U.S. Department of the Interior
U.S. Geological Survey

Prepared in cooperation with the
City of Sioux Falls, South Dakota

Scientific Investigations Map 3393
Sheet 1 of 2

Abstract

The U.S. Geological Survey, in cooperation with the City of Sioux Falls, South Dakota, began developing a groundwater-flow model of the Big Sioux aquifer in 2014 that will enable the City to make more informed water management decisions, such as delineation of areas of the greatest specific yield, which is crucial for locating municipal wells. Innovative tools are being evaluated as part of this study that can improve the delineation of the hydrogeologic framework of the aquifer for use in development of a groundwater-flow model, and the approach could have transfer value for similar hydrogeologic settings. The first step in developing a groundwater-flow model is determining the hydrogeologic framework (vertical and horizontal extents of the aquifer), which typically is determined by interpreting geologic information from drillers' logs and surficial geology maps. However, well and borehole data only provide hydrogeologic information for a single location; conversely, nearly continuous geophysical data are collected along flight lines using airborne electromagnetic (AEM) surveys. These electromagnetic data are collected every 3 meters along a flight line (on average) and subsequently can be related to hydrogeologic properties. AEM data, coupled with and constrained by well and borehole data, can substantially improve the accuracy of aquifer hydrogeologic framework delineations and result in better groundwater-flow models.

AEM data were acquired using the Resolve frequency-domain AEM system to map the Big Sioux aquifer in the region of the city of Sioux Falls. The survey acquired more than 870 line-kilometers of AEM data over a total area of about 145 square kilometers, primarily over the flood plain of the Big Sioux River between the cities of Dell Rapids and Sioux Falls. The U.S. Geological Survey inverted the survey data to generate resistivity-depth sections that were used in two-dimensional maps and in three-dimensional volumetric visualizations of the Earth resistivity distribution. Contact lines were drawn using a geographic information system to delineate interpreted geologic stratigraphy. The contact lines were converted to points and then interpolated into a raster surface. The methods used to develop elevation and depth maps of the hydrogeologic framework of the Big Sioux aquifer are described herein.

The final AEM interpreted aquifer thickness ranged from 0 to 31 meters with an average thickness of 12.8 meters. The estimated total volume of the aquifer was 1,060,000,000 cubic meters based on the assumption that the top of the aquifer is the land-surface elevation. A simple calculation of the volume (length times width times height) of a previous delineation of the aquifer estimated the aquifer volume at 378,000,000 cubic meters; thus, the estimation based on AEM data is more than twice the previous estimate. The depth to top of Sioux Quartzite, which ranged in depth from 0 to 90 meters, also was delineated from the AEM data.

Introduction

The city of Sioux Falls is in the southeastern corner of South Dakota at the junction of Interstate 90 and Interstate 29 (fig. 1). Sioux Falls is a rapidly growing metropolitan area with a population of about 172,000 as of 2015. Between 2000 and 2010, the population of Sioux Falls increased 24 percent, and an 11 percent population increase was estimated between 2010 and 2015 (U.S. Census Bureau, 2015). The population growth, combined with a desire to attract new industries to the city, has motivated the City of Sioux Falls to reappraise the local groundwater resources, including the Big Sioux aquifer.

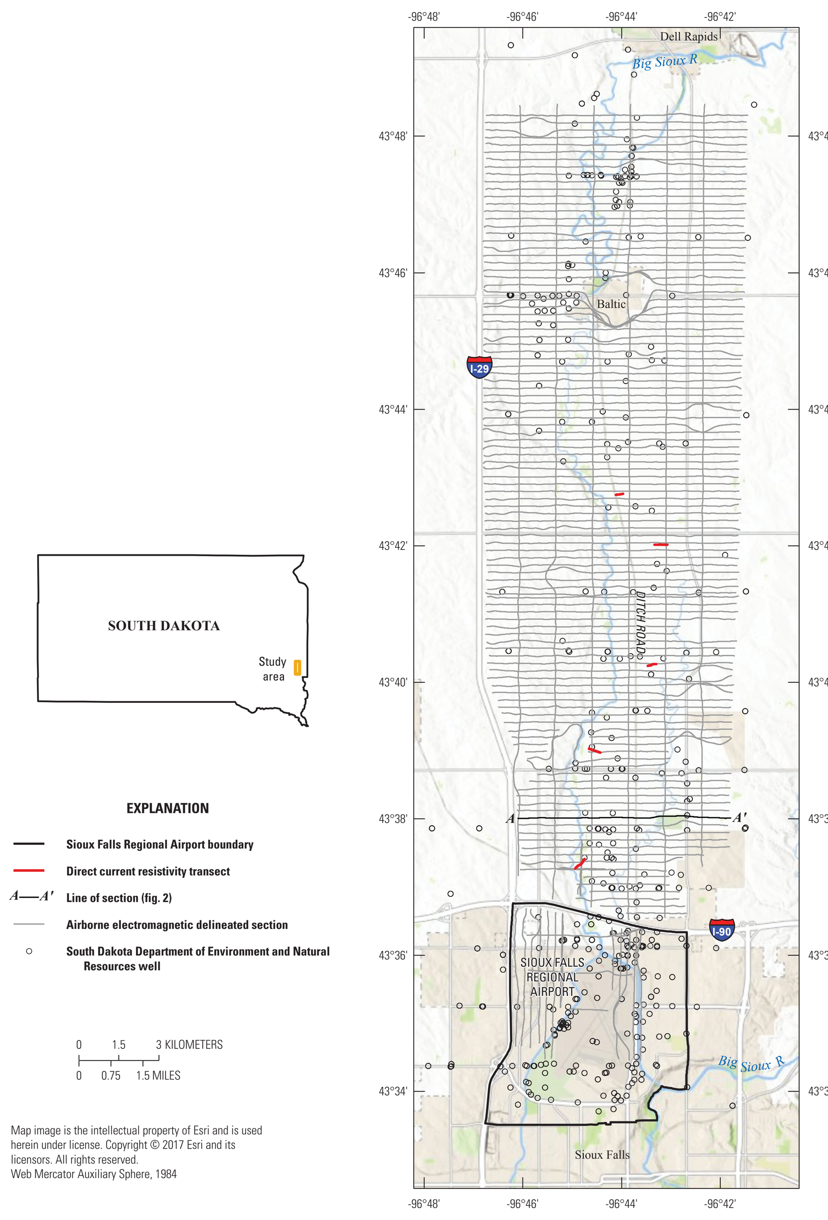

Figure 1. The study area, Sioux Falls Regional Airport, cross section A–A′, airborne electromagnetic delineated cross sections, direct current resistivity transects, and South Dakota Department of Environmental and Natural Resources wells, South Dakota.

The U.S. Geological Survey (USGS), in cooperation with the City of Sioux Falls, South Dakota, began developing a groundwater-flow model of the Big Sioux aquifer in 2014 that will enable the City to make more informed water management decisions, such as delineation of areas of the greatest specific yield, which is crucial for locating municipal wells. Innovative ArcGIS (Esri, 2017) tools are being evaluated as part of this study that can improve the delineation of the hydrogeologic framework of the aquifer for use in development of a more detailed groundwater-flow model, and the approach could have transfer value for similar hydrogeologic settings. Groundwater-flow models also support the development of future monitoring networks, help to understand hydrologic responses to potential groundwater management scenarios and climate extremes, determine potential contaminant source and transport, and determine aquifer storage and sustainable development. Groundwater-flow models that start with improved aquifer geometries and properties, such as those derived from airborne electromagnetic (AEM) surveys, can provide the best information possible to various water-resource managers well into the future.

Traditionally, aquifer boundaries for groundwater-flow models are determined by interpolation of surface observations of geology, recorded well and borehole geology, and geophysical logs (Arihood, 2008; Casey, 1996; Rothrock and Otton, 1947; Thamke and others, 2014). The well geology and geophysical data used in this method only provide hydrogeologic information at a single location, which could be the only point of information for several square miles. The Big Sioux aquifer is composed of material deposited during glacial retreat and advancement, which poses a challenge for mapping buried aquifer channels because these channels cannot be identified from surface geology (Valder and others, 2016). In the last two decades, geophysical techniques, such as AEM surveys, are increasingly being used to support groundwater-flow modeling efforts around the world (Abraham and others, 2012; Ball and others, 2011, 2015; Christiansen and Christensen, 2003; Danielsen and others, 2003). AEM surveys offer nearly continuous measurements that can be used to map alluvial aquifer boundaries and improve estimates of aquifer properties, such as hydraulic conductivity. This information, coupled with well and borehole records, can improve the accuracy of the delineated geometry of aquifer boundaries for input into a groundwater-flow model. By improving the groundwater-flow model, more accurate and representative information of the aquifer can be obtained to make informed decisions on placement of future wells and sustainable water withdrawal rates.

To obtain the most accurate data possible to inform a groundwater-flow model of the Big Sioux aquifer, the City of Sioux Falls contracted with CGG Canada Services to collect AEM data in 2015. This flight was the first application of AEM in South Dakota to characterize water resources. Overall, 870 line-kilometers were flown, and 145 cross-section profiles were generated. A map of the study area depicting the location of the collected AEM data as well as nearby cities, wells, interstates, and rivers are shown in figure 1. CGG provided the final AEM dataset to the City and the USGS Crustal Geophysics and Geophysical Science Center, who inverted the data using the program EM1DFM (Farquharson, 2000) to produce resistivity depth sections for three-dimensional visualization of subsurface electrical variations. A data release document (Smith and others, 2018) is available that contains raw and processed AEM and magnetic data, processed AEM inversions, and a contractor's report describing survey parameters.

The purpose of this map is to describe and show the delineation of the hydrogeologic framework Big Sioux aquifer near Sioux Falls, South Dakota, using AEM methods. The use of innovative ArcGIS (Esri, 2017) tools has provided a qualitative assessment of the hydrogeologic framework and a lower cost solution for characterizing alluvial aquifers for future projects with other municipalities. The methods described herein, combined with the developed ArcGIS tools, offer vastly improved aquifer delineation compared to traditional methods.

Geology and Hydrogeology of the Big Sioux Aquifer

The Big Sioux aquifer, for the most part, underlies the Big Sioux River flood plain, which meanders north to south in eastern South Dakota. The section of the Big Sioux aquifer of interest for this map is situated between Dell Rapids and Sioux Falls (fig. 1). The study area is about 32.2 kilometers (km) by 4.5 km (Valder and others, 2016). The region is characterized by hilly topography, generated by at least two periods of glacial advance and retreat, that varies from smooth rolling plains to very rough knobby hills (Rothrock and Otton, 1947). The geologic units of interest within the study area include Quaternary-age alluvial material (alluvium), Quaternary-age glacial till, and Precambrian-age Sioux Quartzite. The alluvium within the study area is composed of clay, silt, sand, gravel, boulder-size clasts, and locally abundant organic material (U.S. Geological Survey, 2015). Glacial till includes tills from several glacial periods, such as Pre-Illinoian 1, Pre-Illinoian 2, Pre-Illinoian 3, and Late Wisconsin (Tomhave, 1994). Till layers have been characterized as heterogeneous "clay with silt to boulder-size clasts of glacial origin" (U.S. Geological Survey, 2015). Because of the similarity in composition, differentiation between the various till layers was not attempted for this study and these till layers are referred to as the glacial till layer. The glacial till layer is not entirely impervious but will retain water on its surface for a considerable time (Rothrock and Otton, 1947); consequently, the glacial till layer is considered the bottom of the Big Sioux aquifer, except for a few locations where the till was eroded down to the underlying Sioux Quartzite. The Sioux Quartzite has been described as pink or reddish- to tan-colored, siliceous, iron-stained orthoquartzite (sandstone cemented by silica) with mudstone and minor conglomerate layers (U.S. Geological Survey, 2015). The Sioux Quartzite is so thoroughly lithified that the pore spaces of the sandstone have almost entirely filled with cement, which causes the geologic layer to be impermeable (Rothrock and Otton, 1947). If glacial till is not present, then the Sioux Quartzite acts as an impermeable bottom of aquifer layer. Because the two different geologies act as the bottom of aquifer, it was necessary generate two AEM-delineated raster surfaces for input into the groundwater-flow model.

Groundwater resources include both glacial and Precambrian aquifers (Lindgren and Niehus, 1992). The glacial aquifers are composed predominantly of unconsolidated sand and gravel glacial outwash. The Big Sioux and Spilt Rock Creek aquifers are the only glacial aquifers within the study area; however, the aquifers have no known hydraulic connection. The Brandon, Skunk Creek, Pipestone Creek, Beaver Creek, and Slip Up Creek glacial aquifers are nearby but do not affect the study area. The Precambrian aquifer in the study area is contained in the Sioux Quartzite, which is a locally well-fractured and jointed crystalline rock that is used as a source of water in western and east-central Minnehaha County (Lindgren and Niehus, 1992). The amount of water contained within the Precambrian aquifer in the Sioux Quartzite is unknown because the depth and development of the fracture system in the aquifer is not known (Lindgren and Niehus, 1992).

Previous Work on the Big Sioux Aquifer

Rothrock and Otton (1947) described an investigation carried out by the USGS and the South Dakota State Geological Survey (SDGS) in cooperation with the City of Sioux Falls. The volume and shape of the Big Sioux aquifer was determined primarily from test wells drilled for the investigation. Eight lines of wells were in the Big Sioux River Basin. The bottom of the aquifer was drawn by linearly interpolating between the points where information was given by the various wells (Rothrock and Otton, 1947). The hydrogeologic framework results from the Rothrock and Otton (1947) study present the Big Sioux aquifer as a body of sand and gravel averaging 12.2 meters (m) deep, 3.2 km wide, and 29 km long. It is resting in a trough with a clay bottom and sides with bedrock (Sioux Quartzite) boundaries at the north and south end. A simple calculation of the volume (length times width times height) of the delineated aquifer from Rothrock and Otton (1947) estimated the aquifer volume at 378,000,000 cubic meters (m3), assuming the land surface as the top of aquifer.

A digital model of the Big Sioux aquifer was constructed in 1982 (Koch, 1982). The model used a 0.4-km grid network of 77 rows and 18 columns, which resulted in a total of 585 cells within the aquifer. The hydrogeologic framework was based on the known thicknesses of sand and gravel deposits from available well logs. Based on the well data collected by Koch (1982), the Big Sioux aquifer ranged in thickness from 1.2 to 14.6 m.

O'Connor (2017) delineated the Big Sioux aquifer using a subset of the same AEM data collected by CGG used in the study described in this report. The thesis only delineated the bottom of the aquifer, not the Sioux Quartzite, and did not delineate the study area south of Interstate 90, which is included in this study.

The final AEM hydrogeologic framework ranged from 0 to 36.5 m, and the average thickness was 12.3 m. The total volume of the delineated aquifer was 771,000,000 m3 based on the assumption that the top of the aquifer is the land surface elevation (O'Connor, 2017).

Airborne Electromagnetic Methods

AEM surveys have been used for several different purposes. Examples include the measurement of the depth of permafrost in Alaska (Ball and others, 2011), the distribution of brine in groundwater in Colorado and Montana (Ball and others, 2015; Thamke and Smith, 2014), and the mapping of the lower boundaries of alluvial aquifers in Nebraska (Abraham and others, 2012). AEM surveys are carried out by either helicopter or fixed-wing aircraft to characterize aquifers and their geologic setting. AEM systems operate by transmitting radio-frequency signals that interact with the underlying Earth, inducing secondary currents. The secondary currents are a function of the electrical resistivity of the subsurface materials. Materials, such as soils and rocks, have an intrinsic resistivity that controls the relation between the current density and the gradient of the electrical potential (U.S. Environmental Protection Agency, 2016). The electrical resistivity of subsurface geology is affected by the water content and quantity of metallic mineralization, clay, and gravel in the subsurface materials (Abraham and others, 2012). Variations in these properties, in any direction, create variations in the resistivity and, thus, the resulting induced current and the electric potential distribution.

Two types of AEM methods are used to measure the secondary (eddy) currents induced by the transmitted radio-frequency signals. One is the frequency-domain method, in which the signal is a continuous sinusoidal wave and measurements are taken at the same frequency of the original signal (Abraham and others, 2012; Ball and others, 2015). The second method is the time-domain method, in which the radio-frequency signal is a string of pulses and measurements are taken immediately after the pulse is turned off as a function of time. The investigation depth becomes a function of the time interval between pulses and decay rate based on ground conductivity (Lange and Seidel, 2007). Desired investigation depth and level of human development in an area generally determines which of the two methods to use at a particular study area.

To determine the suitability of the Big Sioux aquifer area for use of electromagnetic methods and to help determine which of the two AEM methods to use, the USGS investigated direct current (DC) resistivity along five transects (fig. 1) in April 2015. Electromagnetic methods rely on distinctive contrasts in conductivities (reciprocal of resistivity) in overlying geologic layers to differentiate between them. Results of the DC resistivity investigation revealed distinctive resistivity ranges for each geologic layer that did not overlap, which supported the use of electromagnetic methods. Results from the DC resistivity investigation estimated the alluvial deposits to have resistivities of between 30 and 70 ohm-meters (ohm-m), and the underlying glacial till was generally less than 10 ohm-m.

Based on the results of the preliminary resistivity investigation of the study area and the advantages and disadvantages of the two AEM methods, a frequency domain airborne electromagnetic survey was selected to survey the aquifer (Valder and others, 2016; O'Connor, 2017). A helicopter was equipped with the Resolve frequency domain system (Smith, 2010), which has the capability to image resistivity, dependent on resistivity of materials, to depths of about 80 m (Abraham and others, 2012). The electromagnetic measurements were made at six frequencies ranging from about 400 hertz to about 140,000 hertz, operating with paired transmitter and receiver coils contained in a "bird" (torpedo shaped instrument) suspended from the helicopter about 38 m above the ground.

Once the AEM frequency data were collected and preprocessed, they were then numerically inverted into depth-dependent subsurface resistivity cross sections, also referred to as resistivity-depth sections. Preprocessing included removing noise because of sferics (naturally occurring atmospheric signals), filtering out system noise (system noise is recorded during flight for this purpose), correcting drift, and leveling to correct signal levels for elevation variations.

Resistivity depth-sections and geo-referencing data were exported from Geosoft Oasis montaj (Geosoft, 2017). Python script tools were used to (1) import images into ArcGIS Desktop software, (2) convert profile line data to geographic line features with route measures (along profile), (3) reference profile images to "X-Z space" (X-axis, profile distance; Z-axis, elevation), and (4) use the ArcGIS Desktop software "Near" analysis tool to calculate the perpendicular distance between wells and flight lines. Well data were retrieved online from the Lithologic Logs Database (South Dakota Department of Environment and Natural Resources, 2016). Wells were categorized into six bins based on the perpendicular distance from flight lines. The six bins were 0–25 m, 25–50 m, 50–100 m, 100–150 m, 150–300 m, and 300–1,000 m. The bottoms of all wells (South Dakota Department of Environment and Natural Resources, 2016) within a 1,000-m radius were plotted on the profile images. The predominant resistivity range and color determined from well lithology was used to qualitatively locate the till and quartzite. Emphasis was given to wells with a perpendicular distance of 0–25 m and 25–50 m from flight lines.

An example of relating the resistivity of a profile to geology with a well that is within 25 m (hexagon with dot in the middle) is shown in figure 2. The profile on the far left of figure 2 is resistivity-depth cross section. On the far right of figure 2 is a scale depicting the resistivity ranges of the colors on the resistivity-depth cross section. Located between the resistivity-depth cross section and the resistivity scale is a diagram of the example well that shows the depth (not to scale) of where the resistivity range (color) changes. The lithology of the well shown on the profile is listed in table 1. According to the lithologic log, example well R3–38–89 completely extends through the glacial till to the Sioux Quartzite, which made it an ideal well to relate the resistivity of a profile to known geology. By noting where the resistivity and lithology changed, target geologic units were associated to a resistivity range. In figure 2 the "top soil" and "sand, fine" geologic layers were indistinguishable from each other, which was expected. According to the lithologic log in table 1, the lithology changed from "sand, fine" to "clay, brown, sandy, pebbly (till)" at 3.0 m, which is in the 20–40 ohm-m (light yellow/dark yellow) interval, immediately before it starts changing to 10–20 ohm-m (light green/green). The glacial till layer extends to 26.2 m, which is where the resistivity changes from 10–20 ohm-m (light green/green) to 20–40 ohm-m (light yellow/dark yellow). This extension indicates that the glacial till layer is associated with the 10–20 ohm-m (light green/green) resistivity interval. This well ends a few centimeters into the Sioux Quartzite at 26.3 m, which is where the resistivity changes from 20–40 ohm-m (light yellow/dark yellow) to 70–130 ohm-m (red). This associates the Sioux Quartzite with the 70–130 ohm-m (red) resistivity but the Sioux Quartzite unit rapidly increases in resistivity, to as much as 1,000 ohm-m.

Table 1. Lithologic log of example well in figure 1 (well number R3–38–89), Big Sioux aquifer, South Dakota.

Depth, in meters	Lithology description
0.3–0.6	Topsoil, black.
0.6–3.0	Sand, fine.
3.0–10.7	Clay, brown, sandy, pebbly (till).
10.7–26.2	Clay, gray, sandy, pebbly (till).
26.2–26.3	Quartzite; only few centimeters penetrated.

The ArcGIS Desktop software "Editor" tool was used to digitize hydrogeologic and geologic contacts (in X-Z space) at the selected resistivity ranges to delineate the top of till and top of Sioux Quartzite. Because the till and Sioux Quartzite act as the bottom of the aquifer, both geologic units needed to be delineated for the groundwater-flow model. The delineation (black line on resistivity cross section in fig. 2) of the top till was drawn as a bottom of the aquifer layer. The Sioux Quartzite delineation was drawn as the top of Sioux Quartzite. Python script tools converted X-Z profile lines to XYZ points. All the profile XYZ points were then appended to a single feature layer that was then converted to a raster file using the 3D Analyst ArcGIS tool "IDW" (Inverse Distance Weighted). The resulting raster file is referred to as the "bottom of aquifer raster surface." This process was duplicated for the delineation of the top of Sioux Quartzite. The resulting raster file is referred to as the "top of Sioux Quartzite raster surface."

One of the challenges in the use of AEM data was cultural interference. Manmade structures, such as railroads, buried pipelines, well casings, and other metallic objects, often produce signals that jumble or complicate electromagnetic signals because of the irregular three-dimensional responses of these objects (Watson and others, 2001). Because of the presence of roads, utilities, railroads, wells, and other highly conductive structures in the study area, cultural interference was identified on 55 of the profiles that required correction. Profile correction consisted of linearly interpolating from the point at the start of the cultural interference to the end of the cultural interference. The cultural interference was particularly evident at Sioux Falls Regional Airport (about 4 km north of Sioux Falls) and the railroad track following Ditch Road South from Baltic, South Dakota, toward Sioux Falls (fig. 1). The Sioux Falls Regional Airport had substantial cultural interference from wells and other manmade structures, and from operational radio-frequency transmitters. More than 30 percent of the AEM data collected within the airport area was unusable for interpretation. To increase the number of elevation data points in the airport area, well lithology was used to locate points of top of till and top of Sioux Quartzite. These points were combined with the AEM data to generate the raster files, "bottom of aquifer raster surface" and "top of Sioux Quartzite raster surface."

The aquifer extents (east and west boundaries) were user-defined by examining the resistivity ranges associated with till and aquifer materials to determine where the aquifer ended, and marking the location with a point feature class on the profile view that was plotted on an aerial view map of the study area.

Once the initial interpretations were completed, a group of groundwater hydrologists reviewed the interpretations and selected aquifer boundaries. Each profile was re-examined with information such as flood plain boundaries, river location, cultural interference, and other AEM profiles nearby to see if the interpretation or aquifer boundaries should be modified. If any changes were warranted, notes were made on the profile with what needed to change and the reasons they were changed, and then they were modified manually in ArcGIS. Final raster surfaces were generated once all modifications were completed. An aquifer boundary polygon was drawn by connecting each revised extent pick point sequentially using the "edit tool" in ArcGIS. This aquifer boundary was used to constrain the new bottom of the aquifer raster surface to the AEM observed east and west boundary extents.

In addition to the generation of elevation maps of the bottom of the aquifer and the top of Sioux Quartzite, thickness of the aquifer and depth to top of Sioux Quartzite maps were generated. Because the Big Sioux aquifer is an alluvial aquifer, the top of the aquifer was assumed to be the land surface elevation. A land surface elevation raster layer was created from 1/9 arc-second (3 m) elevation data from the USGS National Map (U.S. Geological Survey, 2017). The thickness of the aquifer and depth to top of Sioux Quartzite maps were calculated by subtracting the bottom of the aquifer elevations and top of Sioux Quartzite elevations from the land surface elevation.

A few elevation discrepancies in top of Sioux Quartzite maps required correction or discussion. Because of the presence of Sioux Quartzite outcrops in the area and observed small errors in delineation, plotting, or both, the top of Sioux Quartzite raster surface was corrected using the ArcGIS "Raster Calculator" and "Mosaic" tools. This correction helped ensure that the top of Sioux Quartzite is never at a higher elevation than the land surface elevation raster, and that the outcropping of Sioux Quartzite matches the land surface elevation raster. It is important to note that there are areas in the map that have a lower level of confidence because of cultural interference and steep drop-offs of Sioux Quartzite that are beyond the AEM investigation depth. These areas of lower level confidence were not delineated, but the raster surface in these areas was generated using interpolation.

Delineation Results

The maps shown in figure 3 illustrate the delineated elevation of the bottom of the Big Sioux aquifer (fig. 3A) and the delineated thickness of the Big Sioux aquifer within the study area (fig. 3B). The total volume of the Big Sioux aquifer was estimated to be 1,060,000,000 m3 based on the assumption that the land surface elevation is the top of the aquifer. The surface area of the aquifer was estimated as 85,000,000 square meters. The predicted aquifer thickness ranged from 0 to 31 m, and the average thickness was 12.8 m. At the north end of the study area (townships 103N and 104N), the bottom of the aquifer maps reveal thick deposits confined to narrow channels that quickly thin out at the edges. At the south end of the study area (townships 101N and 102N), the aquifer extents widen and are characterized by thinner deposits with pockets of thicker deposits (fig. 3B).

The maps shown in figure 4 illustrate the delineated elevation of the top of Sioux Quartzite (fig. 4A) and the delineated depth to the top of the Sioux Quartzite (fig. 4B). Depth to top of Sioux Quartzite was predicted to range from 0 to 90 m. The top of Sioux Quartzite maps reveal Sioux Quartzite near the land surface at the north end of the study area, but glacial till layers become thicker toward the middle and south end of the study area, burying the Sioux Quartzite as much as 90 m in depth. Lower confidence areas (cultural interferences and steep drop-offs) are outlined with hatching in the final top of Sioux Quartzite maps (fig. 4).

A three-dimensional fence diagram of the delineated hydrogeologic framework of the Big Sioux aquifer, represented as cross-sectional slices running north to south and east to west, is shown in figure 5. The changes of depth in the alluvium, glacial till, and Sioux Quartzite layers throughout the study area can be visualized in a single figure.

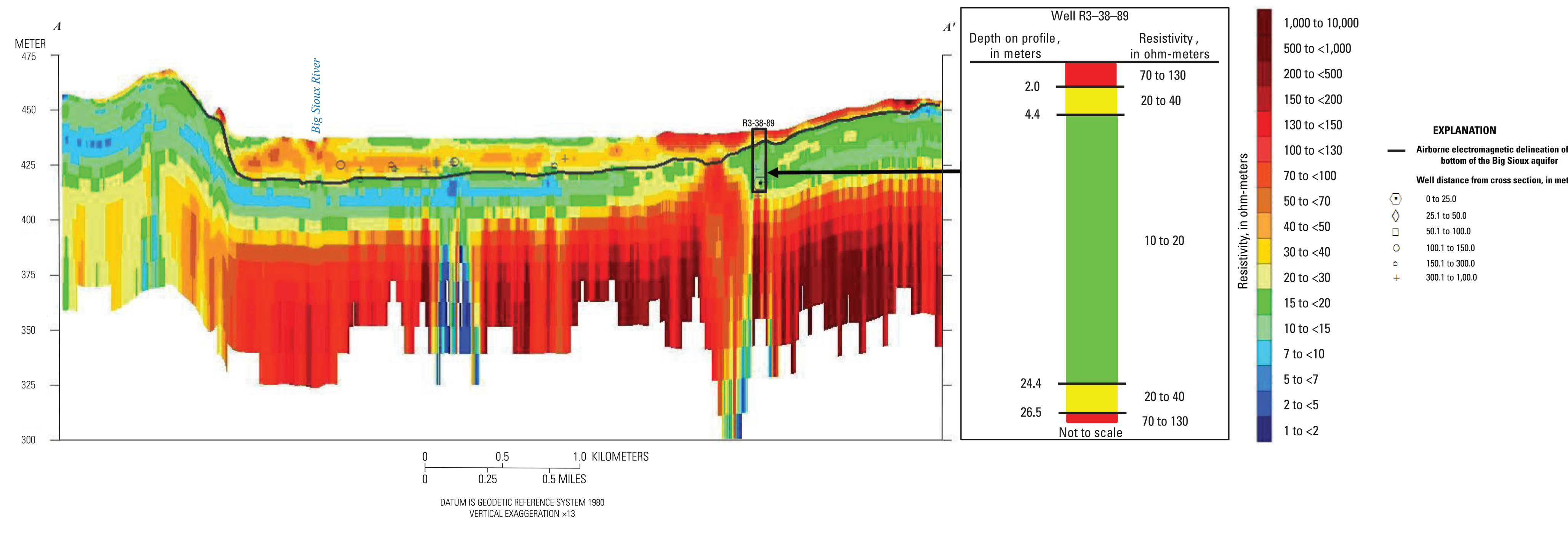

Figure 2. Example of relating resistivity to lithology of well (well number R3–38–89) within 25 meters of a resistivity profile, Big Sioux aquifer, South Dakota.

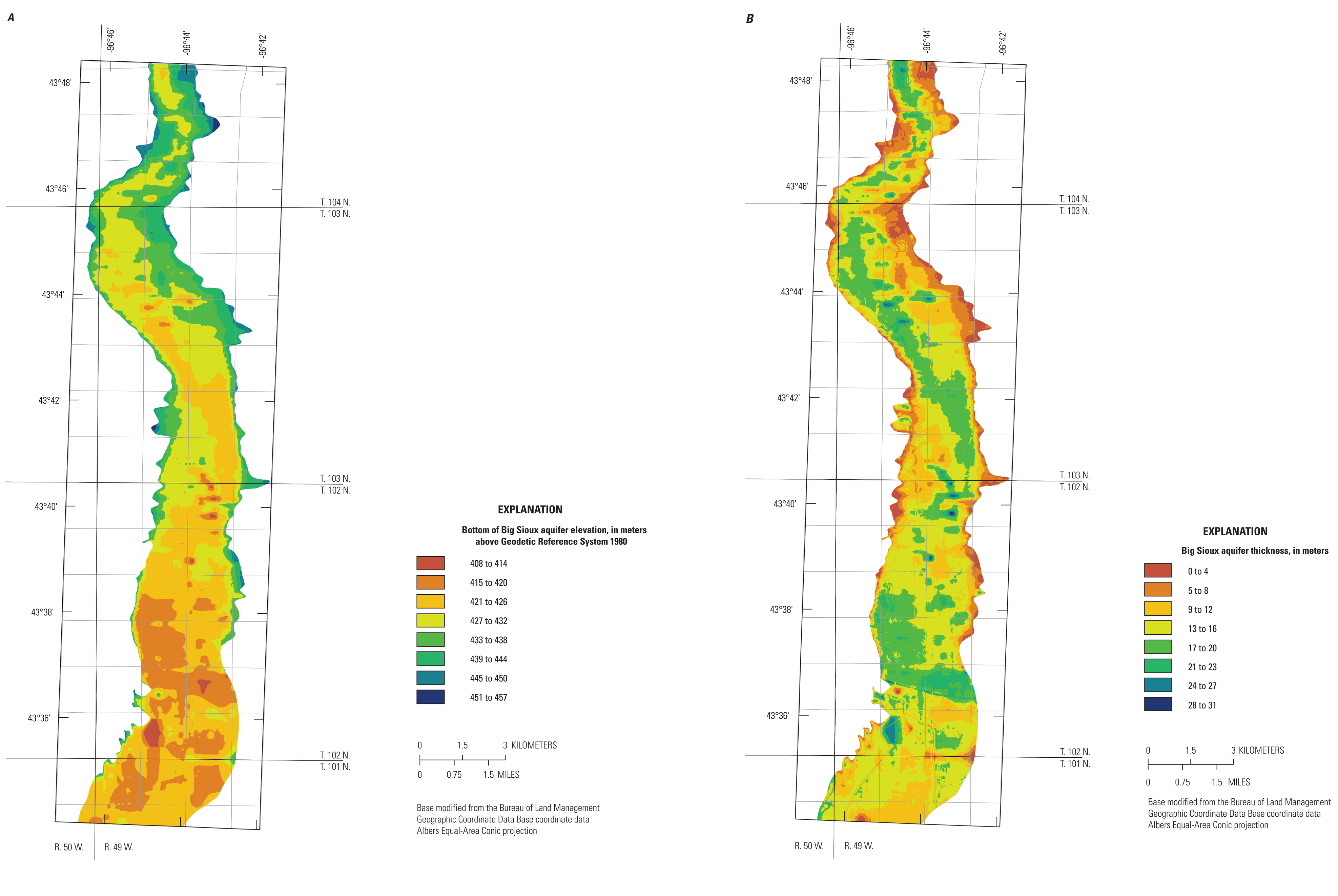

Figure 3. Delineated elevation and thickness of the Big Sioux aquifer, South Dakota. *A*, elevation of the bottom of the Big Sioux aquifer. *B*, thickness of the Big Sioux aquifer.

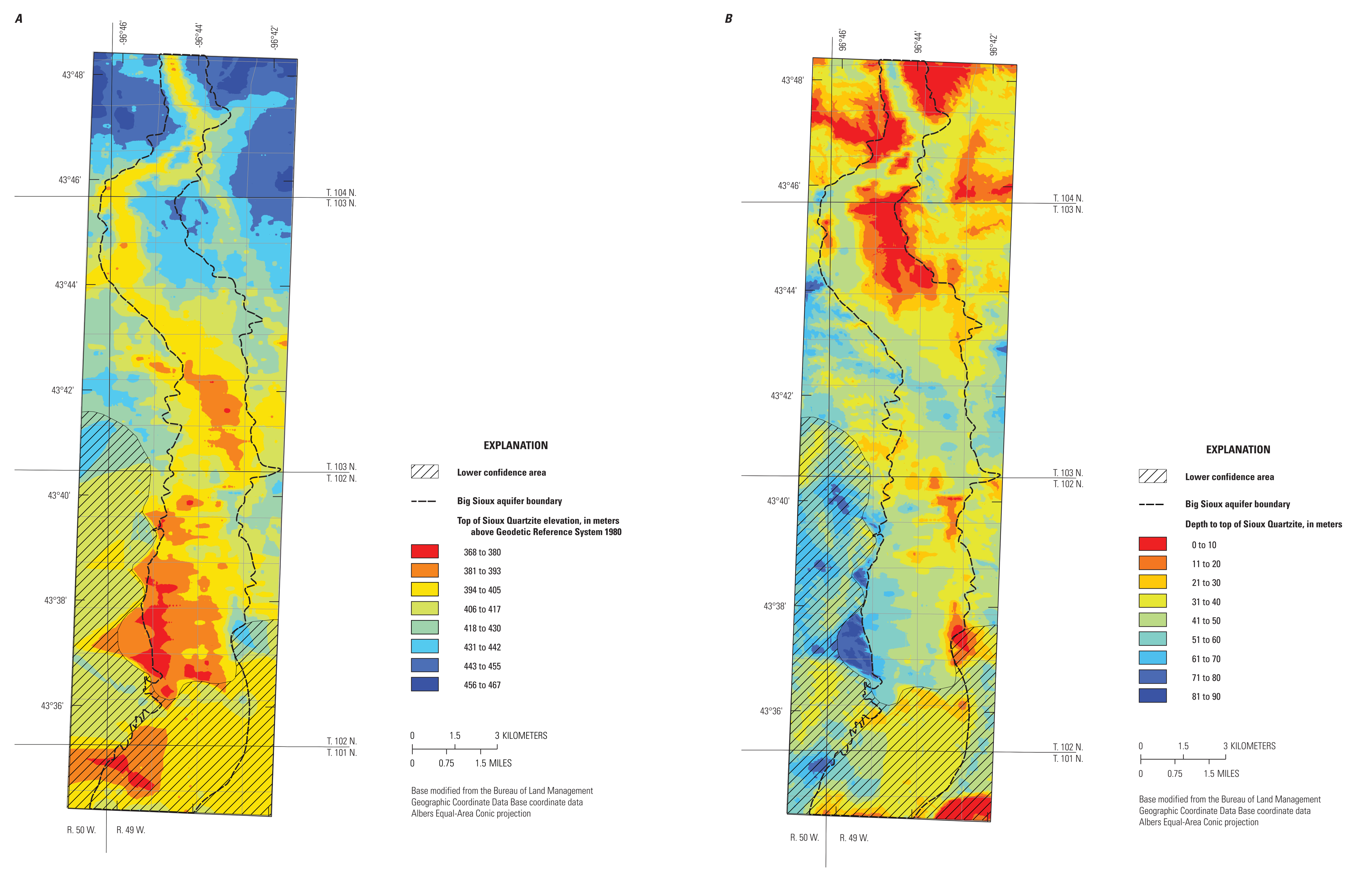

Figure 4. Delineated elevation and depth to the top of Sioux Quartzite, South Dakota. *A*, elevation of the top of Sioux Quartzite. *B*, depth to top of Sioux Quartzite.

Delineation of the Hydrogeologic Framework of the Big Sioux Aquifer near Sioux Falls, South Dakota, Using Airborne Electromagnetic Data

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