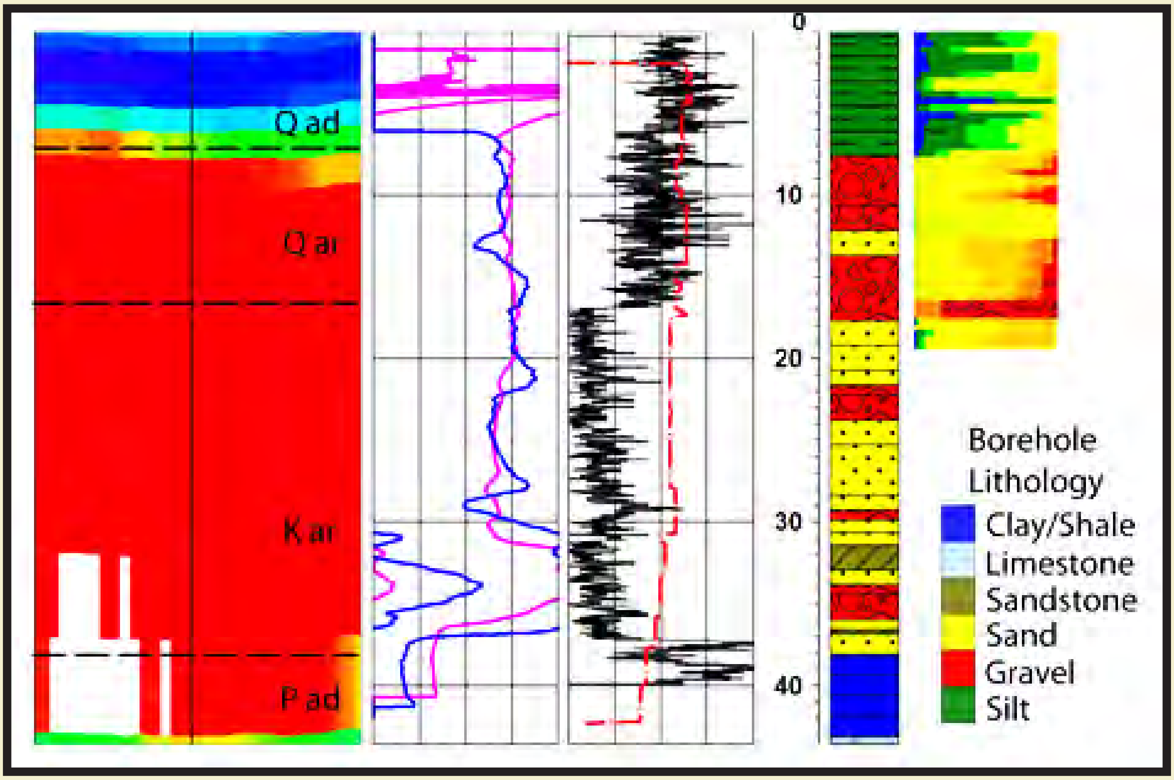
Eastern Nebraska Water Resources Assessment

Three-dimensional hydrostratigraphy of the Platte River Valley near Ashland, Nebraska: Results from Helicopter Electromagnetic (HEM) mapping in the Eastern Nebraska Water Resources Assessment (ENWRA)

Paul R. Hanson, Jesse T. Korus, Dana P. Divine

Edited By David R. Larson



Bulletin 2 (New Series)

Conservation and Survey Division
School of Natural Resources
Institute of Agriculture and Natural Resources
University of Nebraska–Lincoln

Generalized Geologic and Hydrostratigraphic Framework of Nebraska 2011, ver. 2

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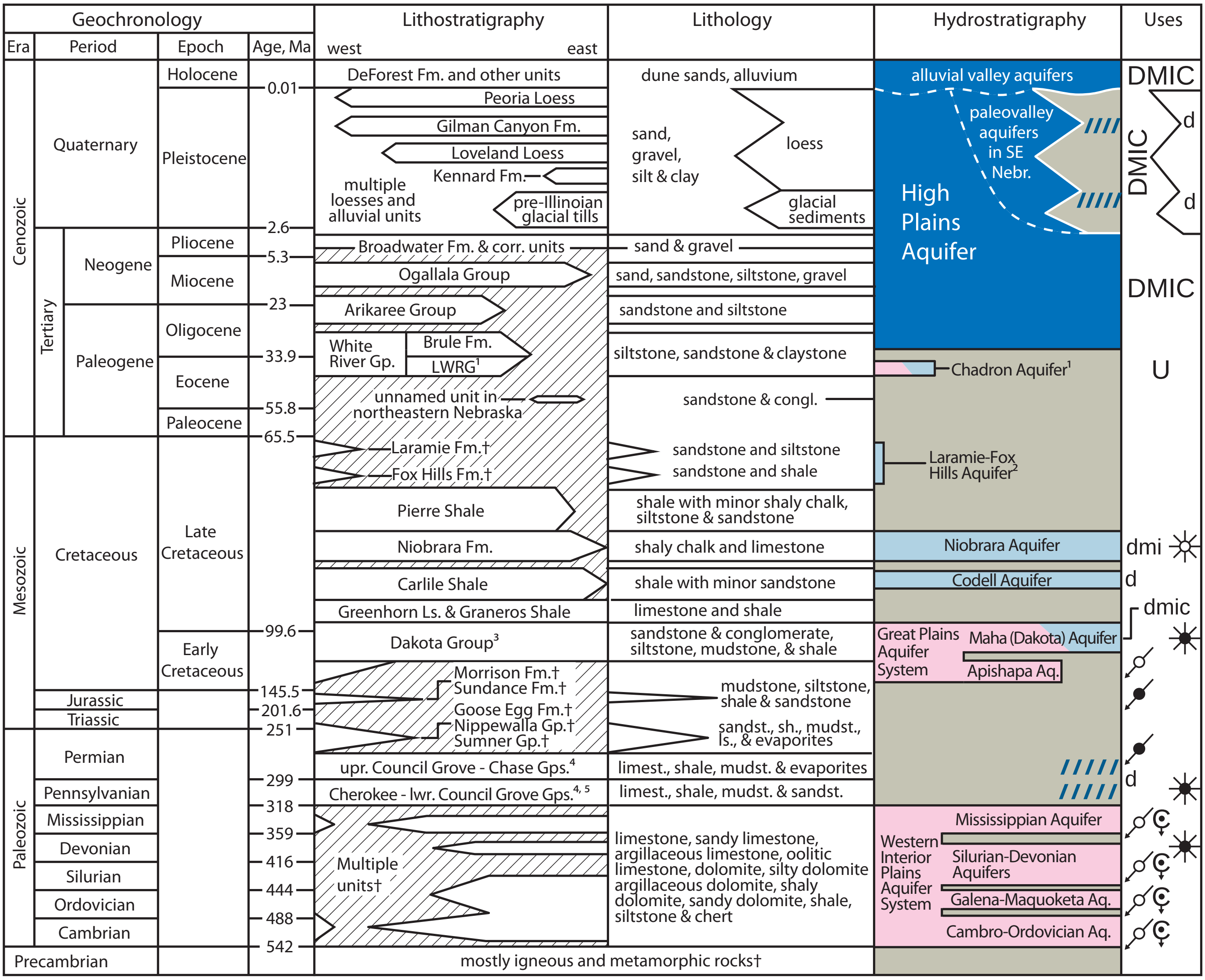

Diagram is not to scale relative to geologic time and stratigraphic thicknesses.

Hydrostratigraphic characteristics and water quality

- primary aquifers with good quality water
- secondary aquifers with good quality water
- secondary aquifers with generally poor quality water
- //// aquitards with local low-yield aquifers
- aquitards

[1] lower White River Group - includes Chamberlain Pass and Chadron Formations according to some authors; "Chadron Aquifer" historically refers to aquifer in lower White River Group

[2] important aquifer in Colorado, but present in Nebraska only in extreme southwestern Panhandle

[3] Dakota Formation in adjacent states

[4] includes correlative units with different names in northwest Nebraska

[5] Cherokee, Marmaton & Pleasanton Groups are not exposed in Nebraska

†present only in subsurface

Groundwater uses and related aspects

- D major domestic use
- d minor domestic use
- I major irrigation use
- i minor irrigation use
- M major municipal use
- m minor municipal use
- C major commercial/industrial use
- c minor commercial/industrial use
- units used for wastewater injection
- units with potential use for wastewater injection
- U unit mined for uranium by in-situ leaching (Dawes Co.)
- unit with potential use for carbon sequestration
- unit producing petroleum or natural gas
- unit with natural gas potential

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University of Nebraska Lincoln

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The Conservation and Survey Division of the University of Nebraska–Lincoln is the agency designated by statute to investigate and interpret the geologically related natural resources of the state, to make available to the public the results of these investigations, and to assist in the development and conservation of these resources. It consists of program areas in geology, water, soils, and remote sensing-geographic information systems.

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Image on cover: HEM resistivities, downhole geophysics and lithologies of Testhole 01-EN-07

Table of Contents

List of Figures and Table

Abstract

This study, part of the Eastern Nebraska Water Resources Assessment (ENWRA), used the results of a Helicopter Electromagnetic (HEM) geophysical survey in conjunction with subsurface data to map the hydrostratigraphy of the Platte River valley and adjacent uplands. Hydrostratigraphic units were interpreted using earth resistivity models from the HEM survey and subsurface data, including Conservation and Survey Division test holes, deep oil and gas well logs, and registered well logs. Thick (80-100 feet or 24-31 meter) deposits of highly conductive materials (clay and silt) limited the effectiveness of the HEM results for hydrostratigraphic mapping in the uplands. However, hydrostratigraphic units in recent and abandoned alluvial deposits of the Platte River, even where covered by 10-15 feet (3-5 m) of fine-grained sediments, could be mapped in detail using the HEM survey results. This study shows that the Platte River and Quaternary aquifer are apparently hydrologically connected throughout the study area, and that the Quaternary and Dakota aquifers are apparently hydrologically connected except where the discontinuous Cretaceous Dakota aquitard separates them. Three-dimensional modeling of hydrostratigraphic units using these methods permits calculation of unit volumes, saturated thicknesses, and estimates of drainable groundwater in the study area.

Introduction and Background

Purpose

The configuration of eastern Nebraska's groundwater resources is a product of the region's geologic past. Eastern Nebraska was periodically glaciated from approximately 2.5 million to 600,000 years ago. The repeated advance and retreat of glaciers resulted in a complex framework of largely Pleistocene aged sediments that overlie the regional bedrock surface, and locally over Pliocene(?)-Pleistocene buried valley deposits (paleovalleys). Relatively large quantities of groundwater exist in these paleovalley deposits and coarse-grained alluvium associated with modern streams, such as the Platte and Elkhorn Rivers (Fig. 1). Groundwater resources below the region's glaciated uplands are locally limited, but are often adequate for domestic purposes. Domestic wells in the region may be found in saturated coarse-grained sediments within or underlying clay-rich glacial tills. Perched aquifers are also an important source of water for domestic wells that are associated with the glaciated deposits of eastern Nebraska (Divine et al., 2009). Perched aquifers are created when downward moving water infiltrates through silt-rich loess, but not through the underlying clay-rich till, leaving saturated sediments above the regional water table (Gosselin et al., 1996).

The uppermost bedrock units in eastern Nebraska are Cretaceous and Pennsylvanian aged rocks. The stratigraphy of these rocks is somewhat complex due to their origins in mixed marine and near-shore marine depositional environments. The Cretaceous rocks are primarily of the Dakota Formation, the lithology of which varies from claystone and shale to sandstone. In locations where the lithology is sandstone, the Dakota may be used as an aquifer, though the water quality is variable and not always potable. The Pennsylvanian units are primarily shales with limestones that act as regionally important aquitards.

As demand for surface water and groundwater continues to grow, so does the need to understand groundwater availability and limitations in the region, the hydrologic connection between different aquifers, and groundwater-surface water interactions. This information is critical to achieving sustainable use of water resources and protecting social, economic, and environmental interests in eastern Nebraska. The Eastern Nebraska Water Resources Assessment (ENWRA) was initiated to address these issues by providing additional geologic and hydrogeologic information and interpretation in Eastern Nebraska (Divine et al., 2009). The project

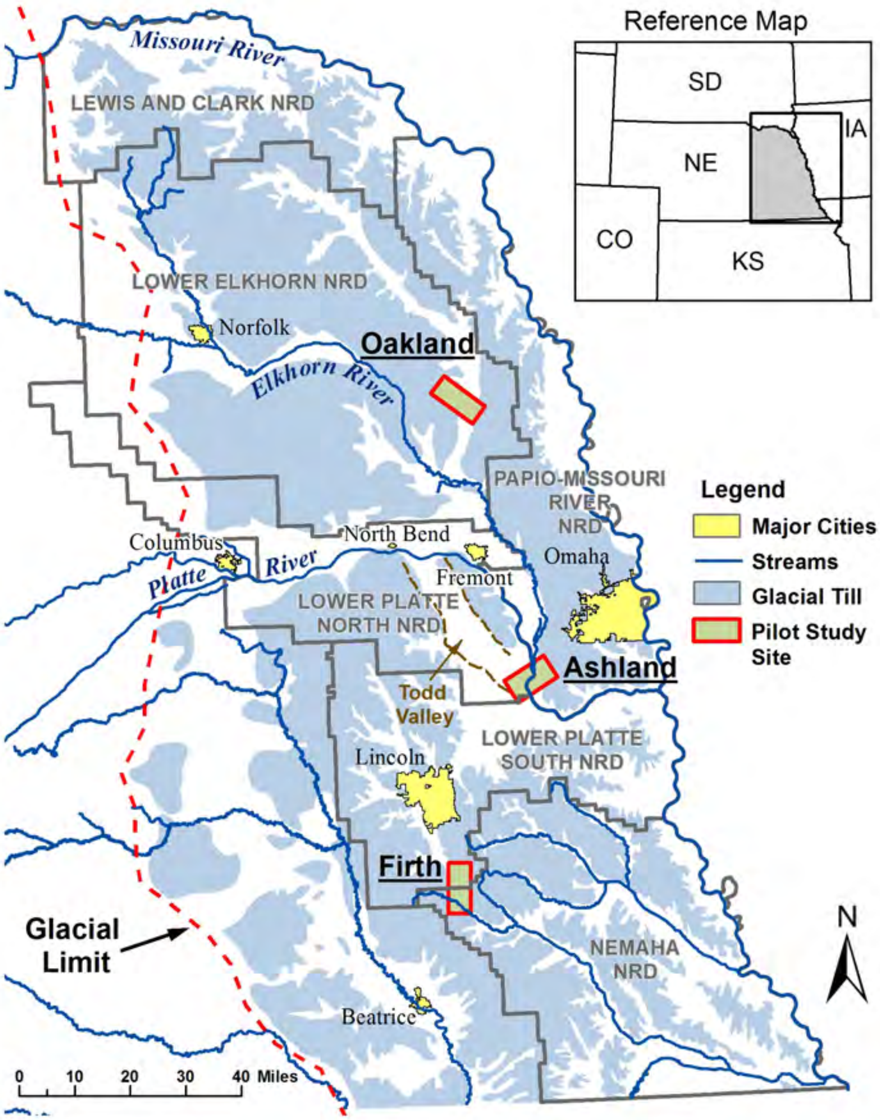

Fig. 1. Map of eastern Nebraska showing the glacial limit and location of the Ashland survey area. Also shown are the Firth and Oakland sites that are part of the Eastern Nebraska Water Resources Assessment (ENWRA) project. The map also shows local Natural Resource Districts (NRDs), the large metropolitan areas and major rivers and streams. The Todd Valley referenced in the text is shown to the northwest of the town of Ashland. Map adapted from Divine et al. (2009).

includes detailed, three-dimensional hydrostratigraphic mapping and hydrogeologic characterization using both traditional and advanced techniques.

This bulletin describes the geologic framework at the ENWRA Ashland pilot study location (Fig. 1). The Ashland pilot study was selected for a variety of reasons. Several different hydrogeologic settings exist in the area: the Pliocene and Quaternary sediments include the current Platte River alluvium, ancestral Platte River terrace deposits and those in the Todd Valley, and glacial till uplands; the bedrock geology has a complex configuration of Cretaceous Dakota Formation sandstones and shales and Pennsylvanian shales and limestones; and a paleovalley of early Cretaceous age is incised in the bedrock (Joeckel et al,. 2004). The area contains municipal wells serving an aggregate population of approximately 650,000. A wide variety of land uses occur within the area, including recreation, irrigated cropland, and sand/gravel mining. The area was also selected because of the wealth of subsurface data available for the region. These data are from the logs of test holes drilled by the Nebraska Conservation and Survey Division (CSD) and the drillers' logs of registered wells that are available from the Nebraska Department of Natural Resources (http://dnrdata.dnr.ne.gov/wellscs/Menu.aspx).

The hydrogeologic framework described in this bulletin is based on both new and existing geologic information. The new information includes approximately 107,000 geophysical soundings produced by a Helicopter Electromagnetic (HEM) survey conducted in 2006 (Smith et al., 2007b; Divine et al., 2009) as well as geologic and downhole geophysical logs from eleven new test holes that were drilled by the CSD (Divine et al., 2009).

Methods

The study area includes the region within and immediately surrounding the HEM survey boundary that is shown in Figure 2. Extending the study area beyond the HEM survey boundary was done to improve our understanding of the region's hydrostratigraphy through the use of data from CSD test holes and registered well logs that are available for the area. Further, the stratigraphy of the study area was directly investigated through drilling a total of eleven test holes in 2007 (Table 1). Cores were obtained from nine test holes using either a Geoprobe or split spoon auger rig system until bedrock was encountered or penetration was denied. Where bedrock was not encountered through coring (the case at eight of the eleven test holes), mud rotary drilling was used to advance the test holes to bedrock. In six of the holes drilled with mud rotary, downhole geophysical logs (gamma ray, resistivity, and caliper) were recorded. In two mud rotary holes, technical difficulties prevented gamma ray and resistivity recordings. In the three locations drilled exclusively with a Geoprobe rig, downhole geophysical data were limited to electrical conductivity.

Cuttings collected from mud rotary drilling were briefly described in the field, and were later described in detail in the laboratory. Cores taken with both the Geoprobe and

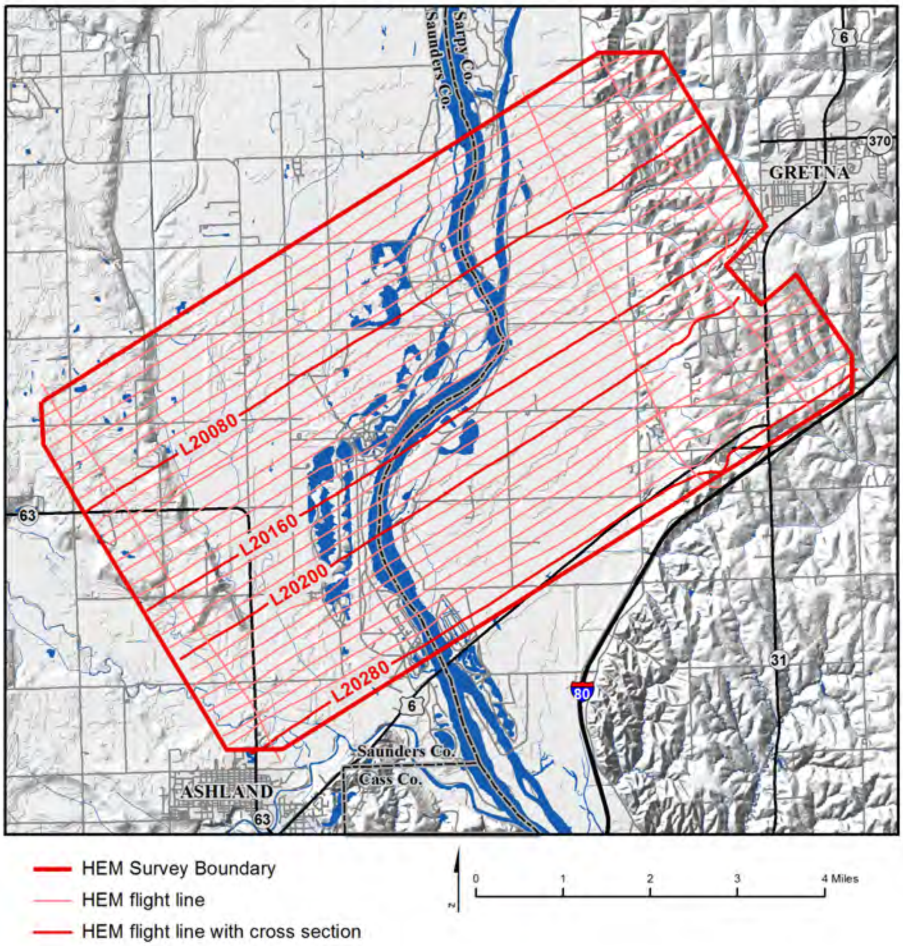

Fig. 2. Map showing the HEM survey boundary and flight lines that were flown in Summer 2006. The flight lines that cross-sections were drawn on are labeled. The flight lines are spaced approximately 890 feet (271 m) apart and HEM soundings were taken every ten feet (3 m). The base map is a hillshade of a digital elevation model (DEM).

Table 1. Ashland core table, showing locations, depths, and methods used for CSD test holes, adapted from Divine et al. (2009).

Test Hole #	Longitude	Latitude	Legal	Elevation (ft)	Cored Depth (ft)	Rotary Depth (ft)
01EN07	-96.315	41.108	T13N R10E 8SE	1078.5	65	143
03EN07	-96.254	41.118	T13N R10E 11NE	1213.1	70	273
04EN07	-96.330	41.089	T13N R10E 20NW	1068.5	49	50
05EN07	-96.309	41.089	T13N R10E 21NW	1066.1	44	46
06EN07	-96.278	41.089	T13N R10E 15SE	1117.4	55	99
07EN07	-96.253	41.089	T13N R10E 24NW	1258.9	70	198
17EN07	-96.369	41.103	T13N R9E 11SE	1072.9	88	--
18EN07	-96.365	41.060	T13N R9E 25SW	1070.7	45	--
19EN07	-96.357	41.060	T13N R9E 36NE	1063.2	80	--
20EN07	-96.272	41.100	T13N R10E 14NW	1165.8	--	197
21EN07	-96.280	41.116	T13N R10E 10NE	1136.0	--	186

Notes: All cores were Geoprobe cores expect for 03-EN-07 and 07-EN-07, which were split spoon
Horizontal Datum NAD 83
Vertical Datum NAVD 88

split spoon auger rig were collected and described in the laboratory. Both cuttings and cores collected during this project are archived at the CSD. Locations of the logs, depths, and coring type are given in Table 1. Sediment descriptions, geophysical logs, and stratigraphic units for the CSD test holes collected for this project are given in Appendix A. In addition to the new test holes drilled for this project, registered well logs from irrigation and domestic wells and those from the Lincoln well field were used to correlate stratigraphic units across the study area.

Analysis of sand, silt, and clay fractions was conducted on selected core samples using a Malvern laser particle size analyzer. Results of the particle size analyses for the CSD test holes drilled for this project are given in Appendix B. Samples were prepared with hydrochloric acid to remove carbonates and sodium hexametaphosphate to disaggregate clays prior to particle size measurement. Gravel percentages were estimated based on gravel weight relative to total sample weight. Because these gravel measurements were done on very small sample sizes, two categories were used: greater than and less than 20% gravel.

This is a pilot study that compared HEM survey data with subsurface geological information to evaluate the use of HEM for defining aquifers in this region of eastern Nebraska. HEM surveys are a relatively rapid method to map the electrical resistivities of both surface and buried geological materials (for specifics on the process see Smith et al., 2007a, 2007b). The primary advantages of HEM surveying are that the survey allows for relatively quick data acquisition from a large area, and the multiple electromagnetic frequencies allow for characterizing geological materials at multiple depths below the ground surface. In addition, the surveys can occasionally penetrate sediments or bedrock units buried to a depth of 320 feet (98 m) or more (Smith et al., 2007b).

A helicopter electromagnetic (HEM) survey was performed in the 36 mi2 (93 km2) study area (Fig. 2). Specific data sets generated during the HEM survey at the Ashland site can be found in Smith et al. (2007b). In brief, the survey was conducted in March 2007 on a flight line spacing of ~ 890 feet (271 m; Fig. 2) and the helicopter flew at a height of ~ 115 feet (35 m) above the ground surface. HEM elevation data are based on the difference between flight elevation as determined by a laser altimeter and the altitude as determined by a Global Positioning System (GPS). Flight elevations were determined by onboard GPS and final ground elevations were corrected using differential GPS. Ground surface elevation errors are expected to be on the order of ± 6.5 ft (2 m)(see Smith et al., 2007b). The survey used six frequencies, ranging from 400 Hz to 114,000 Hz and individual soundings were taken at 11 foot (3.3 m) intervals. The higher electromagnetic frequencies have shallow penetration depths whereas the lower frequencies can penetrate deeper into geological materials.

HEM survey results indicate the resistivity of various earth and man-made materials from which geologists interpret rock or sediment types. Highly resistive materials include sands, sandstones, limestones, or aquifers with low salinity waters, while low resistivity materials are typically clays, shales, or materials containing saline groundwater. The apparent resistivity data collected during the flights were subsequently inverted by the USGS (see Smith et al., 2007b), a process that determines the depth of penetration and resistivity of each individual frequency. Field descriptions of cores and cuttings and other data such as soil maps were used by the USGS to constrain the resistivity models during inversion.

After the inversion was conducted, CSD compared the results of particle size analysis, borehole geophysics, and hydrochemistry from test holes and monitoring wells installed during the study to the inverted HEM profiles. In addition, CSD used registered groundwater wells, oil and gas borehole logs, and other pre-existing data that were not used in the inversion process. We identified hydrostratigraphic unit contacts using subsurface data, and where these contacts correlated to contrasts in resistivity, the contacts were traced along HEM profiles. In some cases, there was no resistivity contrast at the unit contact (i.e. between sand-sandstone or sandstone-limestone), so only borehole data were used for correlation.

Three-dimensional hydrostratigraphic models were generated for each unit in the study area. The models are based on interpreted unit contacts and are used to compute total volume, saturated volume, and estimated drainable groundwater volume for each hydrostratigraphic unit. In order to estimate these variables, polygons were created to represent upper and lower bounding surfaces for the hydrostratigraphic units. First, points were digitized at regularly spaced intervals along the unit contacts in each HEM profile. Point data from each HEM profile were then combined, and elevation values were interpolated to a 2-D grid using minimum curvature and a 50m x 50m cell size. Solid bodies representing the 3-D hydrostratigraphic units were generated by calculating the difference between each hydrostratigraphic unit's upper and lower bounding surfaces. Edge effects were minimized by building the initial model to a greater extent than the study area then cutting it along the edges.

Physical Setting

Bedrock Geology and Stratigraphy

The study area is located between the towns of Ashland and Gretna, Nebraska at the confluence of the Platte and Elkhorn Rivers, and just upstream from the Platte's confluence with Salt Creek (Fig. 2). Bedrock units that directly underlie Quaternary sediments include Pennsylvanian and/or Cretaceous bedrock (Burchett, 1986; Fig. 3). These bedrock units are buried by a variable cover of Quaternary age sediment that ranges in thickness from ~ 40 to over 270 feet (12 to 82 m) in the study area.

Upper Pennsylvanian Stratigraphy

Upper Pennsylvanian age rocks are not subaerially exposed within the survey area, but they are found directly beneath Quaternary age sediments in the southern portion of the HEM survey area (Fig. 3), and underlie Cretaceous rocks through the rest of the area

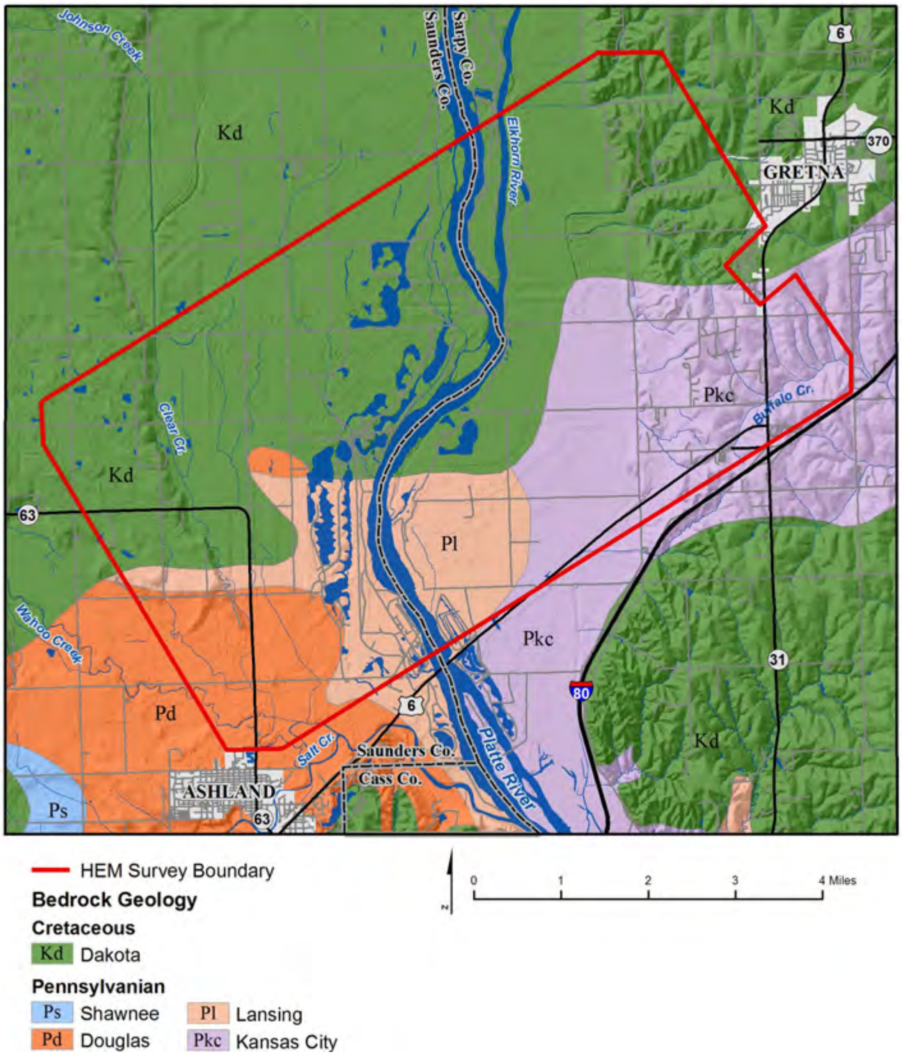

Fig. 3. Bedrock map of the study area overlain on a hillshade of a digital elevation model (DEM). Bedrock units include sandstones and shales of the Cretaceous Dakota Formation, and limestones and shales of the Pennsylvanian Kansas City, Lansing, Douglas, and Shawnee Groups (Map adapted from Burchett, 1986). Both Cretaceous and Pennsylvanian rocks are covered by 40 feet (12 m) or more of Quaternary age sediments in the Platte River valley and by up to 270 feet (82 m) of Quaternary age sediments in the glacial uplands on the eastern edge of the study area.

(Burchett, 1986). Rocks of Upper Pennsylvanian age are comprised of marine sediments including those of the Kansas City, Lansing, Douglas, and Shawnee Groups. The Kansas City, Lansing, and Shawnee Group rocks are primarily inter-bedded limestones and shales, while those of the Douglas Group are dominated by shale with lesser amounts of limestone. Throughout the region Pennsylvanian limestones and shales act as aquitards and the top of these units represents the lower extent of the regional aquifers. The northeast-southwest trending Pennsylvanian rocks shown in Figure 3 were exposed as a paleovalley that was cut in the early Cretaceous (Joeckel et al., 2004).

Cretaceous Stratigraphy

Cretaceous age Dakota Formation rocks and sediments directly underlie Quaternary age deposits in the northwestern half of the study area (Burchett, 1986; Fig. 3). The lower part of the Dakota is composed predominantly of sandstones, but also includes locally significant conglomerates, as well as shales or claystones that were deposited at the eastern margin of the Western Interior Seaway around 95 to 100 million years ago (Brenner et al., 2000; Joeckel et al., 2004). Dakota sandstone outcrops along the eastern edge of the Platte River valley in the southeastern portion of the study area (Fig. 4).

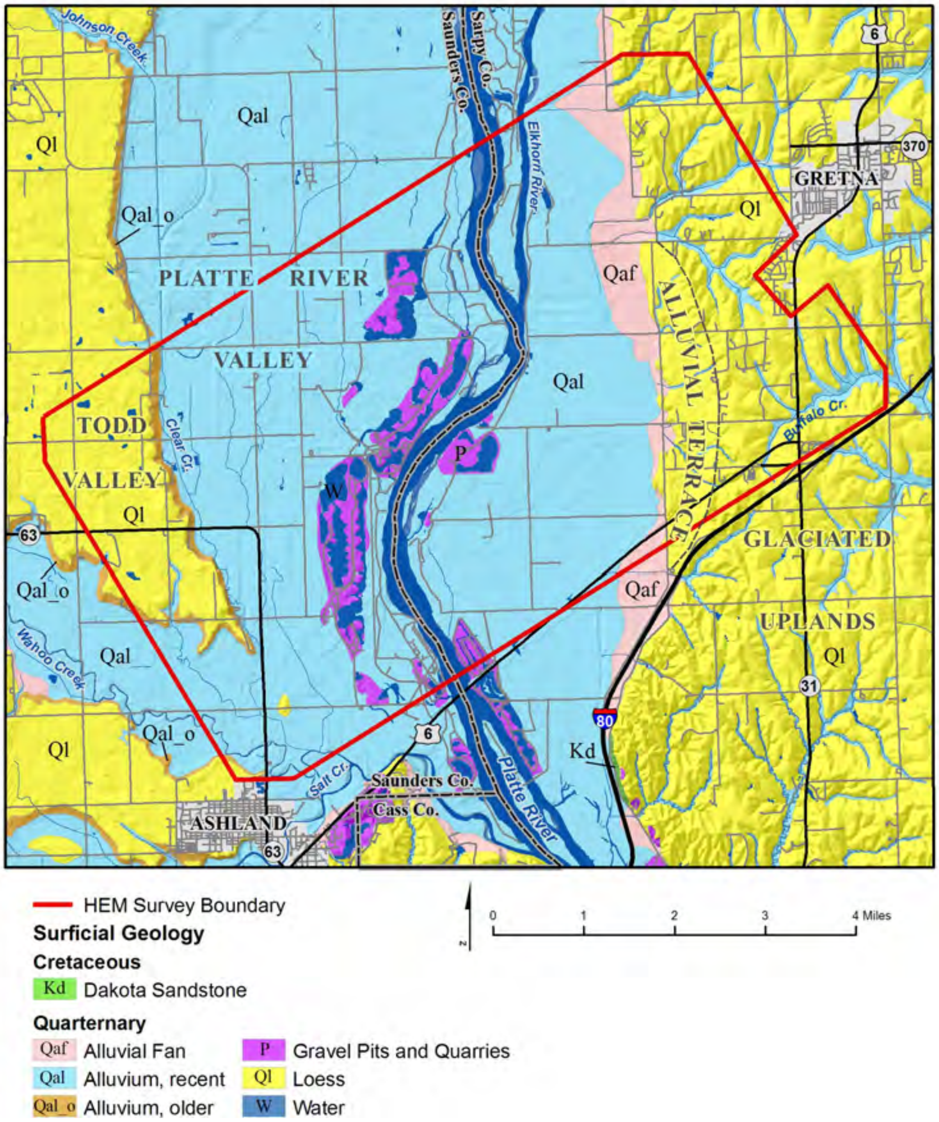

Fig. 4. Surficial geologic map of the study area overlain on a hillshade of a digital elevation model (DEM). The Elkhorn and Platte Rivers and the towns of Ashland and Gretna are labeled. The red boundary shows the limits of the Helicopter Electromagnetic (HEM) geophysical survey. The alluvial terrace, glaciated uplands, Platte River valley, and Todd Valley are labeled. Map is adapted from surficial geologic maps from Mason and Joeckel (2000; 2001a) and Joeckel and Mason (2001).

Quaternary Geology and Stratigraphy

The region's surficial geology is composed primarily of three Quaternary age deposits. From oldest to youngest these include: the glacial till uplands on the eastern edge of the study area, relatively old alluvium in stream terraces and in the Todd Valley fill, and the more recent alluvium found in the current valleys of the Platte and Elkhorn Rivers (Fig. 4). With the exception of the recent alluvium, these sediments are covered by one or more loess deposits.

Loess Stratigraphy

Like much of the surficial geology in eastern Nebraska, rocks or sediments in the study area older than ~ 15,000 years are covered by loess deposits of varying thicknesses. Within the study area, up to three or more identifiable loess units cover the glaciated uplands and the older alluvial deposits. These include the Loveland Loess (deposited ~ 160,000-120,000 years ago; Forman et al., 1992; Forman and Pierson, 2002), the Gilman Canyon Formation (~ 45,000-25,000 years ago; summary of ages from Mason et al., 2007), and the Peoria Loess (~ 25,000-14,000 years ago; Bettis et al., 2003; Mason et al., 2008). The Kennard Formation, a recently named loess believed to be middle Pleistocene in age (Mason et al., 2007), may also be present between Loveland Loess and glacial deposits in the study area (Mason and Joeckel, 2002). Although locally the thicknesses of these units are highly variable, the Kennard and the Loveland Loess can each range from 20-25 feet (6 to 8 m) thick, the Gilman Canyon Formation is generally 2-5 feet thick (0.6-1.5 m), and the Peoria loess is generally up to 25 to 35 feet (8 to 11 m) thick in the study area (Mason, 2001; Mason and Joeckel, 2002; Mason et al., 2007). Together these units can comprise over 60 feet (18 m) of loess that overlie glacial age sediments or bedrock in this part of eastern Nebraska.

Glacial Uplands

The upland landscape is highly dissected by small streams, making them physiographically distinct from the lower relief surfaces of the recent floodplains and the Todd Valley (Fig. 4). The uplands throughout the study area consist of glacial sediments overlain by younger sediments, most commonly one or more loess units. The glacial sediments were deposited during multiple glacial advances that occurred in the early to middle Pleistocene, the latest of which occurred between 780,000 and 640,000 years ago (Boellstorff, 1978a, 1978b; Roy et al., 2004). Glacial sediments include clay-rich tills interspersed with pro-glacial and sub-glacial sand and sand and gravel glaciofluvial deposits. These glaciofluvial deposits are of hydrological importance because they act as local aquifers in eastern Nebraska and the study region. Glacial deposits have been preserved in the uplands along the eastern edge of the study area. However, based on the lack of glacial deposits in the available subsurface sediments, most if not all, glacial sediments have been stripped from the Platte River Valley and from beneath the Todd Valley in the study area.

Alluvium in Terraces and the Todd Valley Fill

The Todd Valley lies between the towns of North Bend and Ashland, Nebraska, and is 28 miles (45 km) long and ranges between 6-8 miles (10-13 km) wide (Lugn, 1935). It is present in the northwestern part of the HEM survey area (Fig. 4). The Todd Valley was first described and named by Condra (1903), who identified the valley as an 'old Platte Channel' that is overlain by loess. The alluvial fill is primarily fine sand that coarsens with depth, and is of variable thickness, but is locally 120-190 feet (37-58 m) deep (Lugn, 1935). Peoria Loess is 20-40 feet (6-12 m) thick overlying the Todd Valley alluvial fill on the valley's northern end; however, this loess blanket thins to the south (Lugn, 1935), and is ~ 9-13 feet (3-4 m) thick near the southern end of the Todd Valley. CSD Test Holes 3-B-62 and 8-A-64 (Burchett and Smith, 1989) that were previously drilled in the southern portion of the Todd Valley show approximately 10-13 feet (3-4 m) of Peoria Loess overlying 100 feet (31 m) of fine to medium sand that coarsens with depth and contains gravel below a depth of 55 feet (17 m). These sandy units comprise the alluvial fill of the Todd Valley, and are underlain by Dakota Formation sandstone and shale. Based largely on the fact it is covered with Peoria Loess, geologists estimate the Todd Valley alluvial fill was deposited prior to Peoria Loess deposition (Lugn, 1935).

In addition to the Todd Valley, loess-covered alluvium of the Platte River is found in terraces along the eastern edge of the Platte River valley (Fig. 4). The relatively low relief surface of this landform results from portions of it being a former floodplain. CSD test holes located in this landform show between 35-45 feet (11-14 m) of silt overlying sand and sand and gravel. The silt caps are primarily loess, while the sand and gravel sediments consist primarily of alluvium that can approach 100-110 feet (31-34 m) thick that in turn lies over Cretaceous and/or Pennsylvanian age bedrock.

Recent Alluvial Units

These deposits include the alluvium found in modern stream valleys, primarily the Elkhorn and Platte Rivers and Wahoo Creek, as well as alluvial fan deposits located along the edge of the uplands (Fig. 4). The alluvial valley of the Platte and Elkhorn Rivers is a dominant feature in the study area, and approaches five miles (8 km) in width (Fig. 4). The alluvial fill is generally capped by 5-15 feet (2-5 m) of silt and clay, overlying a thicker fill of sand

and sand and gravel (Mason and Joeckel, 2002). The alluvial fill is approximately 40-70 feet (12-21 m) thick and directly overlies either Cretaceous or Pennsylvanian rocks. Based on their lack of Peoria Loess cover, the upper portions of the alluvial valley fill were deposited within the past 15,000 years, but the lower portions of the fill may be older.

Alluvial fans are generally silt, sand and clay dominated deposits at the base of slopes. In the study area, these fans are common on the western edge of the uplands where small, fairly steep streams that drain the uplands encounter the broad flat bottom of the Platte River valley (Fig. 4). Alluvial fans are generally thickest adjacent to the uplands, and thin with distance toward the river valley. These deposits are locally eroded by active channels of the Platte and/or Elkhorn Rivers.

Groundwater Resources in the Ashland Area

Aquifers in the Ashland region include those buried within active river valleys, in abandoned alluvial and alluvial terrace deposits, in small sandy deposits associated with glacial tills, and in sandstones of the Dakota Formation. Modern alluvial aquifers include those underlying the Platte and Elkhorn Rivers in the central portion of the study area and under Wahoo and Salt Creeks in the southwestern portion of the study area (Fig. 4). Within the study area, depth to the water table or potentiometric surface in alluvial aquifers is typically less than 15 feet (5 m). Municipal water resources for both Lincoln and Omaha are largely obtained from wells in the Platte River valley. Aquifers also occur in older abandoned deposits of the Platte and Elkhorn Rivers, including sand and gravel in both the Todd Valley and in alluvial terraces found along the eastern edge of the study area (Fig. 4). The water table is commonly within 20 feet (6 m) of the ground surface in these types of deposits within the study area.

Locally important aquifers are found underlying the uplands and are found within or below glacial tills within the study area. These sediments may have been deposited by rivers under two possible environmental settings; in some cases they are glacio-fluvial sediments that are associated with the advance or melting of glaciers from the region, and in others they are preglacial sands and gravels filling bedrock paleovalleys. These deposits are similar to those described by Witzke and Ludvigson (1990) in western Iowa. In these types of aquifers, is the potentiometric surface lies generally greater than 150 feet (46 m) below the land surface. Finally, sandstones of the Dakota Formation are important secondary aquifers. Dakota Formation sediments are commonly in direct contact with the overlying alluvium of the above described aquifers. Within the study area most Dakota Formation rocks and sediments lie below the water table or potentiometric surface. Some high capacity wells are screened over both the Quaternary aquifer and the Dakota sandstone aquifer.

A combined water table/ potentiometric surface contour map of the regionally continuous sand and gravel aquifer made using water levels collected from 35 wells in spring 2009 indicates that groundwater is flowing from the uplands and the Todd Valley into the Platte River valley (Fig. 5). The map clearly shows the drawdown of the water table around the well field that supplies the City of Lincoln. Wells of the Metropolitan Utilities District (MUD) to the north of the HEM survey boundary are also shown. The map does not depict the water table in locally important perched aquifers in the upland area.

Nested wells were installed at each of the ENWRA sites shown in Fig.5 to collect data regarding potential hydraulic connection between water-bearing units. Details regarding the well construction are shown in Appendix A. The highest hydraulic heads were measured in the upland sites 03-EN-07 and 07-EN-07. The heads in these wells reflect a potentiometric surface and do not contribute significantly to this report because all of the screens are below the depth of HEM inversion. Well nest 01-EN-07 is adjacent to the Platte River and water levels in the three shallowest wells in the nest, which are largely controlled by river levels, indicate that the aquifer is confined or semi-confined in the area. The transducer in the deep well at the 01-EN-07 site showed artificial data drift and the data is not presented here. The wells in the remaining three well nests all have very similar head values and represent unconfined water table conditions (i.e. 06-EN-07) or confined to semi-confined conditions (i.e. 04-EN-07 and 05-EN-07).

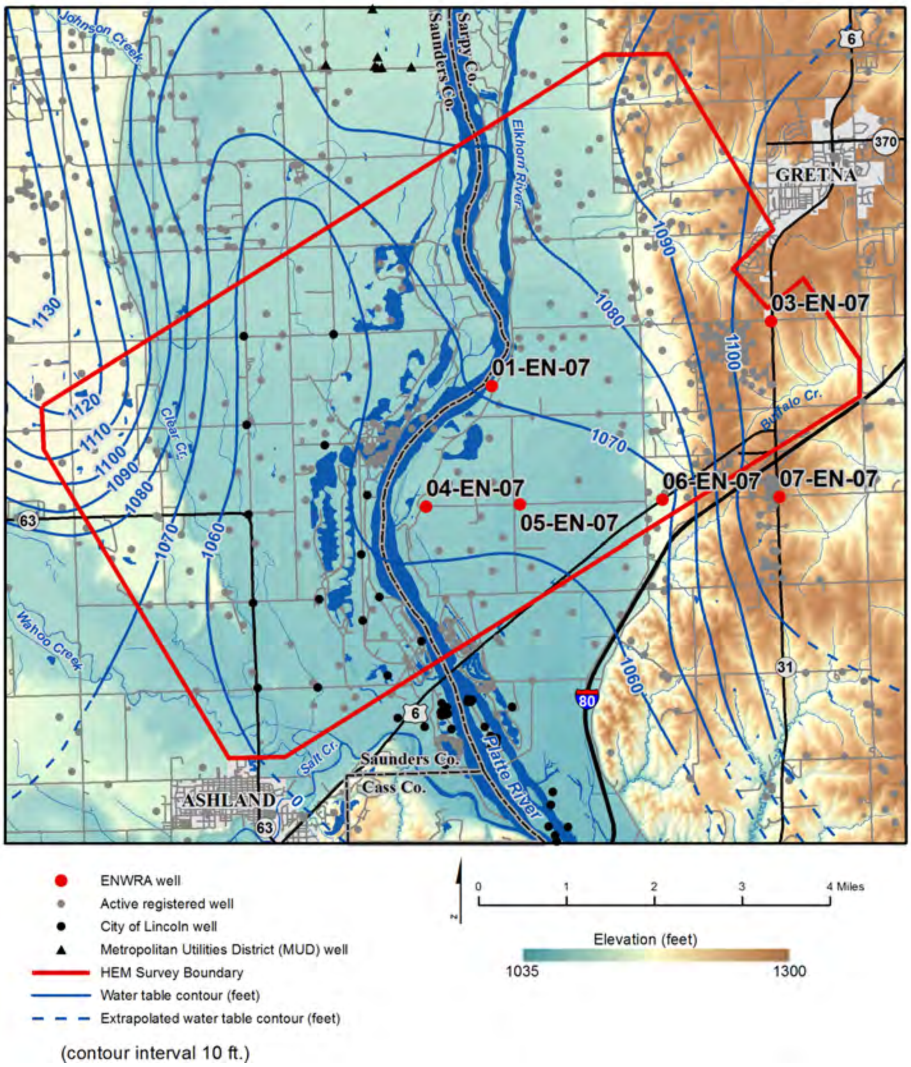

Fig. 5. Map of the water table/ potentiometric surface within the study area generated using spring 2009 water levels. Contours are given in feet. Also shown are the locations of wells drilled for this study (labeled as ending in '07'), and well locations for the Lincoln and Omaha (MUD) well fields.

Interpretation of Geology and Hydrostratigraphy

HEM Survey Results and Assessment

The inverted HEM survey results show the resistivity of geological materials found within approximately 260 feet (79 m) of the ground surface in the Platte River Valley. The quality of the HEM survey data was demonstrated by comparisons with the CSD test holes and registered wells shown in Fig. 6. Low resistivity materials such as silts and clays are shown as cool colors in the HEM survey maps, while high resistivity materials such as sand, gravel, sandstone, and limestone are shown as warm colors (see Fig. 7a and 7b). The overall analysis of the HEM survey indicates that the technique produced very good results for characterizing late Quaternary age alluvial deposits in the study area, including alluvial deposits in the modern stream valleys, the alluvial terrace, and the Todd Valley fill (see Fig. 7a). However, less reliable results were generated in the glaciated uplands because the HEM did not fully penetrate the low resistivity till and loess and we were unable to delineate aquifers using borehole data alone. This is evident in the results for Test Hole 03-EN-07 (see Fig. 7b) and similar test holes drilled in the glaciated uplands.

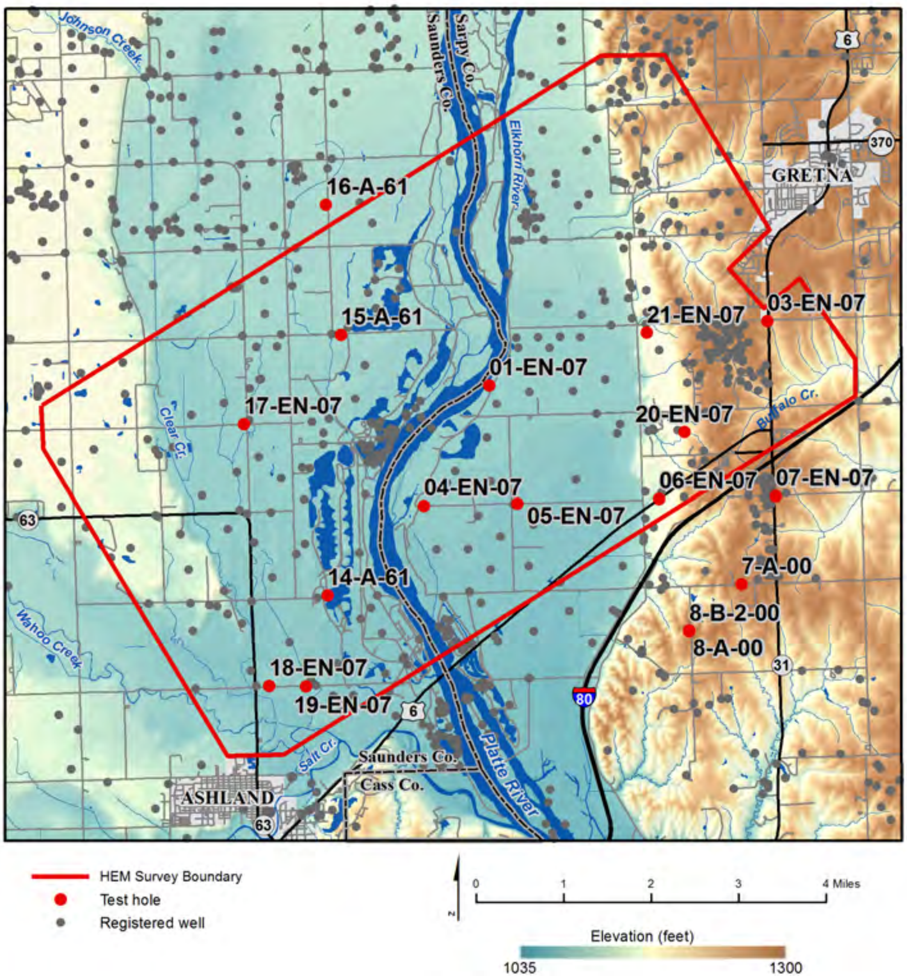

Fig. 6. Map showing locations of CSD test hole and registered well locations the logs of which were used for geologic interpretation. Locations of registered wells are shown as points and CSD test hole locations are shown as red labeled points. Test holes with labels ending in '07' were drilled for this project.

Overall, the depths to buried highly resistive units such as sand, sand and gravel, and sandstone obtained from the well logs showed little or no appreciable difference compared to the HEM survey results. For example, in Test Hole 01-EN-07 the upper ~ 25 feet (8 m) of silt and clay-dominated materials are shown at similar depths in our sample descriptions, analyzed particle size classes, downhole geophysical logs and in the HEM results (Fig. 7a). Where there is no intervening silt and clay unit, the HEM survey could not be used to distinguish between Quaternary sand and sand and gravel, and Cretaceous age Dakota sandstone and sand. This is similar to downhole resistivity results from the area which show little difference between Cretaceous and Quaternary sand and sand and gravel (Fig. 7a). However, the two units can be distinguished visually because of the much higher quantity of potassium feldspar in the Quaternary sediments (Mason and Joeckel, 2002), compared to the much lower values typical of the Dakota sandstone (Witzke and Ludvigson, 1994; Phillips et al., 2007). In addition, gamma logs can be used to distinguish between the two locally (Fig. 7a) as Dakota sandstones typically have lower gamma counts relative to Quaternary sand and gravel. The HEM results also closely agreed with coring, test hole, or drillers' well logs on the depth to Pennsylvanian strata, or the base of the area's alluvial and bedrock aquifers. Pennsylvanian clay and shale units at the base of Test Hole 01-EN-07 show good comparison between the subsurface data and the HEM results (Fig. 7a).

Particular problems with the HEM survey from the Ashland study site include the presence of cultural features and areas where there are thick low resistivity units at the earth's surface. Cultural features, particularly highly resistive features such as pipelines, powerlines, and railroad tracks (Fig. 8) can be identified in the HEM results. Obvious cultural features are identified in the raw data and removed (see Smith et al., 2007b). Less obvious features, however, may still be present in the final inverted HEM data.

The HEM results were more difficult to assess in the glaciated uplands because the quality and quantity of independent subsurface control are limited and the upland geology is more complicated compared to that of the alluvial valley. In addition, the thickness of low resistivity units in the uplands resulted in lower fidelity. Specifically, the combined depths of low resistivity units including loess and clay-rich glacial till in the uplands range from approximately 80 to 100 feet (24-31 m) in thickness. This thickness of low resistivity materials at the land surface results in signal decay, so the overall depth of HEM penetration is not as deep as the other alluvial environments described in this study (see Fig. 7b). However,

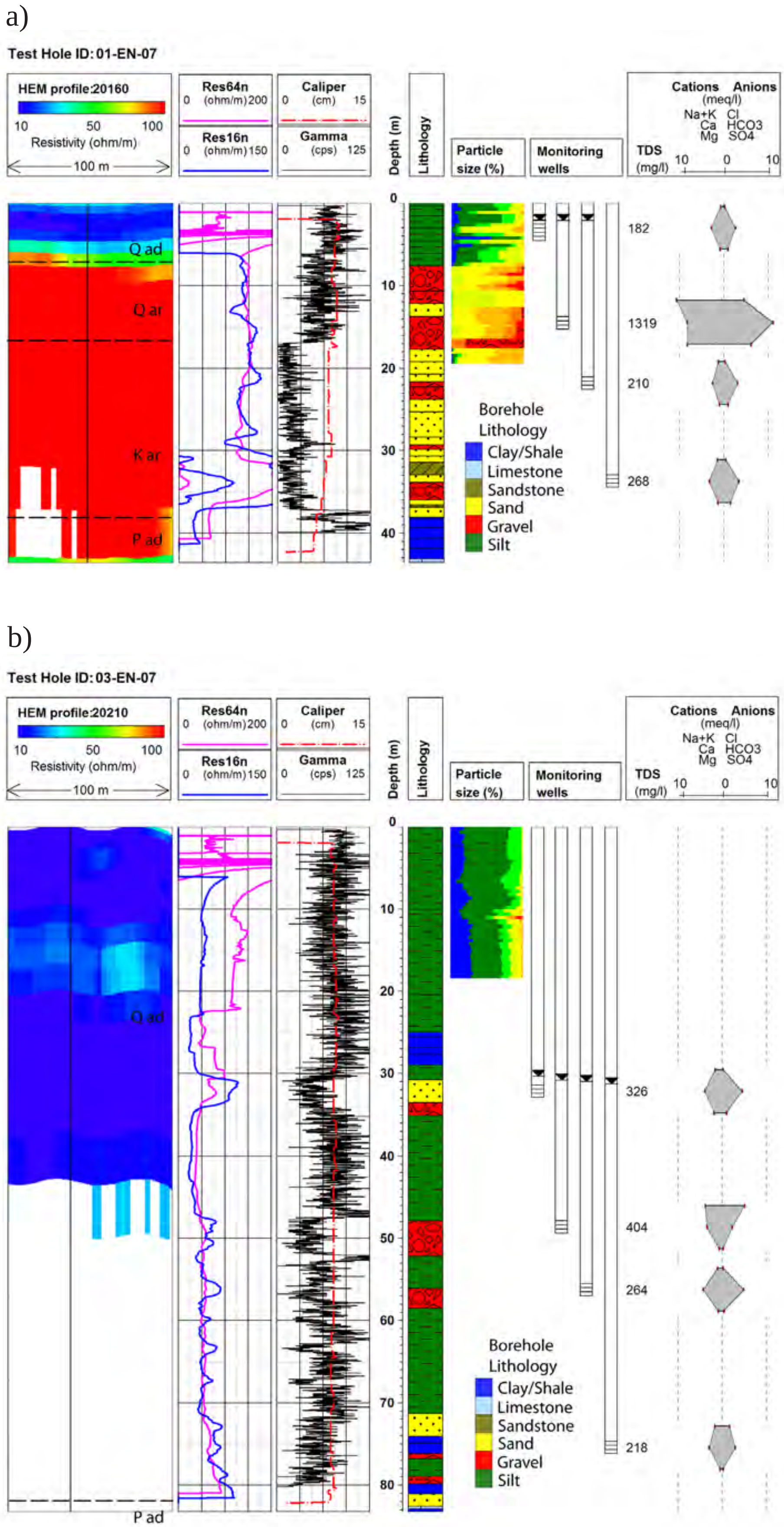

Fig. 7a and 7b. Comparisons of HEM resistivities, downhole geophysics, lithology, particle size analysis, and groundwater chemistry for Test Hole 01-EN-07 (Fig. 7a) and 03-EN-07 (Fig. 7b). HEM resistivities (far left) are shown for a 100 m wide area around the test hole. In Fig. 7a note resistivity contrast between Q ad and Q ar as well as K ar and P ad. Contact between Q ar and K ar at this location is not distinguishable using resistivity data alone. This contact was picked using gamma, lithology, material density, and mineral composition of sand-sized grains in Test Hole 01-EN-07.

HEM survey results do show low resistivity materials on the uplands (Fig. 4) that appear to correspond to the thickness of the loess and clay-rich glacial till units that are mapped in the area (Mason and Joeckel, 2002). In the subsurface, however, there is a poor correlation between highly resistive materials identified from the HEM survey and the available subsurface control.

In contrast to the thick layer of low resistivity materials found on the glaciated uplands, the presence of thinner low resistivity materials in other areas did not adversely affect the HEM results. This is the case in the Platte River alluvial fill, particularly along the western edge of the valley where ~ 10-15 feet (3-5 m) of silt and clay overlie coarser alluvium, sand and sand and gravel (Fig. 7a). The depth of these fine-grained materials from the HEM results closely matched the depth from subsurface data including the CSD test holes drilled for this project. Similarly, the depth of the Peoria loess cover on the Todd Valley was properly determined by the HEM survey (Fig. 7a), and the depths of the underlying sediments also closely agreed with existing subsurface data.

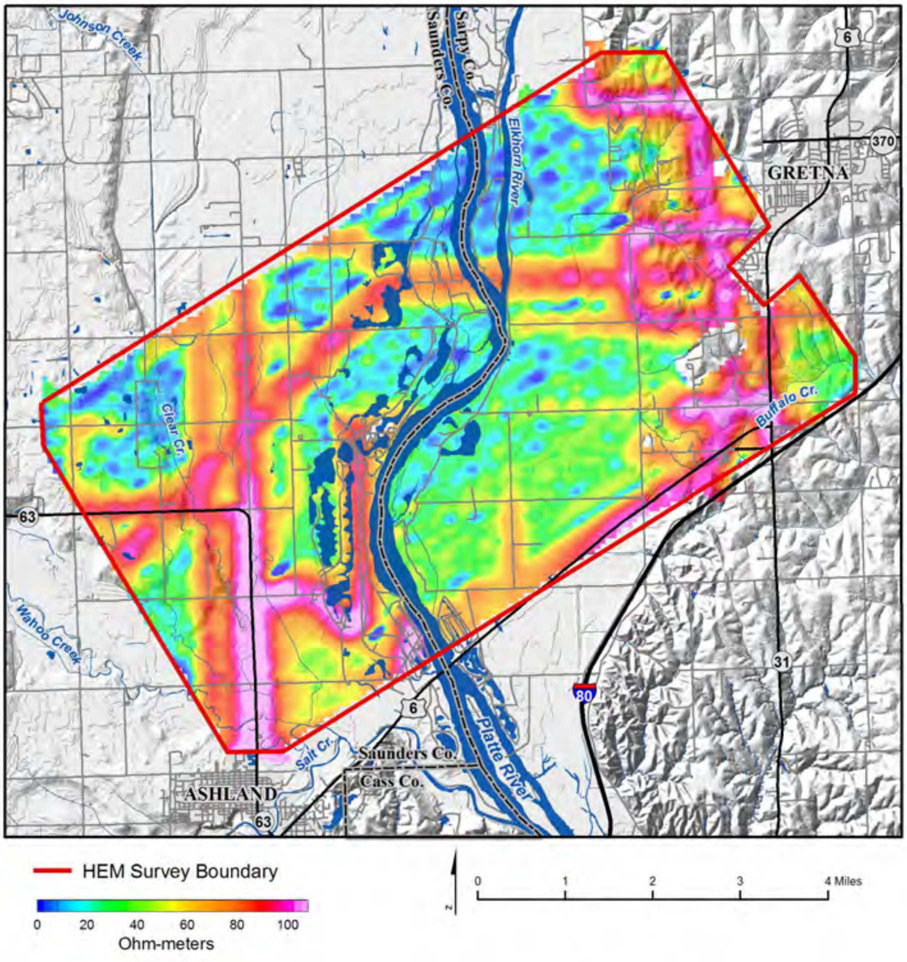

Fig. 8. Map showing high resistivity features from the HEM survey that are attributed to cultural phenomenon, including pipe lines and power lines. Areas in white were not part of the HEM survey.

Hydrostratigraphic Units Interpreted from Inverted HEM Cross-Sections

Using our available subsurface data and HEM results we identified six hydrostratigraphic units for the modern river valleys, the abandoned alluvial deposits, and the Todd Valley. These units are not applicable to the glaciated uplands on the eastern edge of the study area (Fig. 4) as data quality and quantity are not adequate to make reliable interpretations using these techniques. Our hydrostratigraphic units are aquifers and aquitards of various ages, and consist of the following: 1. Quaternary aquitard (Q ad), 2. Quaternary aquifer (Q ar), 3. Undifferentiated Quaternary loess, till, and sub-till deposits (Q u), 4. Cretaceous Dakota Formation aquifer (K ar), 5. Cretaceous Dakota Formation aquitard (K ad), and 6. undifferentiated Pennsylvanian aquitard (P ad).

The Quaternary aquitard (Q ad) has two components. The first component is loess that is found overlying older alluvium including the Todd Valley fill and an alluvial terrace that lies along the eastern edge of the Platte River Valley (Fig. 4). The second component is fine-grained alluvial sediments that are found within the Elkhorn and Platte River valleys (Fig. 4). These overbank sediments are primarily clays and silts that have accumulated on the edges of the valley, distal to the active Elkhorn and Platte River channels. On the eastern edge of the Platte Valley these sediments are thicker because of the presence of alluvial fans that are sourced from the loess covered uplands (Fig. 4).

The Quaternary aquifer materials (Q ar) are primarily sand and sand and gravel that are found throughout the Platte River Valley, beneath the Todd Valley, and within an alluvial terrace along the eastern edge of the Platte River Valley (Fig. 4). Locally this unit includes silty sand and sandy silts.

The undifferentiated Quaternary loess, till, and sub-till deposits (Q u) exist beneath the uplands on the east side of the study area. Below the low resistivity loess and clay-rich tills of the uplands lie coarser high resistivity sediments that serve as locally important aquifers, particularly for domestic wells. Such sand and gravel units are found under creeks that drain the glaciated uplands (Fig. 4).

The Dakota Formation rocks and sediment occur as both aquifer and aquitard materials that lie below Quaternary sediments through much of the study area. The Dakota aquifer (K ar) is primarily composed of sand, sandstone, and conglomerates that locally underlie Quaternary units in the study area. The Dakota aquitard (K ad) is a region of low resistivity shales and claystones that subcrop locally in the eastern portion of the Platte River Valley (Fig. 3). Where present, this unit caps the K ar units.

Finally, Pennsylvanian rocks are considered aquitard material throughout much of eastern Nebraska. Within the study area, the Pennsylvanian aquitard (P ad) is characterized by low resistivity shales and, in some portions of the region, limestones that directly underlie Quaternary alluvium or materials of the Dakota Formation. Limestones generally have moderately high to high resistivities, similar to sand and sand and gravel deposits. Therefore, the presence of limestone in the subsurface was interpreted based on correlations of subsurface data.

Analysis of HEM Depth Slices

Depths of hydrostratigraphic units were determined based on data from registered well logs, CSD test holes, and the inverted HEM cross-sections. Plan view depth slices of HEM results were plotted to show significant changes in resistivity. These depth slices are not planar, but instead portray the measured resisitivities below the ground surface elevations. These chosen depth slices range from 9 to 151 feet (3-46 m) below the ground surface. The uppermost HEM depth slice (9 feet) shows primarily low resistivity materials such as clays and silts (Fig. 9a). These Q ad deposits are primarily overbank alluvial silt and clay deposits in the river valleys or loess that covers the uplands, the Todd Valley, and the terrace on the eastern edge of the Platte River valley Fig. 4. Two areas of Q ar are shown in the 9 foot depth slice. The most prominent of these is the Q ar sandy alluvial sediments deposited along the current course of the Platte and Elkhorn Rivers. This area includes sandy spoil piles from gravel pit mining operations that are found mainly on the western bank of the Platte River (Fig. 4). The second area of Q ar is alluvial sand that is exposed along shoulder slopes of the Todd Valley fill. The subaerial exposure of this sandy material that underlies the loess cover has been noted in soil surveys (Scheinost et al., 2004) as well as in surficial geologic maps by Mason and Joeckel (2001a; 2002). This sediment is shown as Older Alluvium (Qal_o) in Fig. 4. Finally, the Q u deposit is found on the glaciated uplands throughout the eastern edge of the HEM study area (Fig. 9a).

The 23 foot depth slice from the HEM survey shows a dramatic increase in Q ar, and corresponding loss of Q ad (Fig. 9b). The overall higher resistivities indicate a general coarsening of sediments, particularly on the near eastern side of the active Platte River channel. In the Todd Valley the HEM survey has penetrated below the 10-15 foot (3-5 m) thick loess cap and is showing the underlying sandy fill (Fig. 9b). The far eastern and western edges of the Platte River

a)

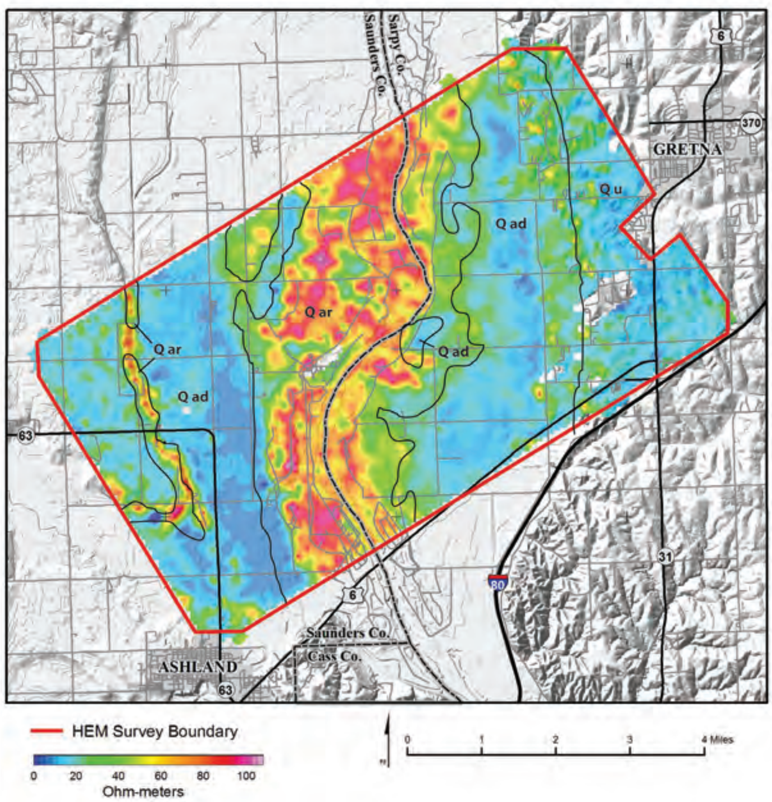

Fig. 9a. Plan view depth slice map showing relative resistivity values from the HEM survey. Depth slice is shown at 9 (3 m) feet. Areas in white were not part of the HEM survey.

b)

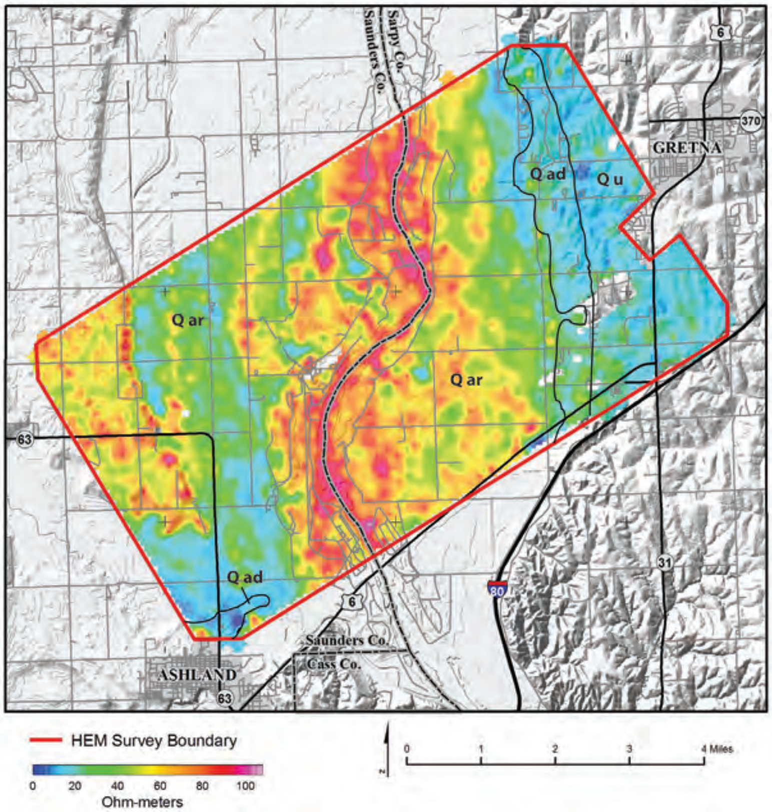

Fig. 9b. Plan view depth slice map showing relative resistivity values from the HEM survey. Depth slice is shown at 23 (7 m) feet. Areas in white were not part of the HEM survey.

c)

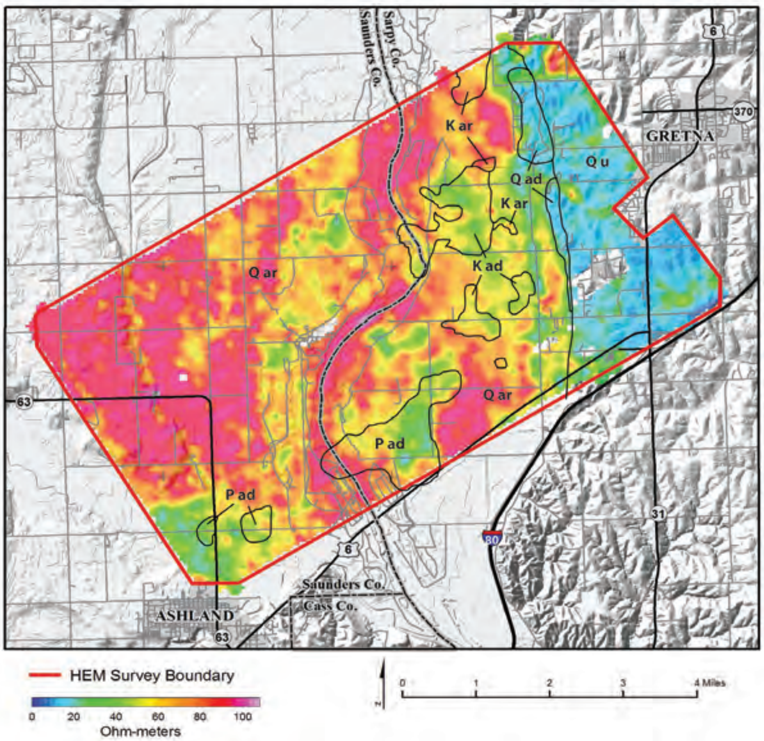

Fig. 9c. Plan view depth slice maps showing relative resistivity values from the HEM survey. Depth slice is shown at 43 (13 m) feet. Areas in white were not part of the HEM survey.

valley, however, remain relatively fine-grained, indicating a thicker fill of overbank sediments in both of these locations. Along the eastern edge of the Platte River this Q ad unit is particularly thick due to the presence of alluvial fans that deposited silt and clay-rich sediments derived from upslope loess (Fig. 4).

Similar to the 23 foot depth slice, the 43 foot depth slice map is dominated by Q ar units in the Platte River Valley (Fig. 9c). However, the Q ar unit in the 43 foot depth slice map is composed of higher resistivity materials indicating it is coarser relative to the Q ar in the 23 foot depth slice map (Fig. 9b). In addition, the Q ad unit found along the uplands on the eastern edge of the map has decreased in area (Fig. 9c). At 43 feet the HEM survey has penetrated below much of the loess cover in the study area, and the lower resistivity Q u materials on the eastern edge of the map are glacial units that underlie loess (Fig. 9c). This map shows the first bedrock subcrops in the Platte River valley. Both K ar and K ad deposits are locally found in the eastern portion of the Platte River valley, and P ad units are found along the southern boundary of the mapping area. K ad and P ad are distinguished on the basis of lithologies in nearby borehole logs and their stratigraphic positions.

The 84 foot HEM depth slice shows the Q ar deposits are pinching out and bedrock is found in greater areal extent throughout the Platte River valley (Fig. 9d). In the far northwestern edge of the mapping area Q ar units remain under the Todd Valley and locally below the active Platte River valley. Q ar units are also found along the eastern edge of the Platte River valley where Q ad deposits had existed in the 43 foot depth slice (Fig. 9c). The northern half of the map is dominated by K ar (Fig. 9d). Toward the southern half of the survey area K ar units pinch out and are present only locally, and instead P ad are found in this region. This overall pattern is similar to that shown in regional bedrock maps (Fig. 3; Burchett, 1986). The P ad units in the southwestern portion of the mapping area contain two distinct lithologies. The lower resistivity materials that are shown along the present course of the Platte River in the south central portion of the survey area are Pennsylvanian shales (Fig. 9d), while Pennsylvanian limestones are the higher resistivity units located to the west of the shales. The limestones, although not distinguishable from sand (Q ar) or sandstone (K ar) in HEM, are indicated by several boreholes in the southwest corner of the study site. At this depth the first highly resistive materials are identified in the uplands, including in the southern uplands and in the northern portion of the survey area (Fig. 9d).

In the HEM depth slice from 151 feet (Fig. 9e), P ad units dominate with minor remnants of K ar found locally. P ad units are primarily shales rather than limestones. K ar units are present under the Todd Valley fill, underlying the northern edge of the study area, and below the eastern edge of the modern Platte River valley (Fig. 9e).

Interpretive cross-sections drawn with the use of the available

d)

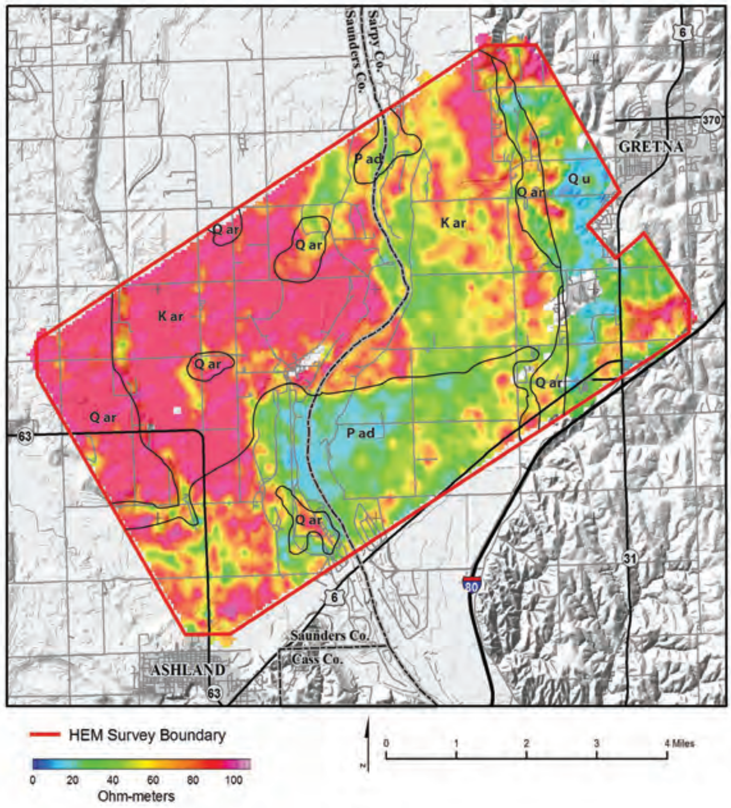

Fig. 9d. Plan view depth slice map showing relative resistivity values from the HEM survey. Depth slice is shown at 84 (26 m) feet. Areas in white were not part of the HEM survey.

e)

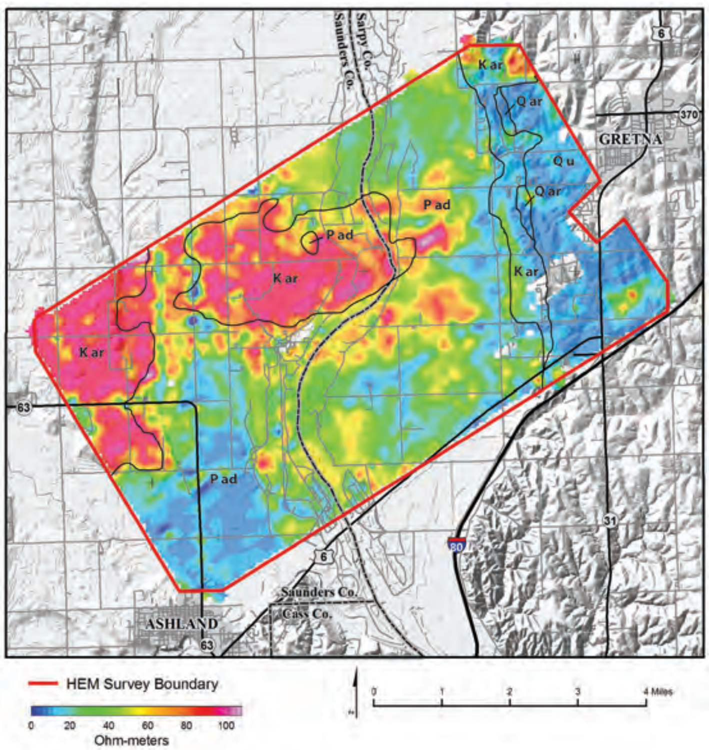

Fig. 9e. Plan view depth slice map showing relative resistivity values from the HEM survey. Depth slice is shown at 151 (46 m) feet. Areas in white were not part of the HEM survey.

subsurface data and the HEM survey results show the relationships between subsurface hydrostratigraphic units. Cross-section 20080 (Fig. 10a) drawn in the northern section of the study area (Fig. 2) shows up to approximately 175 feet (53 m) of Quaternary sediment and Cretaceous rock overlying P ad. The area immediately adjacent to the active Elkhorn and Platte River channels is surrounded by Q ar (Fig. 7). Q ad is found at the land surface along the edges of the Platte River Valley and covering the Todd Valley. Within the Platte Valley Q ad comprises fine-grained overbank alluvium, but the Q ad cover on the Todd Valley is loess. The alluvium within the Platte River valley in most locations coarsens with depth. Throughout most of cross-section 20080, the Platte River Valley alluvium directly overlies K ar except for a small area east of the active Platte River channel where K ad is present. Through most of this portion of the Platte River valley the Q_ar and K_ar units are hydrologically connected. Underlying the K ad and K ar units are low resistivity Pennsylvanian shales (P ad). Cultural features such as pipelines or buried utilities result in a breakdown of the modeling method, and therefore appear as a white area underlying the feature in cross-sections. A good example of this phenomenon is seen in the subsurface of cross-section 20080 (Fig. 10a) immediately to the west of the modern Platte River.

Cross-section 20160 is found in the middle of the HEM survey area (Figs. 2 and 10b). Relative to the cross-section drawn along HEM flight line 20080 this cross-section shows Q ar in the modern Platte River valley that has a greater quantity of silt, particularly in the eastern portion of the valley. The alluvial terrace found along the eastern valley wall has a relatively coarse Q ar fill that underlies a loess cover (Q ad). The Q_ar and K_ar units are again shown as hydrologically connected through much of this cross-section. The K ad unit under the eastern part of the Platte River valley is more extensive than in the previous cross-section. The K ar unit is absent in the west-central part of the valley where Pennsylvanian shale (P ad) directly underlies Quaternary alluvium (Fig. 10b).

In cross-section line 20200 a small remnant of K ar underlies the Todd Valley and the far western edge of the Platte River Valley (Fig. 11a). To the west of the Todd Valley fill is a remnant of Q ad that underlies the Wahoo Creek valley. There is only a remnant of the Q ar fill below the Todd Valley on the western side of the survey line (Fig. 11a). P ad is found directly under the Q ar through much of the valley. The highly resistive units underlying the K ar and Q ar units on the western edge of the cross-section are Pennsylvanian limestones (P ad). In the central portion of the transect these P ad materials are Pennsylvanian shales.

Cross-section 20280 is located along the southern-most HEM survey flight line (Figs. 2 and 11b). In this cross-section both K ar and K ad units are almost entirely missing, with the exception of a remnant fill of K ar on the eastern edge of the Platte River Valley. Q ar is directly underlain by P ad (Pennsylvanian shales) through most of this portion of the study area, but Pennsylvanian limestones are found locally along the study area’s far western edge near Test Hole M90-22R as highly resistive units within P ad.

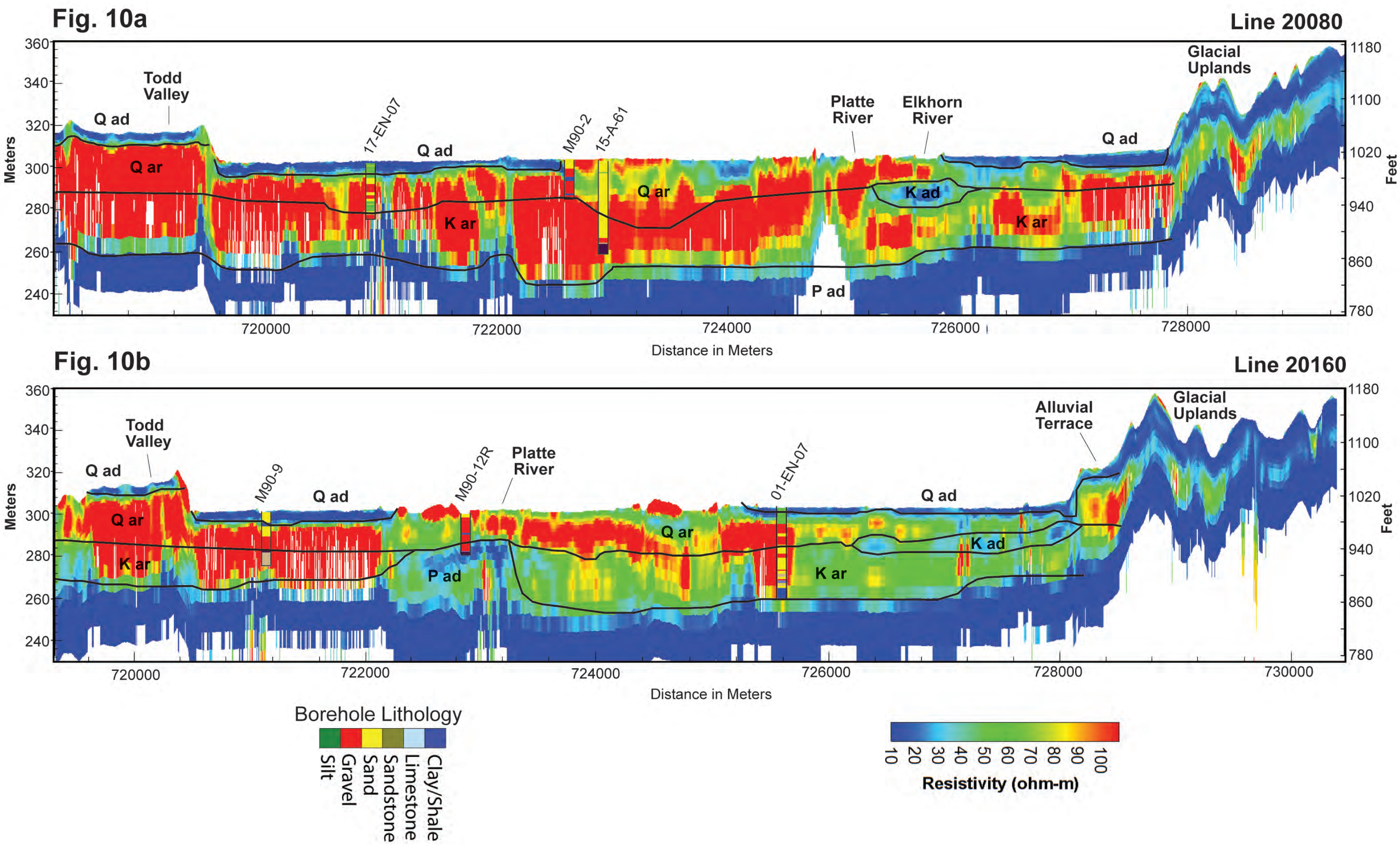

Fig. 10. Interpretive cross-sections of hydrostratigraphic units along HEM flight lines 20080 (Fig. 10a) and 20160 (Fig. 10b). The locations of these individual flight lines are shown on Fig. 2. Hydrostratigraphic units are indicated as Q ad (Quaternary aquitard), Q ar (Quaternary aquifer), K ad (Cretaceous aquitard), K ar (Cretaceous aquifer), and P ad (Pennsylvanian aquitard).

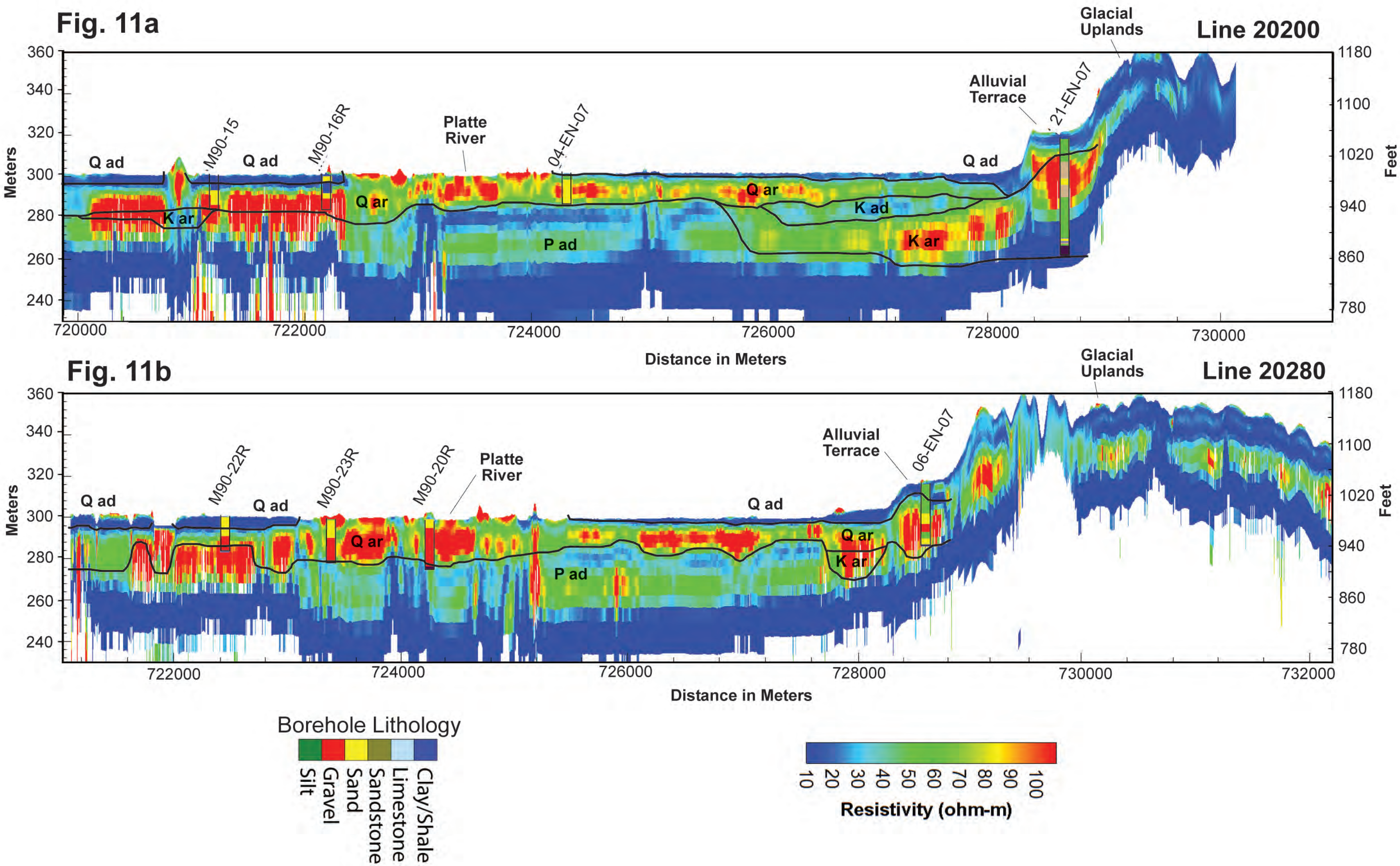

Fig. 11. Interpretive cross-sections of hydrostratigraphic units along HEM flight lines 20200 (Fig. 11a) and 20280 (Fig. 11b). Individual flight line locations are shown on Fig. 2. Hydrostratigraphic units are indicated as Q ad (Quaternary aquitard), Q ar (Quaternary aquifer), K ad (Cretaceous aquitard), K ar (Cretaceous aquifer), and P ad (Pennsylvanian aquitard). Highly resistive units within P ad in the western portion of the cross-sections are limestones.

Three-dimensional hydrostratigraphy and implications for groundwater

A three-dimensional hydrostratigraphic model was constructed using five bounding surfaces: base of aquifer, base of Dakota aquitard, base of Quaternary aquifer, base of Quaternary aquitard, and the HEM-derived digital elevation model (DEM). The base of aquifer is a composite surface representing the base of the Dakota Formation in some areas and the base of the Quaternary aquifer in areas where the Dakota is absent. The base of Quaternary aquitard surface was not interpreted under the uplands area due to the lack of reliable HEM and borehole data at depth.

Figure 12 shows the resulting 3-D hydrostratigraphic model for the bedrock units. The top surface of this model represents the base of Q ar, and therefore, shows the bedrock units that are in contact with the Quaternary aquifer. P ad is the lowermost bedrock unit. It is bounded by an arbitrary lower surface at ~ 754 feet (230 m) which was used for visual representation purposes only (defining the actual thickness of the Lansing and Kansas City Groups is problematic because much of this strata has been mis-correlated in Nebraska and stratigraphic picks made in deep well logs may be inaccurate: R.M. Joeckel, personal communication). The top of P ad is highly irregular and it generally decreases in elevation from southeast to northwest. P ad lies directly below Q ar in the southwestern corner of the study area where it can be as little as 30 ft (9 m) below the land surface. In the remainder of the Platte River Valley, P ad lies beneath the Dakota Group at depths of as much as 180 ft (55 m).

Figure 12 illustrates the discontinuous nature of K ar and K ad. The 3-D model of the Dakota aquifer is bounded on the bottom by the base of the aquifer and on the top by a composite surface consisting of the base of the Dakota aquitard and the base of Quaternary aquifer (where the Dakota aquitard is absent). The calculated volume of this unit is 5.17 x 1010 ft3 (1.47 x 109 m3). The 3-D model of the Dakota aquitard is bounded on the bottom by the base of the aquitard and on the top by the base of Quaternary aquifer. The volume of this unit is 1.98 x 109 ft3 (5.6 x 107 m3). The discontinuities within the Cretaceous units are predicted to have a direct influence on groundwater flow in the study area. K ar pinches out abruptly along the edge of a sub-Cretaceous paleovalley outlined by the contact between K ar and P ad in Figure 12. It can be expected that groundwater flowing toward the south-southeast through K ar (Fig. 5) will be forced to flow upward into the overlying aquifer when it encounters the aquifer boundary. Vertical flow of groundwater between K ar and Q ar is probably restricted, however, in areas where K ad is present. The presence of a pumping well near the K ar/P ad boundary may cause an excessive drop in the water level. However, these affects

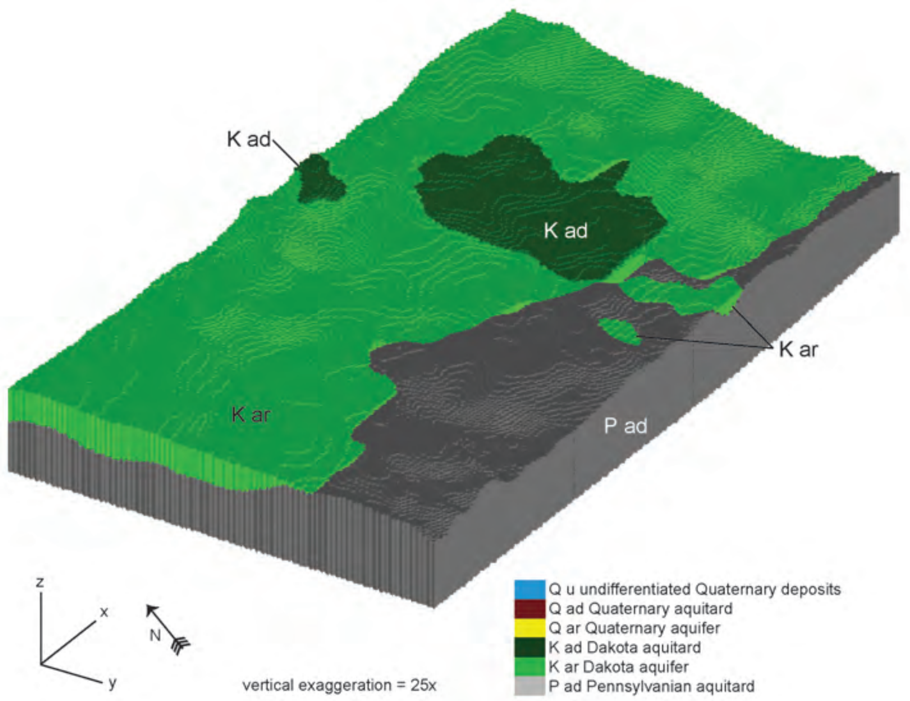

Fig. 12. Three-dimensional model of bedrock hydrostratigraphic units in the study area. See Figure 3 for location, orientation of block model, and comparison with bedrock geologic map.

may be minimized due to the high transmissivity of the overlying aquifer and its connection with the Platte River (see forthcoming discussion).

Figure 13 illustrates the interpretive hydrostratigraphy of Quaternary hydrostratigraphic units. The 3-D model of the Quaternary aquifer (Q ar in Fig. 13) is bounded on the bottom by the base of Quaternary and on the top by a composite surface consisting of the base of Q ad and the HEM-derived DEM (where the aquitard is absent). The volume of this unit is 4.52 x 1010 ft3 (1.28 x 109 m3). The Platte River flows through the area in which Q ar is exposed at the land surface, implying a hydrologic connection between them over the entire study area. In addition, the areas in which Q ar is present at the land surface are of a heightened vulnerability to contamination because thick, continuous aquitard materials are absent. The 3-D model of the Quaternary aquitard is bounded on the bottom by the base of the Quaternary aquitard and on the top by the HEM-derived DEM. The volume of this unit is 9.85 x 109 ft3 (2.79 x 108 m3). The Quaternary aquifer and aquitard models terminate along a line at the western edge of the uplands because separate units could not be differentiated in the HEM profiles east of this line (Fig. 13). Q ad is discontinuous in the Platte River Valley. It is thickest along the eastern valley margin and thins toward the west, where it pinches out along an irregular boundary in the valley. It is absent near the middle of the valley through which the Platte River flows. Q ad is present as a thin mantle over the Todd Valley and the western margin of the Platte Valley. Those areas overlain by Q ad are less vulnerable to contamination entering from the land surface.

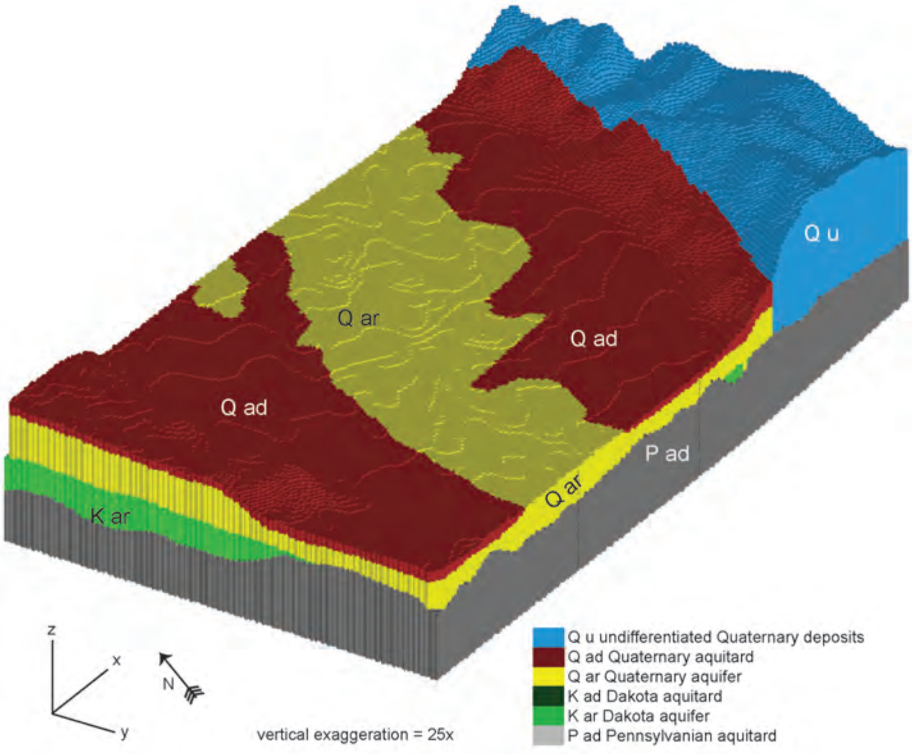

Fig. 13. Three-dimensional model of bedrock and Quaternary hydrostratigraphic units in the study area. See Figure 4 for location, orientation of block model, and comparison with surficial geologic map.

A 3-D model representing undifferentiated Quaternary units was generated for the area beneath the uplands. It is bounded on the bottom by the base of Quaternary aquifer and on the top by the HEM-derived DEM. This model comprises silt, clay, and sand units of variable thickness and extent. The entire unit volume is 2.33 x 1010 ft3 (9.11 x 108 m3). However, no meaningful information on groundwater flow can be derived from this model given the limited detail that exists for th+e hydrostratigraphy of the uplands.

The hydrostratigraphic 3-D models described above represent the saturated and unsaturated portions of the units. To estimate the volume of the saturated portion of the units, a combined water table/potentiometric surface was generated using available water level observations from spring 2009 measurements for the area (Fig. 5). Hydraulic head elevations were determined using a USGS DEM at locations inside the HEM area. The HEM-derived DEM elevation value was then determined for each location, and the difference between the two elevations was computed. This difference was used to adjust the water table/potentiometric surface elevations for points outside the HEM boundary. The resulting contour map is based on points that lie both inside and outside the HEM flight area, but is referenced to the same datum (HEM-derived DEM) as the hydrostratigraphic unit boundaries.

The saturated portion of each hydrostratigraphic unit was calculated by slicing the model by the interpreted water table/ potentiometric surface and calculating the volume that lies below it. The result is shown in Figure 14. The total volumes of the saturated portions of K ar, K ad, Q ar, Q ad, and Q u are 5.19 x 1010 ft3 (1.47 x 109 m3), 1.98 x 109 ft3 (5.6 x 107 m3), 3.74 x 1010 ft3 (1.06 x 109 m3), 3.60 x 109 ft3 (1.02 x 108 m3), 1.65 x 1010 ft3 (4.67 x 108 m3), respectively. These estimated volumes do not separate pore space volume from the total volume. The saturated portions of these units comprise 100% of both Dakota units, 83% of the Q ar, 36% of the Q ad, and 51% of the Q u. The three-dimensional model of the saturated portion of the units (Fig. 14) allows us to resolve details regarding the nature of materials located at the water table or potentiometric surface. This type of detail would not be possible without the HEM survey results and 3-D hydrostratigraphic modeling. The aquifer exists under unconfined conditions in areas where the water table is below the top of Q ar materials. It exists under confined or semi-confined conditions where the potentiometric surface is within Q ad, such as along the eastern and western margins of the Platte River Valley (Fig. 14). The greatest saturated thicknesses occur along the northern and northwestern margins of the study area. Assuming all factors remain constant, these areas would be most suitable for high volume groundwater extraction in the study area. Saturated materials are thinnest in the southern part of the study area and are therefore comparatively more vulnerable to over-development. The direct hydrologic connection between the aquifer and the Platte River, however, will likely limit the impacts to groundwater from any potential future withdrawals.

A potential application of this modeling would be to obtain more accurate estimates of the changes in groundwater in storage through time. The actual volume of groundwater in each unit, however, depends on the porosity of the geologic materials of which they are comprised. Porosity was not measured directly, but is likely to range from 34-60% in silt and clay, 20-50% in sand and gravel, 5-15% in sandstones, 0- 40% in limestones, and 1-10% in shales (Domenico and Schwartz, 1997).

A water budget would be the most useful approach to understanding the groundwater flow system at the study site, but quantifying and analyzing the variables that are incorporated into a water budget are beyond the scope of this project. Rather, we sought to demonstrate methodologies that could be used with similar data sets in other areas. One such methodology is estimating the maximum volume of drainable groundwater for each unit. This calculation provides

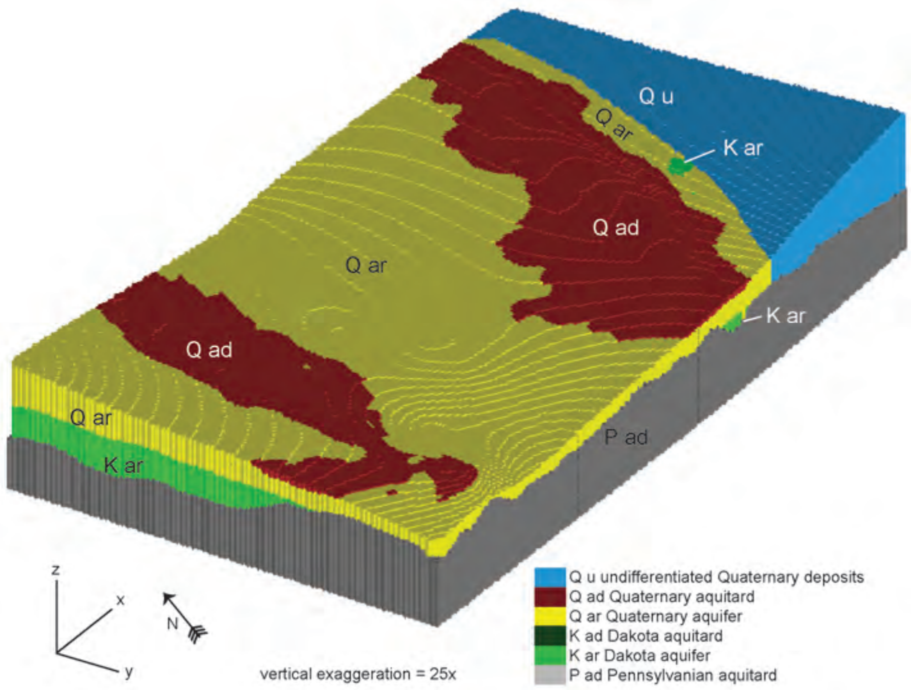

Fig. 14. Three-dimensional model of saturated (below water table or potentiometric surface) bedrock and Quaternary hydrostratigraphic units in the study area. See Figure 5 for location, orientation of block model, and comparison with water table/potentiometric surface map.

a theoretical upper limit for the groundwater that could be pumped from an aquifer, however, the realistic drainable groundwater is expected to be considerably lower due to limitations such as well spacing and pumping efficiency, as well as hydrogeologic factors such as hydraulic gradients and conductivities. Furthermore, such a methodology is not useful in the study area because the connection between the aquifer and the Platte River renders depletion of the aquifer unlikely, and the maximum aquifer yield will likely be limited by the maximum rate of flow between the aquifer and the stream. Nonetheless, calculating drainable groundwater volumes demonstrates the potential usefulness of HEM data for hydrogeological applications in other areas where surface and groundwater are not connected.

To demonstrate this methodology, drainable groundwater was calculated by multiplying the saturated unit volume by an estimated specific yield (Sy) value. Estimates of Sy for each of the hydrostratigraphic units were obtained from existing data and/or other literature. Few aquifer tests have been conducted on the unconfined aquifers of the Dakota Formation in eastern Nebraska. Summerside (2005) determined a Sy value of 0.04 and Singleton (1966) determined Sy values of between 0.01 and 0.035, both from aquifer tests of unconfined sandstones in the Dakota Formation near Lincoln. These values are somewhat lower than the values of 0.15 to 0.20 reported by Keene and Bayne (1976) for the Dakota Formation in Kansas, and the value of 0.15 used by Helgeson et al. (1993) in a regional groundwater flow model of the Dakota. The locally derived values, however, generally fall within the range of representative values of Sy for sandstone obtained from the literature (Morris and Johnson, 1967; Walton, 1988). In keeping with locally derived values for the Dakota Formation, a Sy of 0.05 was used in this analysis.

No information is known regarding the Sy of siltstone units in the Dakota Formation. Sy values for siltstone from the literature typically range from 0.01 to 0.33 (Morris and Johnson, 1967; Walton, 1988). For the purposes of this paper, a value of 0.01 was used because it is the most conservative estimate K ad.

Woodward-Clyde (1996) estimated a Sy of 0.10 for the Quaternary aquifer under the Todd Valley. Ayers (1990) used a value of 0.15 for the Quaternary aquifer (equivalent to unit Q ar in this study) in the Platte River valley within our study area. A value of 0.15 is used here because it is in agreement with representative values in the literature for these types of materials (Morris and Johnson, 1967; Walton, 1988). The Sy of the Quaternary aquitard is estimated to be 0.015 based on Ayers (1990) work on this portion of the Platte River Valley. This value is consistent with representative values for silt and clay (Morris and Johnson, 1967; Walton, 1988).

The volume of drainable groundwater was not estimated for the undifferentiated Quaternary unit below the uplands because of its highly variable lithology and the lack of control on unit volumes. Using the Sy values from above, the estimated volume of drainable groundwater for the Dakota aquifer, Dakota aquitard, Quaternary aquifer, and Quaternary aquitard are 2.59 x 109 ft3 (73.3 x 106 m3), 1.97 x 107 ft3 (0.557 x 106 m3), 5.63 x 109 ft3 (159.3 x 106 m3), and 5.40 x 107 ft3 (1.53 x 106 m3), respectively. These values represent 31.2%, 0.2%, 67.9%, and 0.7% of the total drainable groundwater in the study area, exclusive of the uplands. Although the two aquitard units are characterized as having low hydraulic conductivities, we chose to calculate their theoretical drainable volumes to highlight their comparable volumes and because they may contribute some volume to the surrounding aquifer units during pumping. These estimates are highly dependent on the Sy value used in the calculation. Since the Sy values used here are rough estimates based on data from outside the study area, they should not be used for making detailed management decisions. Improved estimates of the volume of drainable groundwater will require additional data on each hydrostratigraphic unit within the HEM flight area.

Conclusions

Detailed three-dimensional geologic and hydrostratigraphic interpretation is possible through the integration of HEM and subsurface borehole data. Specific conclusions are as follows:

1. In the alluvial areas, HEM permits vastly improved understanding of hydrostratigraphic relationships compared to correlation using borehole data alone.

2. Stratigraphic interpretations were favorable using HEM in the alluvial areas even where thin loess and fine-grained alluvial units, 10-15 feet (3-5 m) thick, exist at the surface.

3. Detailed correlation and interpretation were not possible using HEM in the glaciated uplands. This problem in correlation was due in part to the limited amount of subsurface data and the complex geology of these uplands, but also to the presence of 80 to 100 foot (24-31 m) thick surficial loess and till deposits that are a problem for penetration of the HEM signal.

4. Hydrostratigraphic mapping resolves details concerning the interconnectedness of aquifer and aquitard units at a scale of resolution not previously possible. The Platte River and Quaternary aquifer are apparently hydrologically connected throughout the mapped area. The Quaternary and Dakota aquifers are apparently hydrologically connected throughout the study area except where the discontinuous Cretaceous Dakota aquitard separates them.

5. Three-dimensional modeling of hydrostratigraphic units using the methods of this study permits highly refined calculation of unit volumes, saturated thicknesses, and estimates of drainable groundwater. Our use of these techniques in this setting shows the potential for using these methods in other locations.

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References Cited

Ayers, J.F., 1990, Hydrogeology of the Lower Platte Valley Alluvial Aquifer, Part II: Groundwater Flow Model Update, Project Completion Report. Open File Report OFR-43. Conservation and Survey Division, University of Nebraska-Lincoln, Lincoln, NE. 238 pp.

Bettis III, E.A., Muhs, D.R., Roberts, H.M., Wintle, A.G., 2003, Last glacial loess in the conterminous USA. Quaternary Science Reviews 22, 1907-1946.

Boellstorff, J., 1978a, Chronology of some late Cenozoic deposits from the central United States and the Ice Ages, Transactions of the Nebraska Academy of Sciences 6, 35-49.

Boellstorff, J., 1978b, North American Pleistocene stages reconsidered in light of probable Pliocene-Pleistocene glaciation, Science 202, 305-307.

Brenner, R.L., Ludvigson, G.A., Witzke, B.J., Zawistoski, A.N., Kvale, E.P., Ravn, R.L., Joeckel, R.M., 2000, Late Albian Kiowa-Skull Creek marine transgression, lower Dakota Formation, eastern margin of western interior seaway, U.S.A: Journal of Sedimentary Research, v. 70, no. 4, p. 868-878.

Burchett, R.R., Smith, F.A., 1989, Saunders County Test-Hole Logs, Nebraska Water Survey Test-Hole Report No. 78, Conservation and Survey Division, University of Nebraska-Lincoln, 63 p.

Burchett, R.R., 1986, Geologic bedrock map of Nebraska (1:1,000,000), Nebraska Geological Survey GMC-1.

Condra, G.E., 1903, An Old Platte Channel, American Geologist 31, 361-369.

Divine, D.P., Joeckel, R.M., Korus, J.T., Hanson, P.R., Olafsen Lackey, S., 2009, Eastern Nebraska Water Resources Assessment (ENWRA): Introduction to a Hydrogeologic Study, University of Nebraska-Lincoln, Conservation and Survey Division Bulletin 1 (New Series), 36 p.

Domenico and Schwartz, 1998, Physical and Chemical Hydrogeology, Second Edition, John Wiley & Sons, New York, 506 p.

Forman, S.L., Bettis III, E.A., Kemmis, T.J., Miller, B.B., 1992, Chronologic evidence for multiple periods of loess deposition during the late Pleistocene in the Missouri and Mississippi River valley, United States; implications for the activity of the Laurentide ice sheet, Palaeogeography, Palaeoclimatology, Palaeoecology 93, 71-83.

Forman, S.L., Pierson, J., 2002, Late Pleistocene luminescence chronology of loess deposition in the Missouri and Mississippi River valleys, United States, Palaeogeography, Palaeoclimatology, Palaeoecology 186, 25-46.

Gosselin, D.C., Headrick, J., Chen, X-H, Summerside, S., Tremblay, R., Bottger, K., 1996, Domestic well-water quality in rural Nebraska, Nebraska Conservation and Survey Division Open File Report 52, 150 p.

Helgeson, J.O., R.B. Leonard, Wolf, R.J., 1993, Hydrology of the Great Plains Aquifer System in Nebraska, Colorado, Kansas, and Adjacent Areas. U.S. Geological Survey Professional Paper 1414-E. U.S. Geological Survey (USGS), Reston, VA.

Joeckel, R.M., Mason, J.A., 2001, Surficial geology of the Ashland West Quadrangle (digital map). Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln, scale 1:24,000 [URL http://snr.unl.edu/data/geologysoils/digitalgeologicmaps/digitalgeologicmaps.asp]

Joeckel, R.M., Ludvigson, G.A., Witzke, B.J., Kvale, E.P., Phillips, P.L., Brenner, R.L., Thomas, S.G., Howard, L.M., 2004, Paleogeography and fluvial to estuarine architecture of the Dakota Formation (Cretaceous, Albian), Eastern Nebraska, USA, in Blum, M.D, Marriott, S.B., and Leclair, S.F., eds., Fluvial Sedimentology 7. Special Publication, International Association of Sedimentologists, p. 453-480.

Keene, K.M., Bayne, C.K., 1976, Groundwater from Lower Cretaceous Rocks in Kansas. U.S. Geological Survey Open-File Report 76-776. U.S. Geological Survey (USGS), Reston, VA. 75 pp.

Lugn, A.L., 1935, The Pleistocene Geology of Nebraska, Nebraska Geological Survey Bulletin 10, Second Series, 223 p.

Mason, J. A., 2001, Transport direction of Peoria Loess in Nebraska and implications for loess sources on the central Great Plains. Quaternary Research (New York) 56, 79-86.

Mason, J.A., Joeckel, R.M., 2000, Surficial geology of the Wann Quadrangle (digital map), Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln, scale 1:24,000 [URL http://snr.unl.edu/data/geologysoils/digitalgeologicmaps/digitalgeologicmaps.asp]

Mason, J.A., Joeckel, R.M., 2001a, Surficial geology of the Ashland East Quadrangle (digital map), Conservation and Survey Division, School of Natural Resources, University of Nebraska-Lincoln, scale 1:24,000 [URL http://snr.unl.edu/data/geologysoils/digitalgeologicmaps/digitalgeologicmaps.asp]

Mason, J.A., Joeckel, R.M., 2001b, Late Quaternary geomorphology and sedimentology of the Platte River floodplain, eastern Nebraska, USA, Program and Abstracts, 7th International Conference on Fluvial Sedimentology, p. 195.

Mason, J. A., Joeckel, R.M, 2002, Surficial geology of the Platte River Valley, Fremont to Ashland (Fremont East, Arlington, Valley, Wann, and Ashland East 7.5-Minute Quadrangles), Conservation and Survey Division Open-File Report 68, University of Nebraska, Lincoln [CDROM], 39 p.

Mason, J.A., Joeckel, R.M., Bettis, E.A., III, 2007, Middle to late Pleistocene loess record in eastern Nebraska, USA, and implications for the unique nature of Oxygen Isotope Stage 2, Quaternary Science Reviews 26, 773-792.

Mason, J.A., Miao, X., Hanson, P.R., Johnson, W.C., Jacobs, P.M., Goble, R.J., 2008, Loess record of the last Glacial-Interglacial transition on the northern and central Great Plains, Quaternary Science Reviews 27, 1772-1783.

Morris, D.J., Johnson, A.I., 1967, Summary of hydrological and physical properties of rock and soil materials as analyzed by the Hydrologic Laboratory of the U.S. Geological Survey 1948-1960, U.S. Geological Survey Water Supply Paper 1839-D. U.S. Geological Survey (USGS), Reston, VA.

Phillips, P.L., Jr., Ludvigson, G.A., Joeckel, R.M., González, L.A., Brenner, R.L., Witzke, B.J., 2007, Sequence stratigraphic controls on synsedimentary cementation and preservation of dinosaur tracks: Example from the lower Cretaceous, (Upper Albian) Dakota Formation, Southeastern Nebraska, U.S.A., Palaeogeography, Palaeoclimatology, Palaeoecology 246, 367-389.

Roy, M., Clark, P.U., Barendregt, R.W., Glasmann, J.R., Enkin, R.J., 2004, Glacial stratigraphy and paleomagnetism of late Cenozoic deposits of the north-central United States, Geological Society of America Bulletin 116, 30-41.

Scheinost, S.A., Gross, R.D., Labenz, A.T., Hartung, S.L., 2004, Soil Survey of Saunders County, Nebraska, United States Department of Agriculture, 275 p.

Singleton, 1966, Artificial Recharge of the Dakota Sandstone Aquifer through a Production Well, MS Thesis, University of Nebraska-Lincoln. 111 pp.

Smith, B.D., Grauch, V.J.S., McCafferty, A.E., Smith, D.V., Rodriguez, B.R., Pool, D.R., Deszcz-Pan, M., Labson, V.F., 2007a, Airborne Electrogmagnetic and Magnetic surveys for ground-water resources: A decade of study of the U.S. Geological Survey, in Milkereit, B., Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration, 895-899.

Smith, B.D., Abraham, J.A., Cannia, J.C., Steele, G.V., Hill, P.L., 2007b, Helicopter electromagnetic and magnetic geophysical survey data, Oakland, Ashland, and Firth study areas, Eastern Nebraska, March 2007: U.S. Geological Survey Open-File Report 2008-1018, 16 p.

Summerside, S., 2005, Locating a Sustainable Small Public Water Supply in a Constrained Resource Area of Dakota Aquifer, Nebraska. Abstract, North-Central Geological Society of America Annual Meeting, May 19-20, 2005.

Walton, W.C., 1988, Groundwater Pumping Tests. Lewis Publishers, Inc. Chelsea, MI. 201 pp.

Witzke, B.J., Ludvigson, G.A., 1990, Petrographic and stratigraphic comparisons of sub-till and inter-till alluvial units in western Iowa; Implications for development of the Missouri River drainage, in Bettis, E.A., III, Holocene Alluvial Stratigraphy and Selected Aspects of the Quaternary history of western Iowa, Iowa Geological Survey Guidebook Series No. 9, 209 p.

Witzke, B.J., Ludvigson, G.A., 1994, The Dakota Formation in Iowa and the type area, in Shurr, G.W., Ludvigson, G.A., and Hammond, R.H., eds., Perspectives on the eastern margin of the Cretaceous Western Interior Basin: Boulder, Colorado, Geological Society of America Special Paper 287, p. 43-78.

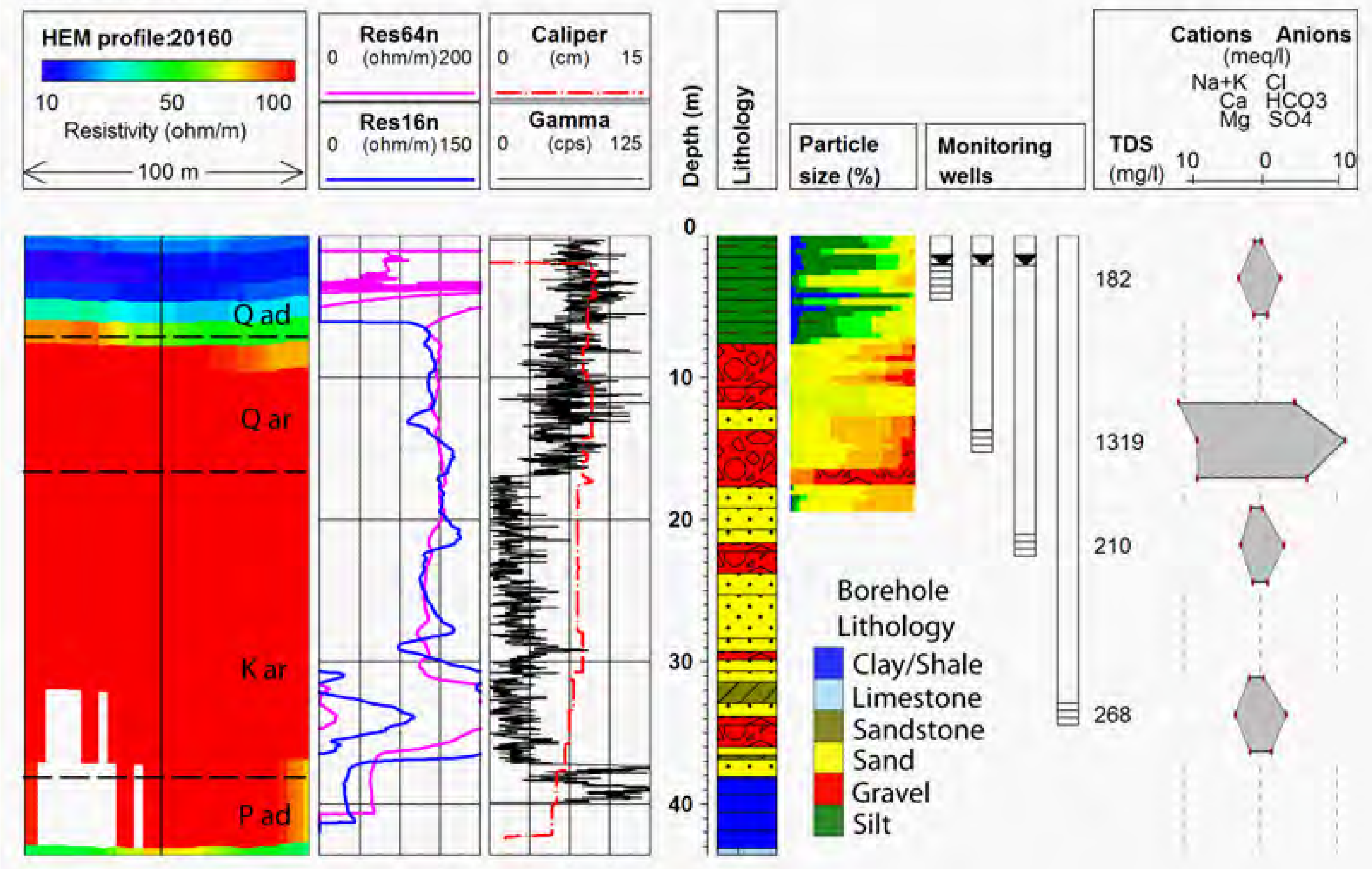
Woodward-Clyde Consultants, 1996, Pumping Tests for Groundwater Containment Removal Action for Former Nebraska Ordinance Plant Operable Unit No. 2 (Groundwater). Woodward-Clyde Consultants, Overland Park, Kansas.

Appendix A

Monitoring wells installed at the Ashland Pilot study site, including screened intervals.

Testhole (Figure 5 and 6)	ENWRA Well ID	Registration ID	Geologic Setting	Geologic Unit	Depth to bottom of well screen (ft bgs)
01-EN-07	ASH-01-15	G-149386	alluvial valley	silt & clay	15
01-EN-07	ASH-01-50	G-149387	alluvial valley	sand & gravel	50
01-EN-07	ASH-01-74	G-149388	alluvial valley	sand & gravel	74
01-EN-07	ASH-01-113	G-149389	alluvial valley	sand & gravel	113
03-EN-07	ASH-03-108	G-149390	glacial till uplands	sand & silt	108
03-EN-07	ASH-03-162	G-149391	glacial till uplands	sand & gravel	162
03-EN-07	ASH-03-187	G-149392	glacial till uplands	sand, silt, clay, gravel	187
03-EN-07	ASH-03-250	G-149393	glacial till uplands	silt & clay	250
04-EN-07	ASH-04-15	G-149394	alluvial valley	sand & silt	15
04-EN-07	ASH-04-32	G-149395	alluvial valley	sand & gravel	32
04-EN-07	ASH-04-45	G-149396	alluvial valley	sand & gravel	45
05-EN-07	ASH-05-15	G-149397	alluvial valley	silt & clay	15
05-EN-07	ASH-05-25	G-149419	alluvial valley	sand & gravel	25
05-EN-07	ASH-05-43	G-149398	alluvial valley	sand & gravel	42
06-EN-07	ASH-06-59	G-149399	terrace	sand	59
06-EN-07	ASH-06-70	G-149400	terrace	sand & gravel	70
06-EN-07	ASH-06-92	G-149420	terrace	sand & gravel	92
07-EN-07	ASH-07-110	G-149421	glacial till uplands	silt & clay	110
07-EN-07	ASH-07-158	G-149422	glacial till uplands	sand & clay/shale	158
07-EN-07	ASH-07-180	G-149463	glacial till uplands	shale/siltstone	180

Test Hole ID: 01-EN-07



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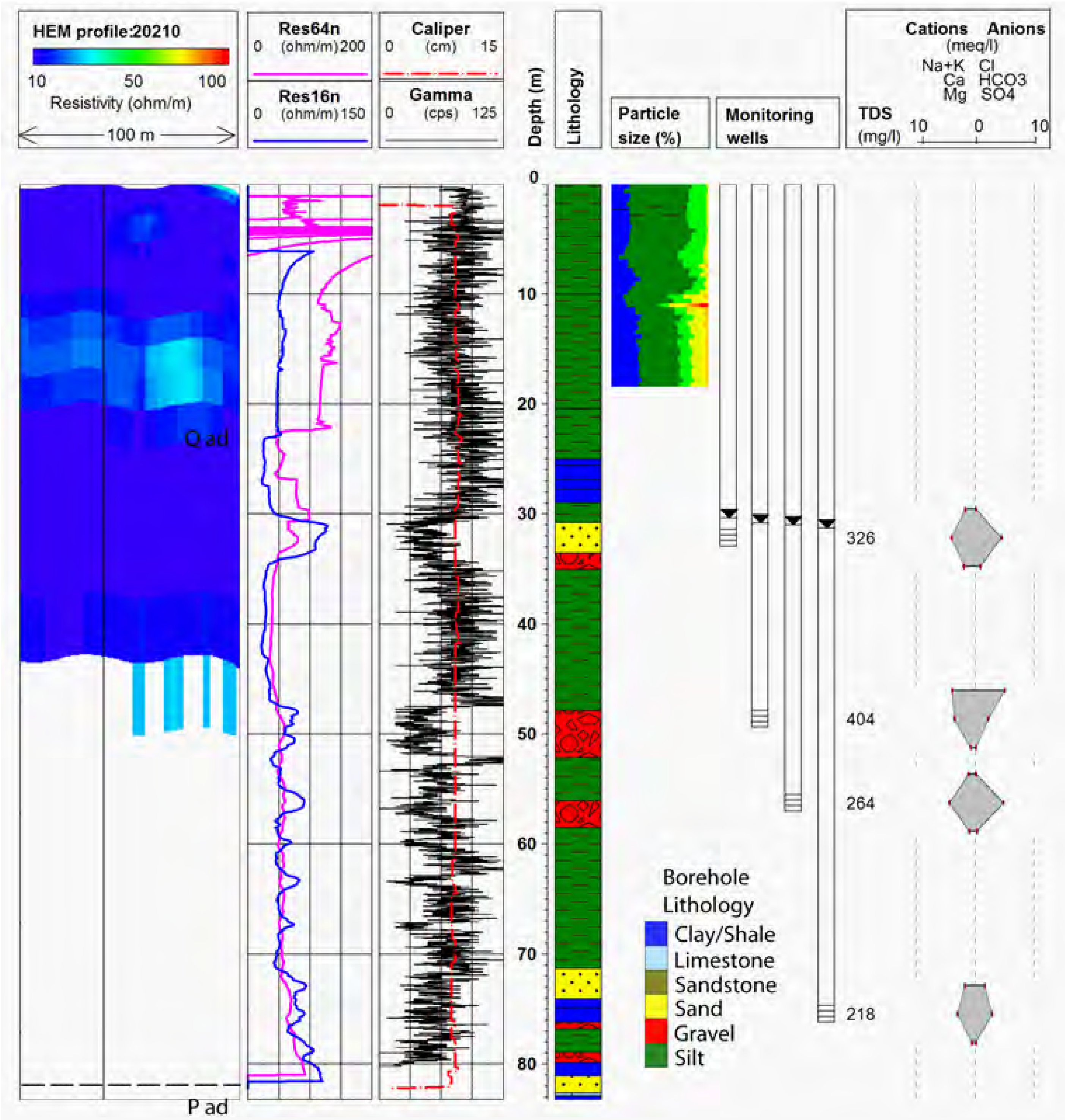

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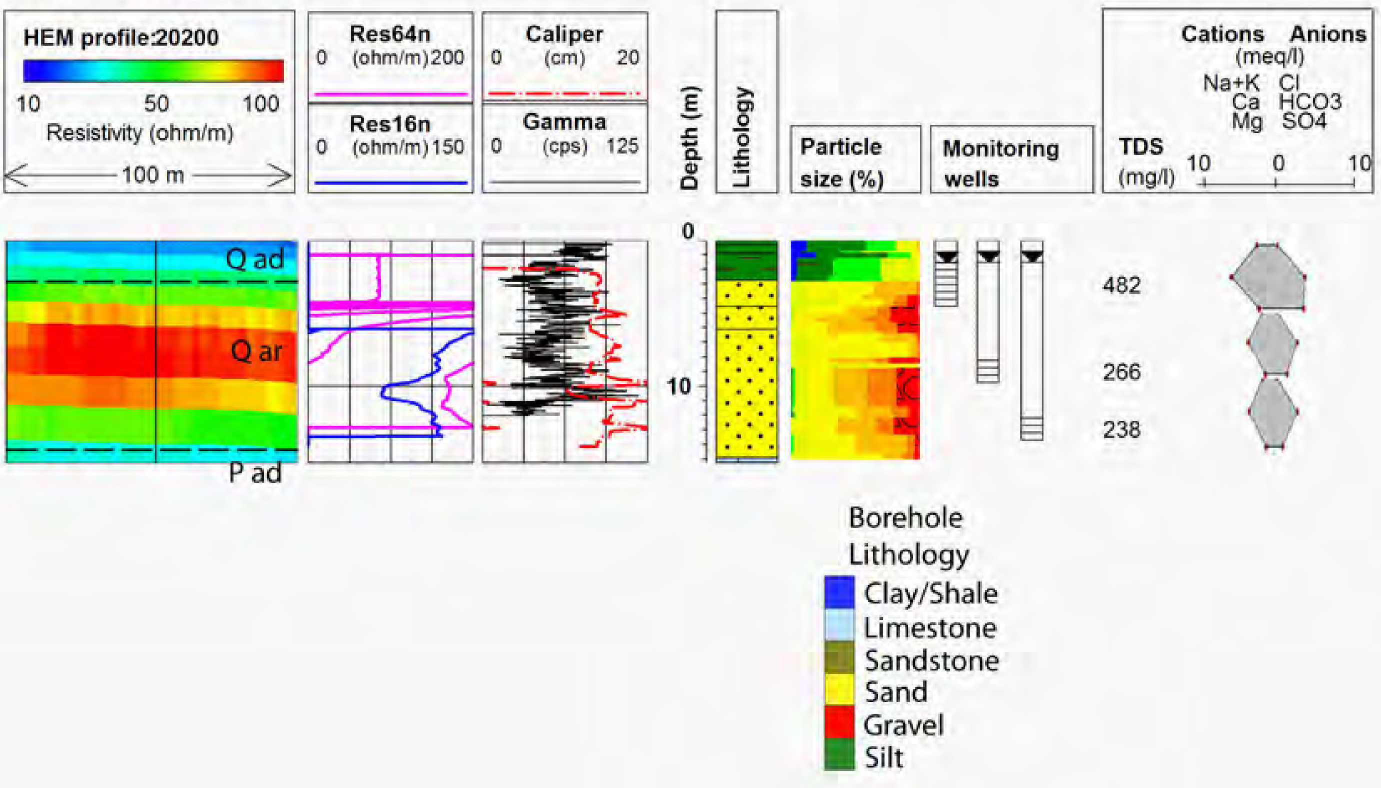

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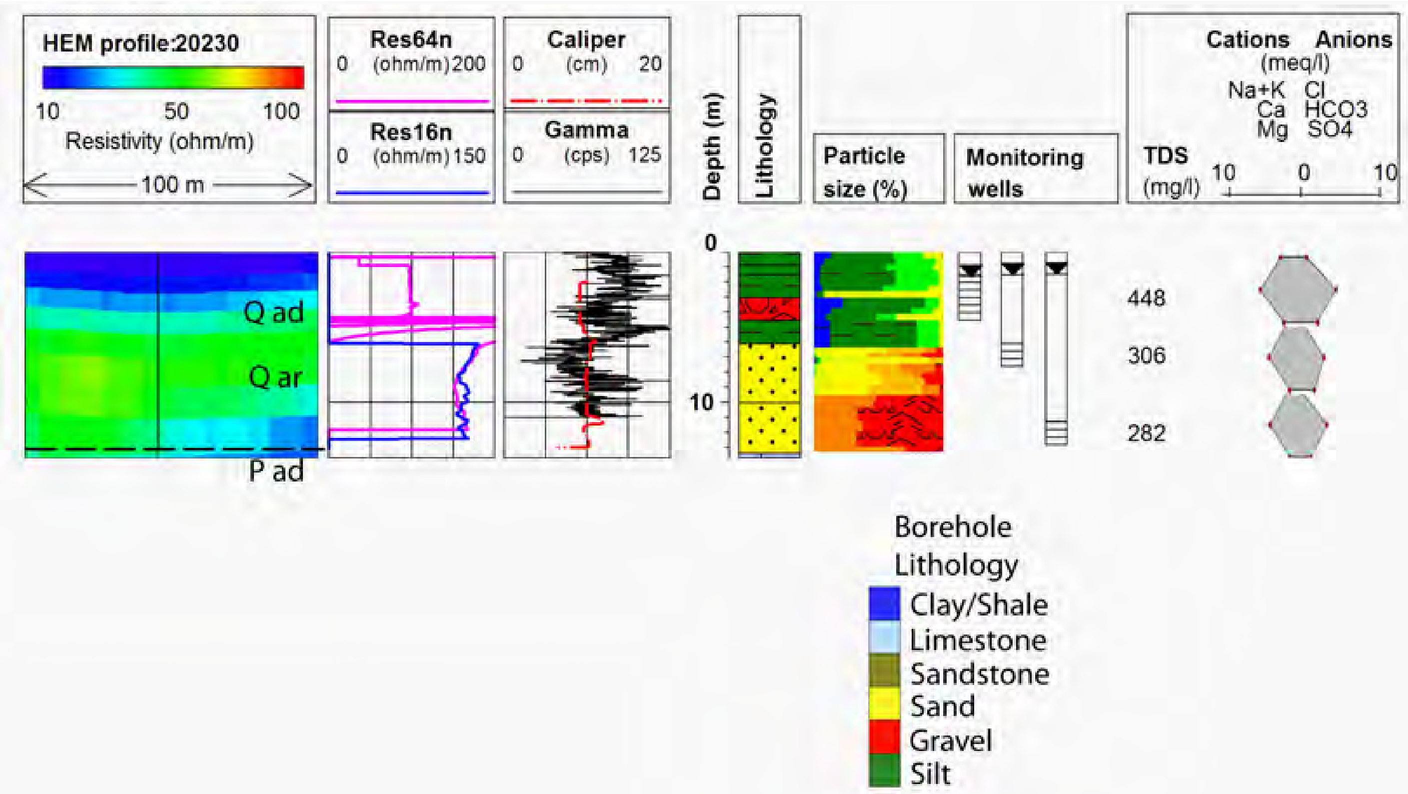

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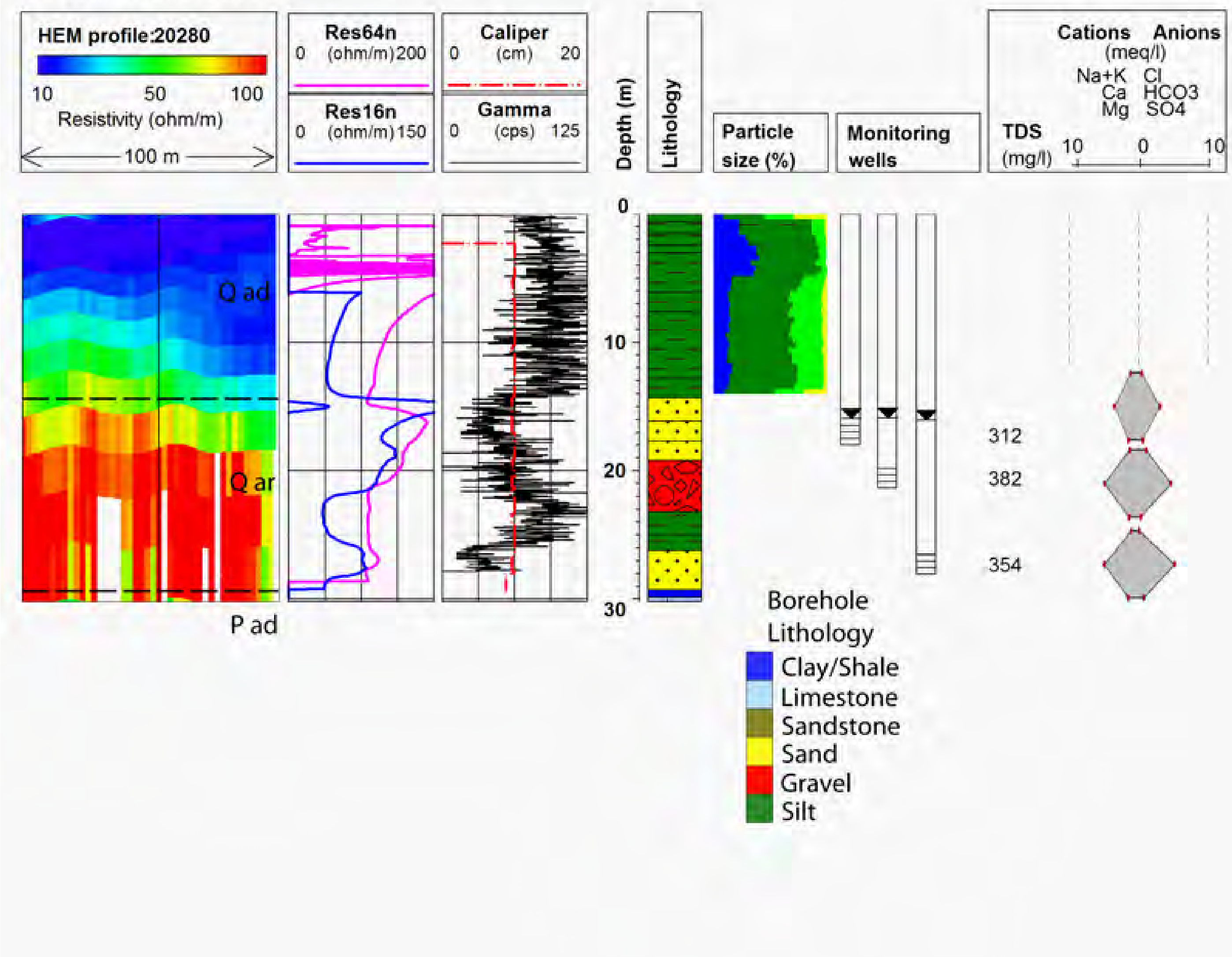

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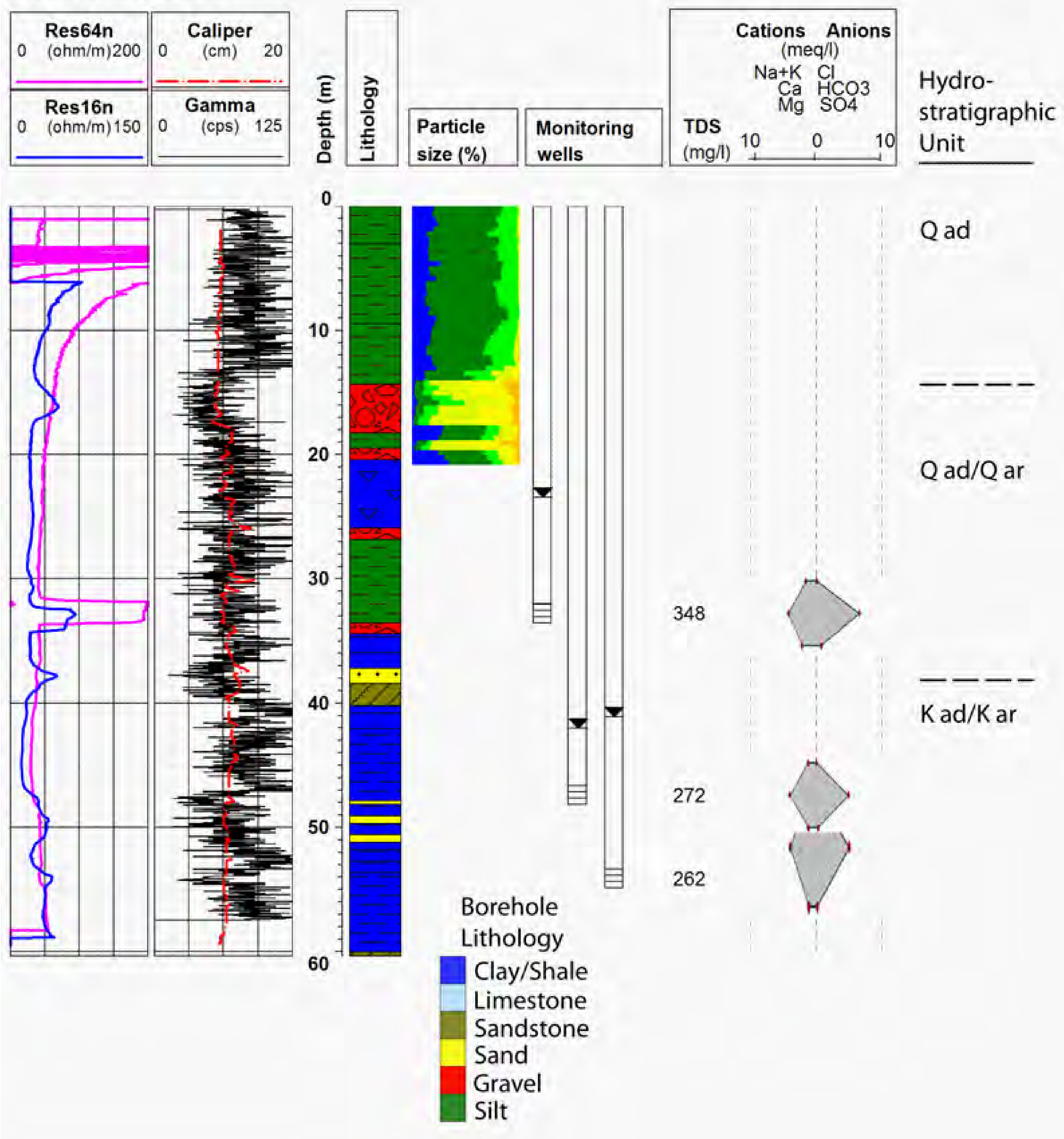

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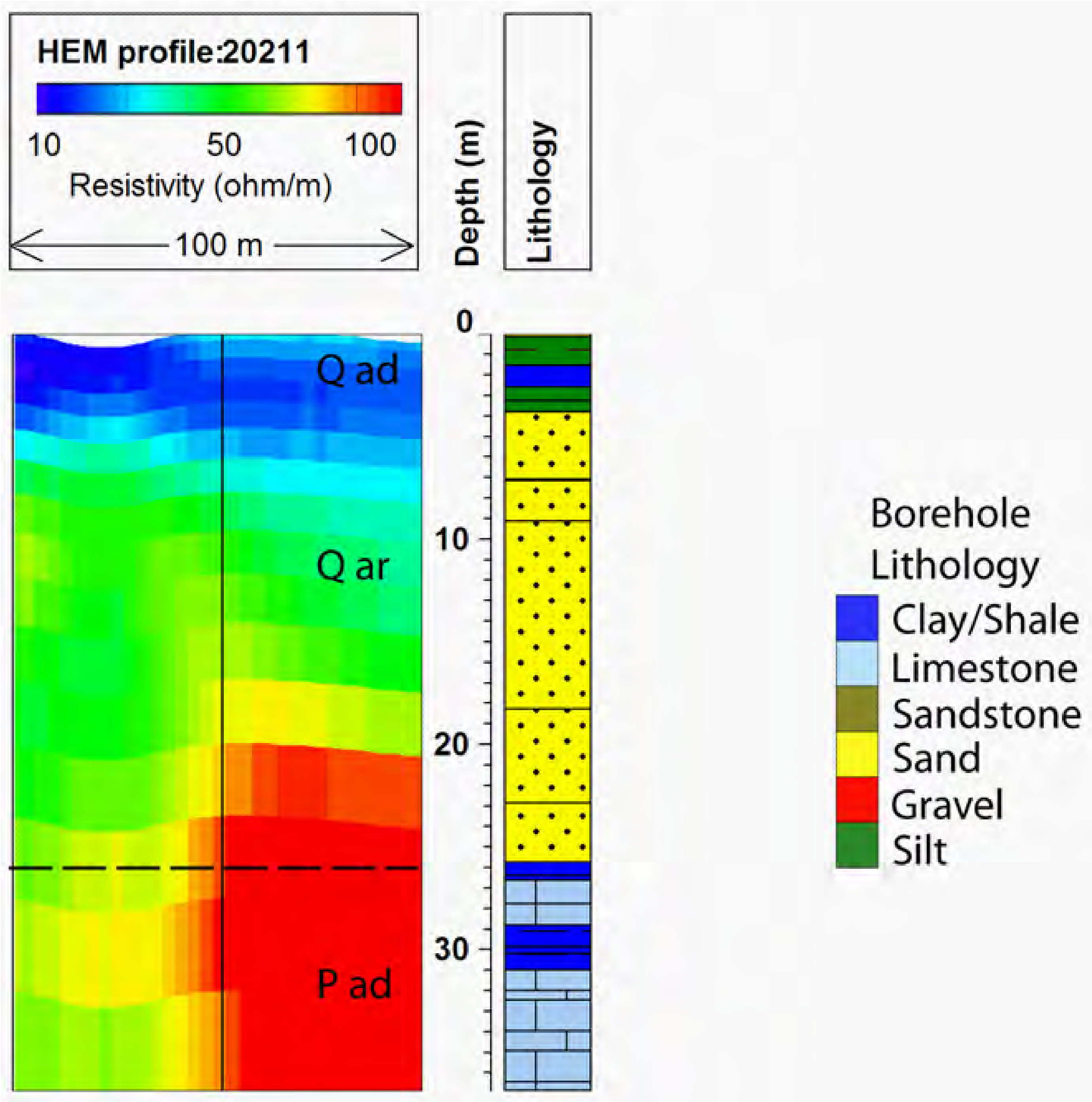

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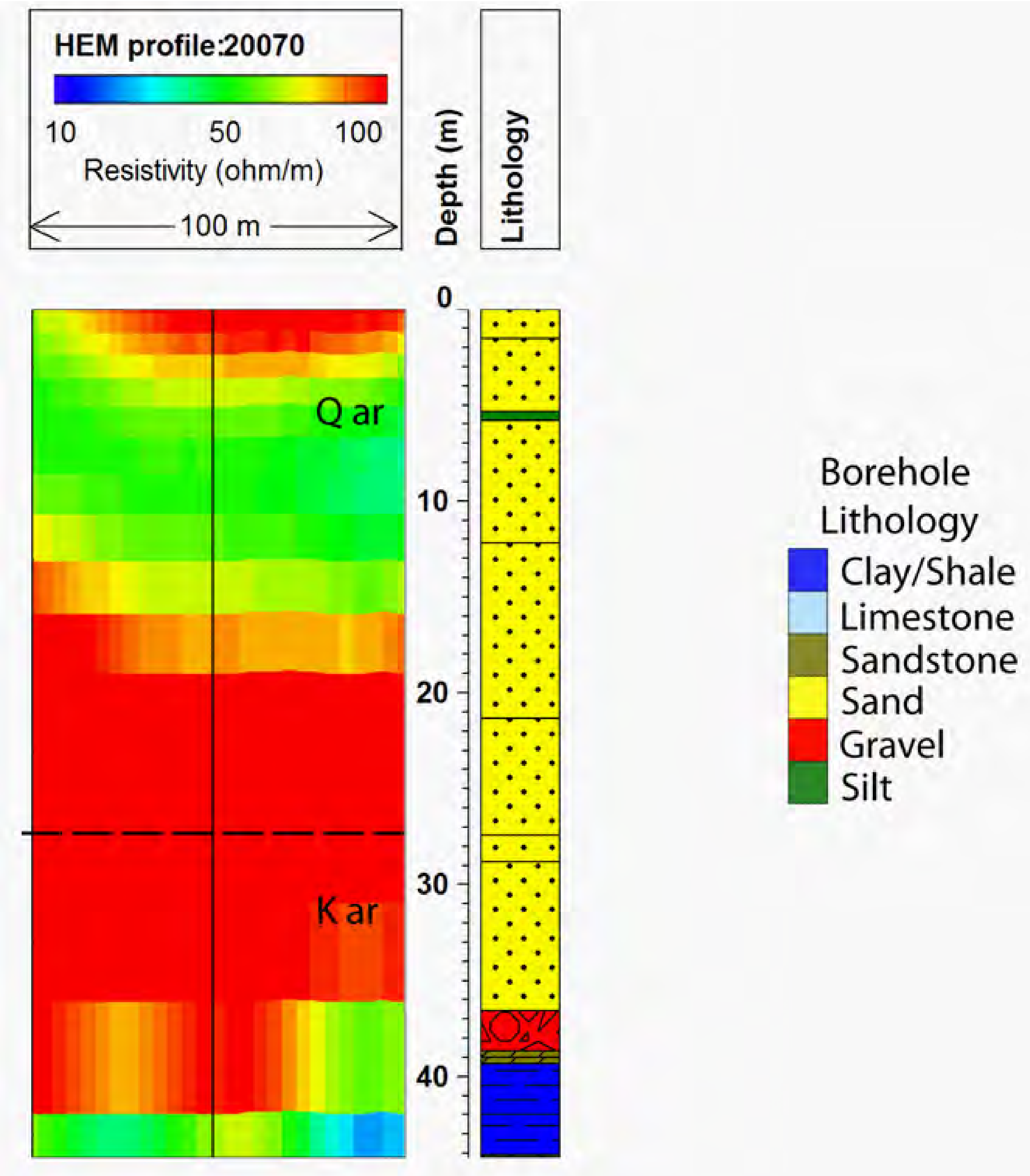

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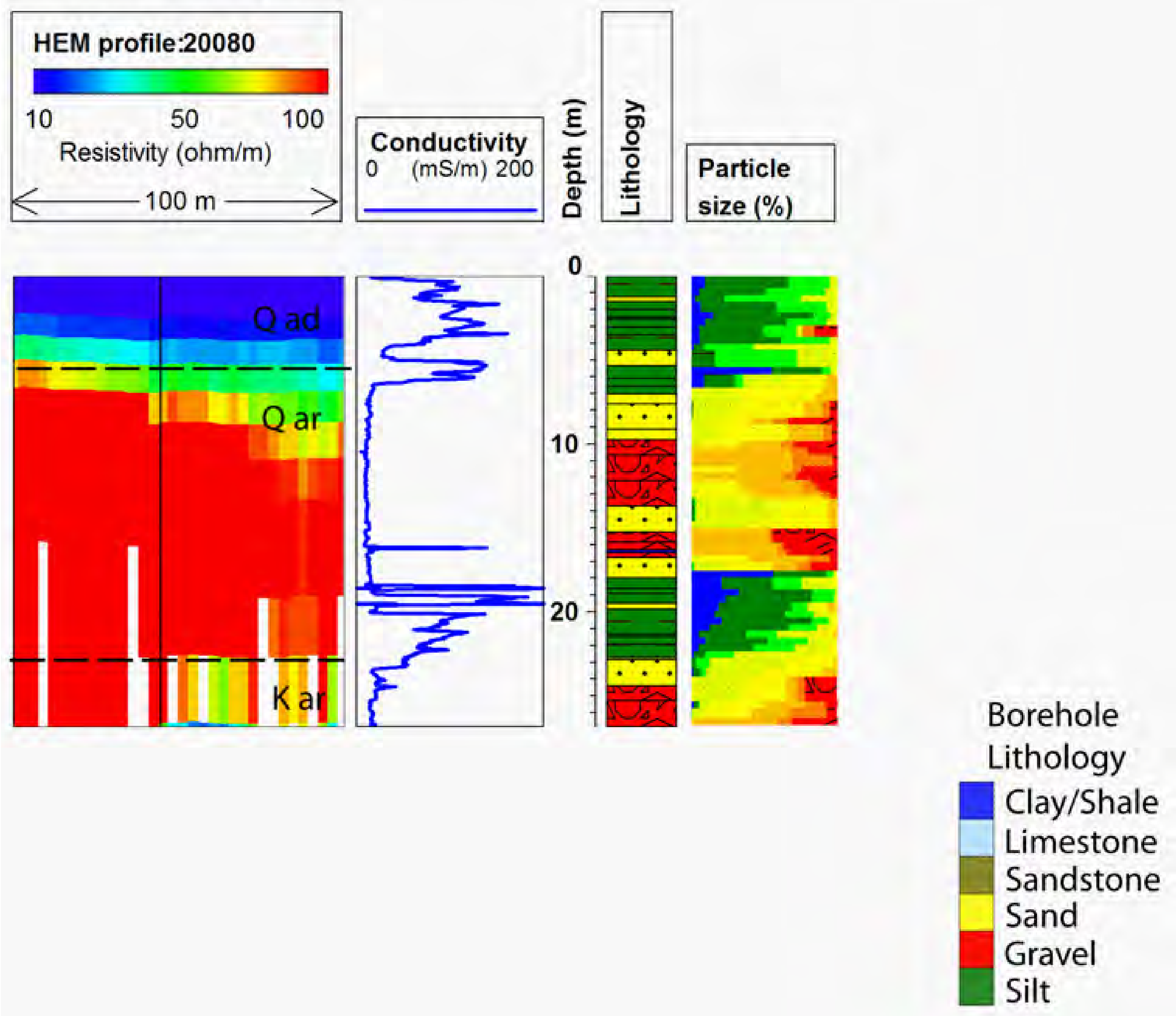

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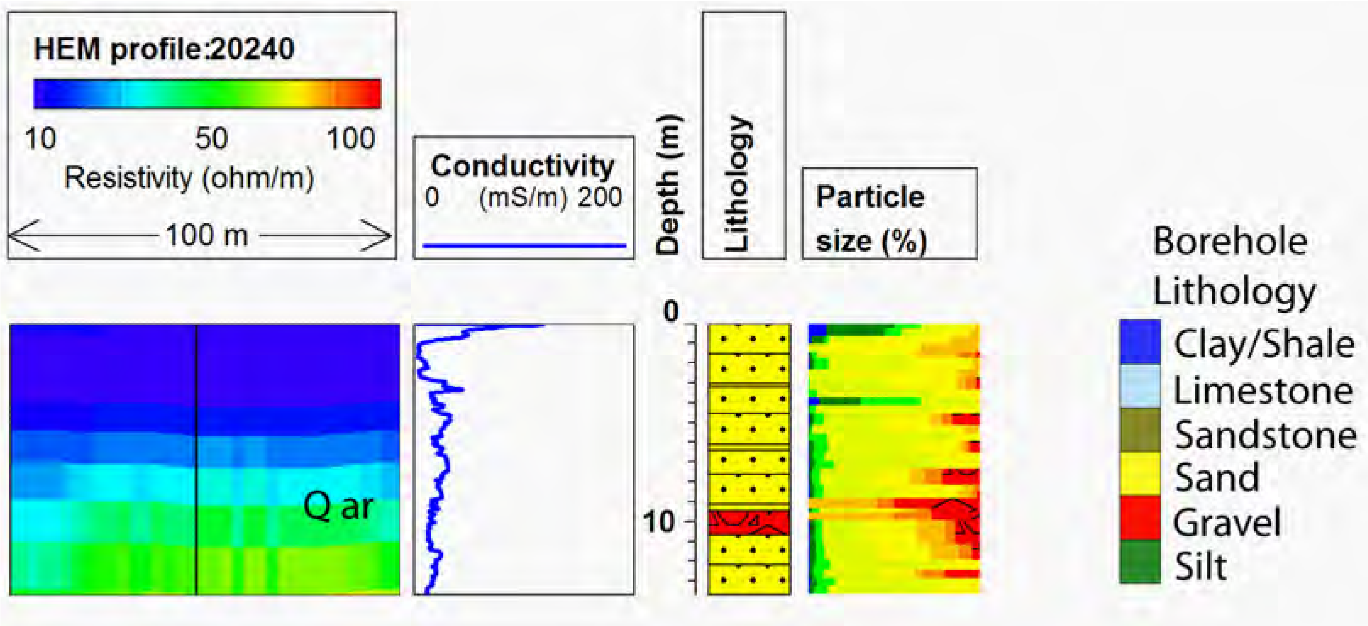

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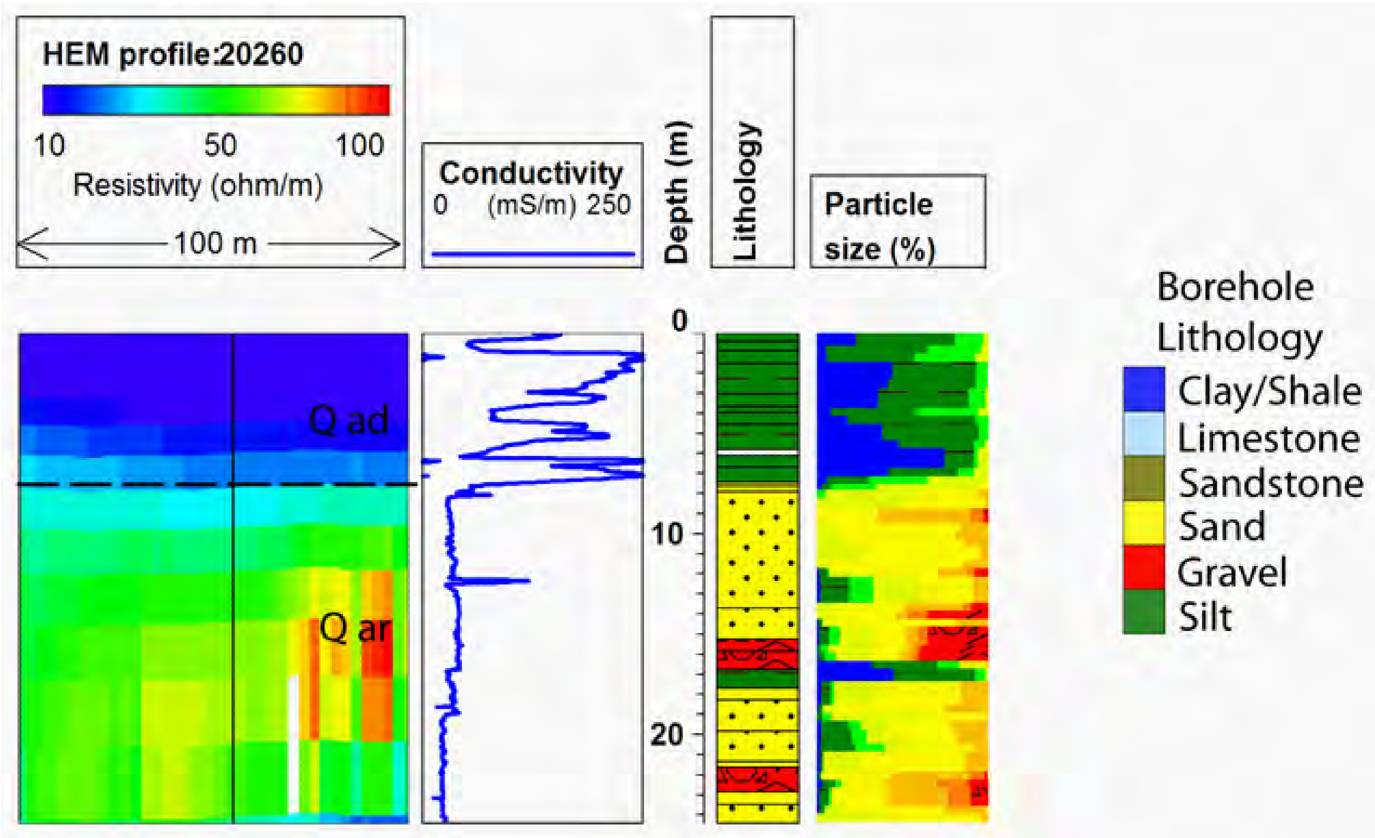

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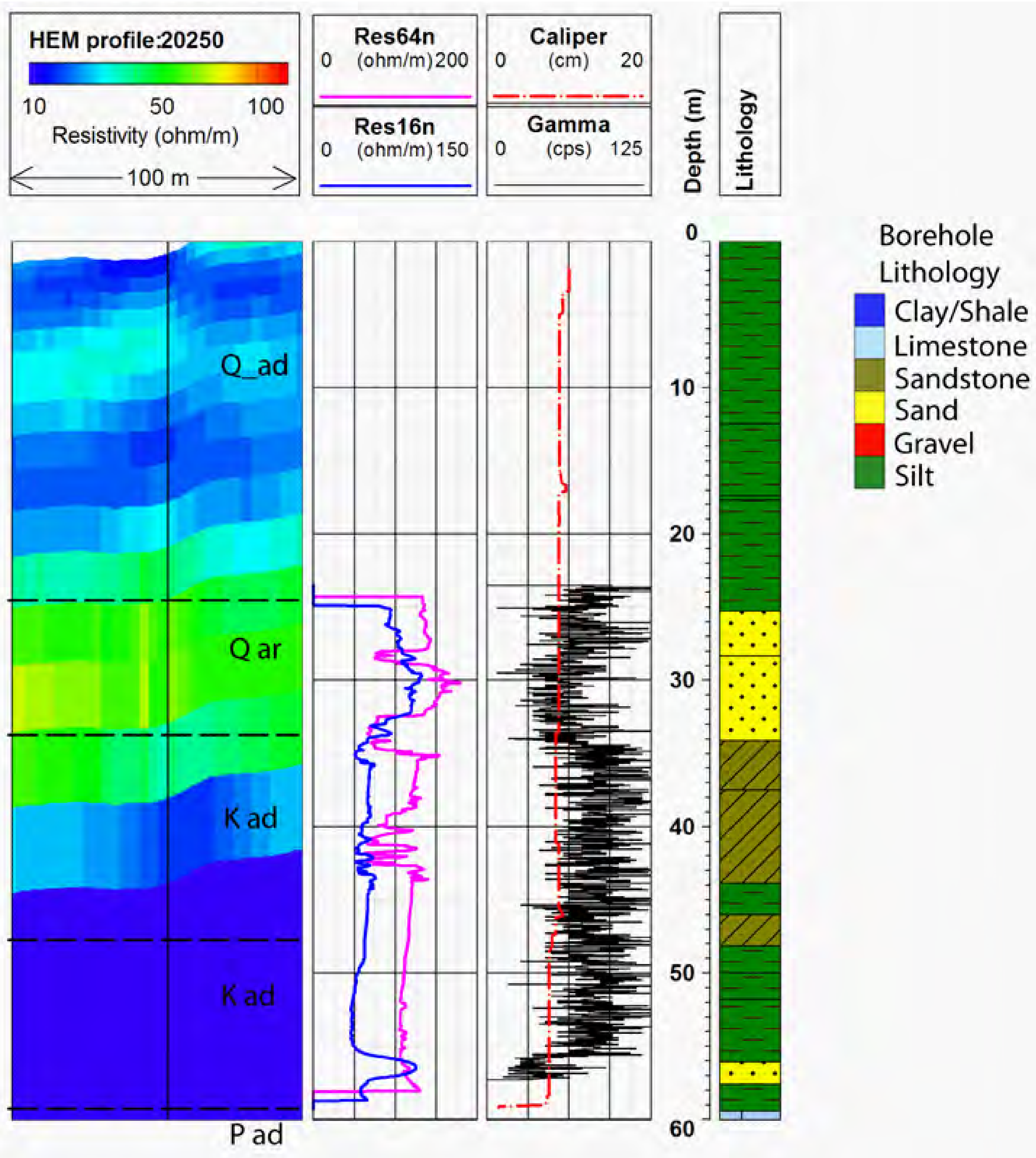

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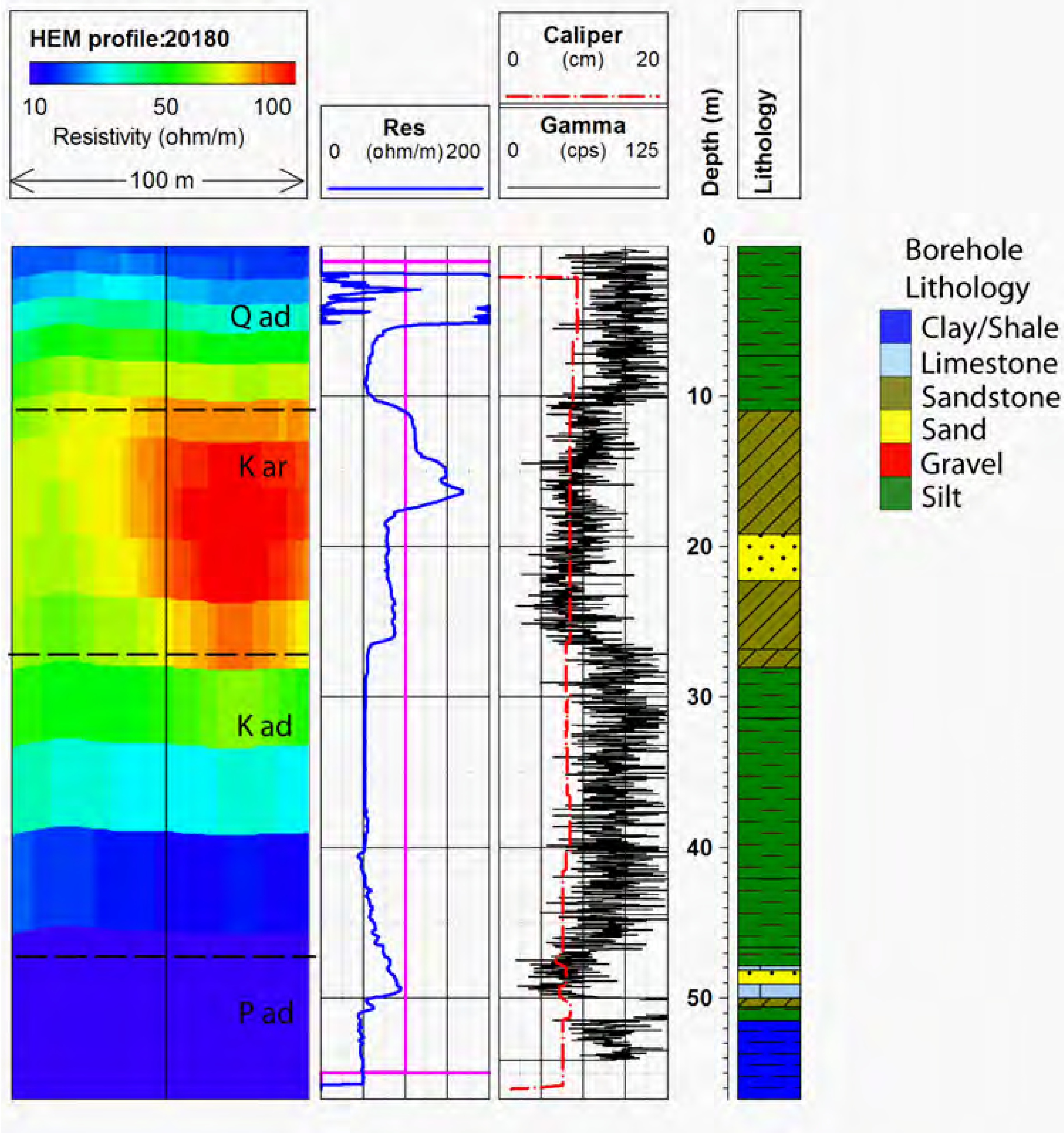

Appendix B

Particle size analysis for Conservation and Survey Division test holes.

Core 01-EN-07

Depth (ft)	Depth (cm)	Clay %	Silt %	Sand %	Gravel %
1.64	50	9	49	42	0
2.95	90	13	51	36	0
4.27	130	4	20	76	0
6.56	200	9	60	31	0
7.87	240	11	58	31	0
9.19	280	4	28	68	0
11.81	360	1	6	93	0
13.12	400	4	27	69	0
14.44	440	56	41	4	0
16.08	490	2	9	89	0
17.39	530	28	53	19	0
18.70	570	10	41	49	0
22.31	680	7	30	63	0
23.62	720	6	35	59	0
24.93	760	3	12	85	0
27.56	840	0	0	97	3
28.87	880	0	0	77	23
30.84	940	0	0	100	0
32.15	980	0	1	90	9
33.46	1020	0	0	76	24
34.78	1060	0	0	91	9
41.34	1260	0	0	100	0
46.59	1420	0	0	97	3
47.90	1460	0	0	89	11
49.21	1500	0	0	89	11
52.49	1600	0	1	89	10
53.81	1640	0	0	86	14
57.41	1750	0	0	19	81
58.73	1790	1	2	97	0
59.71	1820	0	0	99	0
61.02	1860	1	6	92	0
62.34	1900	1	3	94	0
63.65	1940	1	3	94	0

Core 03-EN-07

Depth (ft)	Depth (cm)	Clay %	Silt %	Sand %	Gravel %
0.16	5	14	60	26	0
1.31	40	19	65	16	0
2.62	80	13	67	20	0
3.94	120	20	60	20	0
5.25	160	18	62	20	0
6.56	200	16	62	22	0
11.81	360	19	59	21	0
13.12	400	21	60	19	0
14.44	440	20	68	12	0
17.06	520	19	64	17	0
18.37	560	18	61	21	0
19.69	600	15	60	25	0
21.00	640	14	56	30	0
22.31	680	8	61	31	0
23.62	720	18	56	26	0
24.93	760	17	56	26	0
24.93	760	25	42	33	0
26.25	800	22	59	18	0
27.56	840	24	55	20	0
28.87	880	30	59	11	0
30.18	920	25	60	15	0
31.50	960	20	63	17	0
32.81	1000	17	58	25	0
34.12	1040	12	47	41	0
35.43	1080	14	50	36	0
36.75	1120	17	33	41	9
38.71	1180	25	40	35	0
39.37	1200	32	42	26	0
40.68	1240	30	43	28	0
41.99	1280	26	41	33	0
43.31	1320	28	41	30	0
44.62	1360	26	43	32	0
45.93	1400	32	41	27	0
47.24	1440	26	42	33	0
48.56	1480	28	41	31	0
49.87	1520	30	42	28	0
51.18	1560	28	43	28	0
52.49	1600	27	42	31	0
53.81	1640	29	41	30	0
55.12	1680	29	43	28	0
56.43	1720	28	42	30	0
57.74	1760	29	42	29	0
59.06	1800	31	42	26	0
60.37	1840	28	41	30	0

Core 04-EN-07

Depth (ft)	Depth (cm)	Clay %	Silt %	Sand %	Gravel %
2.30	70	12	46	41	0
2.62	80	7	32	61	0
3.94	120	20	56	24	0
7.87	240	5	28	67	0
9.19	280	3	25	72	0
12.14	370	0	0	100	0
13.45	410	0	0	91	9
14.76	450	0	0	91	9
17.06	520	0	1	77	22
18.37	560	0	0	78	22
20.67	630	0	0	83	17
21.65	660	0	0	99	1
22.97	700	0	0	99	1
26.25	800	0	0	100	0
27.56	840	0	0	76	24
28.54	870	0	0	100	0
37.40	1140	0	1	81	17
38.71	1180	0	1	91	8
39.70	1210	1	2	90	8
43.64	1330	0	0	80	20
47.90	1460	0	0	97	3
49.21	1500	0	0	95	5

Core 05-EN-07

Depth (ft)	Depth (cm)	Clay %	Silt %	Sand %	Gravel %
1.31	40	13	48	38	0
2.62	80	8	55	37	0
3.94	120	5	50	45	0
7.22	220	5	59	37	0
8.53	260	7	48	46	0
9.84	300	2	7	92	0
12.14	370	22	65	13	0
13.45	410	13	62	24	0
14.76	450	9	40	51	0
20.67	630	12	68	20	0
20.67	630	19	62	19	0
21.98	670	0	1	94	5
22.97	700	0	1	83	16
24.28	740	1	3	96	0
24.28	740	1	3	97	0
26.25	800	0	0	94	6
27.56	840	0	1	84	16
28.87	880	0	0	86	14
31.17	950	0	0	97	3
32.48	990	0	0	49	51
33.79	1030	0	0	47	53
36.75	1120	0	0	34	66
37.73	1150	0	0	38	62
39.04	1190	0	0	38	62
42.32	1290	0	0	33	67
43.64	1330	0	0	71	29

Core 06-EN-07

Depth (ft)	Depth (cm)	Clay %	Silt %	Sand %	Gravel %
0.16	5	7	36	57	0
1.31	40	8	37	54	0
5.25	160	22	65	13	0
6.56	200	28	63	9	0
7.87	240	30	61	9	0
10.50	320	38	56	6	0
11.81	360	40	54	6	0
13.12	400	33	57	10	0
14.44	440	37	59	4	0
15.75	480	35	57	8	0
17.06	520	16	64	20	0
18.37	560	16	62	23	0
19.69	600	15	59	26	0
21.00	640	13	55	32	0
22.31	680	13	53	34	0
23.62	720	14	56	29	0
24.93	760	13	54	33	0
26.25	800	13	52	34	0
27.56	840	15	57	28	0
28.87	880	13	55	31	0
30.18	920	14	54	32	0
31.50	960	11	56	33	0
32.81	1000	13	58	30	0
34.12	1040	14	59	27	0
35.43	1080	12	54	34	0
36.75	1120	12	58	30	0
38.06	1160	11	58	31	0
40.68	1240	16	58	26	0
41.99	1280	14	60	26	0
43.31	1320	14	60	26	0
44.62	1360	12	59	29	0
45.93	1400	9	45	46	0

Core 07-EN-07

Depth (ft)	Depth (cm)	Clay %	Silt %	Sand %	Gravel %
1.31	40	20	64	16	0
2.62	80	19	63	18	0
3.94	120	22	56	22	0
5.25	160	24	57	19	0
6.56	200	20	57	23	0
7.87	240	13	58	29	0
10.50	320	16	65	19	0
11.81	360	15	62	23	0
14.44	440	15	64	20	0
15.75	480	27	58	15	0
17.06	520	15	69	16	0
18.37	560	16	66	18	0
19.69	600	22	62	16	0
21.00	640	13	64	23	0
22.31	680	13	66	22	0
23.62	720	14	65	21	0
24.93	760	12	67	21	0
26.25	800	12	69	19	0
27.56	840	17	70	13	0
28.87	880	15	75	10	0
30.18	920	22	66	11	0
31.50	960	21	62	17	0
32.81	1000	19	61	20	0
34.12	1040	18	58	24	0
35.43	1080	17	55	28	0
36.75	1120	17	53	30	0
38.06	1160	13	54	33	0
39.37	1200	13	53	34	0
40.68	1240	18	56	25	0
41.99	1280	19	56	25	0
43.31	1320	22	46	32	0
44.62	1360	11	37	52	0
45.93	1400	12	45	43	0
47.24	1440	3	7	89	0
48.56	1480	2	9	88	0
49.87	1520	2	8	90	0
51.18	1560	3	15	82	0
52.49	1600	5	20	75	0
55.12	1680	3	8	89	0
56.43	1720	1	5	94	0
57.74	1760	1	4	94	0
59.06	1800	29	40	31	0
60.37	1840	27	40	32	0
61.68	1880	25	39	36	0
62.99	1920	4	9	87	0
64.30	1960	2	6	92	0
65.62	2000	24	42	34	0
66.93	2040	30	40	29	0
68.24	2080	34	40	25	0

Core 11-EN-07

Depth (ft)	**Depth** (cm)	**Clay** %	**Silt** %	**Sand** %	**Gravel** %
0.16	5	15	53	32	0
1.31	40	18	62	20	0
2.62	80	22	70	8	0
3.94	120	26	65	9	0
5.25	160	29	61	10	0
6.56	200	27	54	19	0
7.87	240	30	51	18	0
9.19	280	26	55	19	0
10.50	320	30	56	14	0
11.81	360	28	59	13	0
13.12	400	28	59	13	0
14.44	440	28	58	14	0
15.75	480	29	57	14	0
17.06	520	30	58	12	0
18.37	560	24	63	13	0
19.69	600	22	62	17	0
21.00	640	17	55	28	0
22.31	680	5	16	78	0
25.59	780	2	5	68	25
26.25	800	14	41	45	0
27.56	840	12	33	55	0
30.18	920	14	33	53	0
31.50	960	14	38	48	0
32.81	1000	16	56	27	0
34.12	1040	22	63	15	0
35.43	1080	18	61	22	0
36.75	1120	13	60	27	0
38.06	1160	12	61	27	0
40.68	1240	12	49	39	0
45.60	1390	9	24	67	0
46.59	1420	10	29	61	0

Core 12-EN-07

Depth (ft)	Depth (cm)	Clay %	Silt %	Sand %	Gravel %
0.16	5	20	61	19	0
1.31	40	27	50	22	0
2.62	80	27	49	24	0
3.94	120	34	38	29	0
5.25	160	38	33	29	0
6.56	200	29	37	33	0
7.87	240	30	37	34	0
9.19	280	36	39	25	0
10.50	320	26	36	38	0
13.12	400	9	25	66	0
14.44	440	2	6	91	0
18.37	560	3	6	90	0
19.69	600	2	4	93	0
21.00	640	10	29	62	0
22.31	680	30	44	27	0
23.62	720	32	41	27	0
24.93	760	11	57	33	0
26.25	800	12	71	17	0
27.56	840	12	70	18	0
28.87	880	7	20	74	0
30.18	920	8	64	27	0
31.50	960	41	36	23	0
32.81	1000	31	38	31	0
34.12	1040	32	39	29	0
35.43	1080	28	35	33	4
32.81	1000	32	38	30	0
36.75	1120	28	38	34	0
38.06	1160	31	39	29	0
39.37	1200	32	40	28	0
40.68	1240	25	32	37	7
41.99	1280	32	40	29	0
43.31	1320	31	41	28	0
44.62	1360	29	41	30	0
45.93	1400	22	25	44	9
47.24	1440	9	56	35	0
48.56	1480	7	63	31	0
52.49	1600	4	32	64	0
53.81	1640	9	51	40	0
56.43	1720	18	79	3	0
57.74	1760	12	36	52	0
59.06	1800	5	20	75	0

Core 17-EN-07

Depth (ft)	Depth (cm)	Clay %	Silt %	Sand %	Gravel %
3.61	110	6	46	48	0
4.92	150	3	20	77	0
6.89	210	6	52	42	0
8.20	250	15	68	16	0
9.51	290	10	56	34	0
11.81	360	6	44	35	15
13.12	400	6	55	39	0
14.44	440	1	7	91	0
17.72	540	0	16	84	0
19.03	580	55	35	10	0
21.65	660	9	21	70	0
22.97	700	0	0	100	0
24.28	740	0	0	100	0
27.56	840	0	1	94	5
28.87	880	0	0	67	33
32.15	980	0	0	97	3
33.46	1020	0	0	70	30
34.78	1060	0	0	80	20
37.07	1130	0	0	97	3
38.39	1170	0	0	75	25
39.70	1210	0	0	72	28
40.68	1240	0	0	83	17
41.99	1280	0	0	88	12
43.31	1320	0	0	96	4
47.90	1460	0	2	98	0
49.21	1500	0	0	100	0
51.84	1580	0	0	56	44
53.15	1620	0	0	63	37
54.46	1660	0	0	66	34
55.77	1700	0	0	95	5
57.41	1750	0	1	81	18
58.73	1790	56	37	7	0
61.02	1860	21	35	44	0
62.34	1900	33	51	17	0
63.65	1940	24	59	17	0
65.29	1990	19	50	31	0
66.60	2030	16	48	35	0
67.91	2070	21	62	17	0
69.23	2110	13	54	34	0
70.54	2150	5	32	63	0
71.85	2190	10	43	47	0
73.16	2230	5	38	57	0
74.48	2270	1	8	91	0
76.44	2330	0	3	97	0
78.08	2380	1	5	94	0
83.01	2530	0	0	78	22
84.32	2570	1	4	87	8
86.29	2630	0	1	93	7
87.60	2670	0	0	69	31

Core 18-EN-07

Depth (ft)	Depth (cm)	Clay %	Silt %	Sand %	Gravel %
0.66	20	11	40	49	0
1.97	60	11	34	55	0
3.28	100	2	8	90	0
4.59	140	0	0	100	0
5.58	170	1	2	96	2
7.55	230	1	3	96	0
8.86	270	0	0	100	0
10.83	330	0	0	98	2
12.14	370	0	0	100	0
13.45	410	6	24	69	0
14.76	450	0	1	99	0
16.73	510	1	3	80	16
18.04	550	0	2	98	0
19.36	590	0	1	99	0
21.33	650	1	3	91	5
22.64	690	1	2	97	0
23.95	730	1	3	96	0
26.57	810	1	2	76	21
27.56	840	1	3	96	0
28.87	880	1	3	95	1
30.51	930	0	0	50	50
31.17	950	1	2	69	29
32.48	990	0	0	72	28
36.42	1110	1	3	81	14
39.04	1190	1	4	91	4
40.68	1240	1	3	96	0
41.99	1280	1	3	77	20
43.31	1320	2	4	95	0
44.62	1360	1	3	97	0

Core 19-EN-07

Depth (ft)	**Depth** (cm)	**Clay** %	**Silt** %	**Sand** %	**Gravel** %
1.97	60	23	58	19	0
3.28	100	6	59	35	0
4.59	140	6	51	43	0
7.55	230	44	49	6	0
8.86	270	42	52	7	0
12.14	370	36	53	11	0
13.45	410	9	50	42	0
14.76	450	18	74	7	0
17.39	530	38	56	5	0
18.70	570	48	44	8	0
21.98	670	74	18	8	0
23.29	710	42	40	17	0
24.61	750	6	25	69	0
25.59	780	3	6	91	0
26.90	820	0	0	100	0
28.54	870	0	0	100	0
30.84	940	0	0	98	2
32.15	980	0	0	100	0
33.46	1020	0	0	100	0
34.78	1060	0	0	100	0
37.07	1130	0	0	100	0
38.39	1170	0	0	100	0
39.70	1210	2	5	86	7
43.96	1340	2	17	81	0
45.28	1380	0	0	91	9
46.59	1420	0	0	65	35
47.90	1460	1	2	96	0
50.85	1550	2	6	57	35
52.17	1590	1	2	58	39
53.48	1630	1	4	54	41
54.79	1670	32	38	30	0
56.76	1730	45	48	7	0
60.70	1850	3	6	92	0
62.01	1890	1	2	96	0
63.32	1930	0	3	97	0
64.63	1970	3	16	81	0
66.93	2040	3	18	79	0
68.24	2080	2	21	77	0
71.52	2180	2	2	96	0
72.83	2220	1	1	96	2
74.15	2260	3	8	77	12
77.10	2350	2	5	83	10
78.41	2390	2	3	95	0
79.72	2430	0	0	100	0

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