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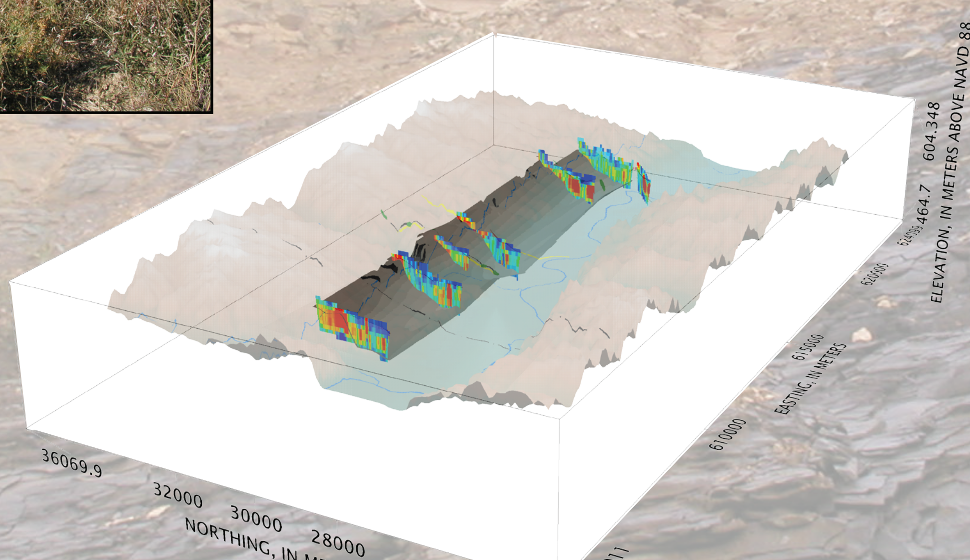
Geophysical Characterization of the Quaternary-Cretaceous Contact Using Surface Resistivity Methods in Franklin and Webster Counties, South-Central Nebraska



Scientific Investigations Report 2009–5092

U.S. Department of the Interior
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Cover: IRIS Syscal R1 Plus resistivity meter (center) and deployment of multi-conductor cables (left); cable setup for towed dipole-dipole array, Geometrics OhmMapper (right).

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Contents

Figures

Conversion Factors and Datums

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Velocity	
kilometer per hour (km/hr)	0.6214	mile per hour (mi/hr)
	Resistivity	
ohm-meter (ohm-m)	3.281	ohm-foot (ohm-ft)

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

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Geophysical Characterization of the Quaternary-Cretaceous Contact Using Surface Resistivity Methods in Franklin and Webster Counties, South-Central Nebraska

By Andrew P. Teeple, Wade H. Kress, James C. Cannia, and Lyndsay B. Ball

Abstract

To help manage and understand the Platte River system in Nebraska, the Platte River Cooperative Hydrology Study (COHYST), a group of state and local governmental agencies, developed a regional ground-water model. The southern boundary of this model lies along the Republican River, where an area with insufficient geologic data immediately north of the Republican River led to problems in the conceptualization of the simulated flow system and to potential problems with calibration of the simulation. Geologic descriptions from a group of test holes drilled in south-central Nebraska during 2001 and 2002 indicated a possible hydrologic disconnection between the Quaternary-age alluvial deposits in the uplands and those in the Republican River lowland. This disconnection was observed near a topographic high in the Cretaceous-age Niobrara Formation, which is the local bedrock. In 2003, the U.S. Geological Survey, in cooperation with the COHYST, collected surface geophysical data near these test holes to better define this discontinuity.

Two-dimensional imaging methods for direct-current resistivity and capacitively coupled resistivity were used to define the subsurface distribution of resistivity along several county roads near Riverton and Inavale, Nebraska. The relation between the subsurface distribution of resistivity and geology was defined by comparing existing geologic descriptions of test holes to surface geophysical resistivity data along two profiles and using the information gained from these comparisons to interpret the remaining four profiles. In all of the resistivity profile sections, there was generally a three-layer subsurface interpretation, with a resistor located between two conductors. Further comparison of geologic data with the geophysical data and with surficial features was used to identify a topographic high in the Niobrara Formation near the Franklin Canal which was coincident with a resistivity high. Electrical properties of the Niobrara Formation made accurate interpretation of the resistivity profile sections difficult and less confident because of similar resistivity of this formation and that of the coarser-grained sediment of the Quaternary-age deposits. However, distinct conductive features were identified within the resistivity profile sections that aided in delineating the contact between the resistive Quaternary-age deposits and the resistive Niobrara Formation. Using this information, an interpretive boundary was drawn on the resistivity profile sections to represent the contact between the Quaternary-age alluvial deposits and the Cretaceous-age Niobrara Formation.

A digital elevation model (DEM) of the top of the Niobrara Formation was constructed using the altitudes from the interpreted contact lines. This DEM showed a general trend of the top of the Niobrara Formation dipping to the southeast. At the north edge of the study site, the Niobrara Formation topographic high trends east-west with an altitude range of 559 meters in the west to 543 meters in the east. Based on the land-surface altitude and the Niobrara Formation DEM, the estimated thickness of the Quaternary-age alluvial deposits throughout the study area was mapped and showed a thinning of the Quaternary-age alluvial deposits to the north, approximately where the topographic high of the Niobrara Formation is located. This topographic high in the Niobrara Formation has the potential to act as a barrier to ground-water flow from the uplands alluvial aquifer to the Republican River alluvial aquifer as shown in the resistivity profile sections. The Quaternary-age alluvial deposits in the uplands and those in the Republican River Valley are not fully represented as disconnected because it is possible that there are ground-water flow paths that were not mapped during this study.

Introduction

To help manage and understand the hydrological and geological conditions in the Platte River system in Nebraska (upstream from Columbus, Nebr.) the Platte River Cooperative Hydrology Study (COHYST), a group of state and local governmental agencies, developed a regional ground-water model (Technical Committee, 2004). Modelers typically use data from test holes and surficial geologic maps to determine the depth and profile of the bedrock surface underlying unconsolidated sediments. Often, existing information either is not present in the area that needs to be defined or is not adequate to confidently determine lateral changes in the geologic structure because test holes are spaced too far apart. The COHYST completed a series of hydrostratigraphic maps for 10 hydrostratigraphic units critical to their ground-water modeling effort (Cannia and others, 2006). Although they used all available data, there was a lack of detailed data in the area that is the focus of this report. This lack of data can lead to uncertainties in estimating the altitude and geographic location of the geologic contact between the alluvial aquifer and underlying bedrock, which in turn can cause uncertainty in saturated thickness, hydrologic boundaries, and hydrologic properties used for ground-water models. These uncertainties can lead to problems in the conceptualization of the simulated flow system and to potential problems with calibration of the simulation. More information regarding the Nebraska COHYST can be found in Technical Committee (2004).

The southern boundary of the COHYST study area lies along the Republican River, an area where insufficient geologic data immediately north of the Republican River led to problems with calibration of the simulation. Several test holes were drilled by the COHYST and the University of Nebraska–Lincoln (UNL) Conservation and Survey Division (CSD) in the Republican River Valley near Riverton and Inavale, Nebr. (fig. 1), to aid in the delineation of hydrostratigraphic units. Geologic descriptions from one transect of test holes drilled during 2001 and 2002 indicated a possible hydrologic disconnection within the Quaternary-age alluvial deposits (hereinafter referred to as Quaternary deposits) between the uplands, or uplands alluvial aquifer, and the Republican River lowland, or Republican River lowland alluvial aquifer (Summerside, 2004). An interpretive hydrogeologic cross section (fig. 2) based on this group of test holes shows a topographic high of the Cretaceous-age Niobrara Formation (hereinafter referred to as the Niobrara Formation), which is the local bedrock (interpreted from Summerside, 2004). This cross section further illustrates that the topographic high of the Niobrara Formation could result in a hydrologic disconnection between the two aquifers that is as much as 0.8 kilometer (km) wide. Combining the discrete-point results of the test-hole program with profile surveys using a surface geophysical method would provide continuous subsurface data along several profiles in the study area (fig. 1). The results of this combined approach then could be used to: (1) provide continuous two-dimensional (2D) profile sections of the subsurface, (2) map the contact between the Quaternary deposits and the Niobrara Formation with much greater lateral data density than that from using test holes alone, and (3) better define the discontinuity of the coarse-grained Quaternary deposits between the uplands and the Republican River lowland. During October to December 2003, the U.S. Geological Survey (USGS), in cooperation with the COHYST, conducted a surface geophysical investigation using 2D-resistivity methods to provide continuous 2D profile sections of the subsurface distribution of electrical resistivity along selected county roads in south-central Nebraska.

Purpose and Scope

The purpose of this report is to document geophysical characterization using surface resistivity methods to map the contact between the Quaternary deposits and the Niobrara Formation along selected profiles in the Republican River Basin near Riverton and Inavale, Nebr. This report presents a general overview of the 2D direct-current (DC) and capacitively coupled (CC) resistivity data collection methods and inverse modeling. An explanation of how the surface geophysical data were used to determine the altitude of the topographic surface of the Niobrara Formation is also included. Presented in this report are 2D inverse-modeling results from six DC and two CC south-north trending resistivity profiles, the interpreted contact between the Quaternary deposits and the Niobrara Formation along six profiles, and a digital elevation model (DEM) interpolation of this interpreted contact.

Acknowledgments

Special appreciation and acknowledgment is extended to James W. Goeke, University of Nebraska West Central Research and Extension Center, for his assistance in developing a better understanding of the Republican River Valley hydrogeology and interpreting the surface geophysical data. The authors also acknowledge Douglas A. Groom of Geometrics, Inc., in San Jose, Calif., for his insight and technical support with data collection and processing of the CC resistivity data.

Description of Study Area

The study area is in the Republican River Basin in the southwestern corner of Webster County, Nebraska, and extends 1.6 km into the southeastern corner of Franklin County. The eastern edge of the study area is about 5.0 km east of the village of Inavale and the western edge is about 1.6 km west of Riverton, in Franklin County (fig. 1). The Republican River is about 0.7 to 2.2 km south of the DC resistivity profiles. Franklin Canal flows west to east through the northern one-half of the resistivity profile area and delivers surface water for irrigation from Harlan County Reservoir, about 40 km west of the study area. The majority of the land in the study area is used for irrigated and dry-land crop production or pasture, with small areas of riparian vegetation and built-up land.

The southeastern Republican River Basin lies in the Great Plains physiographic province (Fenneman, 1946), and more specifically is in the Plains Border section, locally known as the Loess Hills and Canyons (Peckenpaugh and others, 1987; U.S. Geological Survey, 2003). This region is characterized by complex, deeply entrenched drainage patterns and shallow, flat valleys (fig. 3). Small tablelands and rounded uplands are dissected by the numerous tributaries of the Republican River. Moderate to steep slopes rise 10 to 20 meters (m) above the

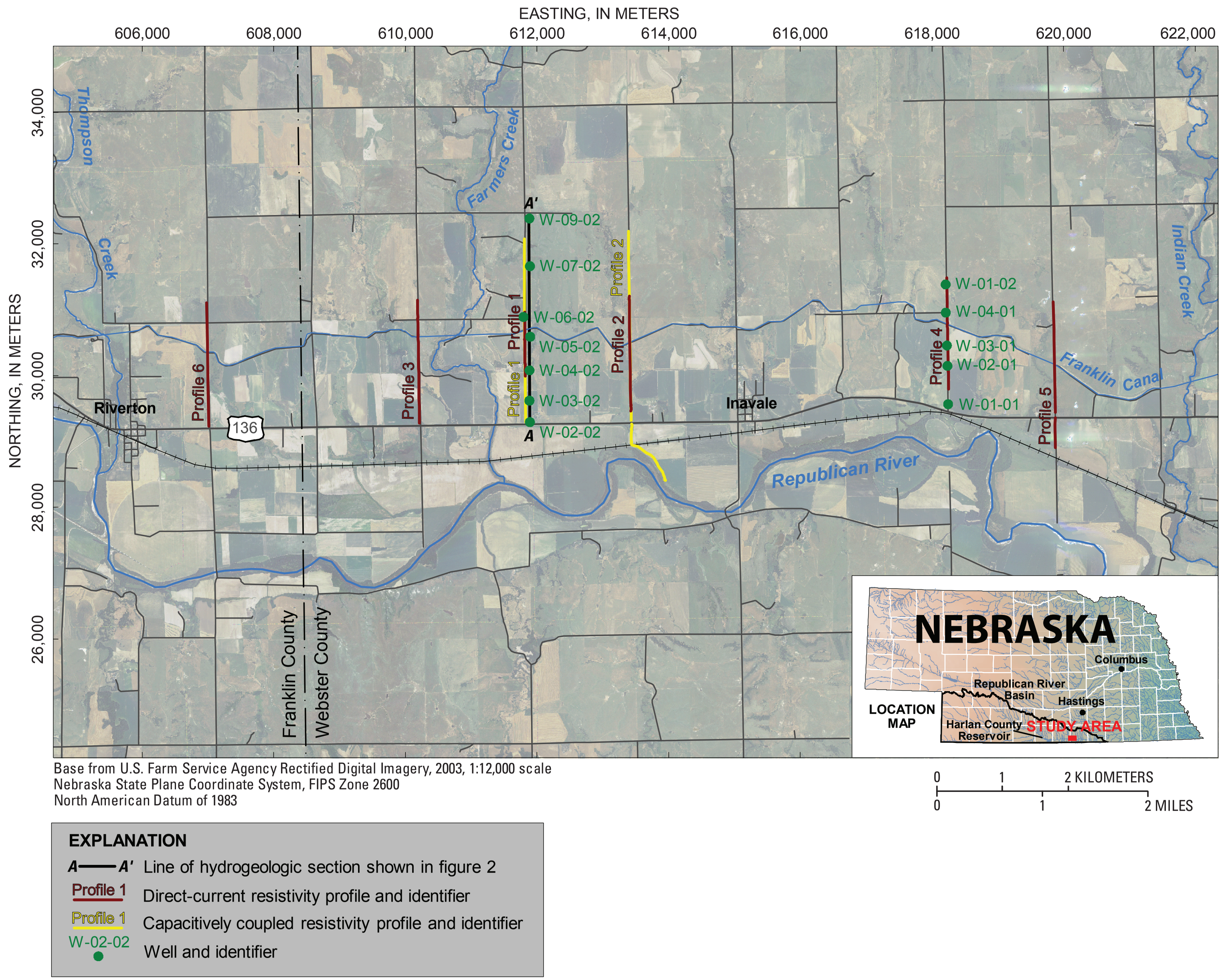


Figure 1. Location of study area, direct-current resistivity survey, and capacitively coupled resistivity survey near the Republican River in Franklin and Webster Counties, Nebraska.

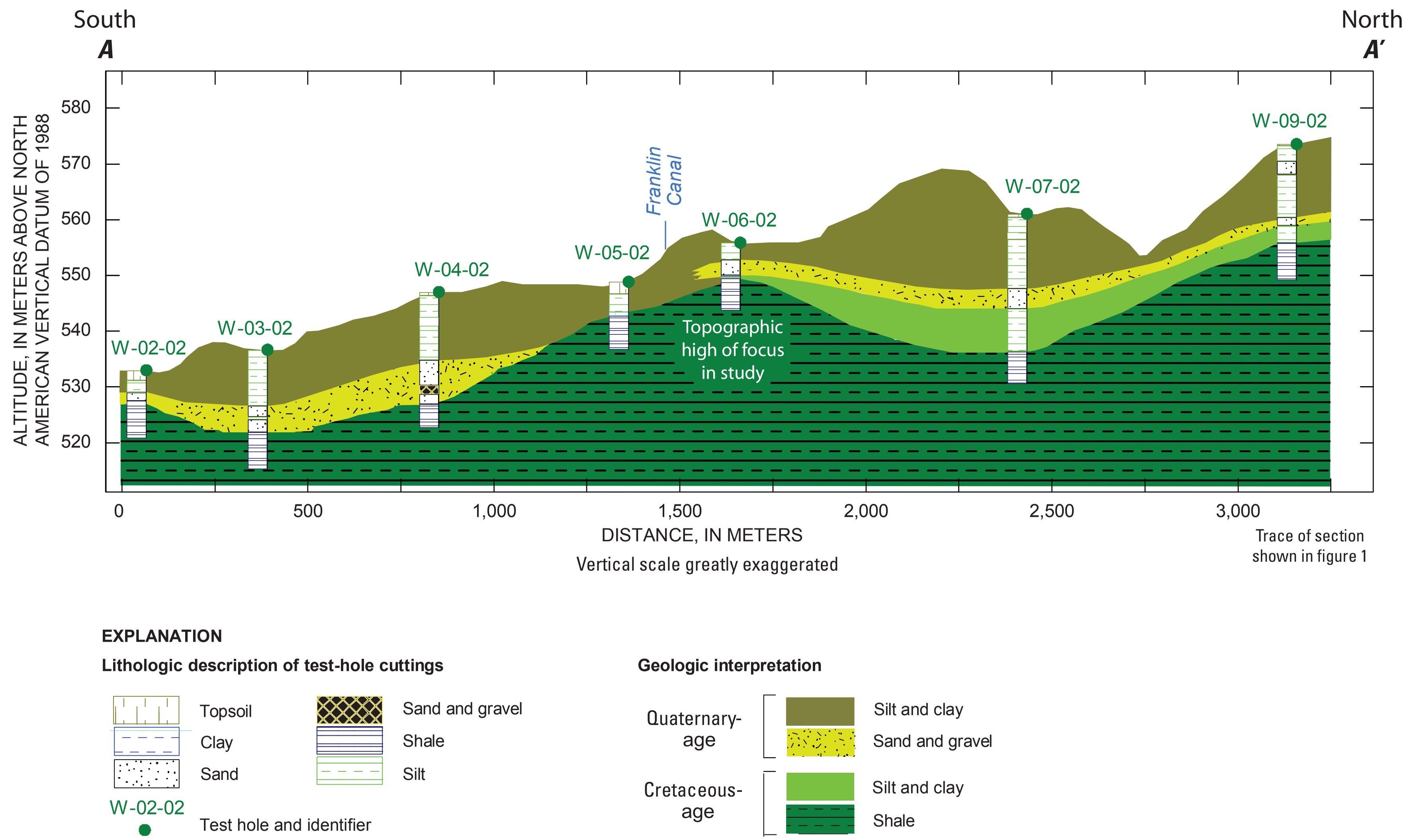


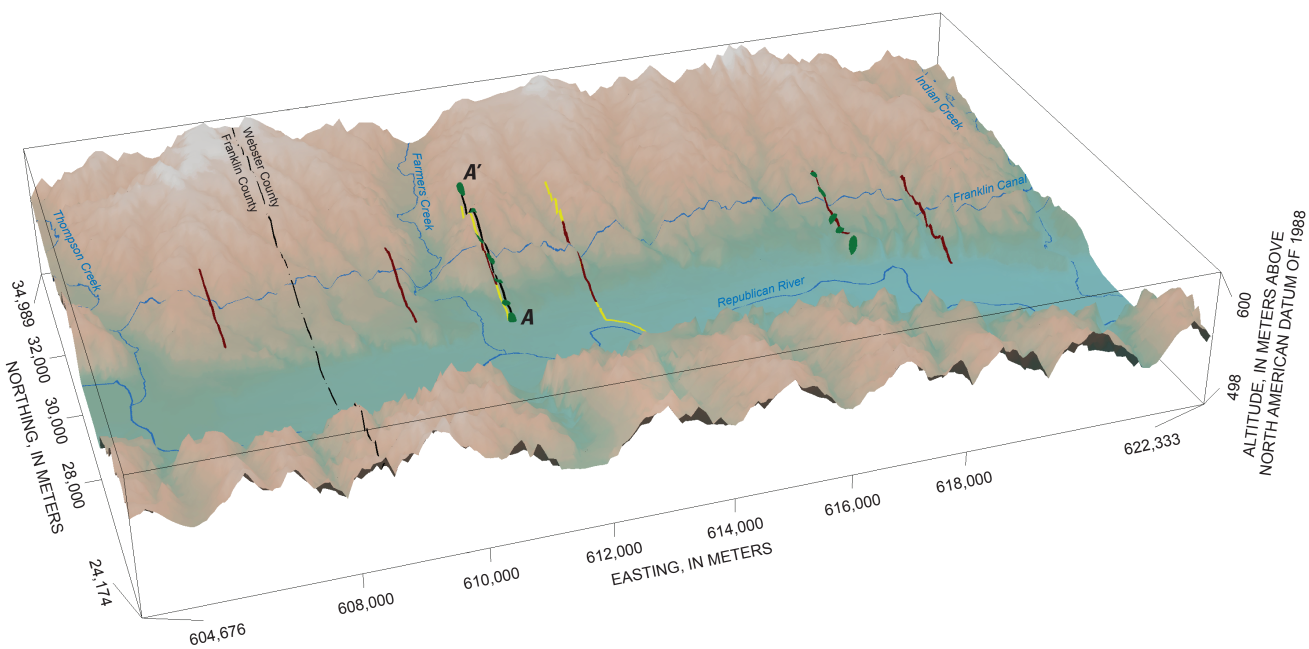
Figure 2. Test-hole lithologic descriptions (interpreted from Summerside, 2004) superimposed on interpreted hydrogeologic cross-section *A-A′* near the Republican River in Webster County, Nebraska.

flood plain on the north side of the Republican River Valley. The topography shows about 85 m of relief, with altitudes ranging from 515 to 600 m above the North American Vertical Datum of 1988 (NAVD 88).

Geology and Hydrogeology

Quaternary deposits of unconsolidated sediment range in size from clay to coarse gravel and lie unconformably on the eroded surface of the Niobrara Formation (Waite and Swenson, 1948). These deposits generally consist of eolian loess, sand dunes, or fluvial clay, silt, sand, and gravel deposits. The fluvial deposits originated from sources to the west and locally from sediment deposited by the tributaries. Sediment from western sources tends to be coarse, while tributary deposits can range from fine to coarse grained. The fine- to coarse-grained sediment was deposited on the flood plain, terraces, side slopes, and uplands. The Niobrara Formation generally consists of impermeable chalk and chalky shale, which locally outcrops at the land surface. The Niobrara Formation occasionally is present at the surface, mostly in deep valleys, and in a few locations near the Franklin Canal, as weathered and broken strata.

In the study area, the Republican River and Farmers Creek (fig. 1) are perennial streams that, depending on the time of year and the altitude of the ground-water table, can be losing or gaining water (Peckenpaugh and others, 1987). As early as the 1940s, irrigation practices throughout this region resulted in a rise of ground-water levels and an increase in base flow of some tributaries on the north side of the Republican River. The altitude of the ground-water table beneath the tablelands 1.5 to 5 km north of the Republican River ranges from 10 to 20 m higher than the altitude of the water table in the flood plain (Ellis, 1981). The regional ground-water flow direction in the study area is primarily north to south.



Base from U.S. Geological Survey National Elevation Dataset, 1999, 10-meter resolution
Nebraska State Plane Coordinate System, FIPS Zone 2600
North American Datum of 1983

EXPLANATION

- A—A′ Line of hydrogeologic section shown in figure 2
- Direct-current resistivity profile
- Capacitively coupled resistivity profile
- Well (symbol may be distorted due to being projected on an elevation model)

Figure 3. Topography of land-surface altitude near the Republican River in Franklin and Webster Counties, Nebraska.

Surface Geophysical Resistivity Methods

Surface geophysical resistivity methods can be used to detect changes in the electrical properties of the subsurface (Zohdy and others, 1974). The electrical properties of soil and rock are determined by water content, porosity, clay content and mineralogy, and conductivity (or reciprocal of electrical resistivity) of the pore water (Lucius and others, 2007). Typically, the resistivity of pore water greatly affects the bulk resistivity of the subsurface. Resistivity measurements can be used to construct graphical images of the spatial distribution of electrical properties of the subsurface. Comprehensive descriptions of the theory and application of DC- and CC-resistivity methods, as well as tables of the electrical properties of earth materials, are presented in Zohdy and others (1974) and Lucius and others (2007).

DC and CC resistivity instruments measure the voltage response of the subsurface from a current field that is applied to it through DC injection or capacitance, respectively. The raw data collected by these instruments are filtered statistically to remove poor quality (noisy) data and then are used to calculate the raw apparent resistivity of the subsurface. The underlying physical principle used to calculate raw apparent resistivity is embodied in Ohm's law. According to Ohm's law, the resistance (R) of earth material can be determined by

$$R = \Delta V/I$$

where

ΔV is the potential difference (voltage drop) measured by the receiver, and

I is the injected current (amperes) applied by the transmitter.

The resistance calculated from resistivity measurements is a specific measurement of the ability of earth material to transmit electrical current that is directly dependent on the geometry and electrode spacing used to obtain that measurement. To obtain a value that is independent of the geometry and electrode spacing resistance, R, measurements are multiplied by a geometric factor (K), unitless, to calculate raw apparent resistivity (ρ_a) represented in the following equation:

$$\rho_a = K\Delta V/I.$$

Apparent resistivity represents the resistivity of a completely uniform (homogenous and isotropic) earth material (Keller and Frischknecht, 1966). To determine the resistivity of non-uniform earth material, as is the case in most field studies, inverse-modeling software is used. Inverse-modeling theory is described for 2D resistivity data in Loke (2004a) and Advanced Geosciences, Inc. (2006). The methods used for 2D–DC and 2D–CC resistivity data acquisition and processing, as well as the application of inverse-modeling methods used in this investigation, were those described in detail in Kress and Teeple (2005) except where otherwise described in the following subsections of this report.

2D–DC and 2D–CC resistivity methods were used to characterize the electrical stratigraphy of the Republican River study area. These methods were used to measure the vertical and lateral variation in the resistivity of the subsurface which then was used to define the contact between the Quaternary deposits and the Niobrara Formation and to better define the disconnection, if any, between the uplands alluvial aquifer and the Republican River lowland alluvial aquifer. The surveys used multiple resistivity methods to achieve a more comprehensive analysis of the subsurface at the Republican River study area. Six 2D–DC and two 2D–CC resistivity profiles ranging from about 1.0 to 4.0 km in length were collected along six south-north profiles (fig. 1). Three of these resistivity profiles were colocated along two test-hole transects (profiles 1 and 4). To define the electrical properties of the Quaternary deposits and Niobrara Formation in the Republican River study area, profiles 1 and 4 were compared to geologic descriptions from nearby test holes. Water levels were collected in fall 2003 at 6 of the 12 test holes, but this information was too sparse to aid in the final interpretation of the inverted resistivity results. These water-level data, which were supplied by the Lower Republican Natural Resources District, Alma, Nebr., are listed in appendix 1 of this report.

Direct-Current Resistivity Survey

An IRIS Syscal R1 Plus DC-resistivity meter (fig. 4A) (IRIS Instruments, 2004) was used to collect voltage values using the Wenner-Schlumberger array along six profiles (fig. 1) in the study area. A Wenner-Sclumberger array is an electrode configuration where all electrodes are linearly spaced with the receiving electrodes placed between the transmitting electrodes. The Syscal R1 Plus was configured with three sets of multi-conductor cables, each cable having 18 electrode terminals (numbered 1–18, 19–36, and 37–54) with 5-m spacing. Stainless steel electrodes were installed in the ground and connected to electrode terminals built into the multi-conductor cables (fig. 4B). After the initial partial section of resistivity data was collected, the first cable of 18 electrodes was moved ahead of the survey line. A second partial section of data then was collected using the 36 electrodes previously deployed (electrodes 19–54) and the 18 electrodes (electrodes 55–72) just redeployed. This process, known as the roll-along technique, was continued until all data along the desired profile length were collected. The data from the set of partial sections were filtered individually and then were combined into a single raw apparent-resistivity data set for the inversion process. Each electrode was geospatially referenced with coordinates collected from a real-time kinematic (RTK) Global Positioning System (GPS) receiver.

A B

Figure 4. (A) IRIS Syscal R1 Plus resistivity meter, used to collect two-dimensional direct-current resistivity data, and (B) deployment of multi-conductor cables.

Capacitively Coupled Resistivity Survey

The OhmMapper TR–4 is a capacitively coupled, resistivity system comprising a transmitter and combination of one to four receivers (Geometrics, Inc., 2004). The towed dipole-dipole array was used to collect CC resistivity data for each profile. Several configurations of dipole lengths and dipole separations were evaluated to optimize depth of penetration and vertical resolution of apparent resistivity for this site. A dipole-dipole array with 10-m dipoles and a 2.5-m minimum dipole separation produced the best results and was used for this investigation. Because it was a four-receiver system, the dipole separations used for final data collection were 2.5, 7.5, 12.5, and 17.5 m. The OhmMapper console (fig. 5A) was used to collect geospatial coordinates from a differentially corrected Global Positioning System (DGPS) receiver, the injection current settings of the transmitter, and voltage data normalized by the magnitude of the injected current, or resistance, from the four receivers. Data were recorded at 1-second intervals with the array being towed at a rate of 3 to 5 kilometers per hour along 6.7 km of county roads and trails (fig. 5B). These data were downloaded as binary files from the OhmMapper console and converted to an American Standard Code for Information Interchange (ASCII) format using MagMap 2000 (Geometrics, Inc., 2001). The raw voltage, injected current, and resistance data values were statistically analyzed to filter the data; then the raw apparent resistivity values were calculated and averaged, or binned, at 5-m intervals along the line

A **B**

Figure 5. (A) Geometrics OhmMapper console, used to collect two-dimensional capacitively coupled resistivity data, and (B) cable setup for towed dipole-dipole array.

for each depth level. Because the vertical accuracy of the DGPS coordinates was poor, the land-surface altitude data incorporated in each profile were derived from 10-m resolution, 7.5-minute USGS digital elevation data. This resulted in some minor altitude differences between the DC-resistivity profiles and the CC-resistivity profiles for the same line, because the RTK GPS data are more accurate than the digital elevation data.

Inverse Modeling of Resistivity Data

To estimate the true subsurface resistivity, an inverse-modeling program develops a 2D model consisting of multiple rectangular cells, each given an individual resistivity value and assumed to be homogeneous and isotropic (Loke, 2004a). The inversion program calculates the system response of that model to produce synthetic, calculated apparent resistivity data. The accuracy of the model is determined by comparing the absolute difference between the calculated apparent resistivity and raw apparent resistivity data. The inversion program attempts to reduce the mean absolute difference by successively altering the cells' resistivity values and recalculating the apparent resistivity (each alteration is known as an iteration). A solution is reached when the mean absolute difference no longer improves appreciably (more than 1 percent) between iterations. This final model represents a non-unique estimate of the true distribution of subsurface resistivity. The inverse-modeling process is described in detail by Loke (2004a) and Advanced Geosciences, Inc. (2006).

The raw apparent resistivity data were processed and inverted with topographic data using the finite-element method with least-squares estimation using RES2DINV version 3.55 (Loke, 2004b). Analysis of apparent resistivities and comparison of both smooth and robust inversion methods indicated that the robust inversion method best modeled the raw apparent resistivity data because of the sharp contrasts between the resistive layers and the conductive layers present. The smooth inversion method gives better results where there are gradual changes in subsurface resistivity, whereas the robust method produces substantially better results where the subsurface geology consists of a number of regions that are almost homogeneous but with sharp boundaries between the different regions (Loke and others, 2003).

Geodatabase

A comprehensive temporal and spatial geodatabase was developed to consolidate new and existing geologic and geophysical data used in this investigation (Shah and Quigley, 2005). The geodatabase was developed using Oasis montaj (Geosoft, Inc., 2008). Oasis montaj software was used to create, manage, and visualize the geodatabase. Geologic descriptions of test-hole cuttings and the inverse-modeling results of the DC- and CC-resistivity data were imported into the geodatabase from ASCII formatted files. The geodatabase was used to produce section maps and for various types of spatial analyses that are useful to understand and visualize the subsurface and to aid the evaluation of DC- and CC-resistivity results.

Each geologic layer from the geologic descriptions of test-hole cuttings was given a specific geologic symbol to represent that layer. These geologic symbols were plotted as section maps using the geospatial data for each geologic layer. The resistivity data were plotted behind the geologic symbols to allow a direct comparison of geology and resistivity. Section maps (for example, fig. 6A) are created by projecting all data within the profile extents, which in this study were 300 m to either side of the trace, onto the trace.

Interpretation of Subsurface Resistivity Data

2D resistivity imaging methods and geologic descriptions of test-hole cuttings were used to map the contact beneath the Quaternary deposits and to locate topographic highs in the Niobrara Formation that can act as a barrier to ground-water flow from the uplands to the Republican River Valley. The topography of the Niobrara Formation was identified by comparing inverse-modeling results for resistivity from eight profiles to the geologic descriptions of test-hole cuttings and by establishing the relation between the subsurface distribution of resistivity and changes in geology identified at the test holes. Geologic descriptions from 12 test holes were used as supporting data for the geophysical interpretation. All profiles are oriented south-north, or nearly perpendicular to the river valley. On profiles with test holes nearby, geologic layers were correlated with a range of resistivity values. Distinguishable features within the inverted resistivity profiles often could be interpreted by observing surficial features, such as Franklin Canal and Farmers Creek. All this information was used to interpret inverted resistivity profiles. The interpretation results were used to map the contact between the Quaternary deposits and the Niobrara Formation and to distinguish finer-grained from coarser-grained Quaternary deposits.

A spatially referenced line was digitally drawn on the resistivity profiles to represent the contact between the Quaternary deposits and the Niobrara Formation. Once contact lines for each profile were digitized, the altitude of these contact lines was interpolated across the study area. The bidirectional gridding method of interpolation was used because this method accurately portrays trends oriented perpendicular to the lines of data (Geosoft, Inc., 2008). Because the profiles were separated by at least 1.5 km, there were many areas within the DEM where the interpolated altitude of the Niobrara Formation was located above the altitude of the land surface. Such areas mainly occurred near the tributaries. Where this happened, the land-surface altitude was used to represent the Niobrara Formation altitude.

Geophysical Characterization of the Quaternary-Cretaceous Contact

In general, the different hydrogeologic units in the Republican River study area have a predictable difference in electrical resistivity based on their mineralogy, rock type, and water content. For example, a 2D-DC resistivity survey of the High Plains aquifer conducted near Hastings, Nebr., identified three distinct electrical units in five of six profiles (Kress and others, 2006). Comparison of resistivity profiles to geologic descriptions of boreholes within the Hastings study site indicated that electrical unit 1 (low resistivity) correlates with the surface soils and loess deposits. Electrical unit 2, which is more resistive than unit 1, correlates with the unconsolidated sand and gravel deposits of the Pleistocene alluvial aquifer. Unit 3, which is less resistive, correlates with the clay and silt of the lower part of the unconsolidated Pleistocene deposits and of the top part of the Niobrara Formation. Geologic units in the Republican River study area have similar electrical contrasts as identified by Kress and others (2006).

Geophysical analysis and comparison of geologic data along profiles 1 and 4 of the Republican River study are presented first because of their proximity to test-hole transects. The interpretations made along these profiles, aided by test-hole geologic information, were extrapolated to the other four profiles that do not have nearby test holes. The remaining four profiles are then presented in sequential order. The color symbology used for the DC and CC resistivity profiles are on different scales because of the various differences in resistivity measurements between the two techniques. The raw and calculated apparent resistivity pseudosections as well as the final inverse-modeling results for all DC resistivity profiles are listed in appendix 2, and for CC resistivity profiles in appendix 3, of this report. A pseudosection is a gridded section of data where the depths of the apparent resistivity data points are approximated based on array type. The depths are approximated because final depths for resistivity values are not calculated until the inversion process.

Profile 1

Profile 1 is about 3.3 km west of Inavale (fig. 1). This profile begins near U.S. Highway 136 and trends north about 2.8 km. Profile 1 corresponds to a DC resistivity profile about 1.0 km long and a CC resistivity profile about 2.8 km long. These profiles are near seven test holes (fig. 6A) for which geologic descriptions of test-hole cuttings (interpreted from Summerside, 2004) were available for comparison of general geologic layers to the contrasting resistivity units in the DC- and CC-resistivity profiles.

The inverse-modeling results for DC resistivity (fig. 6B) indicate three resistivity units—a conductive unit over a resistive unit that overlies another conductive unit. An area of lower resistivity is within the resistive unit at about 1,440 to about 1,760 m from the south end. Comparison of the DC resistivity profile to test hole W–04–02 shows that the Niobrara Formation correlates with the lower conductive unit and the sand and gravel correlate closely with the highly resistive unit. In test holes W–05–02 and W–06–02, the Niobrara Formation correlates with the highly resistive unit and the silt correlates closely with the upper conductive unit.

The inverse-modeling results for CC resistivity (fig. 6C) generally show a less pronounced resistivity contrast between the above-mentioned units throughout the profile than did the DC resistivity results, except for some highly resistive features at about 1,060 to 1,270 m, 1,760 to 2,700 m, and 2,810 to 3,350 m from the south end. There is little vertical variation in resistivity from 560 to 1,060 m and from 1,270 to 1,760 m, but a more resistive unit between two conductive units is still evident. At test hole W–02–02, the Niobrara Formation correlates with the lower conductive unit. The CC-resistivity profile was not deep enough to indicate the resistivity of the Niobrara Formation in test holes W–03–02 and W–04–02. The CC resistivity profile shows low resistivity where geologic descriptions of these test holes indicate sand, that in general, is expected to be more resistive than the surrounding silts, clays, and shale. This is a result of the decrease in signal-to-noise ratio of the dipole-dipole array, making the results at depth less reliable, which was a limitation of the CC-resistivity method when attempting to collect data at depth. At test holes W–05–02 and W–06–02, the Niobrara Formation correlates with higher resistivity. The altitude of the Niobrara Formation declines from test hole W–06–02 to test hole W–07–02. Because of limited depth of penetration of the CC-resistivity method and the increase in the depth of the Niobrara Formation, the total thickness of alluvium could not be mapped at test hole W–07–02 along the CC resistivity profile. The increase in resistivity along the profile at test hole W–07–02 may represent an increase of the relative grain size of the uplands alluvium.

Using both the DC- and CC-resistivity profiles and the geologic descriptions of test-hole cuttings, an interpretive line was drawn to represent the contact between the Quaternary deposits and the Niobrara Formation (fig. 6). Because the CC-resistivity profile in test holes W–03–02 and W–04–02 as well as the DC resistivity profile in test hole W-04-02 do not reach the depth of the Niobrara Formation, the contact line was drawn using the geologic descriptions from test holes W–02–02, W–03–02, and W–04–02. The Niobrara Formation correlates with the resistive unit at test hole W–05–02 (DC-resistivity profile); the location of the contact line had changed from the bottom of the resistive unit in W-04-02 to the top of the resistive unit somewhere between these test holes. Both the DC and CC resistivity profiles indicate a large increase in resistivity of the resistive unit at about 1,760 m, where the Niobrara Formation is interpreted to become resistive to the north. From test hole W–04–02 to about 1,760 m, the contact line follows the bottom of the resistive unit, and from about 1,760 to 2,700 m, the contact line follows the top of the resistive unit. At 2,700 m the resistive unit dips to the bottom of the CC resistivity profile, and the contact line is drawn from

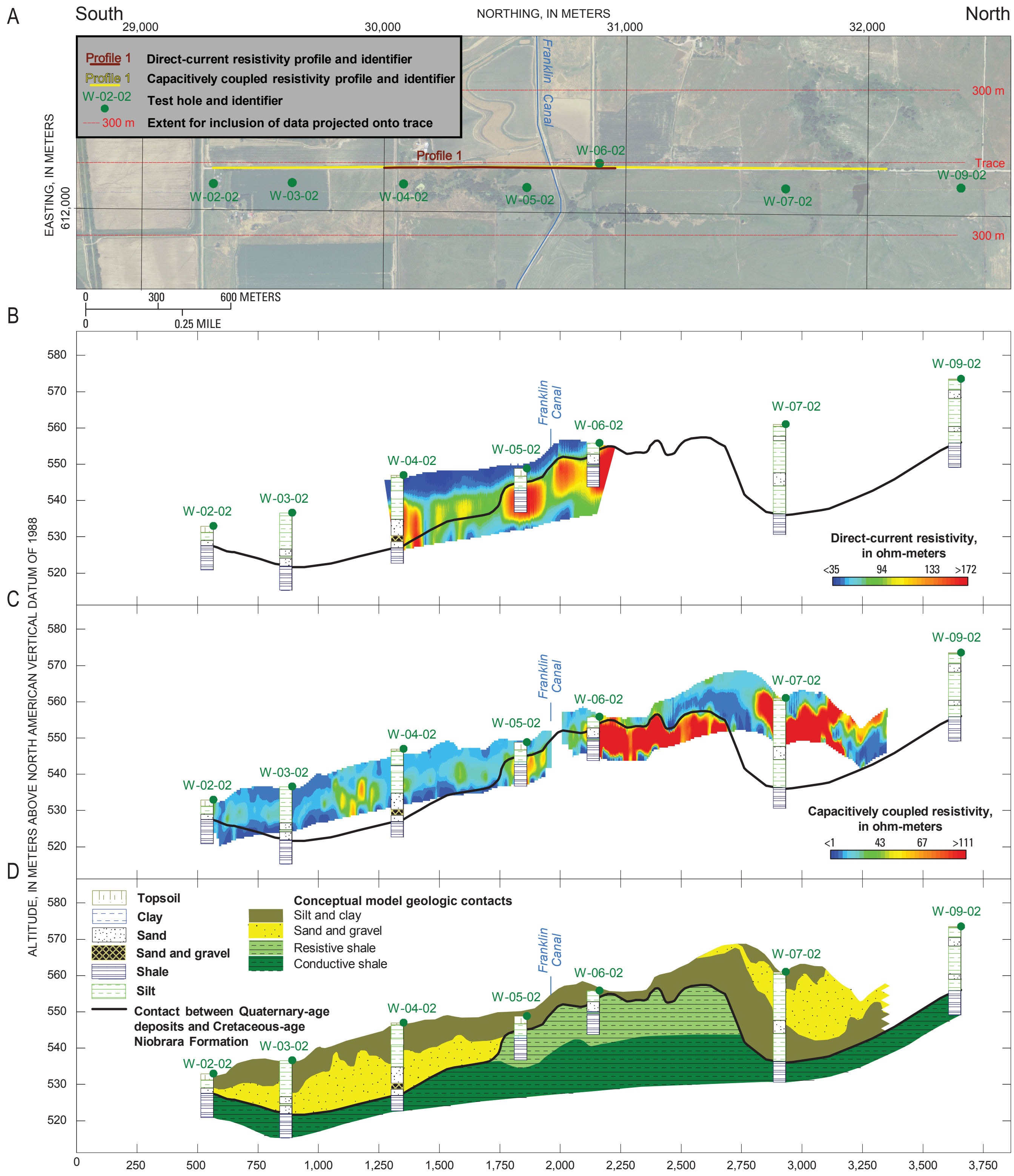


Figure 6. Sections showing (A) location of direct-current (DC) resistivity profile 1, capacitively coupled (CC) resistivity profile 1, and nearby test holes; (B) geologic description of test-hole cuttings superimposed on inverse-modeling results for DC resistivity profile 1; (C) geologic description of test-hole cuttings superimposed on inverse-modeling results for CC resistivity profile 1; and (D) geologic description of test-hole cuttings superimposed on conceptual model based on geologic description and inverse-modeling results for DC resistivity and CC resistivity along profile 1.

the edge of this resistive unit to match the geologic description of test hole W–07–02. Because the DC and CC resistivity profiles do not map the resistivity of the Niobrara Formation at test holes W–07–02 and W–09–02, the contact line is based on the geologic descriptions.

The alluvial deposits were divided into two units: (1) silt and clay, and (2) sand and gravel. The moderately resistive unit on the CC resistivity profile from about 560 to 1,760 m is interpreted to be a sand and gravel unit. The highly resistive feature at about 2,810 to 3,350 m was also interpreted to comprise mainly sand and gravel. Using this information, a conceptual model (fig. 6D) was constructed to illustrate these findings.

Profile 4

Profile 4 is about 3.1 km east of Inavale (fig. 1). This profile begins about 330 m north of U.S. Highway 136 and trends north about 1.7 km. Profile 4 corresponds to a DC resistivity profile near five test holes (fig. 7A) that provide geologic descriptions of test-hole cuttings for comparison of general geologic layers to the resistivity units in the profile.

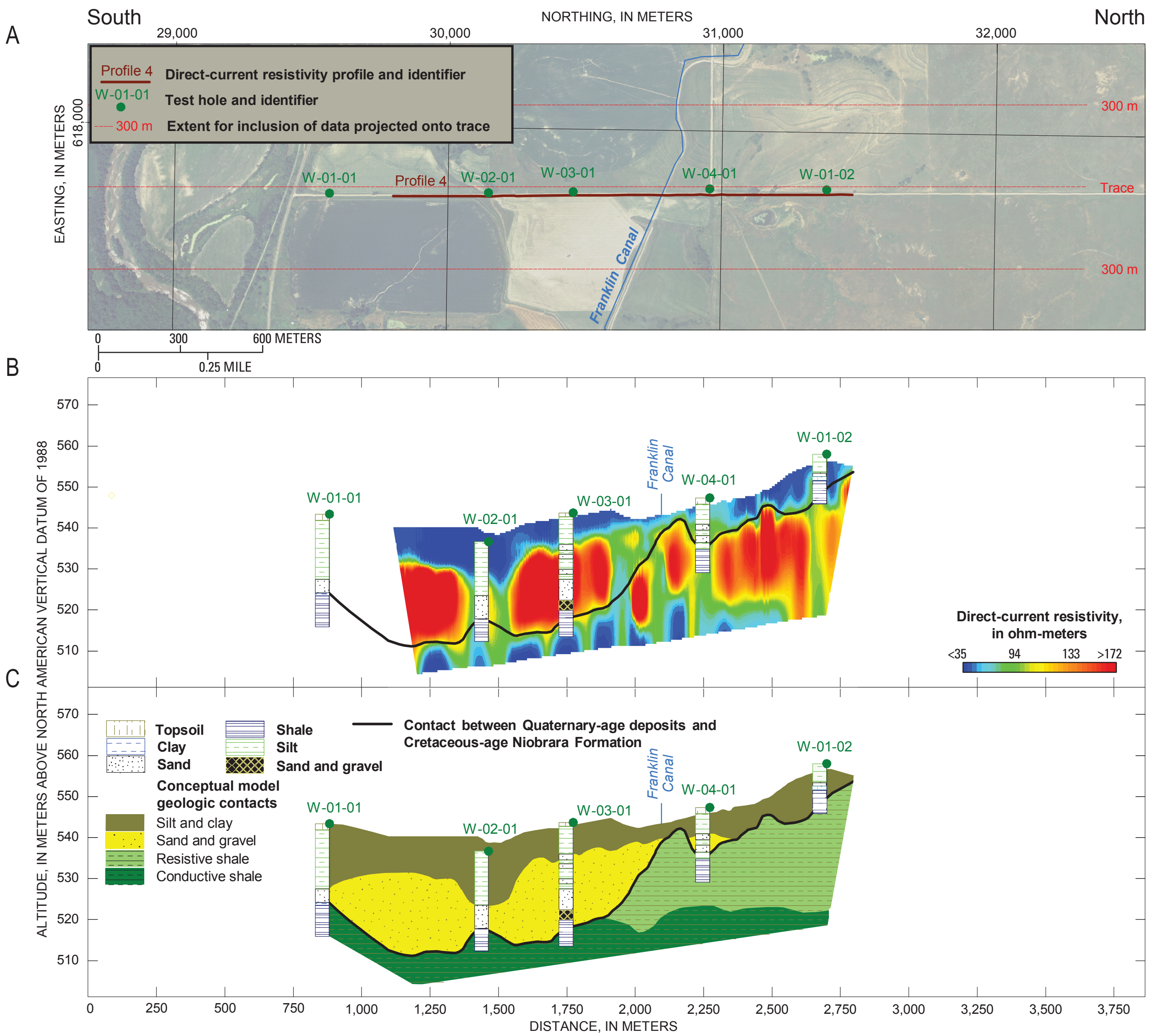


Figure 7. Sections showing (A) location of direct-current (DC) resistivity profile 4 and nearby test holes; (B) geologic description of test-hole cuttings superimposed on inverse-modeling results for DC resistivity profile 4; and (C) geologic description of test-hole cuttings superimposed on conceptual model based on geologic description and inverse-modeling results for DC resistivity along profile 4.

The inverse-modeling results for DC resistivity (fig. 7B) indicate three resistivity units—a highly resistive unit between two conductive units. The resistivity of the highly resistive unit is fairly uniform across the profile with some vertical conductive features sporadically located throughout the profile. A diagonal conductive feature dips to the south from 2,040 to 1,890 m from the south end. At test holes W–02–01 and W–03–01, the Niobrara Formation correlates with the lower conductive unit, and the sand and gravel directly above the Niobrara Formation correlate with the resistive unit. The Niobrara Formation at test holes W–04–01 and W–01–02 correlates with the resistive unit; the upper conductive unit is above the Niobrara Formation.

Because the DC resistivity profile does not extend to test hole W–01–01, the Quaternary-Cretaceous contact line was drawn from the top of the Niobrara Formation, on the basis of the geologic description for the well, to the bottom of the resistive unit at the edge of the profile. The contact line then followed the bottom of the resistive unit to test hole W–03–01. Comparison of the DC resistivity profile to the geologic descriptions indicates that a change in the resistivity of the Niobrara Formation occurs between test holes W–03–01 and W–04–01 which is shown as a diagonal conductive feature from about 1,890 to 2,040 m from the south end. From test hole W–03–01 to about 1,890 m, the contact line follows the bottom of the resistive unit, and from 1,890 m to test hole W–04–01, the contact line follows the top of the resistive unit, continuing along the top of the resistive unit to the end of the profile, about 100 m north of test hole W–01–02.

The alluvial deposits were divided into two units: (1) the upper conductive unit representing silt and clay, and (2) the highly resistive unit, directly above the Niobrara Formation, representing sand and gravel. Using this information, a conceptual model (fig. 7C) was constructed to illustrate these findings.

Conclusion from Profiles 1 and 4

Comparison of the geologic and resistivity data along profiles 1 and 4 (figs. 6 and 7) was used to identify a topographic high in the Niobrara Formation near the Franklin Canal which was coincident with a resistivity high. Generally, on the southern end of the profiles the Niobrara Formation was near the bottom of each resistivity section and had a conductive signature, but to the north where the Niobrara Formation outcrops or nearly appears at the surface it was resistive. This change in the electrical properties of the Niobrara Formation made accurate interpretation of the resistivity profiles difficult and less confident because of the similarity in resistivity of this formation and that of the coarser-grained sediments of the Quaternary deposits. However, distinct features were identified within the resistivity profiles that aided in delineating the contact between the resistive Quaternary deposits and the resistive Niobrara Formation. These conductive features were identified either as a diagonal conductive feature where the alluvial deposits had a resistivity similar to that of the Niobrara Formation or as a large change in resistivity when the alluvial deposits had moderate resistivity. Using this information and with the aid of the test-hole data, a line was drawn on the resistivity profiles to represent the contact between the Quaternary deposits and the Niobrara Formation. It is possible that a lithologic difference, such as an increase in the relative grain size in the Niobrara Formation, may have caused the overall higher resistivity of the bedrock and also made it more resistant to erosion, creating the altitude increase identified by test holes along these profiles. Another possible hypothesis is that this change in resistivity could be caused by change in water content, inferred to be the effect of surface water lowering the resistivity because of multiple years of saturation below and downgradient from the canal. Irrigation to the south of the canal, the supply side, also contributes to the subsurface saturation. North, or upgradient, from the canal, the shale is not affected by infiltration of the surface water and therefore is much drier and is characterized by higher resistivity. These hypotheses will require further sampling and detailed analysis of the test-hole cuttings before further explanation can be given.

Where the contact line was drawn from the conductive Niobrara Formation to the resistive Niobrara Formation, there is a linear conductive feature between the two test holes at the position of the transition in Niobrara Formation resistivity. This conductive feature was identified either as a diagonal conductive feature when the alluvial deposits had a resistivity similar to that of the Niobrara Formation (profile 4) or as a large change in resistivity when the alluvial deposits had moderate resistivity (profile 1). Using the information from these two profiles along with the aid of the test-hole data, a contact line was interpreted along the four remaining resistivity profiles that do not have nearby test holes to verify results.

Profile 2

Profile 2 is about 1.6 km east of profile 1 (fig. 1). This profile is about 4.0 km long with the first 790 m following the alignment of the Republican River and the remainder of the profile trending north. Profile 2 corresponds to a DC resistivity profile about 1.8 km long and a CC resistivity profile about 4.0 km long (fig. 8A).

The inverse-modeling results for DC resistivity (fig. 8B) indicate three resistivity units throughout most of the profile with a resistive unit between two conductive units. At about 2,040 m from the south end, the resistive unit appears at the surface and continues to outcrop until about 2,450 m. The resistive unit is moderately resistive from about 1,140 to 2,040 m except for a highly resistive feature at about 1,460 to 1,670 m. The transition of the Niobrara Formation from conductive to resistive in electrical character was interpreted to occur along the small diagonal conductive feature centered at 1,990 m from the south end.

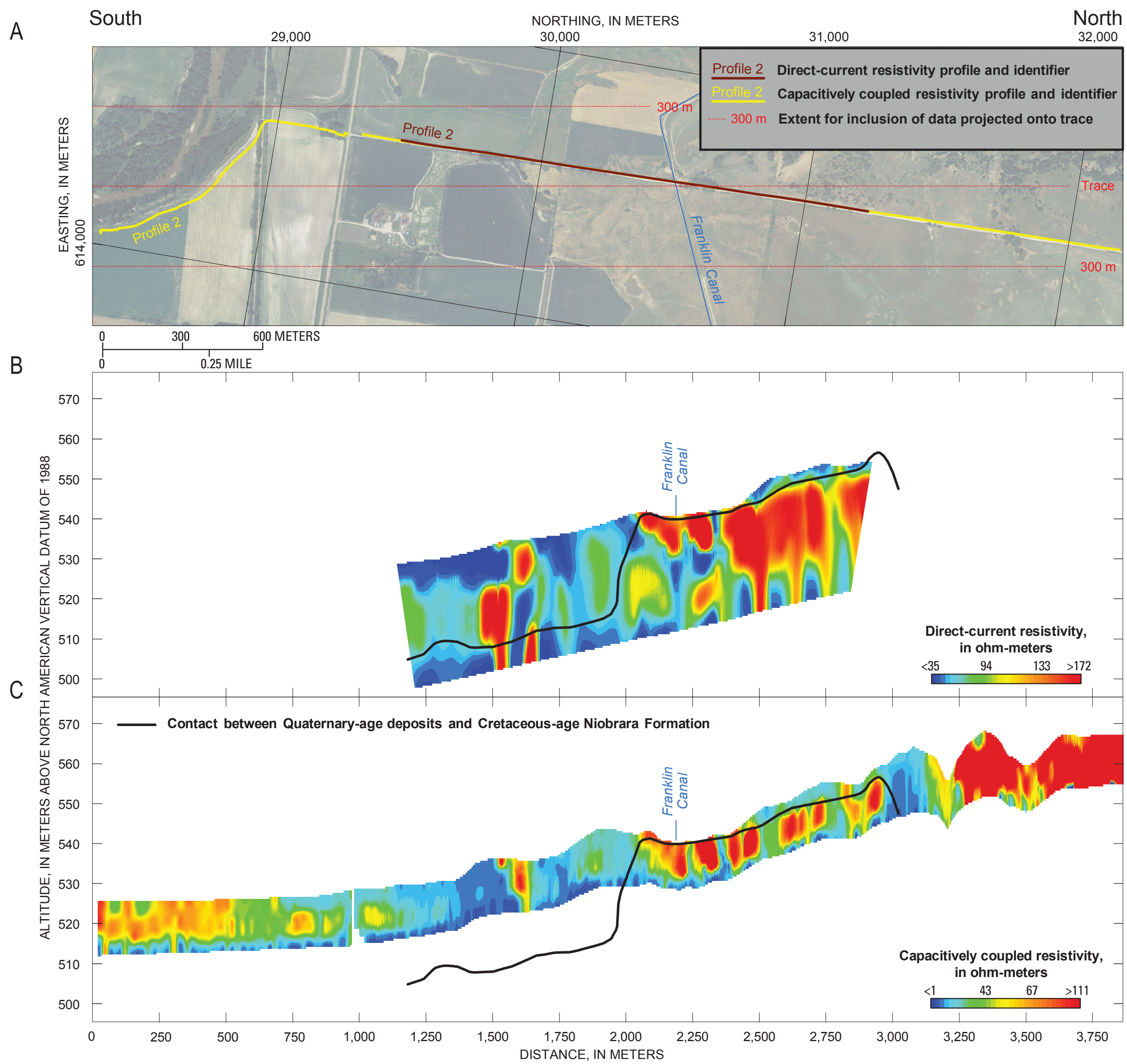


Figure 8. Sections showing (A) location of direct-current (DC) resistivity profile 2 and capacitively coupled (CC) resistivity profile 2; (B) inverse-modeling results for DC resistivity profile 2; and (C) inverse-modeling results for CC resistivity profile 2.

The inverse-modeling results for CC resistivity (fig. 8C) indicate mostly two resistivity units throughout the profile except at about 540 to 1,330 m and 2,450 to 2,970 m where there are three resistivity units—a resistive unit between two conductive units. The resistive unit at about 20 to 1,330 m was interpreted to be Republican River alluvial deposits. A highly resistive feature outcrops from about 2,060 to 2,320 m and extends to about 2,970 m. A near-surface highly resistive feature extending north from about 3,140 m is interpreted to be the upland alluvial deposits.

Using both the DC and CC resistivity profiles, an interpretive line was drawn to represent the contact between the Quaternary deposits and the Niobrara Formation. Because of the limited depth of penetration of the CC resistivity profile, the DC resistivity profile was used to draw the contact from the beginning of the profile to about 1,970 m (fig. 8B).

The Niobrara Formation topographic high was interpreted to begin at about 1,970 m because both the DC and CC resistivity profiles indicated a near-surface highly resistive feature at about 2,050 m and because the DC resistivity profile indicated a diagonal conductive feature at about 1,990 m that was bounded on its north by an increase in resistivity, similar to profile 1. From about 2,050 to about 3,030 m, the contact line follows the top of the resistive unit based on both the DC and CC resistivity profiles. At about 3,030 m the contact line drops to the bottom of the CC resistivity section. From this point north there is no geophysical evidence to indicate the presence of the Niobrara Formation within the depth investigated with the CC resistivity survey.

Profile 3

Profile 3 is about 1.6 km west of profile 1 and begins near U.S. Highway 136, trending north for about 1.9 km (fig. 1). The inverse-modeling results for DC resistivity (fig. 9B) indicate three resistivity units from about 1,050 to 1,750 m and from about 2,500 to 2,860 m from the south end. The data from 1,750 to 2,350 m are relatively low in resistivity and no layers are distinguishable. This low resistivity area could be a result of fine-grained sediments being deposited from nearby Farmers Creek (for further explanation of sediments and depositional environments see Condra (1907)). A resistive unit rises from the bottom of the section to almost appear at the surface from about 2,350 to 2,600 m. The resistive unit from about 1,050 to 1,750 m is presumed to be coarse-grained Quaternary deposits found within the Republican River Valley.

The contact line is below the resistive unit from about 1,050 to 1,750 m. The change in resistivity within the Niobrara Formation unit occurs somewhere within the low resistivity area between 1,750 and 2,500 m. The resistive unit on the north end of the profile that rises from the bottom of the section to near land surface is interpreted to be the resistive unit of the Niobrara Formation; thus the contact line follows the top of the resistive unit from about 2,350 m to the end of the profile.

Profile 5

Profile 5 begins about 490 m south of U.S. Highway 136 and trends north about 2.2 km (fig. 1). Profile 5 is about 1.6 km east of profile 4. Three resistivity units—a resistive unit between two conductive units—are observed throughout the inverse-modeling results for DC resistivity (fig. 9D). The resistive unit is moderately resistive except for some highly resistive features at about 820 to 1,170 m, 1,540 to 1,680 m, and 2,600 to 2,830 m from the south end. The highly resistive features at 820 to 1,170 m and 1,540 to 1,680 m are interpreted to be coarse-grained Republican River alluvial deposits. The resistive feature at about 2,600 to 2,830 m shows a diagonal trend upward (fig. 9D) similar to the diagonal trend in the DC resistivity section for profile 4 (fig. 7B).

The contact line follows the bottom of the resistive unit from the south end of the profile to the highly resistive feature that rises at about 2,600 m. Because this resistive feature was similar to that from profile 4, it is interpreted to be the resistive Niobrara Formation. The contact line follows the top of the resistive unit from about 2,600 m to the north end of the profile. Because the DC resistivity profile was interrupted from about 1,180 to 1,410 m by U.S. Highway 136, and the DC resistivity profile on either side of this gap indicates an upward trend in the top of the Niobrara Formation, the inferred contact line shows a small rise in the Niobrara Formation unit at this location.

Profile 6

Profile 6 is about 3.2 km west of profile 3 (fig. 1). This profile begins near U.S. Highway 136 and trends north about 1.9 km. Three resistivity units—a resistive unit between two conductive units—are observed throughout the DC resistivity results (fig. 9F). From about 1,030 to 2,030 m from the south end, the resistive unit is discontinuous and ranges from moderately resistive to highly resistive; from about 2,050 to 2,870 m, the resistive unit is continuous and highly resistive. A vertical conductive feature at about 2,030 m separates the discontinuously resistive unit from the continuously resistive unit. The discontinuously resistive unit from about 1,030 to 2,030 m is presumed to be coarse-grained sediment within the Republican River Valley Quaternary alluvium.

The contact line follows the bottom of the resistive unit from about 1,030 to 2,000 m. The continuously resistive feature from about 2,050 to 2,870 m is interpreted to be the resistive part of the Niobrara Formation; thus the contact line follows the vertical conductive feature that separates the discontinuously and continuously resistive units at about 2,030 m. From about 2,050 m to the north end of the section, the contact line follows the top of the resistive unit.

Integration of Results

Interpretation of the geophysical resistivity profiles required a thorough understanding of the physical properties of the rocks and the effects of surface-water leakage from the canal. The contact line on each resistivity section (figs. 6–9) follows a general trend in the top of the Niobrara Formation as it rises abruptly from south to north to approach the land surface. In most cases this rise occurred near the Franklin Canal and coincided with the location on each profile where the resistivity of the Niobrara Formation changed from relatively conductive to resistive. A smaller Niobrara Formation topographic ridge is about 1.2 km south of the previously discussed Niobrara Formation high on profiles 1, 3, 4, and 5. This same ridge was found in profile 2, but there it is about 600 m away from the Niobrara Formation high. This small Niobrara Formation ridge was not evident at profile 6 because the ridge seems to closely parallel the river, and the southern end of

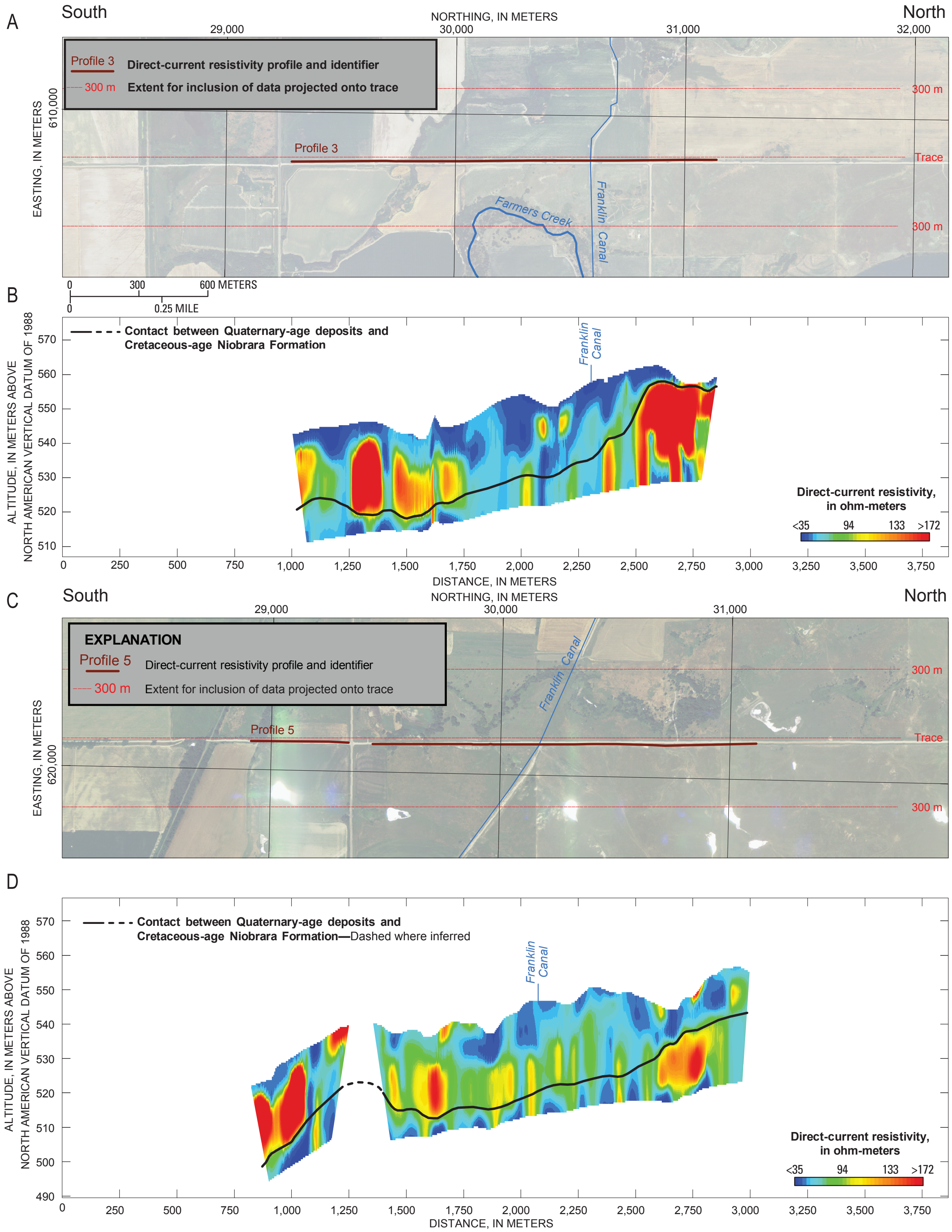


Figure 9. Sections showing (A) location of direct-current (DC) resistivity profile 3; (B) inverse-modeling results for DC resistivity profile 3; (C) location of DC resistivity profile 5; (D) inverse-modeling results for DC resistivity profile 5; (E) location of DC resistivity profile 6; and (F) inverse-modeling results for DC resistivity profile 6.

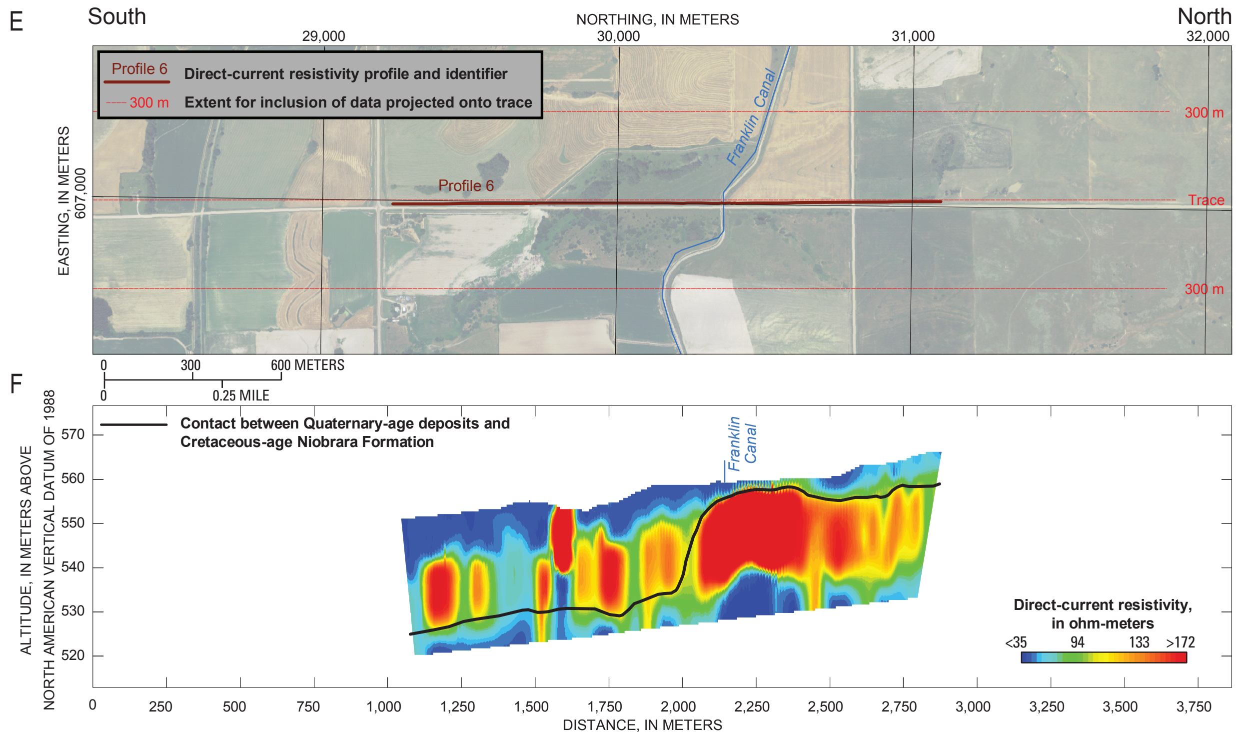


Figure 9. Continued.

profile 6 is not located close enough to the river to include this ridge.

Digital Elevation Model of the Top of Niobrara Formation

The altitude of the top of the Niobrara Formation along each profile was interpolated across the study area to create a digital elevation model (DEM) that could be superimposed on a regional land-surface DEM to compare the altitude of the top of the Niobrara Formation to the altitude of the land surface (fig. 10). Because the profiles are spaced far apart from each other, the DEM is highly interpolated between the profiles and is not represented to be the actual altitude but an estimated altitude. This Niobrara Formation DEM shows that the altitude of the top of the Niobrara Formation generally decreases from northwest to southeast with the lowest altitudes north and west of Inavale in the Republican River Valley near profile 2. The southern Niobrara Formation topographic ridge, represented as a dashed line in figure 10, is small in scale relative to the whole study area but appears to follow the contour of the river valley. The northern Niobrara Formation topographic high has an altitude of about 559 m to the west and descends to about 543 m to the east.

Thickness of the Quaternary-Age Alluvial Deposits

Using the land-surface DEM and the Niobrara Formation DEM, the thickness of the Quaternary deposits was mapped (fig. 11). Within the mapped area, the Quaternary deposits are thin at the north and become thicker to the south. When compared to the Niobrara Formation DEM, this thinning of the Quaternary deposits corresponds with the rise of the top of the Niobrara Formation to the topographic high. One observation from this map is that the Quaternary deposits seem to be thin along the whole stretch of Farmers Creek, but this thinning probably reflects the topographic low of the land surface there. There is another area of thin Quaternary deposits near the southern edge of the map. This thinning of the Quaternary deposits may be partly a result of the southern Niobrara Formation topographic ridge mentioned above, but it also corresponds to the topographic low of the land surface where it descends to the bottomland east of Inavale.

On the basis of the Niobrara Formation DEM and the thickness map, the authors conclude that the Niobrara Formation topographic high outcrops or nearly appears at the land surface for a substantial distance in the east-west extent, and can act as a barrier to ground-water flow from the uplands to the river. Present day north-south trending tributaries to the

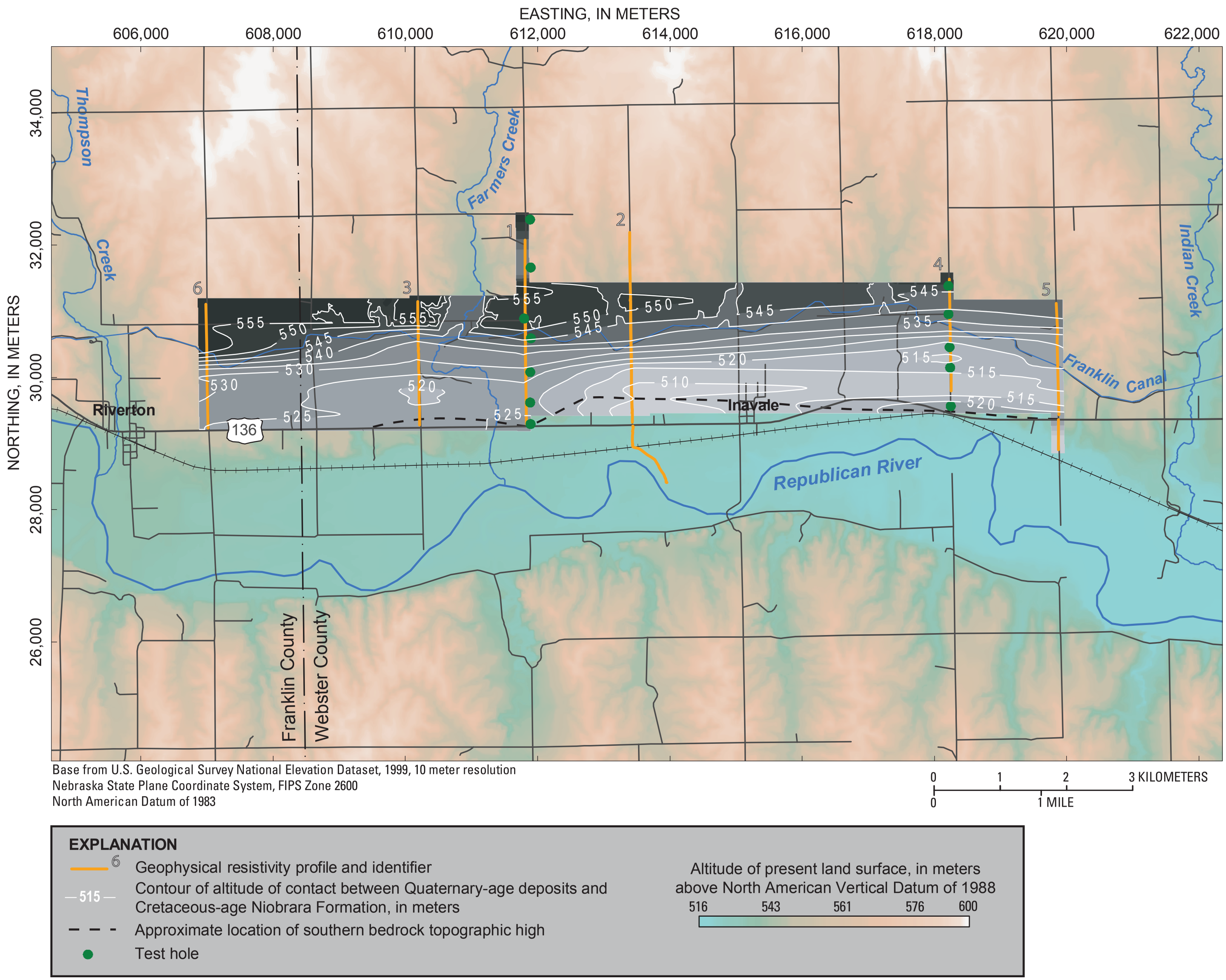


Figure 10. Altitude of contact between Quaternary-age alluvial deposits and Cretaceous-age Niobrara Formation near the Republican River in Franklin and Webster Counties, Nebraska.

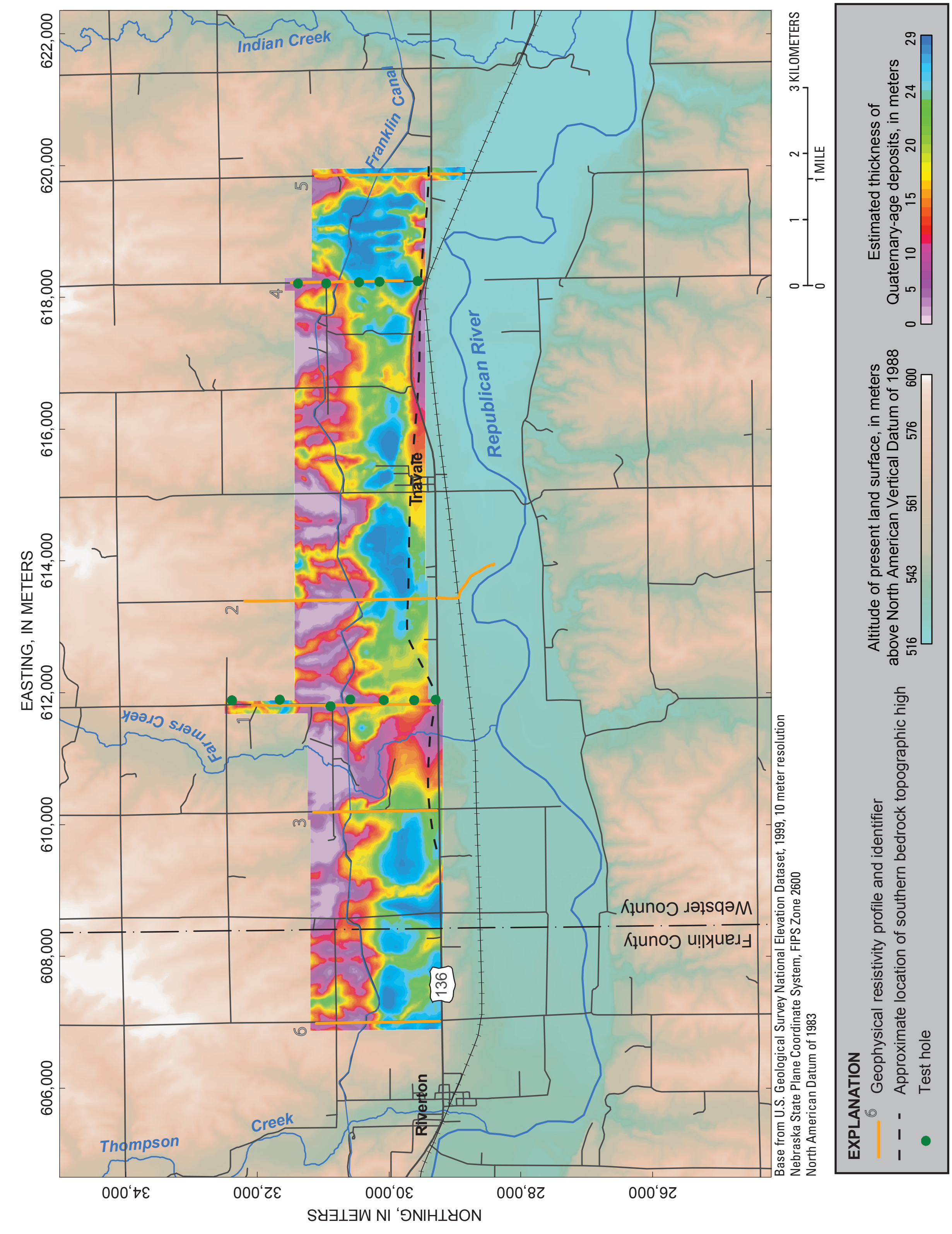


Figure 11. Thickness of Quaternary-age alluvial deposits near the Republican River in Franklin and Webster Counties, Nebraska.

river breach the bedrock ridges at 1.5- to 5-km intervals, providing a path for ground water to either discharge to the tributary or continue as subsurface flow to the river. Ground-water flow in the subsurface through undetected pathways through the Niobrara Formation topographic highs is a possibility but no such flow paths were mapped during this study. For these reasons, the uplands alluvial aquifer and the Republican River lowland alluvial aquifer are not represented as fully disconnected throughout the study area. At present (2008), there are no published ground-water-flow model results for this area.

Summary

A regional ground-water model was developed by the Nebraska Cooperative Hydrology Study (COHYST), a of state and local governmental agencies, to help manage and understand the Platte River system. The COHYST completed a series of hydrostratigraphic maps for 10 hydrostratigraphic units critical to their ground-water modeling effort. All available test-hole data and surficial geologic maps were used to estimate the altitude and geographic location of the geologic contact between the Quaternary-age alluvial deposits and the Niobrara Formation, but the lack of detailed geologic data resulted in uncertainties in those estimates. These uncertainties produce uncertain or incorrect estimates of saturated thickness, hydrologic boundaries, and hydrologic properties used for ground-water models and can lead to problems with conceptualization of the simulated flow system and to potential problems with calibration of the simulation.

The southern boundary of the COHYST study area lies along the Republican River, where an area with insufficient geologic data immediately north of the Republican River led to model-calibration problems. Geologic descriptions from several test holes drilled by COHYST and University of Nebraska-Lincoln Conservation and Survey Division in the Republican River Valley near Riverton and Inavale, Nebraska, during 2001 and 2002 indicated a possible hydrologic disconnection between the Quaternary deposits of the uplands and the Quaternary deposits of the Republican River lowland. An interpretive hydrogeologic section showed a topographic high of the Niobrara Formation that could result in the hydrologic disconnection being up to 0.8 km wide. During October to December 2003, the U.S. Geological Survey, in cooperation with the COHYST, conducted a surface geophysical investigation using direct-current (DC) and capacitively coupled resistivity imaging methods. The purpose of this report is to document the application of two surface geophysical two-dimensional (2D)-resistivity methods to map the contact between the Quaternary deposits and the Niobrara Formation along selected profiles in the Republican River Basin near Riverton and Inavale. Six 2D–DC profiles, with line lengths ranging from 1.7 to 4.0 km long were collected along six south-north profiles.

Profiles 1 and 4 followed the same profile trace as the two test-hole transects at these sites. These profiles were interpreted first because of their proximity to test-hole transects. The resistivity results for these two profiles were compared to the geologic descriptions of test-hole cuttings and to any surficial features that could help explain features found in the resistivity data. The geologic descriptions from these test holes were used to distinguish the electrical properties of the Quaternary deposits and the Niobrara Formation in the Republican River study area. This information was applied to interpret the remaining four profiles.

In all of the profiles, there was generally a three-layer subsurface interpretation with a resistor located between two conductors. Comparison of the geologic and resistivity data along two of the profiles indicated that a topographic high in the Niobrara Formation near the Franklin Canal is coincident with a resistivity high. Generally, on the southern end of each section the Niobrara Formation was near the bottom and had a conductive signature, but farther north the Niobrara Formation appeared at or near the surface and had become resistive. This variation in the electrical properties of the Niobrara Formation made accurate interpretation of the resistivity sections difficult and less confident because of similar resistivity of this formation and that of the coarse-grained sediment of the Quaternary deposits. However, distinct conductive features were identified within the resistivity sections that aided in delineating the contact between the resistive Quaternary deposits and the resistive Niobrara Formation. Using this information and the test-hole data, a line was drawn on the resistivity sections to represent the contact between the Quaternary deposits and the Niobrara Formation. A lithologic contrast, such as an increase in the relative grain size in the Niobrara Formation, may have caused the overall higher resistivity of the bedrock and also made it more resistant to erosion, producing the increase in altitude identified by test holes along these profiles. Another possible hypothesis is that this change in resistivity could be caused by change in water content, inferred to be the effect of infiltrated surface water lowering the resistivity because of multiple years of saturation below and downgradient from Franklin Canal.

The contact line on each resistivity section indicated a general trend in the top of the Niobrara Formation as it rises abruptly from the south to north to approach the surface, in most cases near the Franklin Canal. A smaller Niobrara Formation topographic ridge was noticeable on five of the six profiles and is located about 1.2 km south of the aforementioned Niobrara Formation topographic high except at profile 2, where the small Niobrara Formation ridge is about 600 m south from the Niobrara Formation high.

A digital elevation model (DEM) of the contact between Quaternary deposits and the Niobrara Formation across the study area showed that the top of the Niobrara Formation is highest in the northwest corner and slopes downward to the southeast with its lowest altitudes north and west of Inavale in the Republican River Valley. The altitude of the northern Niobrara Formation topographic high is maximum in the west (559 m) and descends to about 543 m in the east. The southern

Niobrara Formation ridge is small in scale compared to the whole study area, but generally parallels the river. The estimated thickness of the Quaternary deposits indicated thinning within the Quaternary deposits that approximately corresponds to the northern Niobrara Formation topographic high.

The Niobrara Formation topographic high outcrops or approaches the land surface, which could deflect the flow of ground water from the uplands alluvial aquifer from its southward path to the Republican River alluvial aquifer. Present-day north-south trending tributaries to the river, spaced at 1.5- to 5-km intervals, could provide a path for ground water from the uplands alluvial aquifer to either discharge to the tributary or continue as subsurface flow to the Republican River, alluvial aquifer. It is possible that there are other ground-water flow paths through the topographic high that were not mapped during this study, thus the two aquifers are not represented as fully disconnected.

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Appendixes 1–3

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Appendix 1. Test-hole location, depth, and 2003 water level, Webster County, Nebraska.

[m, meter; NAVD 88, North American Vertical Datum of 1988; bls, below land surface; N, north; °, degree; W, west; -----, not available]

Test-hole identifier (fig. 1)	Year drilled	Legal description	Latitude (decimal degrees)	Longitude (decimal degrees)	Land-surface altitude (m above NAVD 88)	Test-hole depth (m bls)	Depth to water, fall 2003 (m bls)[1]
W-01-01	2001	T2N R12W S36 DDAD	N 40.091075°	W 98.613322°	543.4	27.4	16.92
W-02-01	2001	T2N R12W S36 DAAA	N 40.096311°	W 98.613325°	536.7	24.4	-----
W-03-01	2001	T2N R12W S36 ADAA	N 40.099100°	W 98.613358°	543.7	30.2	20.54
W-04-01	2001	T2N R12W S36 AAAA	N 40.103594°	W 98.613469°	547.3	18.3	7.89
W-01-02	2002	T2N R12W S25 DADD	N 40.107444°	W 98.613417°	558.0	12.2	-----
W-02-02	2002	T2N R12W S33 CCCC	N 40.089515°	W 98.687871°	533.0	12.2	1.92
W-03-02	2002	T2N R12W S33 CCBB	N 40.092449°	W 98.687891°	536.7	21.3	-----
W-04-02	2002	T2N R12W S33 BCCC	N 40.096598°	W 98.687793°	547.0	24.4	-----
W-05-02	2002	T2N R12W S33 BBCC	N 40.101191°	W 98.687580°	548.9	12.2	-----
W-06-02	2002	T2N R12W S29 DDDD	N 40.103900°	W 98.688728°	555.9	12.2	5.30
W-07-02	2002	T2N R12W S28 CBBB	N 40.110831°	W 98.687430°	561.1	30.5	-----
W-09-02	2002	T2N R12W S28 BBBB	N 40.117362°	W 98.687412°	573.6	24.4	4.27

[1] Water-level data were collected and supplied by the Lower Republican Natural Resources District, Alma, Nebraska.

Appendix 2. Raw Apparent Resistivity Pseudosections, Calculated Apparent Resistivity Pseudosections, and Inverse-Modeling Results for Direct-Current Resistivity Profiles.

The raw apparent resistivity pseudosection, calculated apparent resistivity pseudosection, and inverse-modeling results for each of the direct-current resistivity profiles are presented herein. A pseudosection is a gridded section of data where the depths of the apparent resistivity data points are approximated based on array type. The depths are approximate because final depths for resistivity values are not calculated until the inversion process. Profile 5 was processed in two sections because the data were collected in two sections to avoid interruption of the profile by U.S. Highway 136.

All images are as directly exported from RES2DINV, version 3.55. A pseudosection plot shows gridded values. Raw apparent resistivity values are the actual values calculated from the normalized voltage collected from the direct-current resistivity unit. Calculated apparent resistivity values are the values that the inversion program calculates from the inverse-model-resistivity values. The calculated apparent resistivity values are then compared to the raw apparent resistivity values to estimate the absolute error. The inversion program attempts to reduce the absolute error by successively altering the inverse-model-resistivity values and recalculating the calculated apparent resistivity (each alteration is known as an iteration). A solution is reached when the absolute error no longer improves appreciably (more than 1 percent) between iterations. These sections are plotted with axes of depth and distance, in meters; and with a color-coded resistivity scale, in ohm-meters.

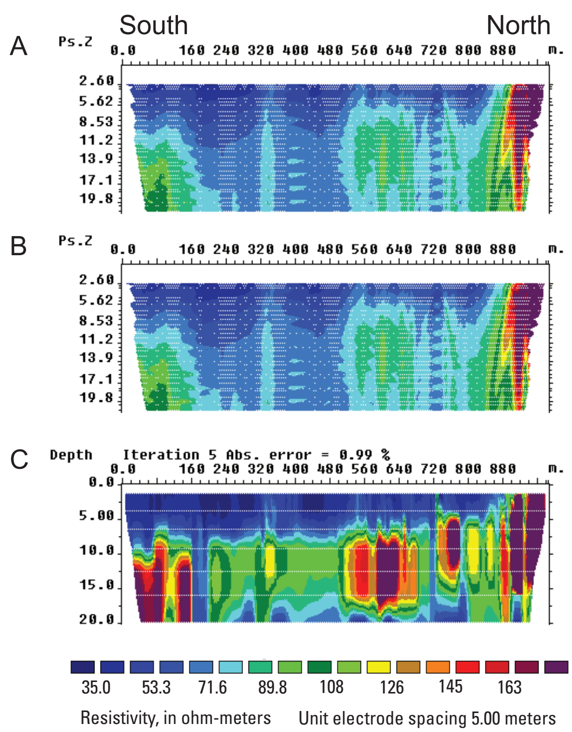

Figure 2.1. Sections showing (A) raw apparent resistivity pseudosection, (B) calculated apparent resistivity pseudosection, and (C) inverse-modeling results of direct-current resistivity profile 1. (Sections are plotted with axes of estimated depth and distance, in meters; and with a color-coded resistivity scale, in ohm-meters.)

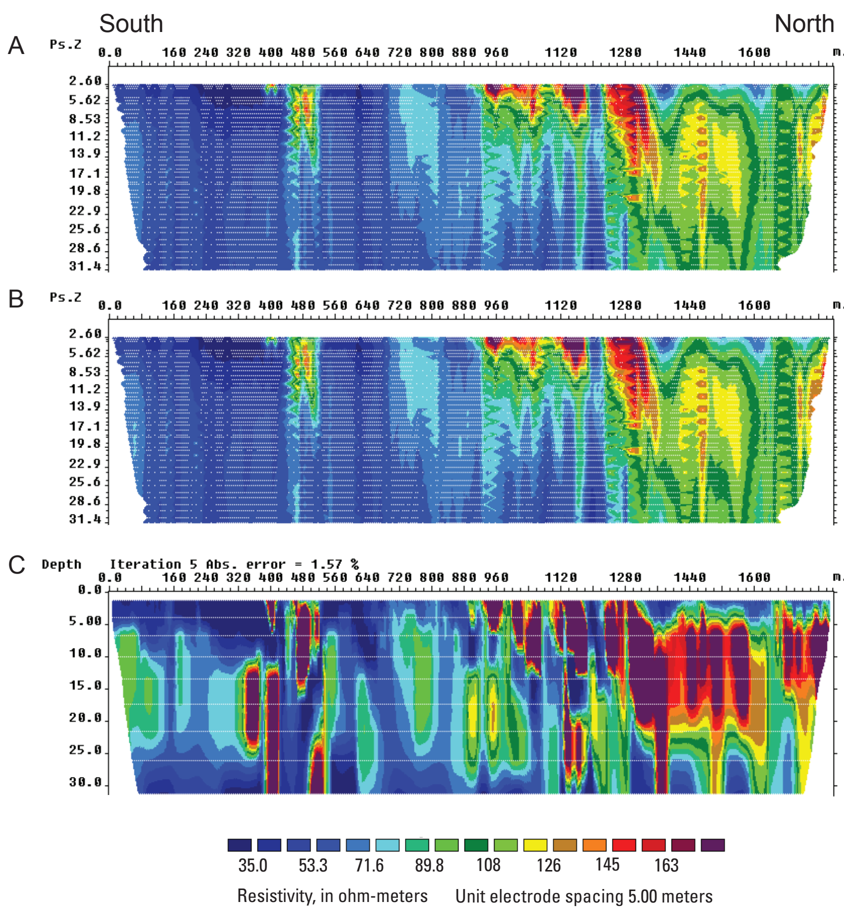

Figure 2.2. Sections showing (A) raw apparent resistivity pseudosection, (B) calculated apparent resistivity pseudosection, and (C) inverse-modeling results of direct-current resistivity profile 2. (Sections are plotted with axes of estimated depth and distance, in meters; and with a color-coded resistivity scale, in ohm-meters.)

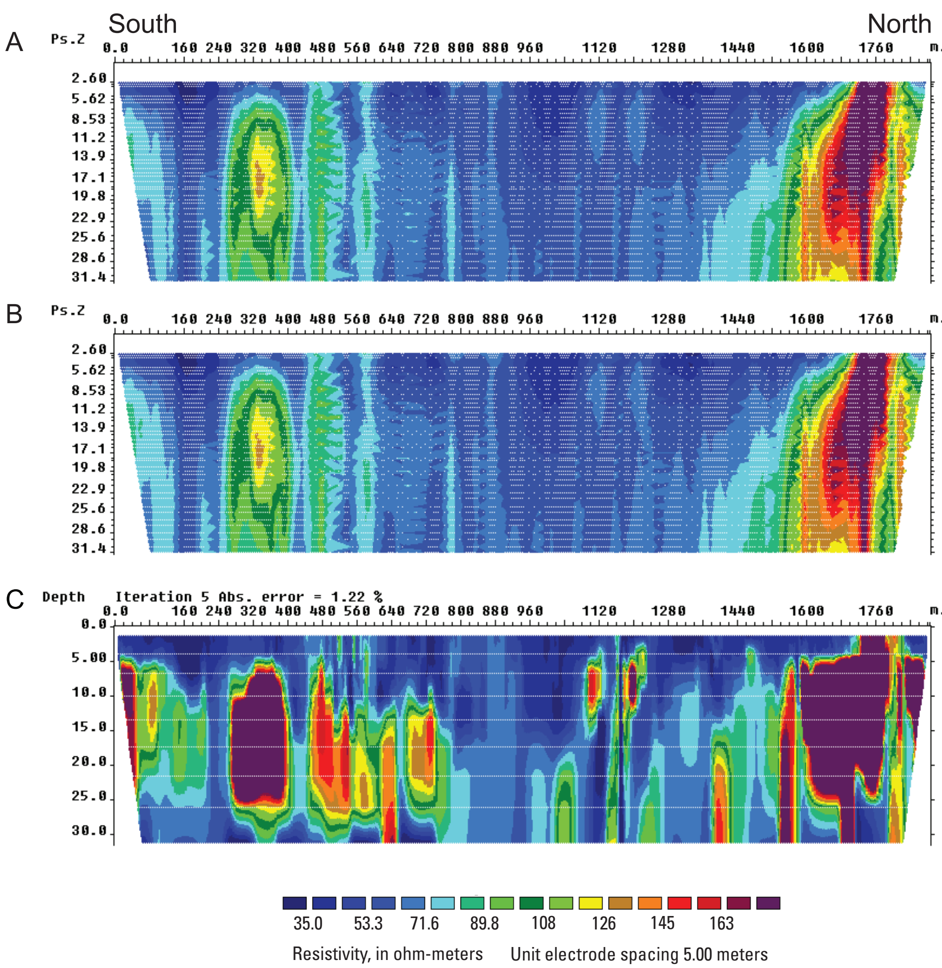

Figure 2.3. Sections showing (A) raw apparent resistivity pseudosection, (B) calculated apparent resistivity pseudosection, and (C) inverse-modeling results of direct-current resistivity profile 3. (Sections are plotted with axes of estimated depth and distance, in meters; and with a color-coded resistivity scale, in ohm-meters.)

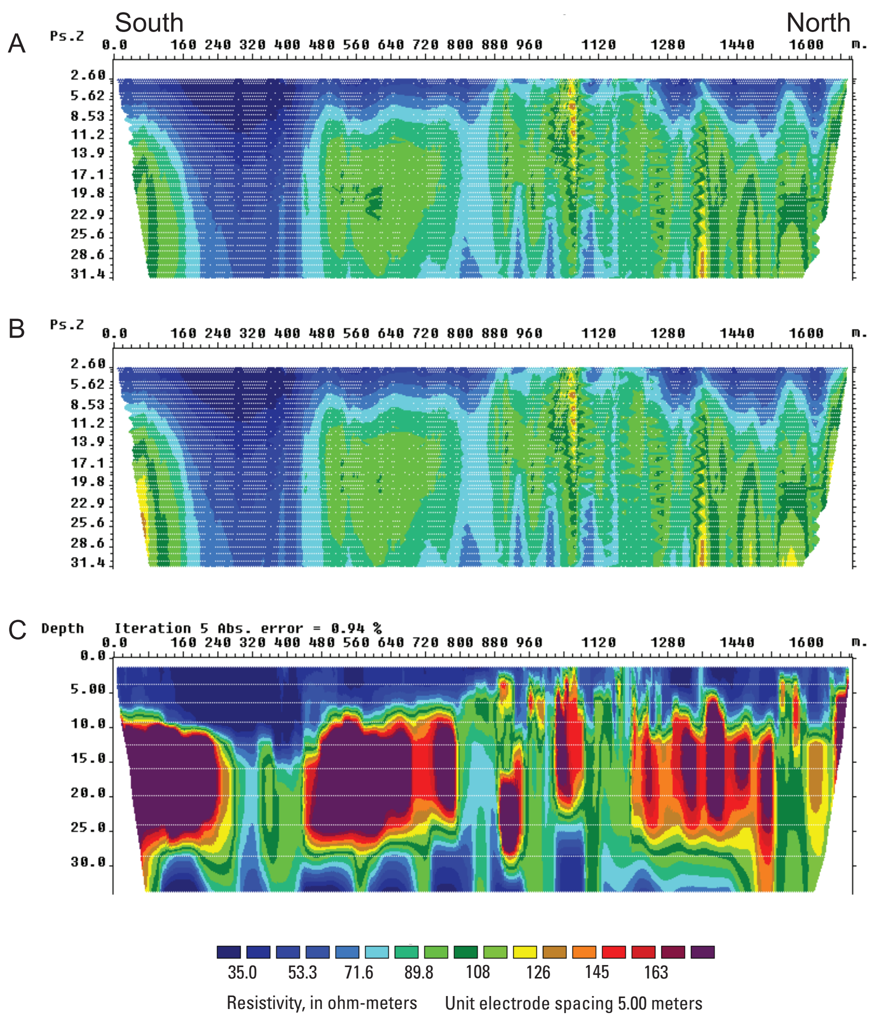

Figure 2.4. Sections showing (A) raw apparent resistivity pseudosection, (B) calculated apparent resistivity pseudosection, and (C) inverse-modeling results of direct-current resistivity profile 4. (Sections are plotted with axes of estimated depth and distance, in meters; and with a color-coded resistivity scale, in ohm-meters.)

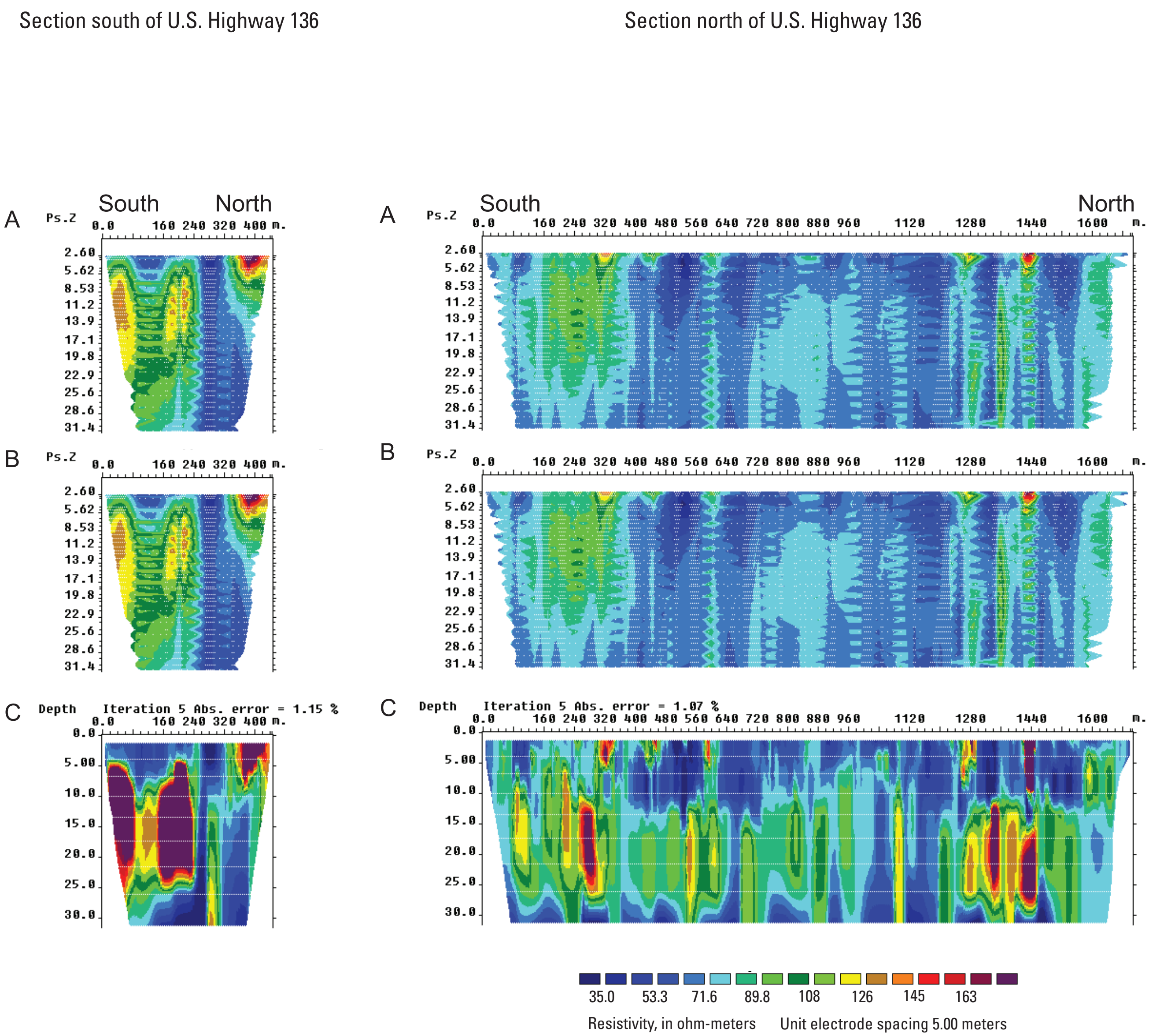

Figure 2.5. Sections showing (A) raw apparent resistivity pseudosection, (B) calculated apparent resistivity pseudosection, and (C) inverse-modeling results of direct-current resistivity profile 5 south and north of U.S. Highway 136. (Sections are plotted with axes of estimated depth and distance, in meters; and with a color-coded resistivity scale, in ohm-meters.)

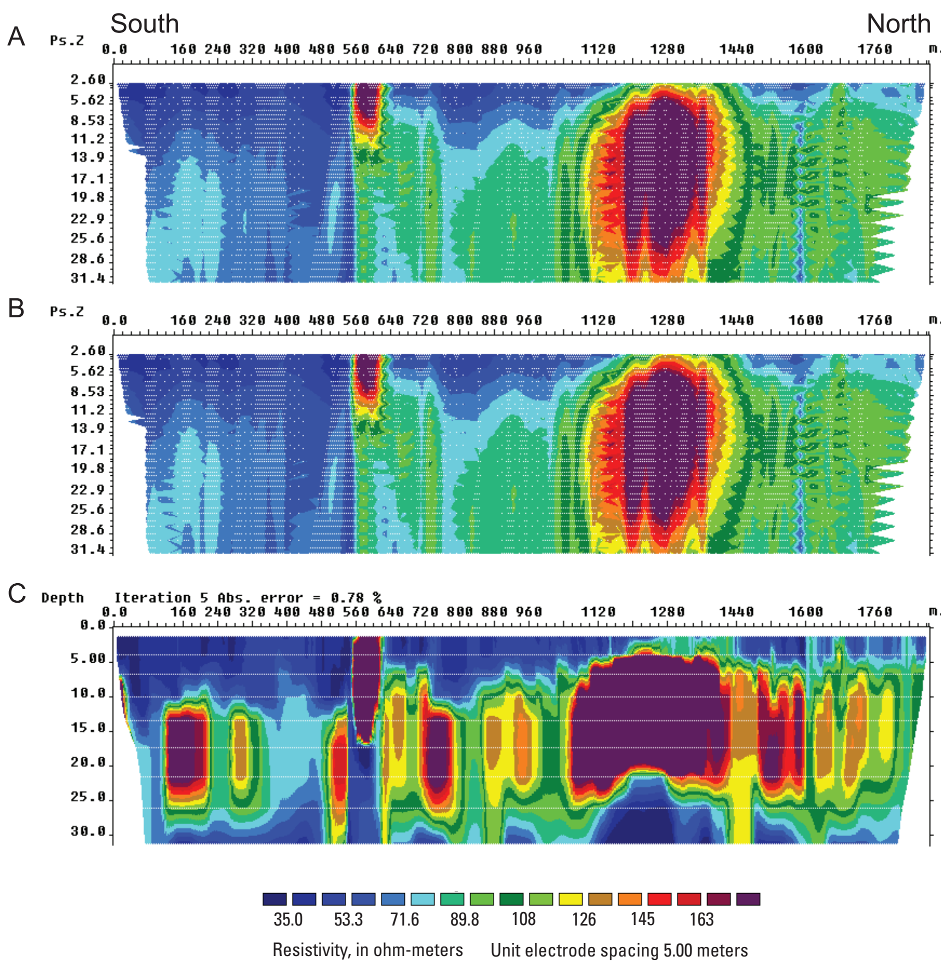

Figure 2.6. Sections showing (A) raw apparent resistivity pseudosection, (B) calculated apparent resistivity pseudosection, and (C) inverse-modeling results of direct-current resistivity profile 6. (Sections are plotted with axes of estimated depth and distance, in meters; and with a color-coded resistivity scale, in ohm-meters.)

Appendix 3. Raw Apparent Resistivity Pseudosections, Calculated Apparent Resistivity Pseudosections, and Inverse-Modeling Results for Capacitively Coupled Resistivity Profiles.

The raw apparent resistivity pseudosection, calculated apparent resistivity pseudosection, and inverse-modeling results for each of the capacitively coupled resistivity profiles are presented herein. A pseudosection is a gridded section of data where the depths of the apparent resistivity data points are approximated based on array type. The depths are approximate because final depths for resistivity values are not calculated until the inversion process. Both profiles were processed in two sections because the data were collected in two sections to avoid an obstruction near Franklin Canal for profile 1 and an interruption by U.S. Highway 136 in profile 2.

All images are as directly exported from RES2DINV, version 3.55. A pseudosection plot shows gridded values. Raw apparent resistivity values are the actual values calculated from the normalized voltage data collected from the capacitively coupled resistivity unit. Calculated apparent resistivity values are the values that the inversion program calculates from the inverse-model-resistivity values. The calculated apparent resistivity values are then compared to the raw apparent resistivity values to estimate the absolute error. The inversion program attempts to reduce the absolute error by successively altering the inverse-model-resistivity values and recalculating the calculated apparent resistivity (each alteration is known as an iteration). A solution is reached when the absolute error no longer improves appreciably (more than 1 percent) between iterations. These sections are plotted with axes of depth and distance, in meters; and with a color-coded resistivity scale, in ohm-meters.

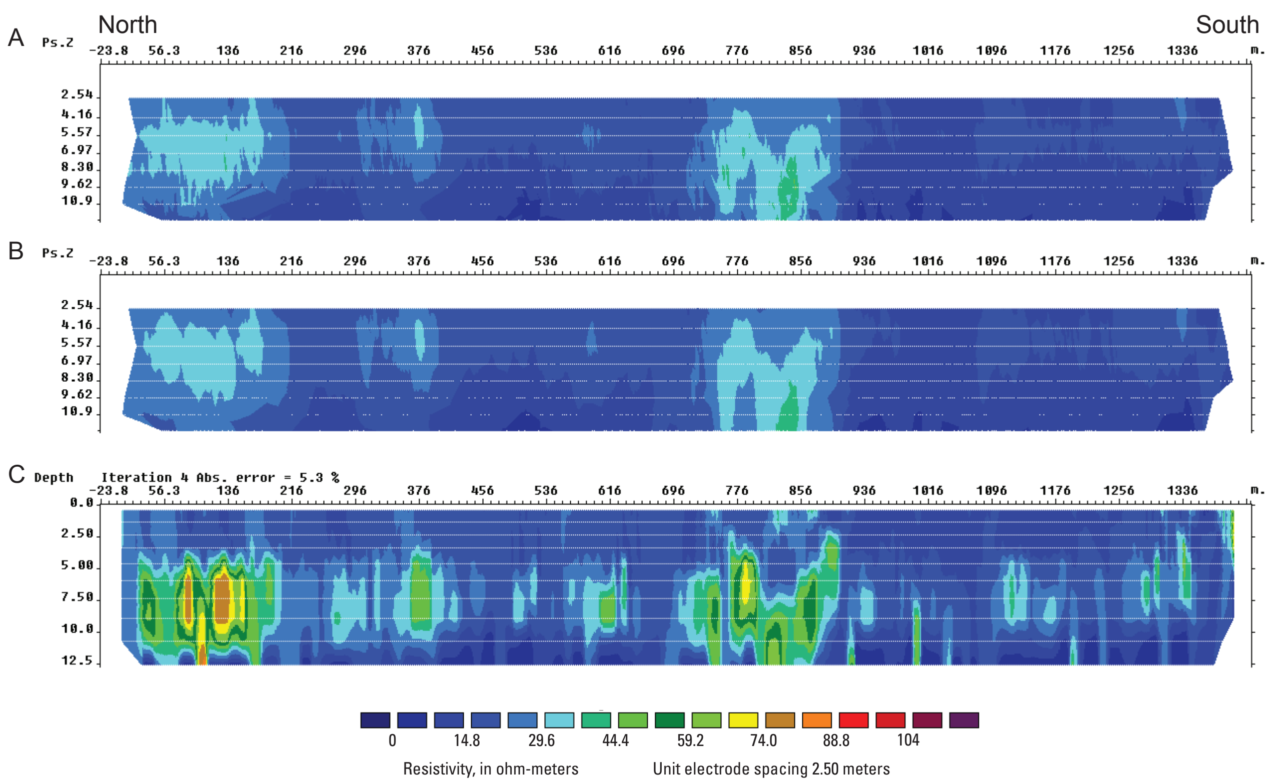

Figure 3.1. Sections showing (A) raw apparent resistivity pseudosection, (B) calculated apparent resistivity pseudosection, and (C) inverse-modeling results of capacitively coupled resistivity profile 1 south of Franklin Canal. (Sections are plotted with axes of estimated depth and distance, in meters; and with a color-coded resistivity scale, in ohm-meters.)

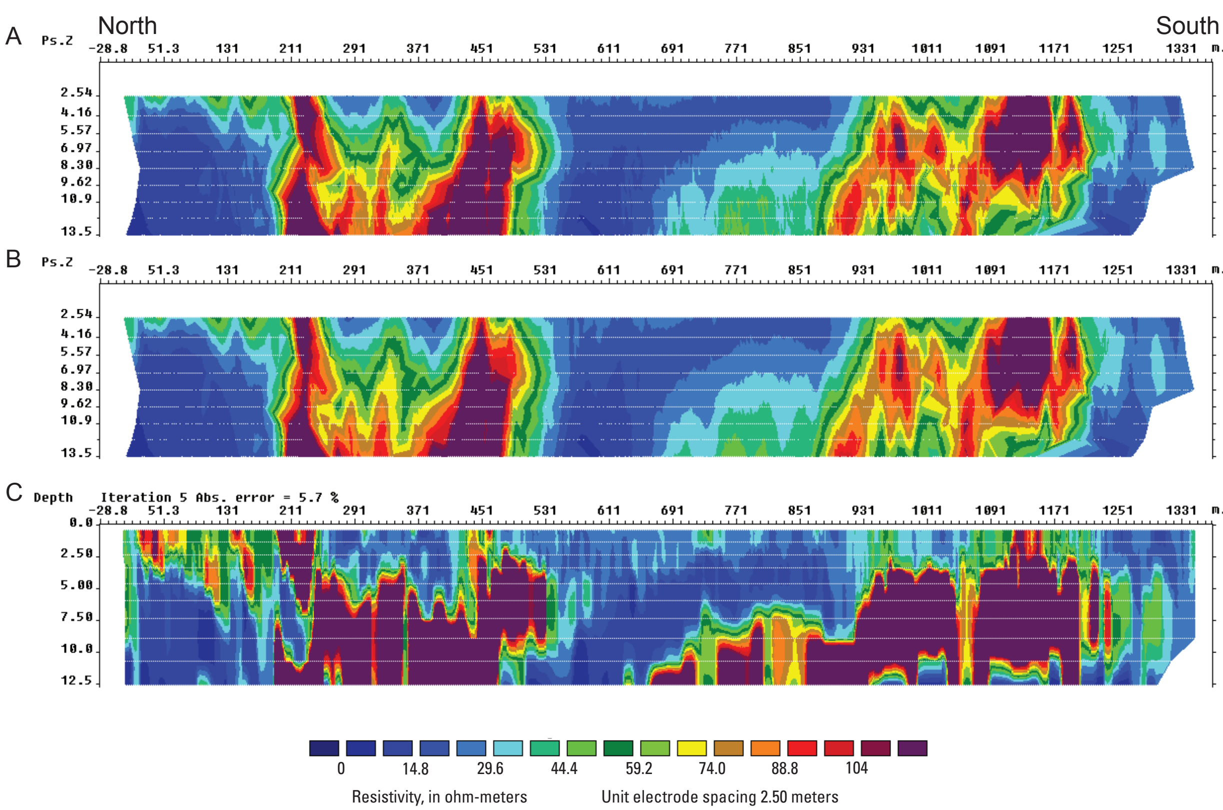

Figure 3.2. Sections showing (A) raw apparent resistivity pseudosection, (B) calculated apparent resistivity pseudosection, and (C) inverse-modeling results of capacitively coupled resistivity profile 1 north of Franklin Canal. (Sections are plotted with axes of estimated depth and distance, in meters; and with a color-coded resistivity scale, in ohm-meters.)

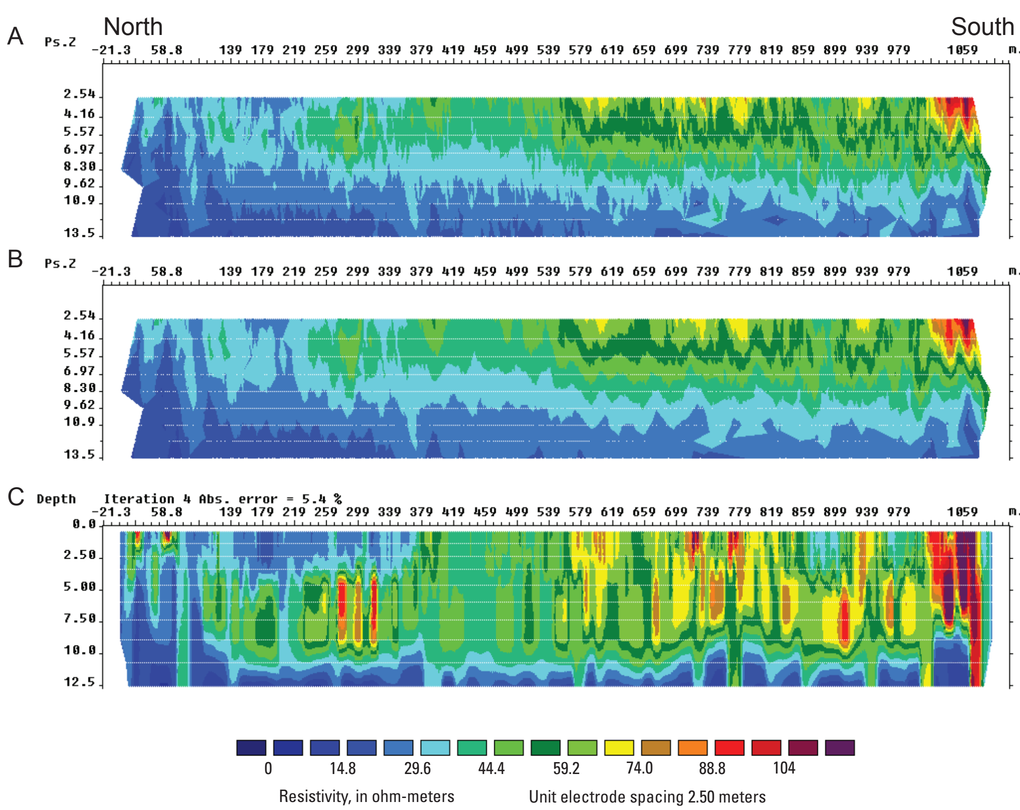

Figure 3.3. Sections showing (A) raw apparent resistivity pseudosection, (B) calculated apparent resistivity pseudosection, and (C) inverse-modeling results of capacitively coupled resistivity profile 2 south of U.S. Highway 136. (Sections are plotted with axes of estimated depth and distance, in meters; and with a color-coded resistivity scale, in ohm-meters.)

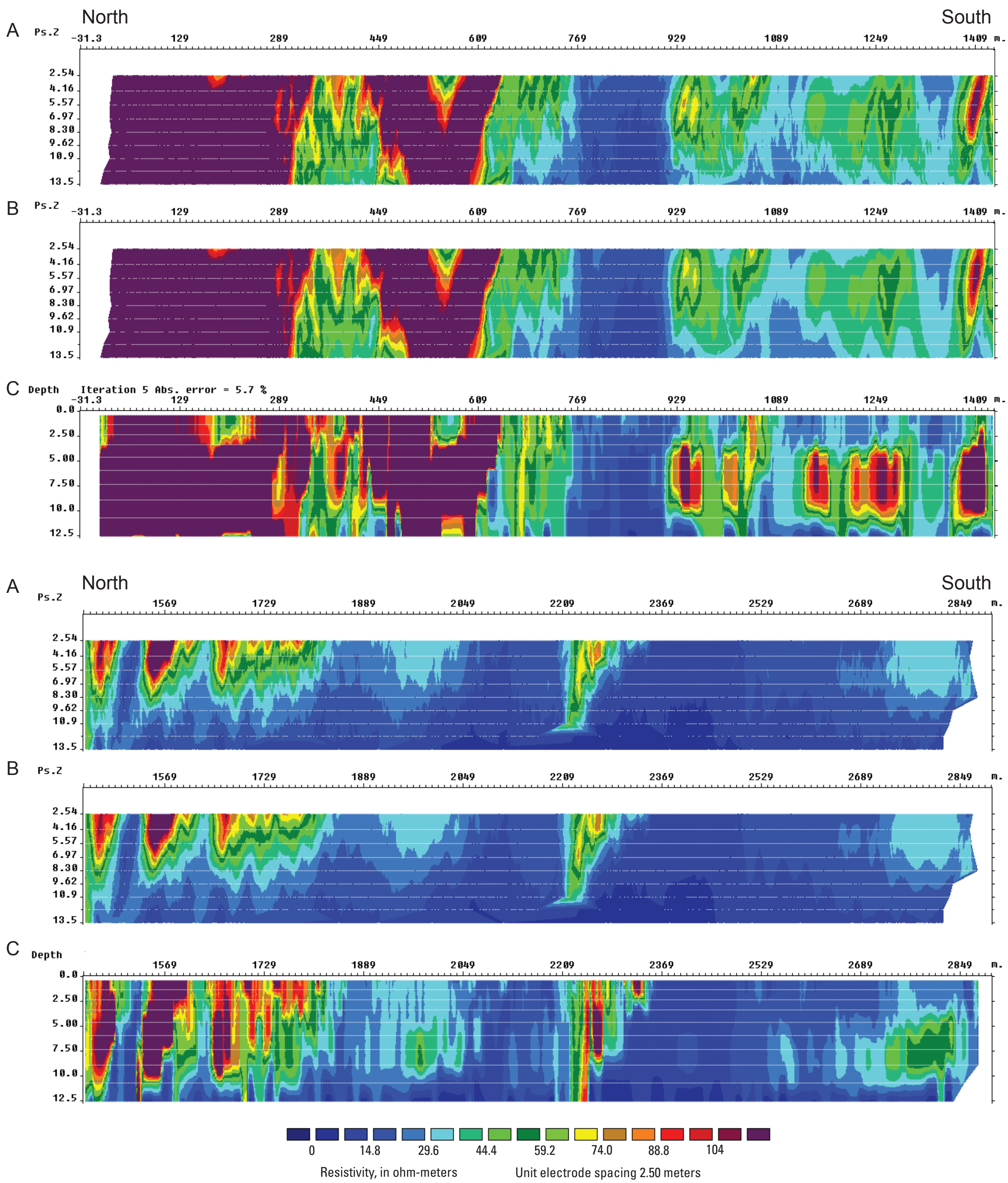

Figure 3.4. Sections showing (A) raw apparent resistivity pseudosection, (B) calculated apparent resistivity pseudosection, and (C) inverse-modeling results of capacitively coupled resistivity profile 2 north of U.S. Highway 136. (Sections are plotted with axes of estimated depth and distance, in meters; and with a color-coded resistivity scale, in ohm-meters.)

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