at almost all of the survey sites, there is too much data to present here. For the sake of brevity, only the Wenner array and the dipole-dipole array from two representative cases, the Beavertail channel-fill (BTC102 and BTC103) and the Schoonrewoerd channel-fill and braid-plain (NL9309101 and NL9309103), are presented.

7.2.1. Methods for this Field Experiment

In general, this field experiment involved collecting three data sets on each survey line: one with a Wenner array, one with a Wenner-Schlumberger array, and one with a dipole-dipole array. The equipment was not moved between each series of measurements. The data sets were assessed by qualitatively comparing their associated ERGI profiles.

Quantitative comparison was not possible because there is no method to determine the difference between an ERGI profile and the subsurface. The percent RMS (root mean square) error included with the ERGI profile by the inversion software can not be used for quantitative comparisons because it is a measure of the fit between the model and the data and has nothing to do with the relationship between either the model or the data and the 'real world'.

The data from the Beavertail channel-fill was collected using a Wenner array followed by a dipole-dipole array on a 56 electrode survey line with a 1 m electrode spacing. The survey was 55 long and was designed to collect information up to 12 m deep. To keep all the ERGI surveys across the Beavertail channel-fill comparable, the first electrode for BTC102 and BTC103 was located at meter 82 along the survey line. The data from the Schoonrewoerd channel-fill was collected using a dipole-dipole array followed by a Wenner array on a 21 electrode survey line with a 10 m electrode spacing. The survey was 200 m long and was designed to collect information from up to 32 m deep.

7.2.2. Results/Discussion

A preliminary assessment of the array test results indicates that for some surveys the ERGI profile from the Wenner array data was much cleaner, clearer, and easier to interpret than the ERGI profile from the dipole-dipole data (e.g. Figure 19). For other surveys, the ERGI profile from the Wenner array data was very similar to the ERGI profile from the dipole-dipole array data (e.g. Figure 20).

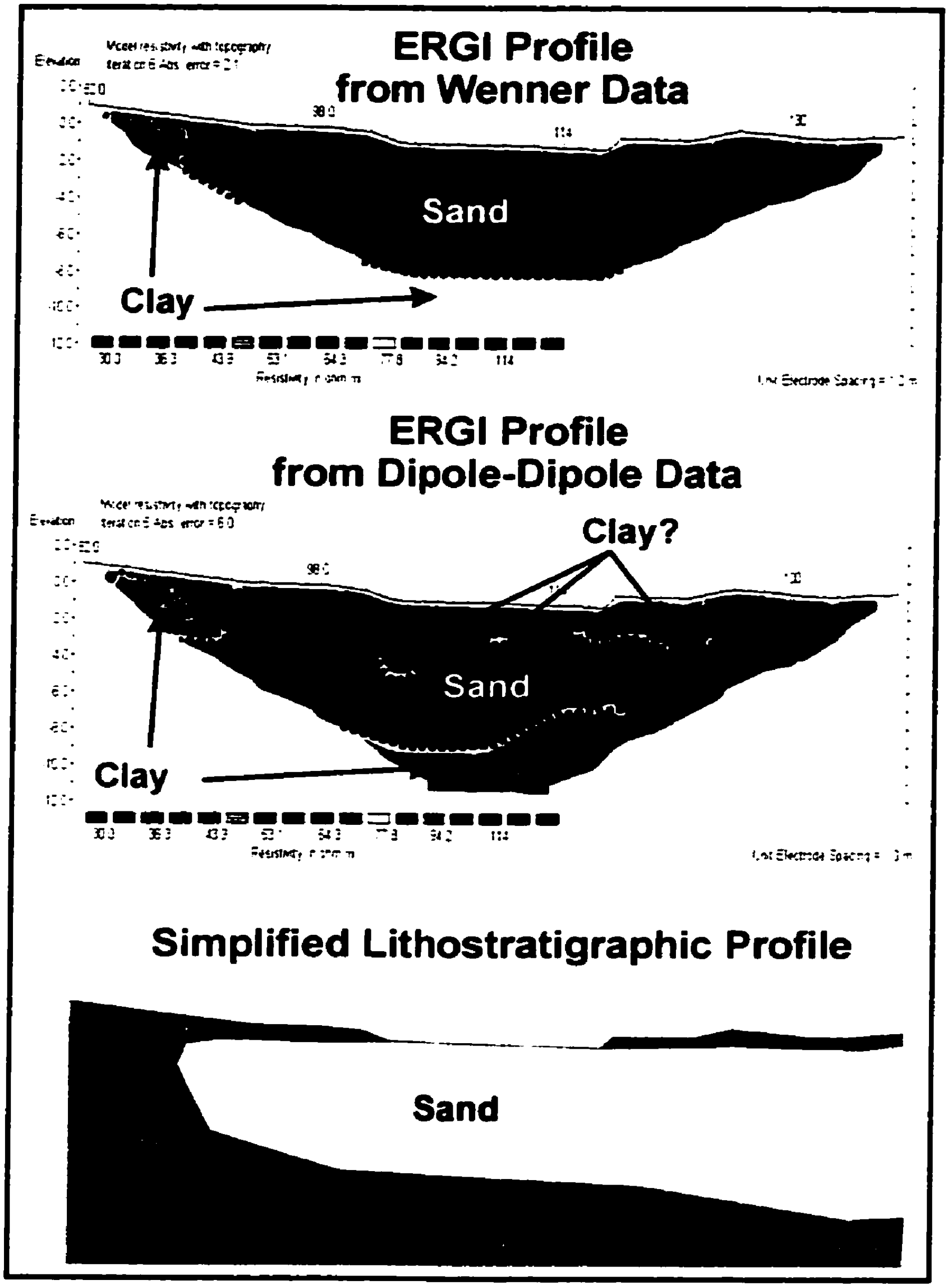


Figure 19 Comparison of two ERGI profiles collected with different electrode arrays on the Beavertail channel-fill. The first profile was collected with a 1 m spacing Wenner array and was immediately followed by a 1 m spacing dipole-dipole array survey. A simplified lithostratigraphic profile based on Vibracores and other ERGI Profiles is included to reference what should *be in the 1 m ERGI profiles.*

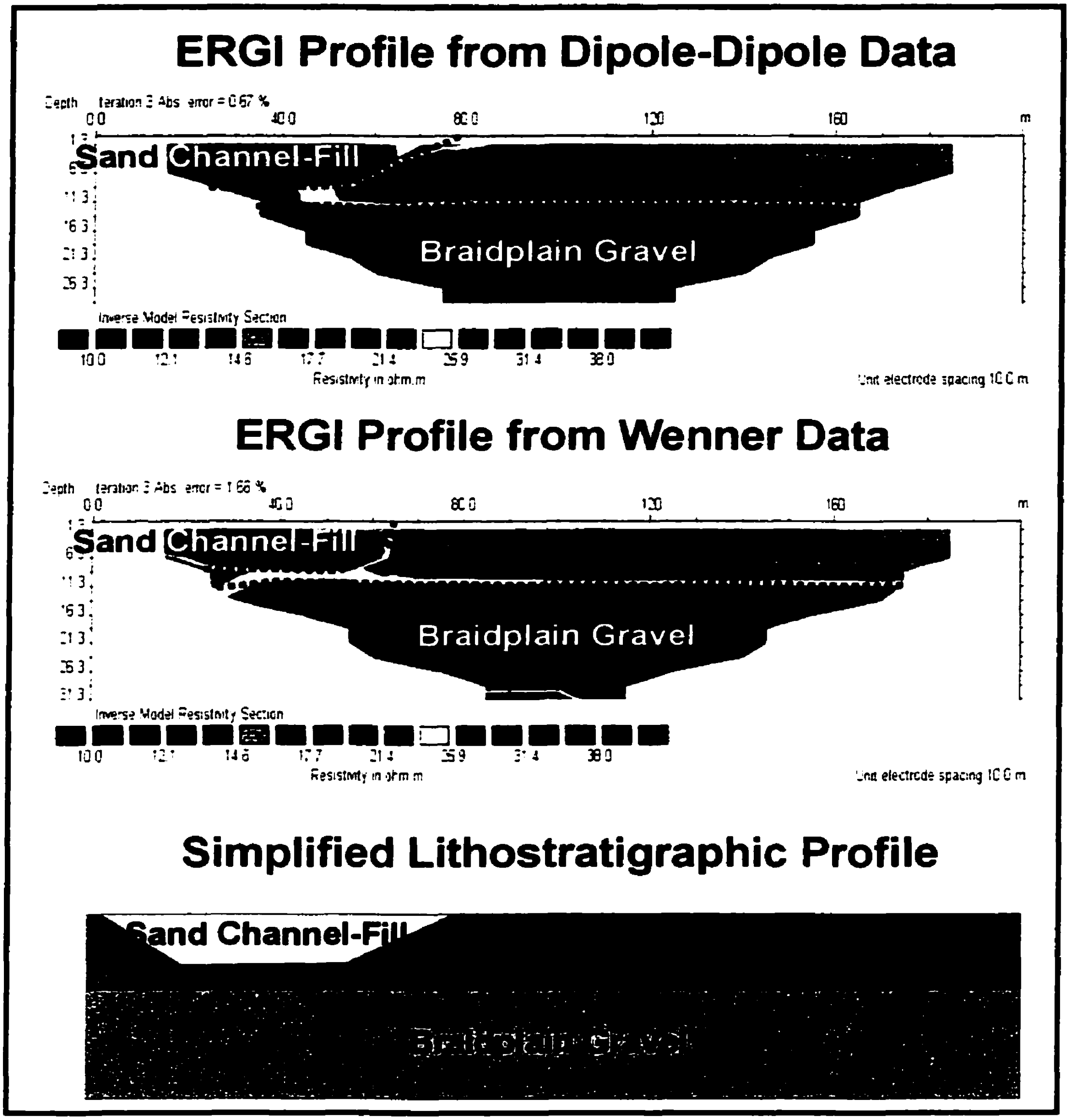


Figure 20 Comparison of two ERGI profiles collected with different electrode arrays on the Schoonrewoerd channel-fill and braidplain. The first profile was collected with 10 m spacing dipole-dipole array and was immediately followed by a 10 m spacing Wenner array survey. A simplified lithostratigraphic profile based on hand cores (Makaske, 1998) is included to reference what should *be in the 10 m ERGI profiles.*

After numerous array tests it became apparent that if the dipole-dipole array data was collected before the Wenner array data (e.g. Figure 20), the ERGI profiles were very similar. If the dipole-dipole array data was collected after the Wenner array data (e.g. Figure 19), the ERGI profiles were considerably different.

The results of the electrode array field experiment indicate that the timing of data collection affects the results of the electrode array comparisons, which implies that repeating measurements on a survey line somehow alters the electrical behavior of the subsurface or the interface between the electrode stakes and the subsurface. Given an awareness of the temporal signal, the array test results suggest that the Wenner array provides a better ERGI profile than the dipole-dipole array (Figure 21).

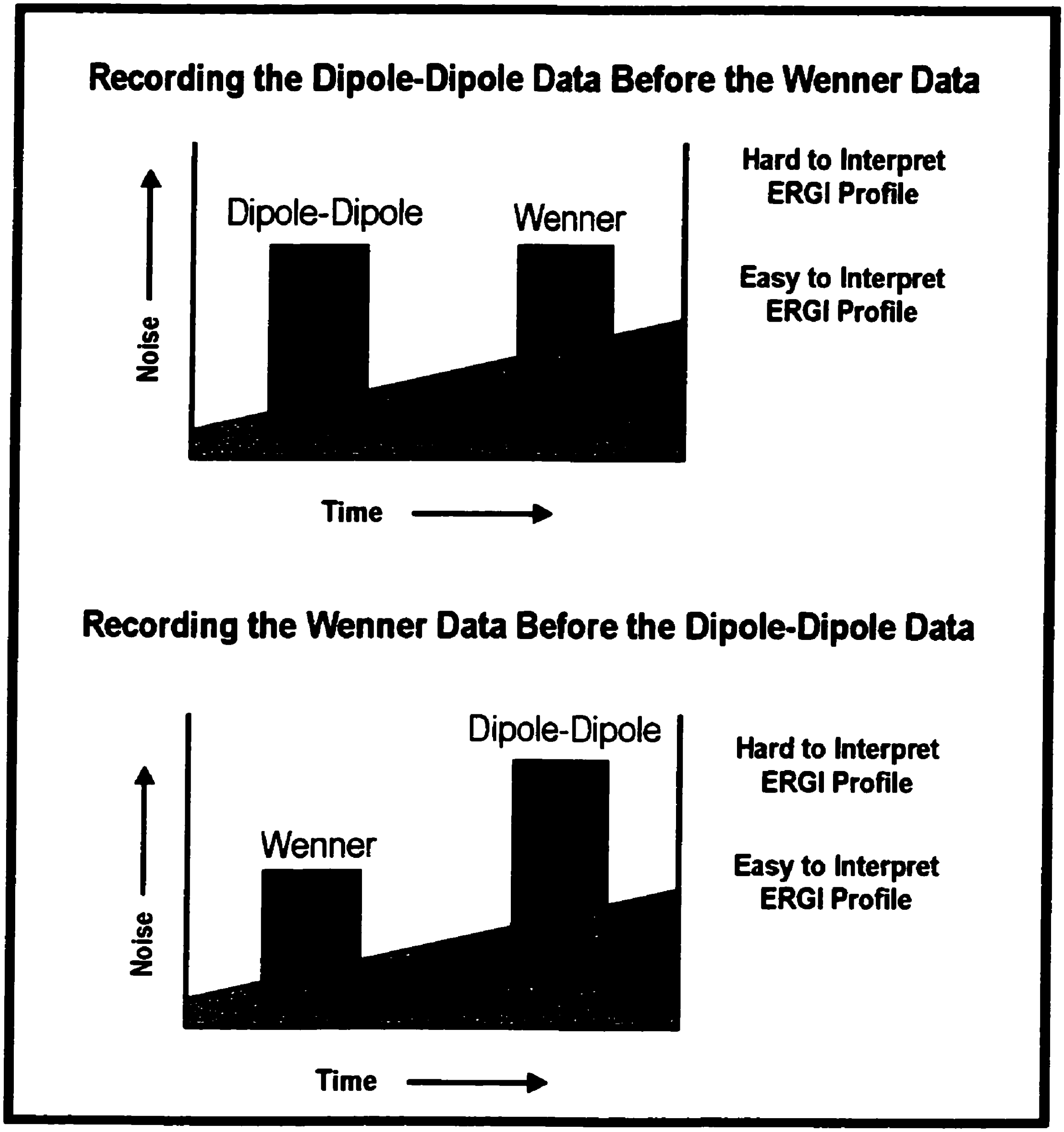


Figure 21 A conceptual model showing the influence of time related signal noise on the outcome of a comparison between electrode arrays. Here the Wenner array is shown to have less intrinsic noise than the dipole-dipole array, but the comparison is heavily weighted by which array is collected first.

7.3. Cumulative Electrode Charge-Up Effect Field Experiment

Back-to-back repeated surveys on the same survey line appear to lead to poorer and poorer quality ERGI profiles. This problem has not been previously reported. A possible cause for the decrease in profile quality is increasingly noisy data due to 'cumulative electrode charge-up effects'.

Electrode charge-up is thought to occur at the interface where electrical current passes from the electrode stakes into the ground (Dahlin, 2000). Although nothing physically passes through this interface, electrical current is transferred across it. The current is transferred across the interface by a build-up (or deficit) of free electrons in the electrode stake and a corresponding build-up of positive (or negative) ions in the pore fluids in the ground surrounding the electrode stake. As the current flows, the build-up increases and eventually gets large enough to produce a non-linear increase in the resistance of the circuit and results in erroneous apparent resistivity measurements (Dahlin, 2000).

ERGI data collection is designed to avoid charge-up effects. Resistivity measurement equipment involves four electrodes to avoid immediate electrode charge-up during current transmission overwhelming the voltage measurement. Each apparent resistivity measurement recorded into a data set is actually the average of a series of measurements with opposite polarity. This minimizes noise while avoiding short-term electrode charge-up effects. The set of resistivity measurements for an ERGI profile is collected in a pattern that avoids using a current electrode (A or B) as a potential electrode (M or N) for as long as possible in an effort to eliminate mid-term electrode charge-up effects (M. Langmanson, pers comm., 2000).

Long-term subtle effects of electrode charge-up are unknown. This field experiment was conducted to assess long-term cumulative electrode charge-up at a site with a collection of unnamed buried paleochannels near the Lek River, approximately 14 km east of Rotterdam, the Netherlands (surveys CS0101 through CS0108).

7.3.1. Methods for this Field Experiment

Data for the cumulative electrode charge-up effects field investigation was collected on a 28 electrode survey line with a 5 m electrode spacing. The survey was 275 m long and was designed to collect information from up to 43 m deep. Seventeen data sets were collected without moving the data collection equipment (Figure 22); 9 electrical contact resistance tests, 4 Wenner array surveys, and 4 Wenner-Schlumberger array surveys. A contact test was run before any other data collection. A contact test was the collected after each of the other measurements. The Wenner and Wenner-Schlumberger surveys were alternated. The electrical contact resistance tests were designated R1 through R9. The Wenner array surveys were designated W1 through W4. The Wenner-Schlumberger array surveys were designated S1 through S4.

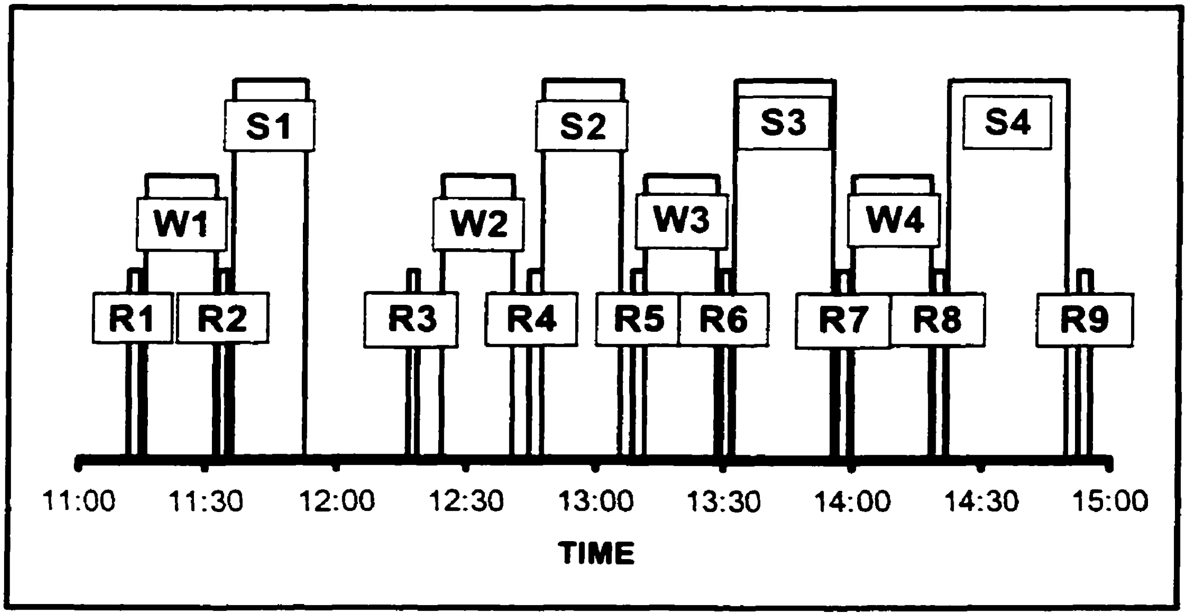


Figure 22 Timing and duration for the components of the Cumulative Electrode Charge-Up Field Experiment. The electrical contact resistance tests are R1 through R9. The Wenner array surveys are W1 through W4. The Wenner-Schlumberger array surveys are S1 through S4.

For data analysis, the first contact resistance test (R1), the first Wenner array survey (W1), and the first Wenner-Schlumberger array survey (S1) were treated as the 'standard'. All subsequent data sets were compared to the standard.

Standard statistical tests could not be used to assess the difference between the data sets because each measurement corresponds to a specific set of 'real-world' conditions at a specific location. The mean and standard deviation within the data sets provides information about the lithoarchitecture of the subsurface rather than anything about the data itself.

If the subsurface conditions remain constant and the measurement process does not change, repeat data sets should have identical data rather than just identical means and standard deviations. The goal of this field investigation was to determine if the measurement process was altering conditions sufficiently that repeat data sets are not identical.

A simple tool to test for and assess the difference between repeat data sets is to examine the 'bias' between individual measurements (e.g. $W1_i - W2_i$: Bland and Altman, 1983; 1986; Pollock et al, 1992). A second technique used to assess differences between data sets is Passing-Bablok regression analysis. The Passing-Bablok method can handle data that is not normally distributed and that has error on both axes. Because of this, it is capable of detecting very small differences between 'real world' data sets (Passing and Bablok, 1983; Payne, 1997).

Statistical comparison of the data sets was run using Microsoft® Excel 2000 and Analyze-It™. Although Analyze-It™ is a macro for Excel; it does not use Excel's flawed statistical functions (see McCullough, 1998; 1999).

A comparison between the repeat ERGI surveys was made on the % RMS fit for the third iteration of data inversion to assess the influence of any differences between the repeat data sets on the subsequent ERGI profiles.

The bias between W1 and W2 was examined in detail. An assessment was made to determine if the distribution of bias between individual apparent resistivity measurements (W1i – W2i) had any relationship with the two key apparent resistivity measurement parameters: horizontal location along the survey line (x(W1i)) and electrode spacing ($a(W1_i)$).

7.3.2. Results/Discussion

The repeated electrical contact resistance tests show no changes large enough to indicate cumulative electrode 'charge-up' effects (Figure 23). The resistance tests have a maximum bias of -0.85 % and showed no trend over the 3 hours and 43 minutes of the experiment. The Passing and Bablok method comparison found that there was no significant difference between the nine tests. If this series of surveys triggered cumulative electrode charge-up effects, the electrical contact resistance test was unable to detect it.

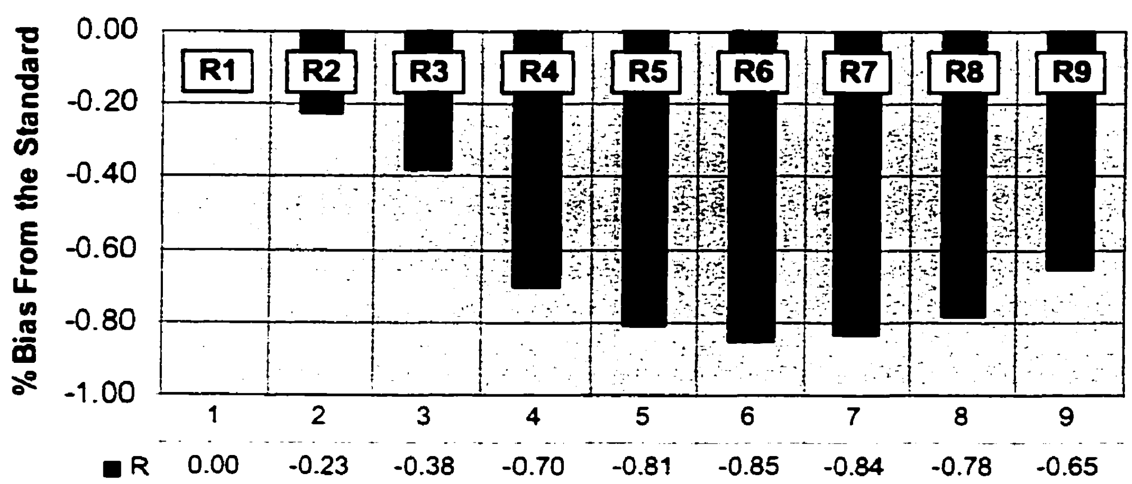
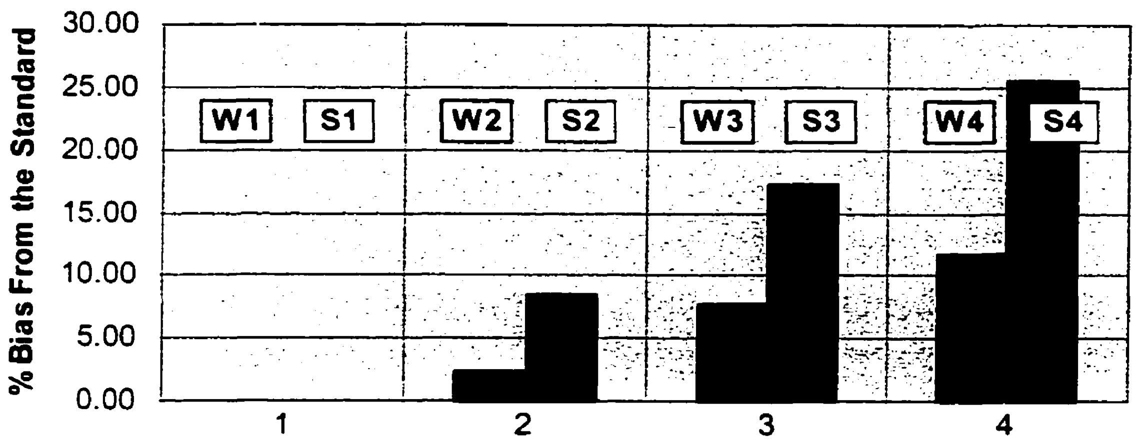


Figure 23 Graph showing the percent bias from the standard for the repeated electrical contact resistance tests (R1 through R9). As R1 was the standard for the comparisons, there was 0.00 % bias for R1.

There are substantial changes to the apparent resistivity measurements from the repeated Wenner array and Wenner-Schlumberger array data that are consistent with the existence of a cumulative electrode 'charge-up' effect (Figure 24). There was sizeable bias built up even after the first test. The bias between W1 and W2 was 2.29%. The bias between S1 and S2 was 8.41%. The bias increases for each subsequent test, climbing to an astonishing 25.49% for S4. The Wenner-Schlumberger array data shows larger biases for all the tests than the Wenner array data. The Passing and Bablok method comparison found that there was a significant difference between the standard and all subsequent tests.



	1	2	3	4
■ W	0.00	2.29	7.75	11.65
■ S	0.00	8.41	17.30	25.49

Figure 24 Graph showing the percent bias from the standard for the repeated Wenner (W1 through W4) and Wenner-Schlumberger (S1 through S4) array surveys. As W1 was the standard for the Wenner comparisons, there was 0.00 % bias for W1. The same is true of S1 for the Wenner-Schlumberger comparisons.

These results do not prove the existence of long term subtle electrode charge-up effects. However, the fact that repeated surveys do not produce identical data sets and that the difference between the data sets increases with the number of repeats, proves that some factor, such as electrode charge-up, was definitely having a deleterious effect on the data.

Decreasing data quality intuitively leads to higher % RMS model fit (poorer fit) for the corresponding ERGI profiles. This assumption holds true for the data sets collected for the cumulative electrode charge-up experiment (Figure 25). The % RMS model fit increased from 0.9 % to 16.8 % over the four Wenner array ERGI profiles and from 2.4 % to 21.2 % over the four Wenner-Schlumberger array ERGI profiles. The increase in % RMS model fit for the repeated surveys reflects the decreasing quality of the data and indicates that it was procedurally incorrect to qualitatively compare ERGI profiles from repeated surveys on the same survey line.

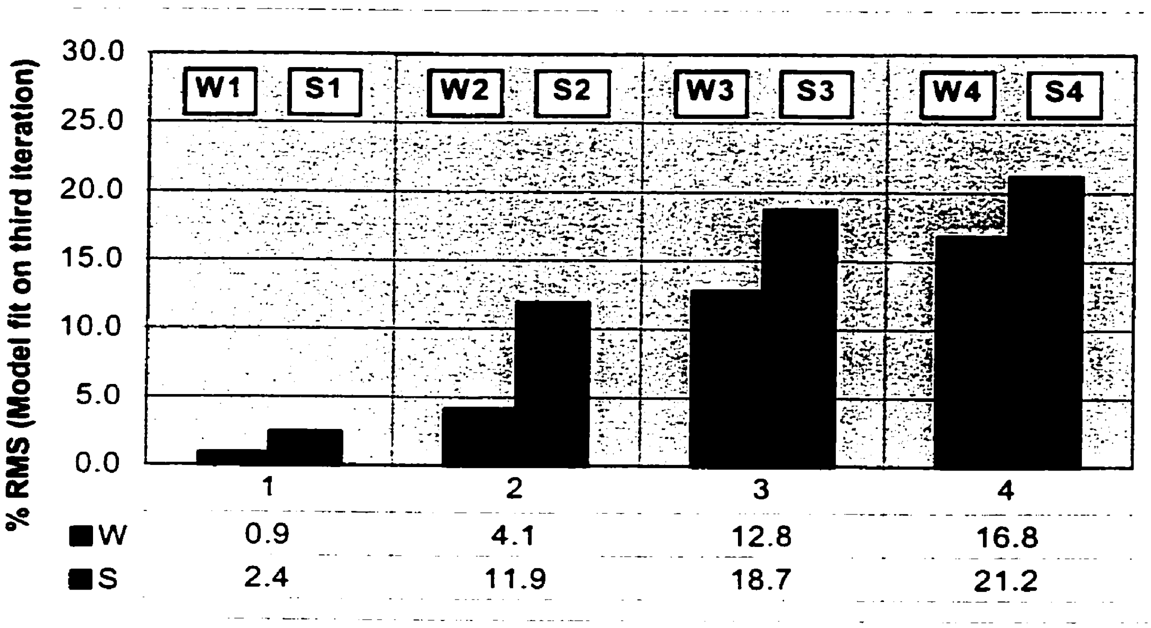


Figure 25 Graph showing the % RMS model fit for the third iteration of the data inversion for the repeated Wenner (W1 – W4) and Wenner-Schlumberger (S1 – S4) array surveys.

A closer examination of the bias between two data sets provides information about where and when cumulative electrode charge-up effects are occurring within a data set. The spatial distribution of the bias along the survey line shows that the measurements with the largest bias occur near the center of the survey line (Figure 26). The only procedural difference between measurements made near the center of the survey line and those made near the ends is that measurements near the center can use larger electrode spacings than those at the end. The bias distribution shown in Figure 26 indirectly associates large electrode spacings with larger bias.

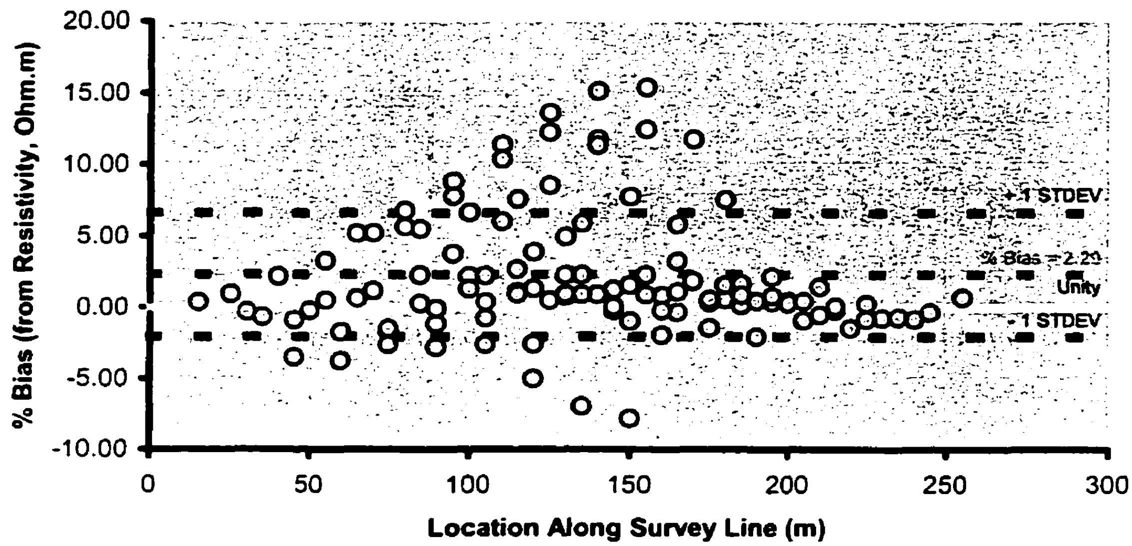


Figure 26 Distribution plot of the bias between individual repeated measurements ($W1_i$ – $W2_i$) vs. the horizontal location of the measurement along the survey line ($X(W1_i)$).

Directly comparing the distribution of bias with the electrode spacing clearly indicates that larger electrode spacings produce larger bias (Figure 27). Because measurements with the largest spacings also have the largest depth, bias caused by cumulative electrode charge-up effects will generate more perturbations in the lower portions of ERGI profiles. This can be seen in Figure 19 where the top half of the two profiles are very similar, but the bottom half is distinctly different.

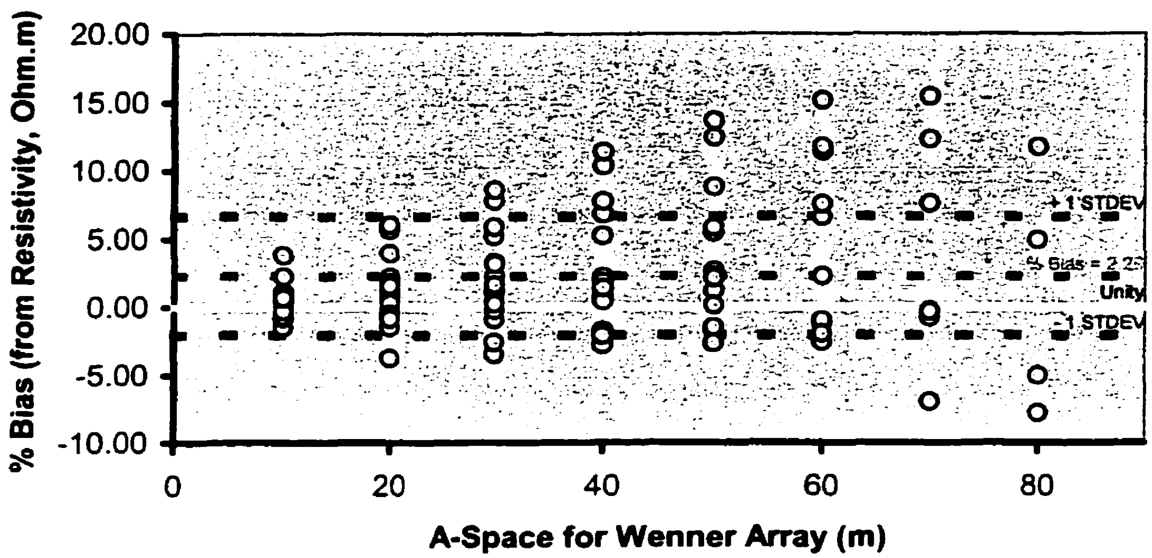


Figure 27 Distribution plot of the bias between individual repeated measurements ($W1_i - W2_i$) vs. the electrode spacing ($a(W1_i)$) of the measurement.

The results from the cumulative electrode charge-up experiment prove that long-term charge-up effects lead to decreasing data quality and decreasing ERGI profile quality even after only one repeated survey on the same survey line. The cumulative electrode charge-up effects are greatest for large electrode spacings and manifest themselves in the lower portion of later ERGI profiles. Further study is required to determine how long a ‘resting’ period must be observed to be sure that conditions have ‘reset’ between repeat surveys so that investigations testing different arrays, different electrode stakes, different instrument settings, et cetera can be completed without cumulative electrode charge-up effects.

CHAPTER 8. CONCLUSIONS

ERGI profiles accurately portray lithology, stratigraphy, and geometry of buried sand and gravel fluvial deposits. Variations in the modeled resistivity values represent different lithologies. Geometries of homogeneous deposits are represented by zones of similar resistivity values. For example, mud-encased sand-filled channels appear as channel-shaped high resistivity anomalies. Vibracores confirm that such anomalies correctly represent the lithology and geometry of the 'real-world'.

Methodology refinements suggested by this thesis make ERGI field work simpler and more reliable. Future improvements to the equipment and software are expected to solve some of the problems with ERGI investigations in fluvial environments. One problem is the decrease in data quality associated with repeated surveys on the same survey line, possibly caused by cumulative electrode charge up effects. This inability to collect repeat data sets restricts researcher's efforts to assess different data collection techniques or instrument settings. Further work is suggested to better understand and mitigate this problem. The problem of dry or frozen sediments will likely remain unresolved. Dry or frozen sediments lack a carrier for the electrical current used during resistivity measurement and can not be studied using ERGI.

The field experiments in this thesis indicate that ERGI is a remarkable geophysical tool. It detects complex lithofacies changes and maps geometries. It functions equally well in conductive sediments (silt-clay, organic, brackish, or saline) and in resistive sediments (sand, gravel, or peat). This means that ERGI can detect and delineate resistive bodies buried in conductive sediments. ERGI is going to be the next shallow geophysical revolution for investigating fluvial and other Quaternary-aged depositional successions.

Remember: Resistance is not futile!

REFERENCES

Abbado, D., and Filgueira-Rivera, M., 2000. High Resolution DGPS Long Profile of the Anastomosed Reach of the Columbia River, British Columbia, Canada, Unpublished Data, University of Nebraska.

Abdul Nassir, S.S., Loke, M.H., Lee, C.Y, and Nawawi, M.N.M., 2000. Salt Water Intrusion Mapping by Geoelectrical Imaging Surveys, Geophysical Prospecting, 48, 547-661.

Archie, G.E., 1942. The Electrical Resistivity Log as an Aid to Determining Some Reservoir Characteristics. Transactions of the American Institute of Mining, Metallurgical, and Petroleum Engineers, 164, 389-409.

Barker, R.D., 1989. Depth of Investigation of Collinear Symmetrical Four Electrode Arrays, Geophysics, 54, 8, 1031-1037.

Barker, R.D., 1992. A Simple Algorithm for Electrical Imaging of the Subsurface, First Break, 10, 2, 53-62.

Beard, L.P., Hohmann, G.W., and Tripp, A.C., 1996. Fast Resistivity/IP Inversion Using A Low-Contrast Approximation, Geophysics, 61, 1, 169-179.

Berendsen, H.J.A., 1994, Handleiding: Voor Fysisch Geografisch Veldwerk in het Laagland Negende Druk, Vakgroep Fysische Geografie, Universiteit Utrecht.

Berendsen, H.J.A., 1998. Bird's-Eye View of the Rhine-Meuse Delta (The Netherlands), Journal of Coastal Research, 14,3, 740-752.

Berendsen, H.J.A., and Stouthamer, E., 2000. Late Weichselian and Holocene Paleogeography of the Rhine-Meuse Delta, The Netherlands, Paleogeography, Paleoclimatology, Paleoecology, 161, 311-335.

Bland, J.M., and Altman, D.G., 1983. Measurement in Medicine: The Analysis of Method Comparison Studies, Statistician, 32, 301-317.

Bland, J.M., and Altman, D.G., 1986. Statistical Methods for Assessing Agreement Between Two Methods of Clinical Measurement, The Lancet, 307-310.

Broughton Edge, A.B., and Laby, T.H., 1931. The Principles and Practice of Geophysical Prospecting: The Report of the Imperial Geophysical Experimental Survey, Cambridge University Press, Cambridge.

Burger, H.R., 1992. Electrical Resistivity, Chapter 5 in: Exploration Geophysics of the Shallow Subsurface, Prentice Hall, New Jersey, 241-316.

Chang, R., 1991. Electrochemistry, Chapter 19 in: Chemistry, McGraw-Hill, New York, 779-818.

Christensen, N.B., 2000. Difficulties in Determining Electrical Anisotropy in Subsurface Investigations, Geophysical Prospecting, 48, 1-19.

Dahlin, T., 1996. 2D Resistivity Surveying for Environmental and Engineering Applications, First Break, 14, 7, 275-283.

Dahlin, T., 2000. Short Note on Electrode Charge Up Effects in DC Resistivity Data Acquisition Using Multielectrode Arrays, Geophysical Prospecting, 48, 181-187.

Dahlin, T., and Loke, M.H., 1998. Resolution of 2D Wenner Resistivity Imaging as Assessed by Numerical Modeling, Journal of Applied Geophysics, 38, 237-249.

Dahlin, T. and Owen, R., 1998. Geophysical Investigations of Alluvial Aquifers in Zimbabwe, Proceedings: 4th European Environmental and Engineering Geophysics Society Meeting, Barcelona, Spain, 14-17 September 1998.

Daily, W. and Ramirez, A.L., 2000. Electrical Imaging of Engineered Hydraulic Barriers, Geophysics, 65, 1, 83-94.

Dey, A., and Morrison, H.F., 1979. Resistivity Modeling for Arbitrarily Shaped Three-Dimensional Structures, Geophysics, 34, 615-632.

Edwards, L.S., 1977. A modified Pseudosection for Resistivity and IP, Geophysics, 42, 5, 1020-1036.

El-Behiry, M.G. and Hanafy, S.M., 2000. Geophysical Surveys to Map the Vertical Extension of a Sinkhole: a Comparison Study, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, February 20-24, Arlington, Virginia.

El-Hussain, I., Holbrook, J. and Sneed, C., 2000. Integrating Geophysical and Geological Methods to Delineate Buried Paleochannels in the New Madrid Seismic Zone of Southeastern Missouri, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, February 20-24, Arlington, Virginia.

Federal Geodetic Control Subcommittee and GPS Interagency Advisory Council, 2000. Comparison of Positions With and Without Selective Availability: Full 24 Hour Data Sets, Retrieved May 28, 2001 from the World Wide Web: http://www.ngs.noaa.gov/FGCS/info/sans_SA/compare/ERLA.htm

Gettys, W.E., Keller, F.J., and Skove, M.J., 1989. Current and Resistance, Chapter 24 in Physics, McGraw-Hill Book Company, New York.

Gilson, E.W., Nimeck, G., Bauman, P.D. and Kellett, R., 2000. Groundwater Exploration in Prairie Environments, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, February 20-24, Arlington, Virginia.

Gilvear, D., Winterbottom, S., and Sichingabula, H., 2000. Character of Channel Planform Change and Meander Development: Luagwa River, Zambia, Earth Science Processes and Landforms, 25, 421-436.

Geological Survey of Canada (1972), Map 1326A; geology; Lardeau (east half), British Columbia; scale 1:50,000. Ottawa: Geological Survey of Canada.

Geological Survey of Canada (1979a), Map 1501A; geology; McMurdo (east half), British Columbia; scale 1:50,000. Ottawa: Geological Survey of Canada.

Geological Survey of Canada (1979b), Map 1502A; geology; McMurdo (west half), British Columbia; scale 1:50,000. Ottawa: Geological Survey of Canada.

Geological Survey of Canada (1980), Diagrammatic structure sections (...) to accompany Map 1501A, McMurdo (east half) and Map 1502A, McMurdo (west half), scale 1:50,000. Ottawa: Geological Survey of Canada.

Griffiths, D.H., Turnbull, J., and Olayinka, A.I., 1990. Two-dimensional Resistivity Mapping with a Computer Controlled Array, First Break, 8, 4, 121-129.

Harwood, K., and Brown, A.G., 1993. Fluvial Processes in a Forested Anastomosing River: Flood Partitioning and changing Flow Patterns, Earth Surface Processes and Landforms, 18, 749-751.

Hazen, M.E., 1990. Fundamentals of DC and AC Circuits, Saunders College Publishing, New York.

Heritage, G.L., and Broadhurst, L.J., 1998. Modeling Stage-Discharge Relationships in Anastomosed Bedrock-Influenced sections of the Sabie River System, Earth Surface Processes and Landforms, 23, 455-465.

Knighton, A.D., and Nanson, G.C., 1993. Anastomosis and the Continuum of Channel Pattern, Earth Surface Processes and Landforms, 18, 613-625.

Kunetz, G., 1966. Principles of Direct Current Resistivity Prospecting, Geoexploration Monographs, 1,1.

Leopold, L.B., Wolman, M.G., and Miller, J.P., 1964. Fluvial Processes in Geomorphology, W.H. Freeman and Company, San Francisco.

Locking, T., 1983. Hydrology and Sediment Transport in an Anastomosing Reach of the Upper Columbia River, B.C., Unpublished Masters Thesis, University of Calgary, 107 p.

Loke, M.H., 1999. Electrical Imaging Surveys for Environmental and Engineering Studies: A Practical Guide to 2D and 3D Surveys, Unpublished Short Training Coarse Lecture Notes, Universiti Sains Malaysia, Penang, Malaysia.

Loke, M.H., 2000. RES2DINV Software User's Manual (version 3.44)

Loke, M.H. and Barker, R.D., 1996. Rapid Least Squares Inversion of apparent Resistivity Pseudosections by a Quasi-Newtonian Method, Geophysical Prospecting, 44, 131-152.

Maillol, J.M.; Ortega-Ramirez, J.; Bandy, W.L.; and Valiente-Banuet, A., 2000. Contribution of Electrical Resistivity Methods to Paleoenvironmental Reconstruction and Groundwater Exploration in the Chihuahua Desert, Mexico, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, February 20-24, Arlington, Virginia.

Maillol, J.M., Seguin, M.K., Gupta, O.P., Akhauri, H.M., and Sen, N., 1999. Electrical Resistivity Tomography Survey for Delineating Uncharted Mine Galleries in West Bengal India, Geophysical Prospecting, 47, 103-116.

Makaske, B., 1998. Anastomosing Rivers: Forms, Processes, and Sediments, Utrecht: Koninklijk Nederlands Aardrijkskundig Genootschap/Faculteit Ruimtelijke Weteschappen, Universiteit Utrecht (Nederlandse Geografische Studies 249).

McCullough, B.D., 1998. Assessing the Reliability of Statistical Software: Part I, The American Statistician, 52, 4, 358-366.

McCullough, B.D., 1999. Assessing the Reliability of Statistical Software: Part II, The American Statistician, 53, 2, 149-159.

Miall, A.D., 1996. The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology, Springer-Verlag, New York.

Moorman, B.J., 1990. Delineation of Lithofacies using GPR, Unpublished Masters Thesis, University of Calgary.

Passing, H. and Bablok, W., 1983. A New Biometrical Procedure for Testing the Equality of Measurements from Two Different Analytical Methods: Application of Linear Regression Procedures for Method Comparison Studies in Clinical Chemistry, Journal of Clinical Chemistry and Clinical Biochemistry, 21, 709-720.

Payne, R.B., 1997. Method Comparison: Evaluation of Least Squares, Deming, and Passing/Bablok Regression Procedures Using Computer Simulation, Annals of Clinical Biochemistry, 34, 319-320.

Pollock, M.A., Jefferson, S.G., Kane, J.W., Lomax, K., MacKinnon, G., and Winnard, C.B., 1992. Method Comparison – A Different Approach, Annals of Clinical Biochemistry, 29, 556-560.

Quinn, A., 1982. Crevasse Splay Deposits: A Study of the Geomorphology and Sedimentology in an Anastomosing Fluvial Systems, Unpublished Masters Thesis, University of Calgary, 167 p

Reynolds, J.M., 1997. An Introduction to Applied and Environmental Geophysics, John Wiley and Sons, New York.

Ritz, M., Robain, H., Pervago, E., Albouy, Y., Camerlynck, C., Descloitres, M., and Mariko, A., 1999. Improvement to Resistivity Pseudosection Modeling by Removal of Near Surface Inhomogeneity Effects: Application to a Soil System in South Cameroon, Geophysical Prospecting, 47, 85-101.

Roy, A. and Apparoa, A., 1971. Depth of Investigation in Direct Current Methods, Geophysics, 36, 5, 943-959.

Schumm, S.A., Eskine, W.D., and Tilleard, J.W., 1996. Morphology, Hydrology, and Evolution of the Anastomosing Ovens and King Rivers, Victoria, Australia, GSA Bulletin, 108, 10, 1212-1224.

Smith, D.G., 1972. Aggradation and Channel Patterns of the Alexandra–North Saskatchewan River, Banff National Park, Alberta, Canada, in: O. Slaymaker and H. McPherson ed., Mountain Geomorphology, Tantalus Research, Vancouver.

Smith, D.G., 1983a. Anastomosed Fluvial Deposits: Modern Examples from Western Canada, Special Publications International Association of Sedimentologists, 6, 155-168.

Smith, D.G., 1983b. Vibracoring Fluvial and Deltaic Sediments: Tips on Improving Penetration and Recovery, Journal of Sedimentary Petrology, 54, 2, 660-663.

Smith, D.G., 1986. Anastomosing river deposits, sedimentation rates and basin subsidence, Magdalena River, northwestern Colombia, South America, Sedimentary Geology, 46, 177-196.

Smith, D.G., 1992. Vibracoring: Recent Innovations, Journal of Paleolimnology, 7, 137-143.

Smith, D.G., 1998. Vibracoring: A New Method for Coring Deep Lakes, Paleogeography, Paleoclimatology, Paleoecology, 140, 433-440.

Smith, D.G. and Putnam, P.E., 1980. Anastomosed River Deposits: Modern and Ancient Examples in Alberta, Canada, Canadian Journal of Earth Sciences, 17, 1396-1406.

Smith, D.G. and Smith N.D., 1980. Sedimentation in Anastomosed River Systems: Examples from Alluvial Valleys Near Banff, Alberta, Journal of Sedimentary Petrology, 50, 1, 0157-0164.

Sting/Swift User's Manual ver 3.0.10 Feb 2001

Telford, W.M., Geldart, L.P., Sheriff, R.E., and Keys, D.A., 1990. Applied Geophysics, 2nd Edition, Cambridge University Press, Cambridge.

Tong, L. and Yang, C., 1990. Incorporation of Topography into Two-Dimensional Resistivity Inversion, Geophysics, 55, 3, 354-361.

Törnqvist, T.E., 1993. Fluvial Sedimentary Geology and Chronology of the Holocene Rhine-Meuse Delta, The Netherlands, Utrecht: Koninklijk Nederlands Aardrijkskundig Genootschap/Faculteit Ruimtelijke Weteschappen, Universiteit Utrecht (Nederlandse Geografische Studies 166).

van Dijk, G.J., Berendsen, H.J.A., and Roeleveld, W., 1991. Holocene Water Level Development in the Netherlands River Area; Implications for Sea-Level Reconstruction, Geologie en Mijnbouw, 70, 311-326.

Ward, S.H., 1990. Resistivity and Induced Polarization Methods, in S.H. Ward ed., Geotechnical and Environmental Geophysics, Volume 1, 147-190.

Wolfe, P.J., Richard, B.H., Hauser, E.C. and Hicks, J.D., 2000. Identifying Potential Collapse Zones under Highways, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, February 20-24, Arlington, Virginia.

APPENDIX A. GUIDELINES FOR ERGI SURVEYING

This appendix is intended as an easy to use reference that will provide a researcher will all the basic information necessary to conduct an effective ERGI surveying campaign. It is a combination of results from informal, inferential, and anecdotal ERGI methodology experiments, an extensive review of published and unpublished research, and three years of dedicated experiential learning. The material is presented in an informal tone and is organized into categories that should prove relevant to a researcher in the field.

The two following appendixes should also be useful for researchers conducting ERGI surveys. Appendix B describes electrode arrays in more detail than there was room for within chapter 4 and 5. Appendix C breaks the entire ERGI surveying process down into 12 easy to follow steps.

A.1 ERGI Site Selection

- Sediments of interest should have a high resistivity contrast. Often contrast simply stems from a reasonable grain size difference (silt clay vs. sand gravel). Subtle contrasts can be imaged if there are no high contrast materials in the survey to overwhelm the difference between the signals from the low contrast materials.
- Sediments image best if they are massive: without internal structure or bedding. Although for most of our projects no real anisotropic problems will

occur, the method can not discern a difference between a mixture of sand and mud and finely interbedded sand and mud.

- Lateral facies changes greatly enhance the clarity of the profiles and the ease of interpretation. ERGI is, as discussed here, a 2D method and there are better methods to answer 1D questions.
- ERGI profiles work best if there are no lateral facies changes to either side of the survey line; try not to ask a 2D method to answer a 3D question.
- The water table will be displayed in ERGI profiles. It is best to know in advance the approximate depth of the water table so that it is not accidentally interpreted as a lithofacies change.
- Low contact resistance (resistance between the electrode stake and the ground) is critical to good data, so sites with moist conductive sediments at the surface produce the best profiles. Although ERGI data can be collected with dry sand and gravel or scree at the surface, it's more work and produces noisier data.
- Straight surveys produce the best data. Curves in the survey line violate the assumptions in equation 5 resulting in erroneous resistivity measurements. A curve may actually generate a fallacious feature in the ERGI profile similar to a buried channel.

A.2 ERGI Resolution and Depth of Investigation

- Depth of penetration for an ERGI measurement is not worth discussing because it is for all practical purposes infinite.
- Depth of investigation is a term used in this thesis to describe the depth where half of the electrical current flowing for an apparent resistivity measurement flows above this depth and half flows below. All material above the depth of investigation and a large amount of the material below the depth of investigation contributes to the measurement.
- Depth of investigation is approximately 1/5 of the survey line's total length. Although formulas exist to calculate the exact depth of investigation for each electrode array (Roy and Apparoa, 1971; Barker, 1989; Ward, 1990), they are only accurate for 100 % homogeneous materials.
- Resolution of the ERGI profiles is approximately 1/2 of the electrode spacing (pers. comm., Loke, 1999). Resistivity measurements decrease in resolution with depth, so we have to say either that the resolution or the mathematical uncertainty of the ERGI profiles increases with depth.
- Depth of investigation and resolution are a trade-off dependant on the electrode spacing and the total number of electrodes. For example, 56 electrodes spaced 12 m apart measured with a Wenner electrode array produces an ERGI profile 110 m deep with 6 m resolution. Conversely, 56

electrodes spaced 2 m apart measured with a Wenner electrode array produces an ERGI profile 18.3 m deep with 1 m resolution.

A.3 ERGI Data Improvement

- Keep all connectors clean! Keep covers on connectors until they are in use. Blow the connecters out with air to remove dust and debris every time you connecting them. Every five or ten surveys blow the connectors out with electrical contact cleaner.

- Clean the electrodes! Simply brushing the electrode with fine or medium steel wool every other survey will result in a substantial decrease in noise.

- Inspect the edges of the platforms on the electrode stakes. All contact between the electrode and the stake occurs on the inside edges of the top and front of the electrode stake platform. If this edge becomes burred by bashing against other stakes while in transport or by poor mallet technique while driving the stakes into the ground, contact between the stake and the electrode is substantially reduced and noisier data will result. A quick pass with a file eliminates this problem.

- Do not wiggle the electrode stakes. Tripping on the cable, adjusting the electrode, rotating the electrode so you can see the number, etc alters and most likely decreases the area of contact between the electrode stake and the ground and noisier data will result. ALWAYS put the electrode on the stake before inserting it into soft ground, this makes a HUGE difference to data quality.

- Placing slack cable to one side, laid out so that it does not loop or cross itself, eliminates any chance of self-induced inductive noise in the cable. However, it will get in your way and perhaps trip you (see above). A happy medium is to spread it out as much as possible, but always to the same side of the survey chain so that foot or vehicle travel along the survey is possible in a cable free zone.
- Less current means better data. Use the lowest possible amperage setting that provides clean data to reduce charge-up effects, get much cleaner data, and avoid INOVL errors.
- Longer measurement cycles (see the Sting/Swift User Manual for details, 2001) improve the data. However, if you are doing everything else right, it will be a negligible improvement. For regular surveys, use the shortest time cycle to obtain the most data in the least time. For problem surveys, consider longer cycles and bring a book.
- Surveys should image around twice the depth of the target of interest. ERGI profiles are much clearer and easier to interpret if the model has sufficient data to 'resolve' the bottom and sides of features.
- If at all possible, reduce your contact resistance. Keep it below 1 kΩ!

A.4 Electrical Contact Resistance

Contact resistance is a measure of how well electrical current can pass from the electrode stakes into the ground. Often achieving and maintaining low contact resistance is difficult and frustrating. However, a single electrode stake with high contact resistance will produce 'striping' in the resistivity pseudo-section. If several adjacent electrode stakes have high contact resistance, it may lead to artificial features in the resultant ERGI profile. Note that repeated contact resistance tests may lead to 'charge-up effects' and noisy data.

The 'built-in' contact resistance test in AGI's Sting simply records the electrical resistance between each electrode and it's neighbour. Because only two electrodes are used for the measurement, it is not a resistivity measurement and tells us very little about the sediment except for its ability to pass electrical current to and from an electrode stake.

For the best data, contact resistance should be below 1 kΩ. Lower is better. Other researchers have collected useful, albeit noisy, resistivity data at MΩ's of contact resistance. At that level, only the coarsest interpretation would be possible.

- Often simply reinserting the electrode into the ground in a new hole will resolve the problem.

- Sometimes a half-liter of salt water is necessary to build up a 'bulb' of conductive sediment around the stake. We've found pickling salt to be the best value.
- In particularly dry sediments, wetting the ground around the stake is not enough. When crossing open sand on crevasse-splays we dug a shallow trench (10 cm deep by 30 cm wide) along the entire survey line, covered the base of the trench with salt, and poured copious water into the trench (10 liters/meter). We would leave the site overnight then follow standard salting and wetting procedures to collect data the next day. Other researchers claim to have used sponges saturated with salt solution or even saturated diapers to increase the area of electrical contact (L. Langmanson, pers. comm., 2000).
- In loose materials, such as open matrix scree, other researchers have had success using long electrode stakes (>2m of rebar) and large sponges at the ground's surface to obtain reasonable contact resistance (D. Chapellier, pers. comm., 2000).
- Highly electrically conductive sediments can have odd contact resistance behavior a few hours after a hard rain. The deeper the electrode stakes penetrate the ground, the more inconsistent the readings and the more errors encountered. By resetting the stakes into the ground to about 5 cm of penetration, problems may be avoided.
- In frozen ground, we have had moderate success penetrating through to unfrozen sediments by driving the stakes in a great depth. Other researchers

have had success using large (2.5 cm X 1.25 m) stainless steel electrode stakes to obtain contact with frozen ground (G. Nimek, pers. comm., 2001)

- If you are considering ERGI at a site, but are hesitant because the ground appears too dry to get good contact, set up 2 to 4 electrodes right beside your vehicle and do a contact resistance test. If the contact resistance is extremely high for this 'quick and dirty' test, you'll know *before* you've spent an hour setting up an entire survey that extraordinary measures would be necessary to achieve sufficiently low contact resistance for the full line.
- On long survey lines, use two-way radios to communicate between the researcher running the contact test and the researcher troubleshooting the electrodes and electrode stakes. This vastly speeds up the process of getting a troublesome line into production.

A.5 Error Codes on the Sting

A setting on the Sting controls whether data collection stops on an error code or not. For most surveys, it is better to miss some data due to an error than to slow down production. However, contact resistance tests stop on errors. Always chase down and solve errors that occur during a contact resistance test.

For a contact resistance test, if the Sting stops on an error, you can repeat the failed measurement by pressing F1, or you can continue on to the next measurement by pressing F2. The most efficient method is to record all errors, continuing the test after each error, and trouble shoot the entire survey at once.

When you are ready to retry, set the test parameters to a few electrodes before your problem and start the contact test over.

A.5.1 The HVOVL Error Code

The HVOVL error code (high voltage overload) means that the Sting can not establish a current through the AB circuit. HVOVL errors are usually caused by cable connection problems, by power problems, or by extreme electrical contact resistance.

- You will get a HVOVL if the Sting's battery pack is low even if you are working with an external battery!
- You will get a HVOVL if the Swift is not turned on or if it shuts down due to low power.
- You will get a HVOVL if you are requesting to use electrodes that are not connected to the system (e.g. having electrodes 29-56 hooked up but the control file asks for 1-28).
- You will get a HVOVL if the cable or one of the electrodes is damaged and communication is interrupted. This can be tested by moving the Sting and Swift to the other end of the cable and determining which electrodes can be 'seen' from the other end.
- On rare occasions, this error shows up due to contact problems between an electrode, its stake, and the ground. We've had these occur due to a piece of grass being between the electrode and the stake.

A.5.2 The TXOVL Error Code

The TXOVL error code (transmitter overload) means that the signal through the AB circuit (current) is fluctuating. You have variable contact resistance in the AB circuit. Unless there are large IP or SP effects going on, simply treat as a contact resistance problem and solve it.

A.5.3 The INOVL Error Code

The INOVL error code (input overload) means that the input amplifier has been overwhelmed by the signal through the MN circuit (measurement). In other words, the voltage being measured is too high for the meter. Usually the Sting automatically steps down the current, which subsequently drops the voltage and solves the problem. If the Sting is unable to make a reading even after stepping down the current, the INOVL error code is displayed.

If you are losing a great deal of data to INOVL errors, consider reducing the max current on the Sting: remember that less current leads to better readings. Other possible solutions include resetting the problem electrode stakes in new holes or resetting the entire survey with larger electrode spacing.

A.6 General Improvements to ERGI Field Operations

- Don't use the cable shipping crates supplied by the equipment manufacturer while in the field. Use smaller plastic boxes with one cable (14 electrodes) per box. This makes cable coiling much faster. Any commercially available plastic box is lighter than the shipping crates, and only having one cable per box really increases their ease of mobility. Any commercially available plastic box is more user friendly than the shipping crates because they don't have nasty sharp metal corners that tear equipment and researchers.

- Obtain a two-wheeled lawn cart to haul around the equipment in the field. Coiling cable into a box on a cart is much easier on the researchers' backs than leaning over all day and reduces the number of times the cable box must be lifted.
- Always take more rubber bands with you for attaching the electrodes to the stakes than you think you could ever use. Nothing is more aggravating than running out of rubber bands after spending many hours getting to a site and spending most of an hour setting up a survey…
- Use some form of survey flags, such as wire stake seismic flags, to mark off the end of your survey chain and various points along the survey chain. This makes setting up a straight survey much easier. It also makes locating the ends of your survey simple if further investigation is required on a later date.
- The most data in the least time can be gathered by first collecting a large spacing survey, then collecting smaller spacing surveys over targets of interest as shown in the preliminary survey. We prefer conducting a 10 m, a 5 m, and then a 2 m survey at each location. Frequently the 10 m survey is the only survey to cover the entire horizontal extent of the survey site.

- Avoid all livestock and in particular cattle! They find the resistivity gear very interesting and quite tasty. A cow is quite capable of inflicting substantial damage to the resistivity gear by simply having a chew or two or by stepping on the cable.

A.7 ERGI Data Processing

- RES2DINV is simple to use and the manual (Loke, 2000) is excellent.
- The simplest way to obtain a clear and easy to understand ERGI profile is to 'overparameterize the model'. Use the *Thickness of Model Layer Increase* option to set the model layer thickness to 0.5 or 0.25 of the electrode spacing, the layer thickness increase to 1.0, and allow the number of model blocks to exceed the number of data points. This vastly improves the apparent resolution, but because the data resolution has not improved, overparamaterizing decreases the certainty of the ERGI profile, particularly in the lower portion of the profile.
- Try all of the different settings and parameters available, but take good notes so you can reproduce, and justify, your results.
- Often a slight modification to the contour intervals or the colors of your ERGI profile will make interpretation much simpler. When comparing two or more profiles, consider using the same contour intervals for all the profiles. This may not be effective if the range of resistivity values in the profiles varies widely.

- For buried mud-encased sand channel-fills and crevasse-splay sheet-sands the *Horizontal/Vertical Flatness Filter*, the *Limit Range of Model Resistivity*, the *Reduce Effect of Side Blocks*, the *Use Robust Model Constraint*, and the *Use Topographic Correction* options typically produce the clearest ERGI profiles.

- Some ERGI data sets lend themselves to processing with one dimensional data inversion software. 1D inversions typically define the resistivity of layers and the thickness of the layers. This information is very useful for layered sedimentary deposits and much better constrained than an ERGI profile produced by RES2DINV. However, any 2D sedimentary structures will turn a 1D inversion into gibberish.

- Software, such as RESIX2D by Interpex, inverts 2D resistivity data into bodies with boundaries. This may be a better data inversion approach to investigate buried mud-encased sand channel-fills and crevasse-splay sheet-sands than the smooth cell-based approach used by RES2DINV.

A.8 AGI's Command Creator

- Command Creator is the software AGI provides to produce command files that control data collection on the Sting/Swift resistivity system. It is simple to use and very helpful for visualizing the data collection process.

- Note that Command Creator Version 1.2.1 has a 'bug' that doubles the estimated depth of investigation for dipole-dipole surveys.

- Note that Command Creator Version 1.2.1 has a 'bug' that keeps roll-along files from having the correct horizontal location for the first electrode. For example the first electrode on the first 14 electrode roll of a 2 m spacing survey line is 28 meters from the start of the survey line, but Command Creator will always set the first electrode position to zero. A simple way to work around this problem is to set the X-location in the *Array Set-up* option on the Sting to the correct location for the first electrode.

A.9 'Roll-Along' Surveying for ERGI

- Rolling fewer electrodes maintains the greatest depth of data. If you are not surveying to the maximum depth for an array, rolling more electrodes (28 instead of 14) may allow for a faster survey with little loss of data. Look at all options in command creator before making your decision.
- Roll along surveys can be very time efficient if you disconnect the first cable (e.g. 1-14) as soon as it is out of use, but while measurements are still occurring on the other cables (e.g. 15-56). Use command creator to determine which measurement is the last to use a particular electrode and after that measurement is collected, disconnect the cable and move it to it's location as required by the next round of data collection.
- Note that the command file for the fifth 14 electrode roll on a 56 electrode line is the same command file as the first roll! Remember to change the X-location for the first electrode though…

- Although data sets that contain many 'roll along's can slow down processing, your only limitation to the size of your data set is time, computer memory, and processing power. RES2DINV's set up program, Jacobwin, can be set to allow 2000 electrodes in one data set. The question becomes, what information are you gaining from such a large and difficult to handle data set? Could a larger spacing survey provide you with the outline you need then use several 'point' surveys for more detail where necessary? Or is the situation 1D enough to use overlapping 1D inversions?

APPENDIX B. UNDERSTANDING ELECTRODE ARRAYS FOR ERGI SURVEYS

The electrode selection command file running on the Sting determines the array type used for the survey. Different arrays have different depths of investigation, vertical sensitivity, and horizontal sensitivity. Each array also has a different vulnerability to noise. There are three different four-electrode arrays commonly used for multi-electrode resistivity surveying: the Wenner array, the Wenner-Schlumberger array, and the Dipole-Dipole array.

An array is simply the arrangement of the electrodes and the manner in which they are spread apart to increase the region of investigation's depth. The electrodes are set up AMNB for both the Wenner and Wenner-Schlumberger arrays. For the Dipole-Dipole array, the electrodes are set up ABMN.

To increase the depth of investigation for a Wenner array, the electrodes are spread apart while keeping the inter electrode distances even. To increase the depth of investigation for a Wenner-Schlumberger array, the current electrodes are spread apart, but the potential electrodes are kept as close together as possible while maintaining a reasonable voltage reading. To increase the depth of investigation for a Dipole-Dipole array, the inner dipole distance is maintained while the inter dipole distance is increased.

With the multi electrode arrays used for ERGI surveys, the distance between the electrodes is fixed (e.g. they are often set up 2 m apart). The command file can change the location of an apparent resistivity measurement by changing which electrodes it uses in the array. For example, the command file could use electrodes 1, 2, 3, and 4 to make the first measurement and then 2, 3, 4, and 5 for the next. Although both measurements have a 2 m electrode spacing the first is centered at 5 m along the survey line, while the second is centered at meter 7.

The command file also changes the depth of subsequent apparent resistivity measurements by changing which electrodes it uses in the array. For example, on the same survey line described above, the command file could use electrodes 4, 6, 8, and 10 to make the first measurement and 1, 5, 9, and 13 for the next. Although both measurements are centered 14 m along the survey line, the first has a 4 m electrode spacing and the second has an 8 m electrode spacing.

Note that for survey line set up, the term 'electrode spacing' describes the distance between each electrode and it's neighbours along the survey line, but for measurements, the term describes the distance between the electrodes actually used for data collection! For the last measurement described above, the survey line's electrode spacing was 2 m, but the measurement used every fourth electrode for a measurement electrode spacing of 8 m.

APPENDIX C. THE ERGI 12 STEPS...

1. Set up a survey chain in a straight line over the portion of the subsurface to be mapped.
2. Place the electrode stakes beside the survey chain at the chosen electrode separation.
3. Distribute the electrode cable along the survey chain with the electrodes adjacent to an electrode stake; place the slack cable to one side of the survey chain as neatly as possible.
4. Double check that the electrode and stake are at the correct location then: If the ground is soft (mud, grass, loose sand or gravel), attach the electrode to the stake, then insert the stake into the ground so that the electrode is one or two finger widths above the surface. If the ground is hard (packed gravel, till), drive the stake into the ground with a mallet until the electrode platform is one or two finger widths above the ground, then attach the electrode to the stake.
5. Set up the Sting and Swift and connect all necessary cables (they are coded and self-explanatory).
6. Run a contact resistance test. All electrodes should be below 1 kΩ.
7. Once all the settings are correct on the Sting, collect a data set (Press *Mea*).
8. While the data set is being collected, consider collecting topographic data for the survey line.
9. Download the data set to the laptop.
10. Convert the data set from a stg (AGI format) file to a dat file (RES2DINV format).
11. Invert the data.
12. Disassemble the equipment in the opposite order it was set-up.

APPENDIX D. COORDINATES FOR ALL OF THE DATA PRESENTED IN THE BODY OF THE THESIS

The coordinates for the ERGI surveys and for the vibracores were collected with a hand held GPS receiver. No corrections have been applied to the coordinates. Locations from the upper Columbia River, B.C., are described using Universal Transverse Mercator (UTM) coordinates relative to the WGS84 datum. Locations from the Rhine-Meuse Delta, the Netherlands are described using Dutch national grid system (NLRD - Rijksdriehoeksmeting Nederland) coordinates relative to the Bessel1842 datum.

	Start		End	
	Easting	**Northing**	**Easting**	**Northing**
ERGI Surveys				
BTC102	532171	5651760	532131	5651722
BTC103	532171	5651760	532131	5651722
BTC301	532230	5651817	532625	5652198
BLM101	532257	5651773	532403	5651893
BTS201	532365	5651566	532443	5651634
BTS401	532354	5651696	532442	5651586
HMS101	533527	5650415	533599	5650494
HMS201	533503	5650466	533586	5650398
Vibracores				
BTS2-74	532421	5651615		
HMS1-23.3	533543	5650432		

Table 1 UTM Coordinates for data from the upper Columbia River, B.C.

	Start		End	
	Easting	**Northing**	**Easting**	**Northing**
ERGI Surveys				
CS101	110235	436094	110217	435827
CS102	110235	436094	110217	435827
CS103	110235	436094	110217	435827
CS104	110235	436094	110217	435827
CS105	110235	436094	110217	435827
CS106	110235	436094	110217	435827
CS107	110235	436094	110217	435827
CS108	110235	436094	110217	435827
NL9309101	116905	431075	116927	431275
NL9309103	116905	431075	116927	431275
NL9309201	116905	431075	116921	431187

Table 2 NLRD coordinates for data from the Rhine-Meuse Delta, the Netherlands.

APPENDIX E. META-DATA AND PSEUDOSECTIONS

This appendix includes meta-data and pseudosections for all of the ERGI profiles included in this thesis. The meta-data includes diagrams showing the relative size and location of the surveys when they either overlap or intersect and tables that show the timing of data collection for all portions of each ERGI survey.

Both the measured apparent resistivity pseudosections and the calculated apparent resistivity pseudosections have been included as a qualitative tool to assess the ERGI data sets. Pseudosections are diagrams that show apparent resistivity values plotted against pseudo-depth. Neither measured apparent resistivity values (what the instrument records in the field) or calculated apparent resistivity values (what the inversion process generates during data modeling) can be plotted against real depth (see Chapter 4 ERGI Theory). No interpretation or analysis should be attempted on apparent resistivity pseudosections.

The resistivity images for each survey are presented in the standard format for output from RES2DINV:

1. The measured apparent resistivity pseudosection.
2. The calculated apparent resistivity pseudosection.
3. The inverse modeled resistivity section (ERGI profile).

E.1 Data from the Upper Columbia River, British Columbia

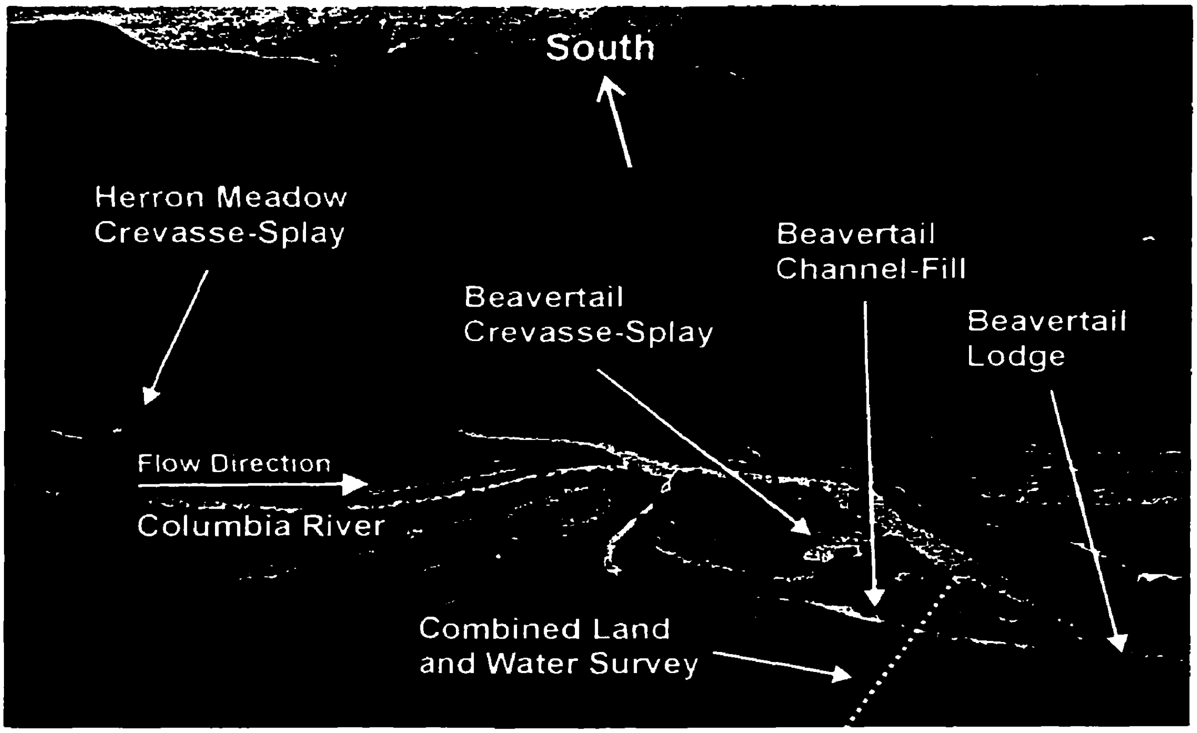


Figure 28 Oblique aerial photograph showing the relative location of the ERGI study sites on the upper Columbia River in British Columbia. The reach of river shown in the photo is approximately 2.5 km long.

Location	Survey Series	Survey Number	Survey Goal	See Thesis Section
Beavertail Channel-Fill	BTC1	BTC101 BTC103	Comparing Arrays	7.2
"	BTC3	BTC301	Combining Land and Water	7.1
"	BLM1	BML101	Imaging Channel-Fills	6.1
Beavertail Crevasse-Splay	BTS2 BTS4	BTS201 BTS401	Imaging Crevasse-Splays	6.2
Herron Meadow Crevasse-Splay	HMS1 HMS2	HMS101 HMS201	Imaging Crevasse-Splays	6.2

Table 3 Location, survey series, survey number, survey goal, and cross-reference thesis section number for data from the upper Columbia River, B.C.

E.1.1 Beavertail Channel-Fill and Area, B.C.

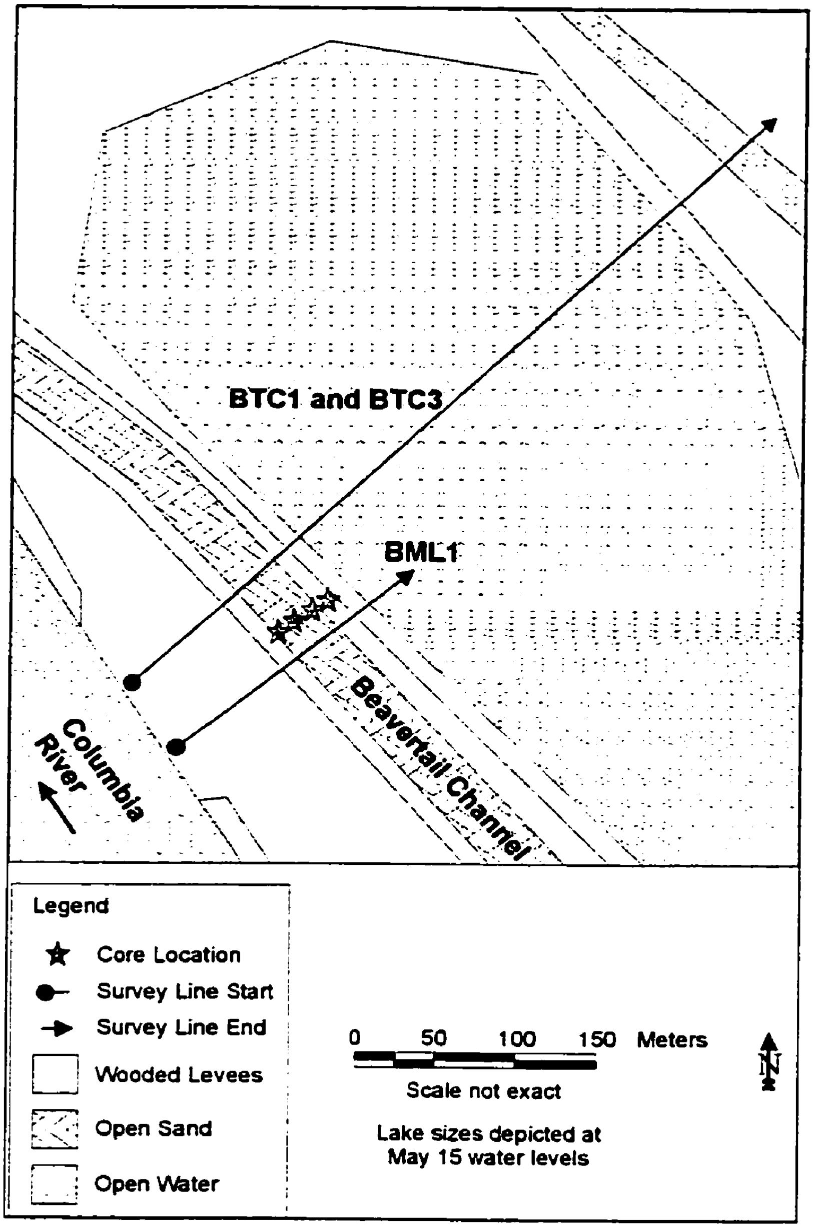


Figure 29 Diagram showing the relative location of the ERGI surveys conducted across the Beavertail channel-fill and area.

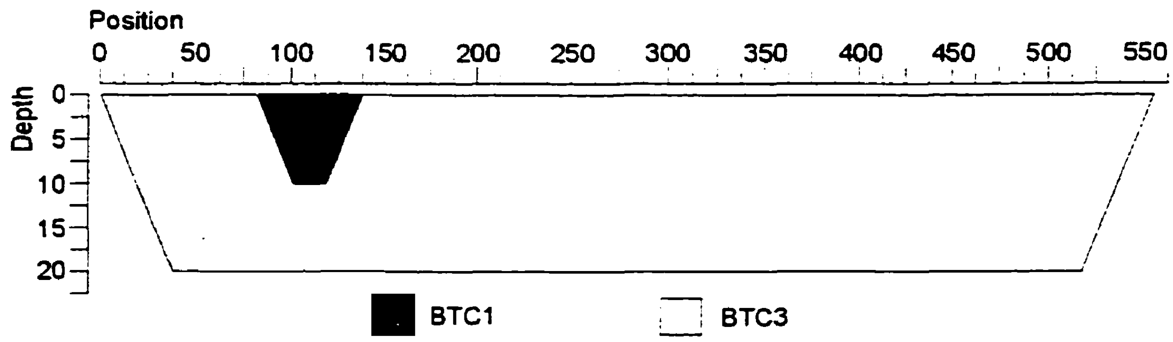


Figure 30 A diagrammatic representation of the relative size and location of ERGI survey series BTC1 and BTC3. Survey BTC301 (series BTC3) was collected for the combination land and water ERGI survey field experiment (see section 7.1).

	Spacing	Array	Electrodes	Portion	Date	Time	Comments
BTC102	1 m	W	56	All	07-Apr-00	15:44	
BTC103	1 m	D	56	All	07-Apr-00	17:11	
BTC301	5 m	W	56	Main	09-Apr-00	15:39	
				Roll 1 (28)	17-Apr-00	14:55	
				Roll 1a(28)	17-Apr-00	15:46	Roll 1 repeated due to lost data
				Roll 2 (28)	18-Apr-00	12:05	
				Roll 2a(28)	18-Apr-00	13:46	Roll 2 repeated due to lost data (polarity reversed)
BML101	2 m	W	56	Main	27-Apr-00	16:42	
				Roll 1 (14)	28-Apr-00	9:57	
				Roll 1a(14)	13-May-00	14:10	Roll 1 repeated due to lost data
				Roll 2 (14)	28-Apr-00	12:05	All data completely lost due to instrument failure.
				Roll 2a(14)	13-May-00	15:28	Roll 2 repeated due to lost data
				Roll 3 (14)	13-May-00	16:49	
				Roll 3a(14)	13-May-00	17:45	Roll 3 repeated due to lost data

Table 4 Meta-data for ERGI surveys on the Beavertail channel-fill and area. In this table, the Wenner electrode array is represented by the symbol 'W' and the dipole-dipole array is represented by the symbol 'D'.

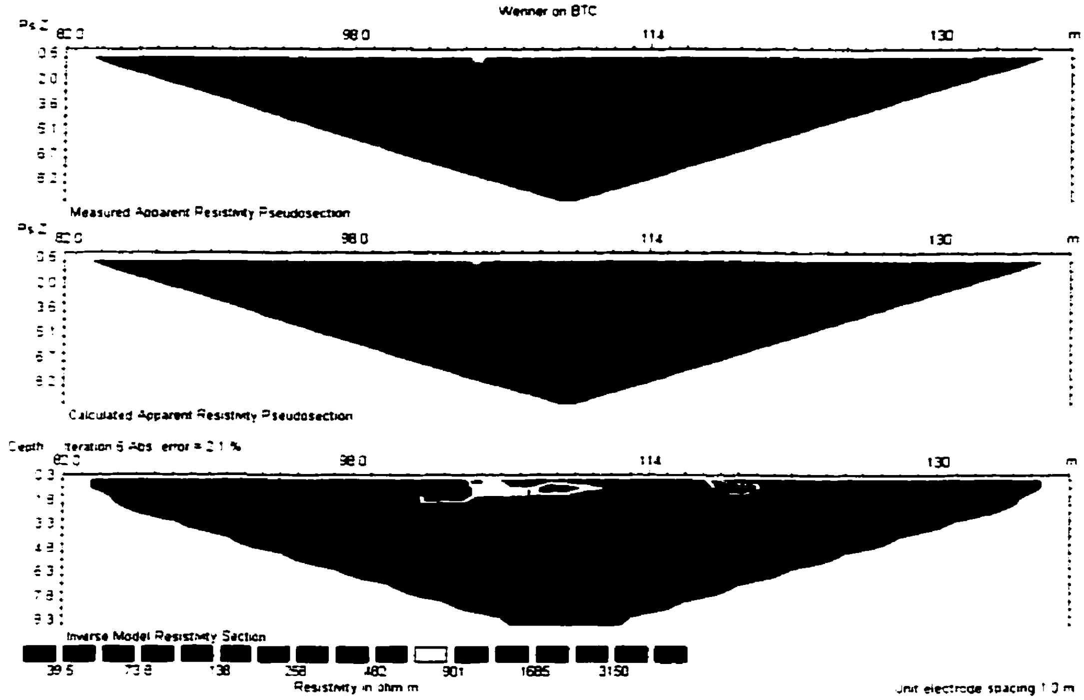


Figure 31 ERGI Survey BTC102.

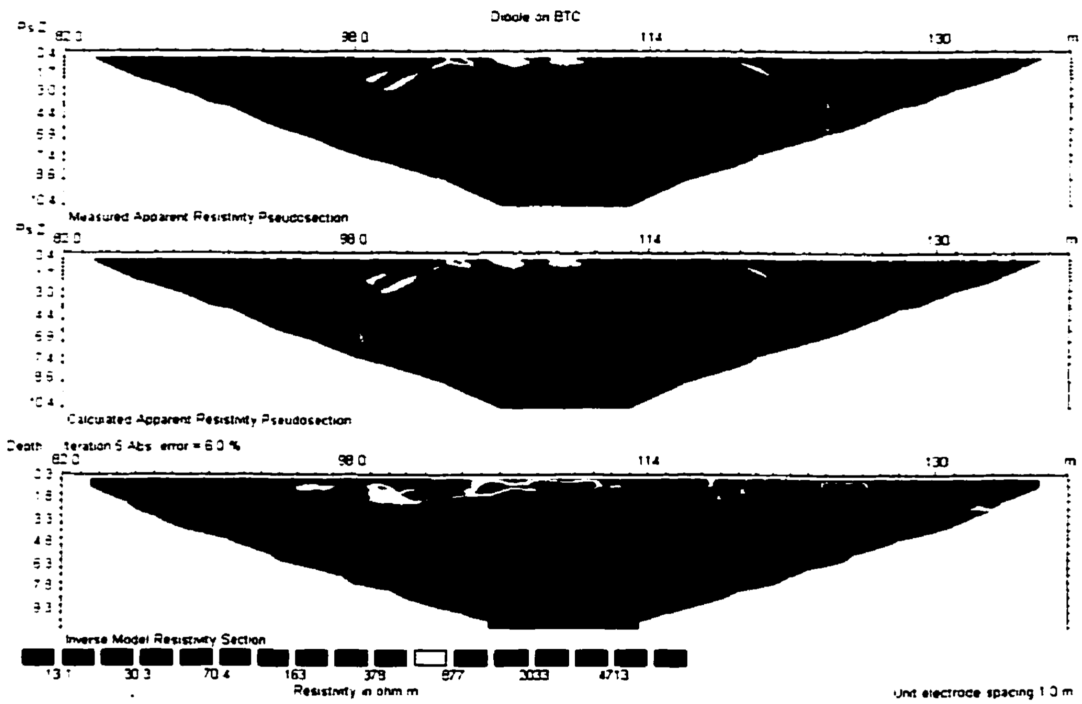


Figure 32 ERGI Survey BTC103.

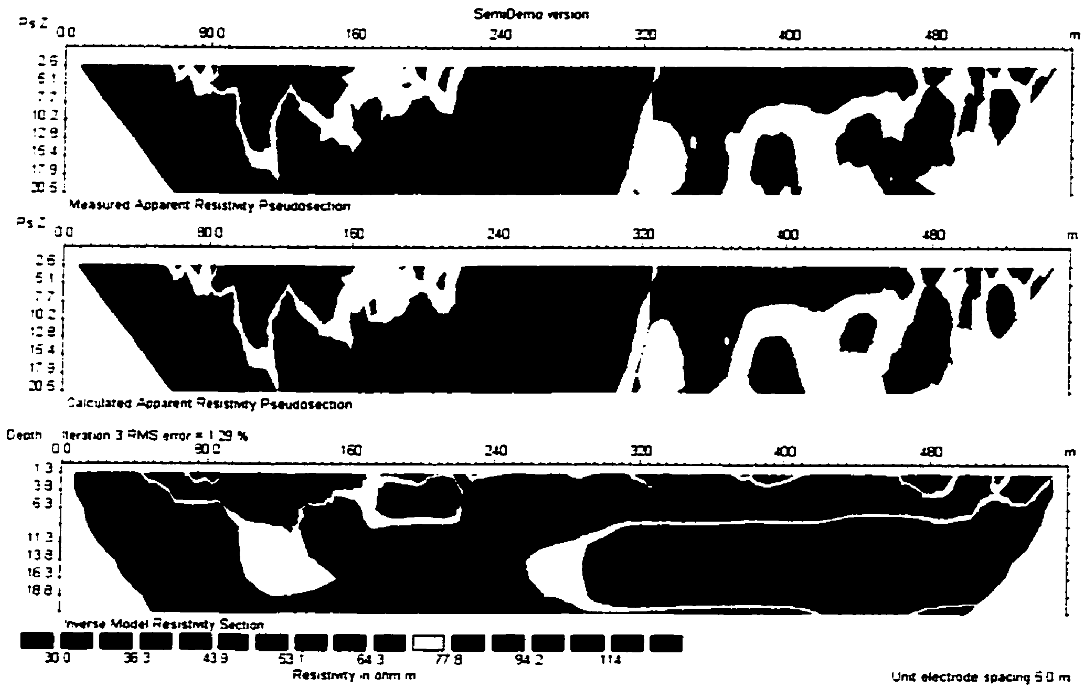


Figure 33 ERGI Survey BTC301.

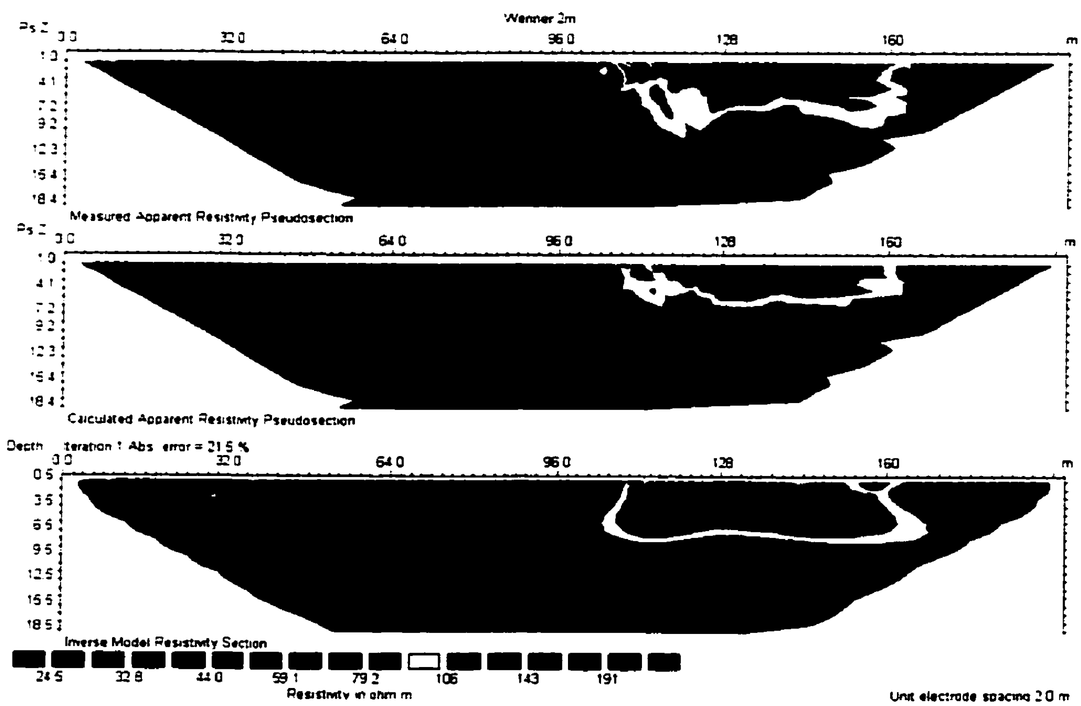


Figure 34 ERGI Survey BML101.

E.1.2 Beavertail Crevasse-Splay, B.C.

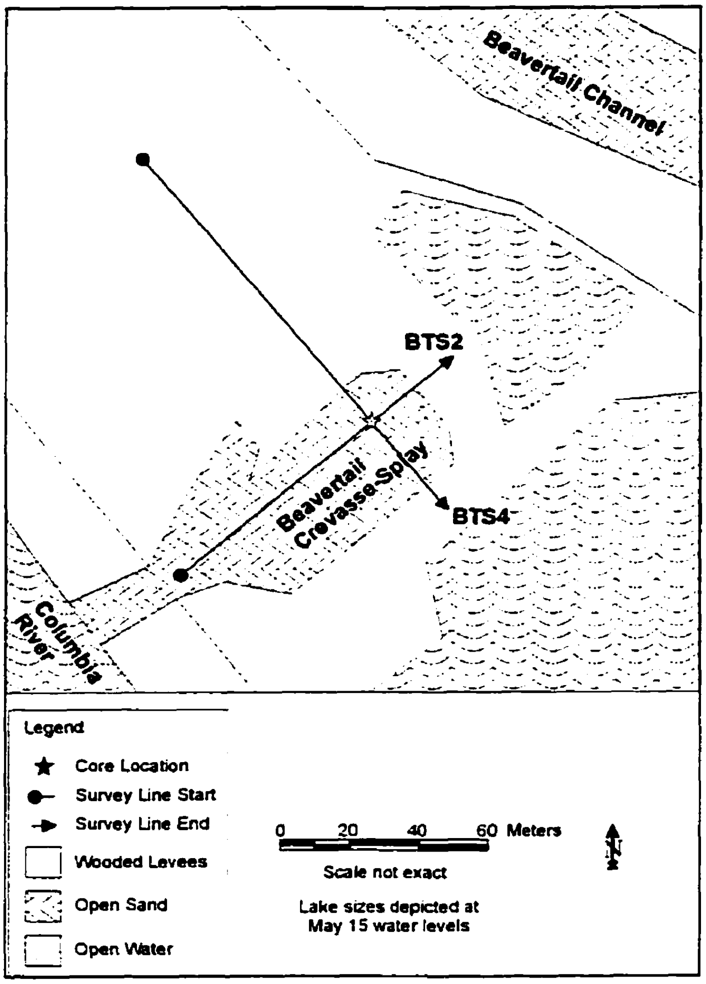


Figure 35 Diagram showing the relative location of ERGI surveys BTS2 and BTS4 on the Beavertail Crevasse-splay.

	Spacing	Array	Electrodes	Portion	Date	Time	Comments
BTS201	2 m	W	54	All	14-May-00	16:51	
BTS401	2 m	W	56	Main	16-May-00	16:26	
				Roll 1 (14)	16-May-00	17:55	

Table 5 Meta-data for ERGI surveys BTS2 and BTS4 on the Beavertail Crevasse-splay. In this table, the Wenner electrode array is represented by the symbol 'W'.

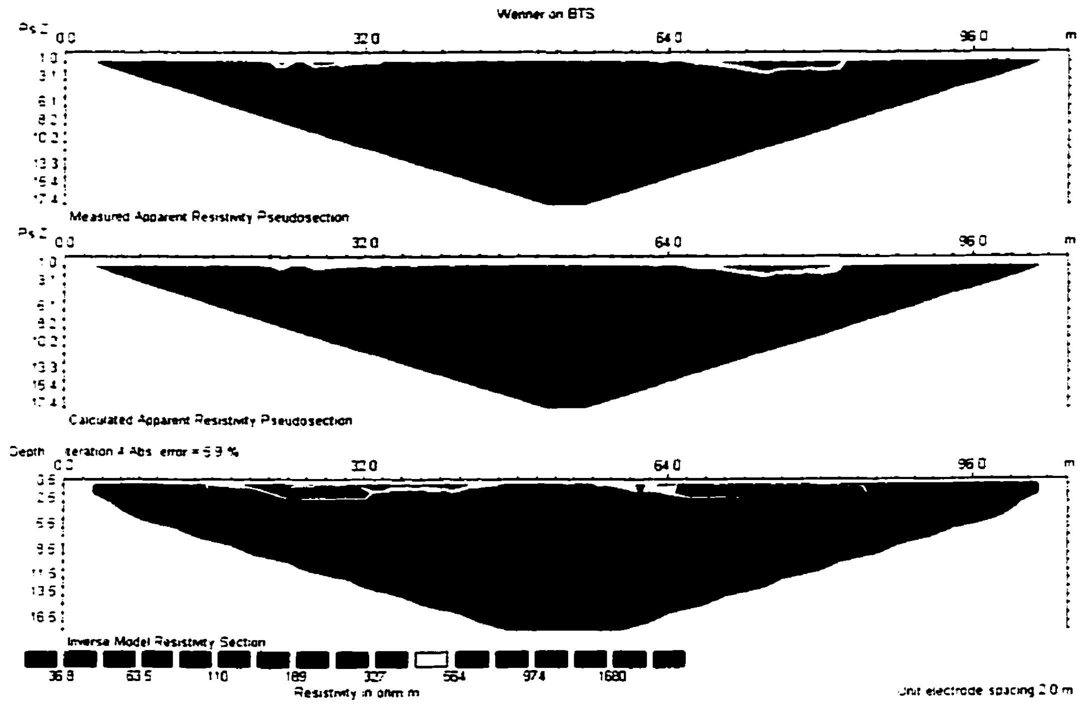


Figure 36 ERGI survey BTS2

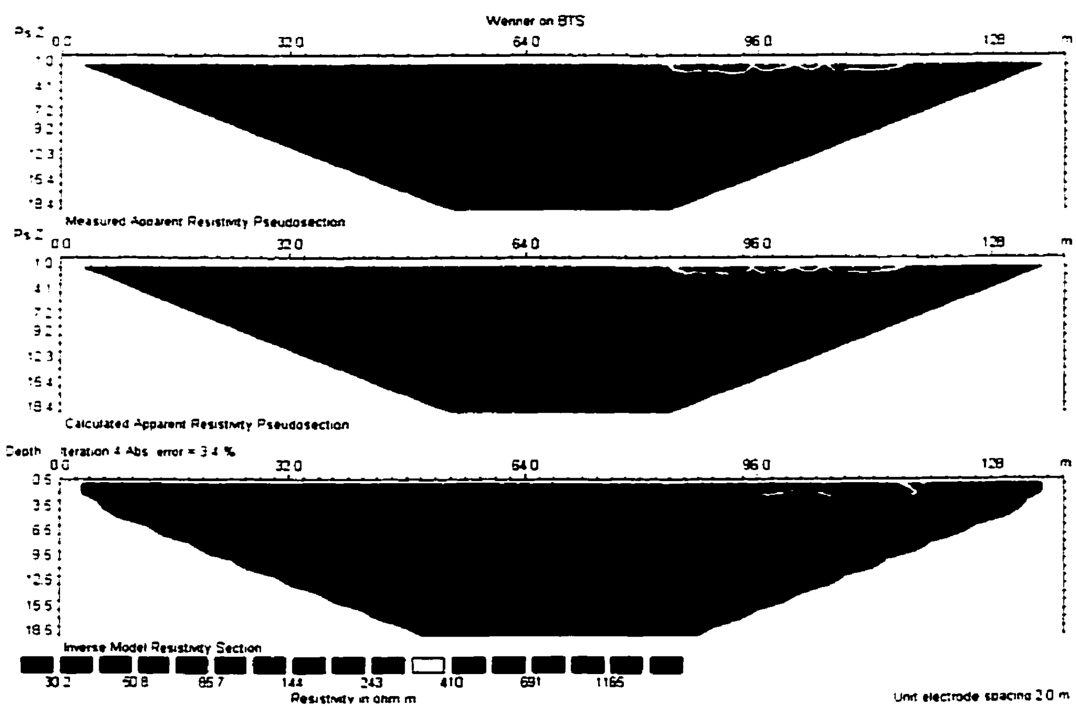


Figure 37 ERGI survey BTS4

E.1.3 Herron Meadow Crevasse-Splay, B.C.

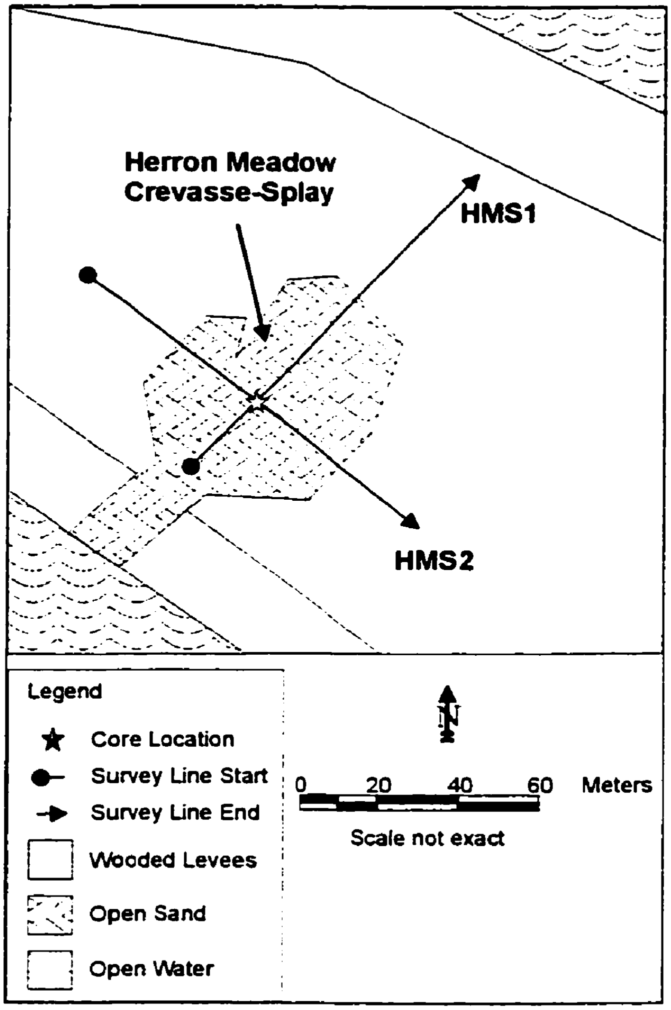


Figure 38 Diagram showing the relative location of the 2 ERGI surveys conducted on the Herron Meadow Crevasse-Splay.

	Spacing	Array	Electrodes	Portion	Date	Time	Comments
HMS101	2 m	W	51	All	21-May-00	11:08	
HMS201	2 m	W	56	All	21-May-00	13:08	

Table 6 Meta-data for the ERGI surveys on the Herron Meadow crevasse-splay. In this table, the Wenner electrode array is represented by the symbol 'W'

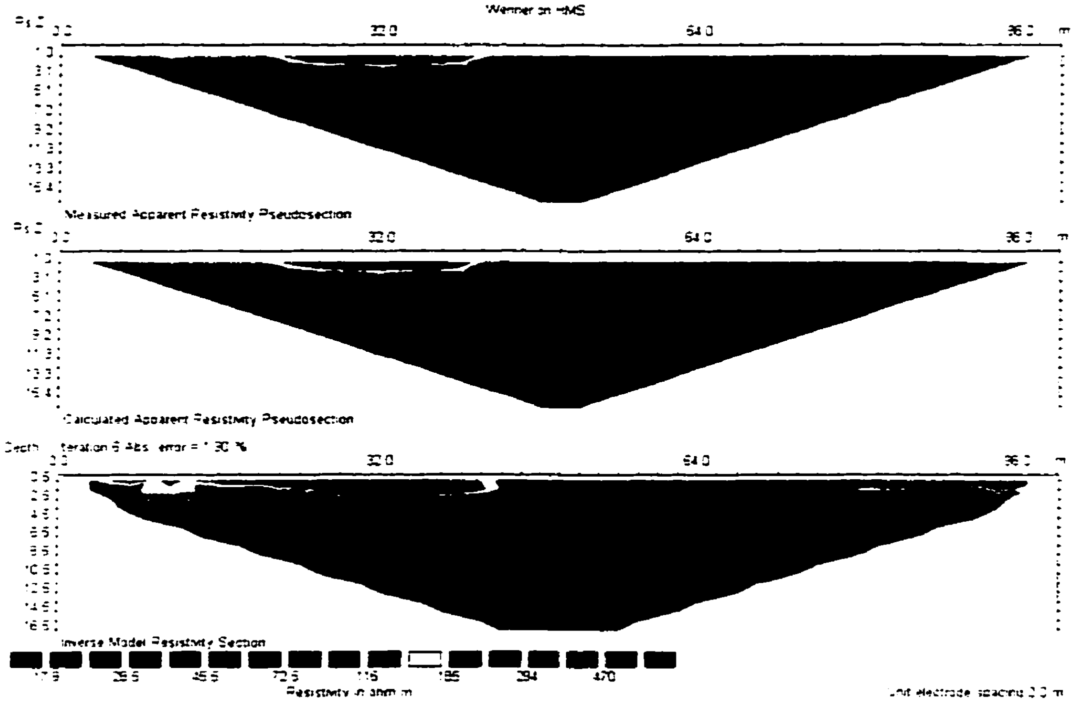


Figure 39 ERGI survey HMS1.

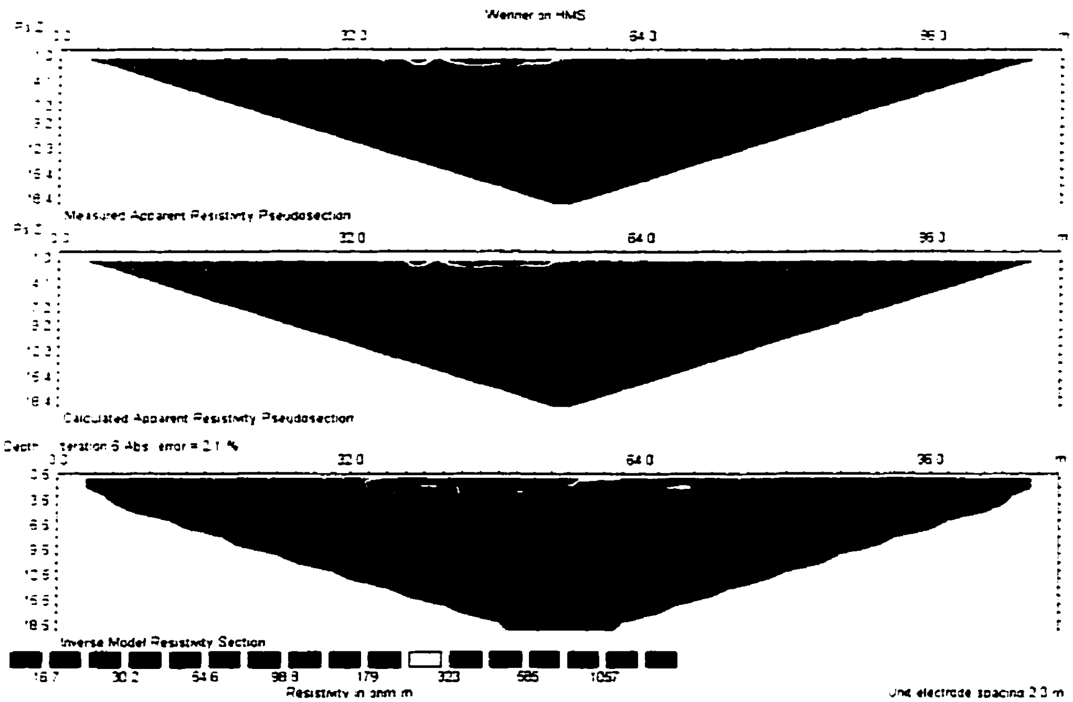


Figure 40 ERGI survey HMS2

E.2 Data from the Rhine-Meuse Delta, the Netherlands

Location	Survey Series	Survey Number	Survey Goal	See Thesis Section
Schoonrewoerd Channel-Fill	NL93091	NL9309101 NL9309103	Comparing Arrays	7.2
"	NL93092	NL9309201	Imaging Channel-Fills	6.1
Unnamed Channel-Fill by the Lek River	CS1	CS101 CS102 CS103 CS104 CS105 CS106 CS107 CS108	Examining Cumulative Electrode Charge-up	7.3

Table 7 Location, survey series, survey number, survey goal, and cross-reference thesis section number for data from the Rhine-Meuse Delta, the Netherlands.

E.2.1 Schoonrewoerd Channel-Fill, the Netherlands

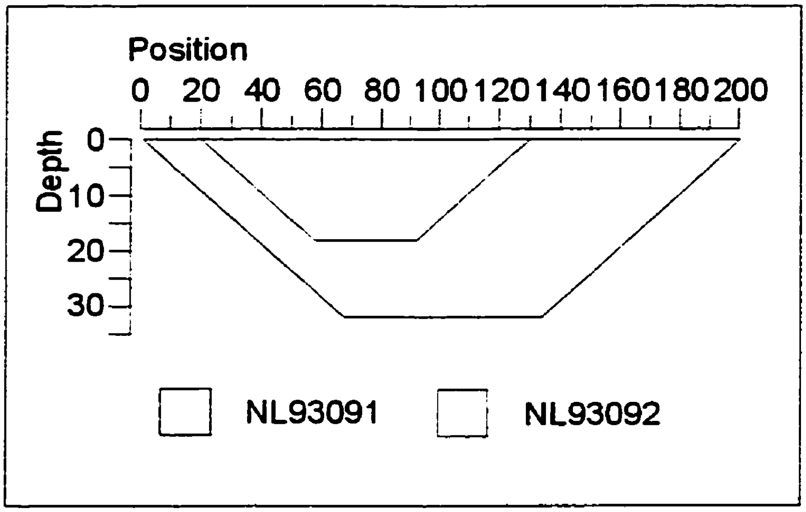


Figure 41 A diagrammatic representation of the relative size and location of the ERGI surveys on the Schoonrewoerd channel-fill.

	Spacing	Array	Electrodes	Portion	Date	Time	Comments
NL9309101	1 m	W	21	All	07-Sep-00	11:44	
NL9309103	1 m	D	21	All	07-Sep-00	12:31	
NL9309201	2 m	W	56	All	07-Sep-00	14:15	

Table 8 Meta-data for ERGI surveys on the Schoonrewoerd channel-fill. In this table, the Wenner electrode array is represented by the symbol 'W' and the dipole-dipole array is represented by the symbol 'D'.

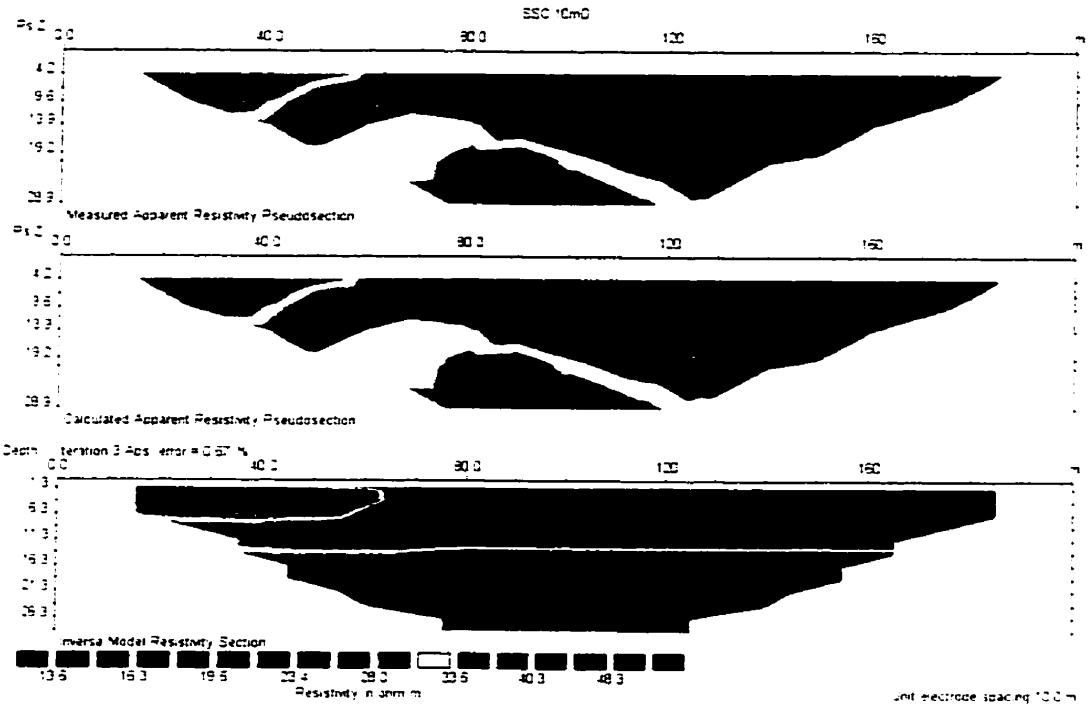


Figure 42 ERGI survey NL9309101.

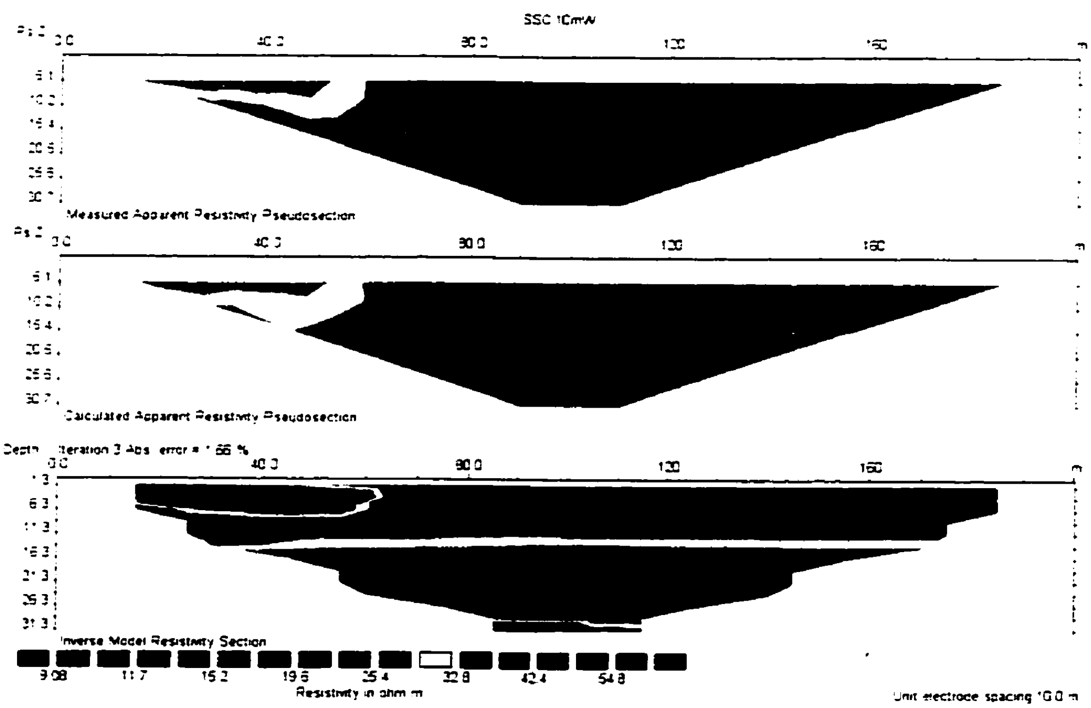


Figure 43 ERGI survey NL9309103.

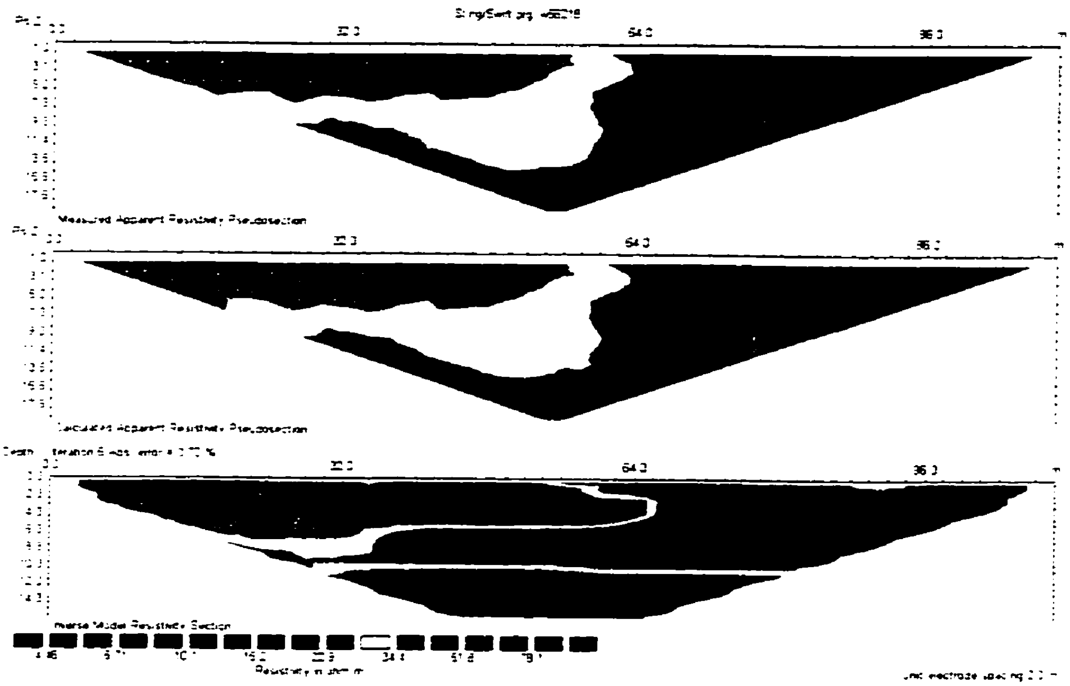


Figure 44 ERGI survey NL9309201.

E.2.2 Unnamed Channel-Fills by the Lek River, the Netherlands

	Spacing	Array	Electrodes	Portion	Date	Time	Comments
CS101	10 m	W	28	All	21-Sep-00	11:16	
CS102	10 m	S	28	All	21-Sep-00	11:36	
CS103	10 m	W	28	All	21-Sep-00	12:24	
CS104	10 m	S	28	All	21-Sep-00	12:47	
CS105	10 m	W	28	All	21-Sep-00	13:11	
CS106	10 m	S	28	All	21-Sep-00	13:32	
CS107	10 m	W	28	All	21-Sep-00	13:59	
CS108	10 m	S	28	All	21-Sep-00	14:52	

Table 9 Meta-data for ERGI surveys at the study site adjacent to the Lek River. In this table, the Wenner electrode array is represented by the symbol 'W' and the Wenner-Schlumberger array is represented by the symbol 'S'.

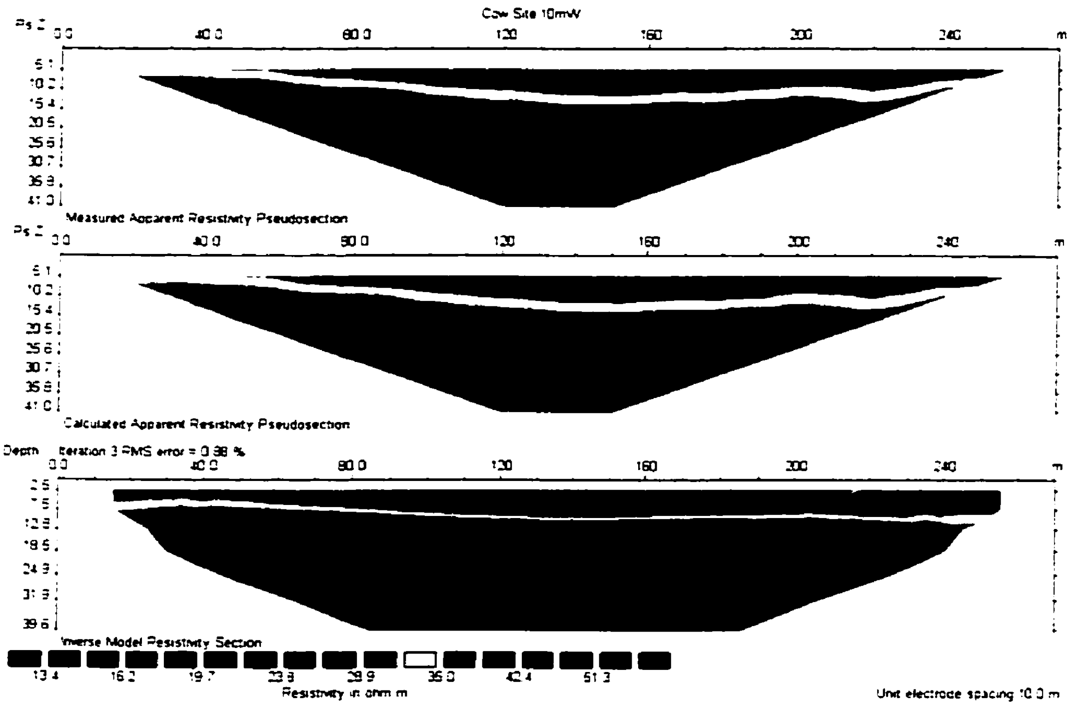


Figure 45 ERGI survey CS101.

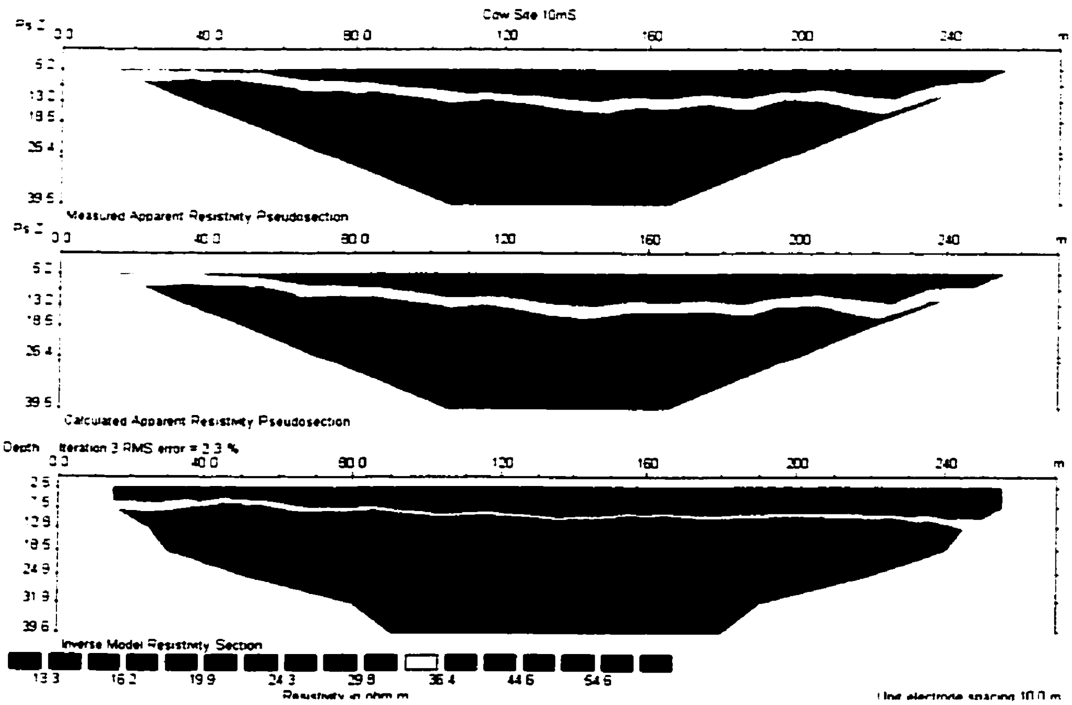


Figure 46 ERGI survey CS102.

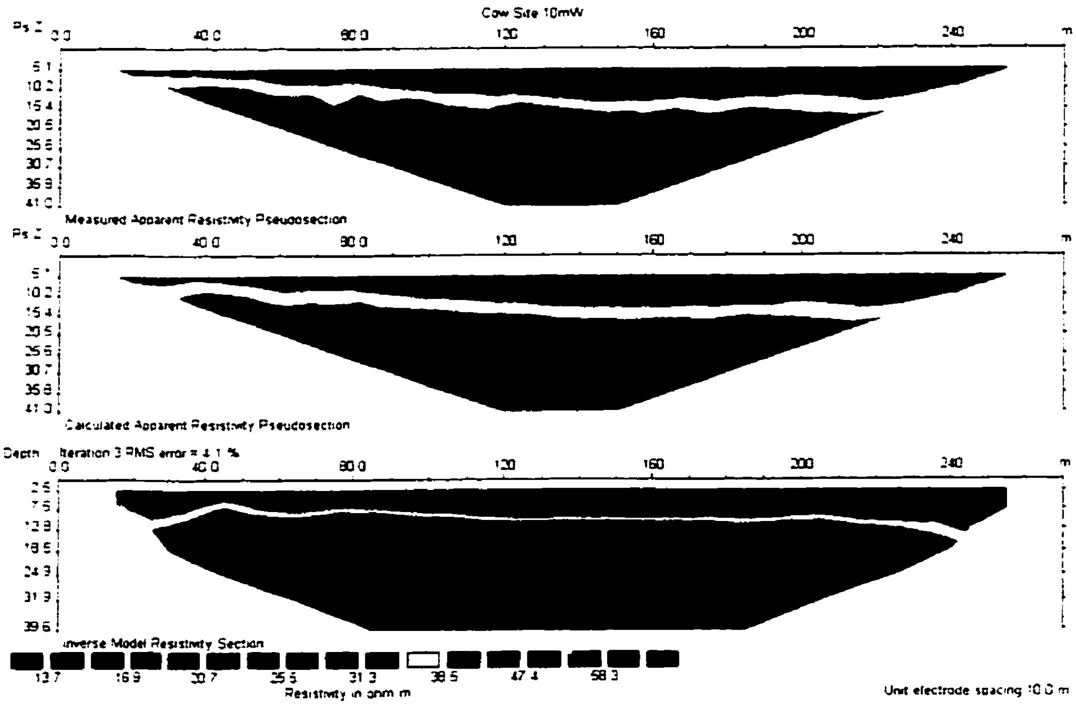


Figure 47 ERGI survey CS103.

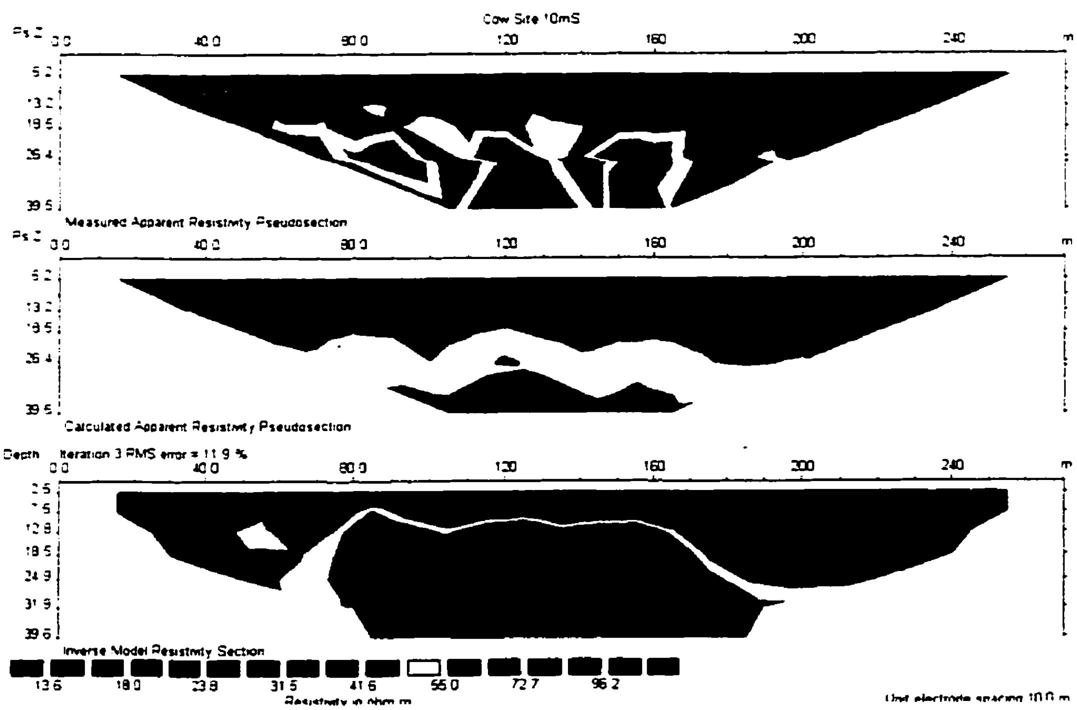


Figure 48 ERGI survey CS104.

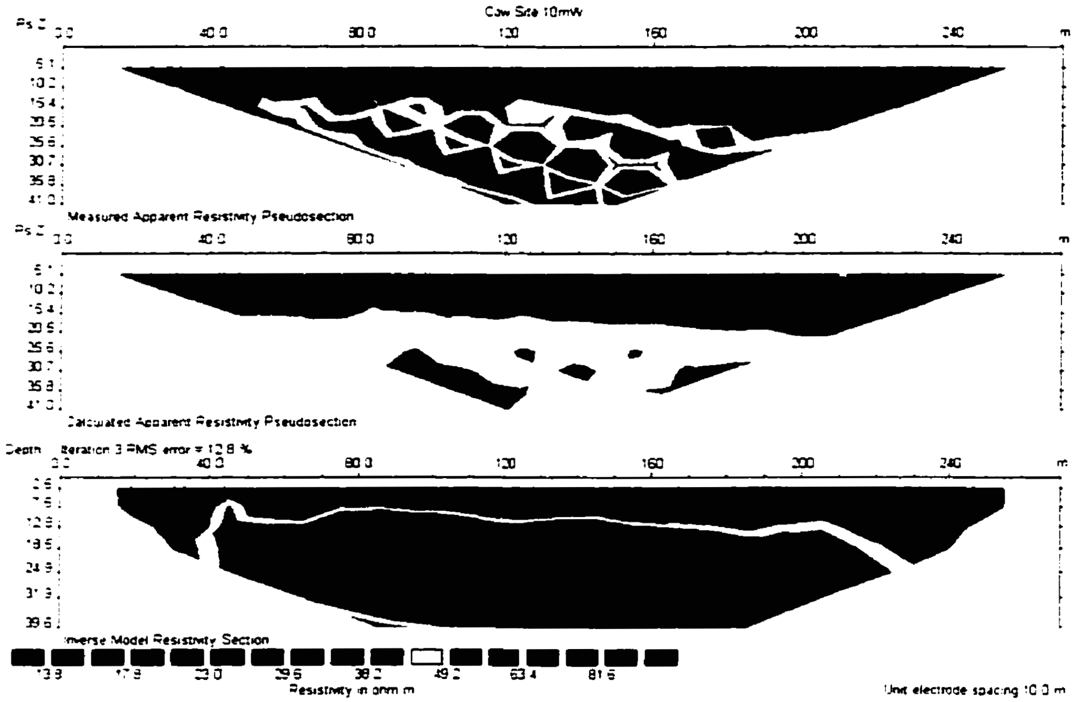


Figure 49 ERGI survey CS105.

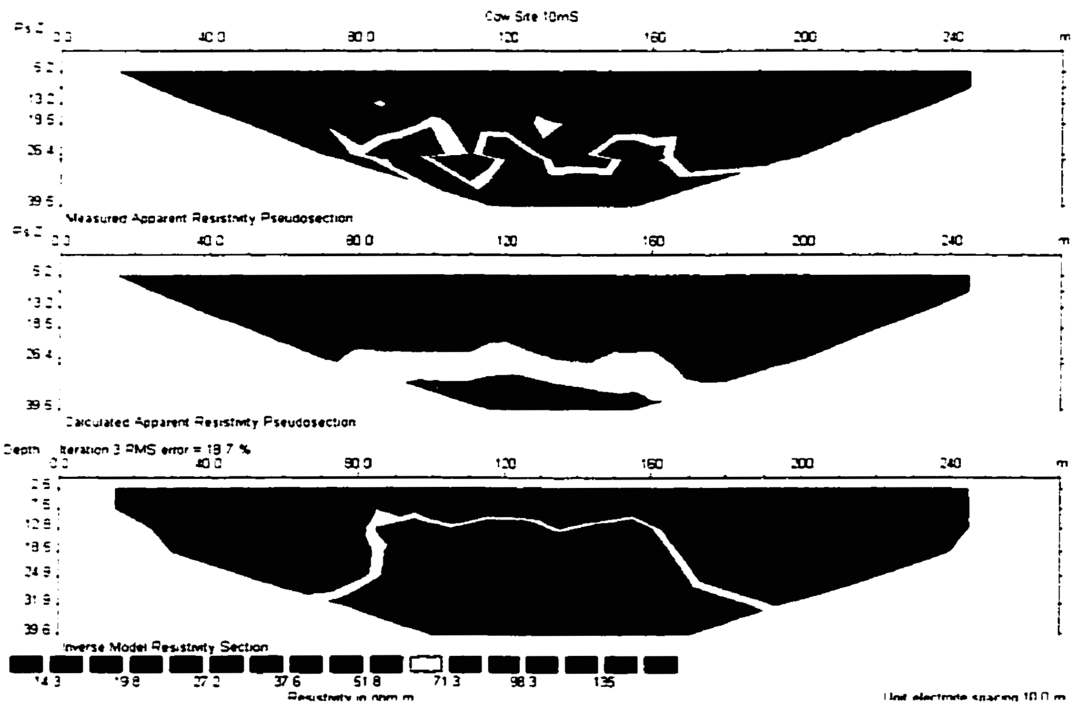


Figure 50 ERGI survey CS106.

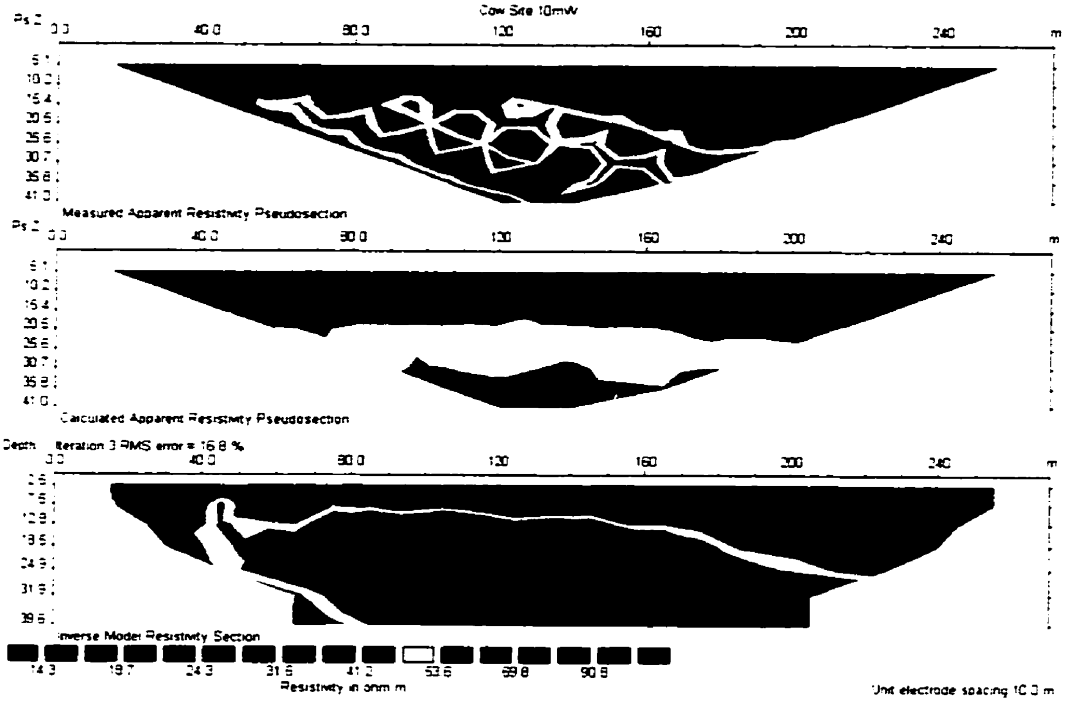


Figure 51 ERGI survey CS107.

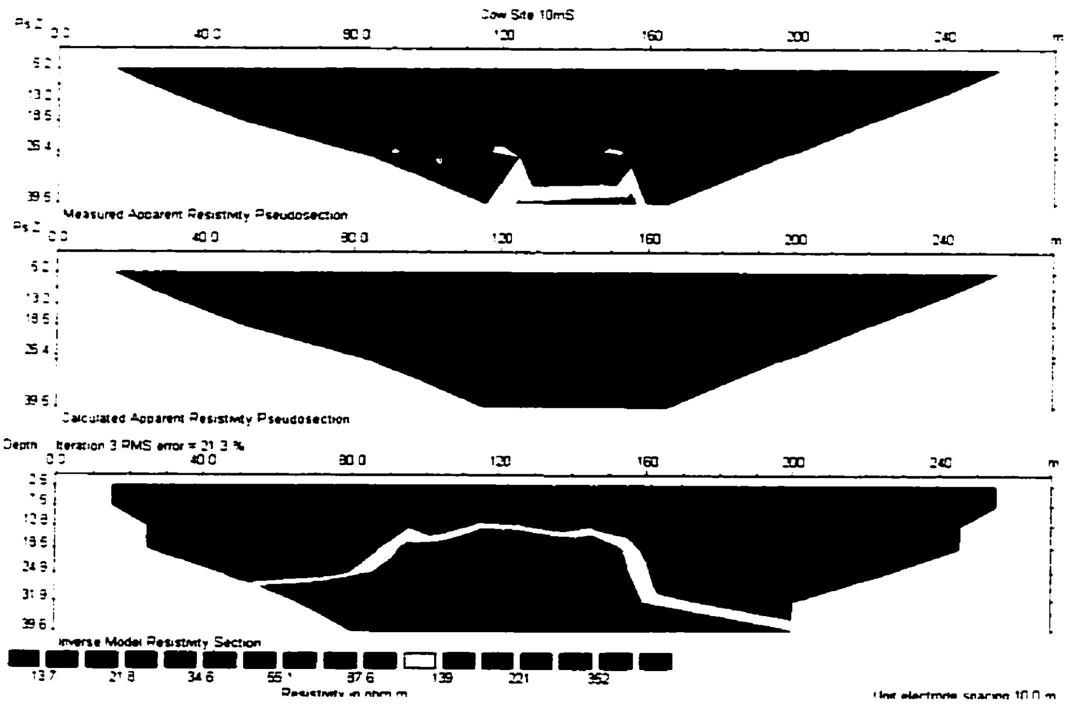


Figure 52 ERGI survey CS108.