Ground Water Monitoring&Remediation

# Direct-Push Electrical Conductivity Logging for High-Resolution Hydrostratigraphic Characterization

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## Abstract

Fine-scale hydrostratigraphic features often play a critical role in controlling ground water flow and contaminant transport. Unfortunately, many conventional drilling- and geophysics-based approaches are rarely capable of describing these features at the level of detail needed for contaminant predictions and remediation designs. Previous work has shown that direct-push electrical conductivity (EC) logging can provide information about site hydrostratigraphy at a scale of relevance for contaminant transport investigations in many unconsolidated settings. In this study, we evaluate the resolution and quality of that information at a well-studied research site that is underlain by highly stratified alluvial sediments. Geologic and hydrologic data, conventional geophysical logs, and particle-size analyses are used to demonstrate the capability of direct-push EC logging for the delineation of fine-scale hydrostratigraphic features in saturated unconsolidated formations. When variations in pore-fluid chemistry are small, the electrical conductivity of saturated media is primarily a function of clay content, and hydrostratigraphic features can be described at a level of detail (<2.5 cm in thickness) that has not previously been possible in the absence of continuous cores. Series of direct-push EC logs can be used to map the lateral continuity of layers with non-negligible clay content and to develop important new insights into flow and transport at a site. However, in sand and gravel intervals with negligible clay, EC logging provides little information about hydrostratigraphic features. As with all electrical logging methods, some site-specific information about the relative importance of fluid and sediment contributions to electrical conductivity is needed. Ongoing research is directed at developing direct-push methods that allow EC logging, water sampling, and hydraulic testing to be done concurrently.


## Introduction

Hydrogeologic investigations are often hampered by insufficient information about the site-specific hydrostratigraphic features that control ground water flow and solute transport. Field and modeling studies in a wide variety of geologic settings have shown the importance of a detailed description of aquifer heterogeneity for applications ranging from prediction of contaminant transport (Sudicky and Huyakorn 1991) to design of effective remediation schemes (National Research Council 1994; Hyndman et al. 2000) to assessment of stream-aquifer interactions (Butler et al. 2001). Although numerous studies have demonstrated the critical role played by fine-scale hydrostratigraphic features, information about such features is usually quite limited. In this paper, we examine an approach that has the potential to characterize hydrostratigraphic features at a level of detail that has rarely been possible in routine field investigations.

Geologic logs and wellbore-geophysical methods are common sources of detailed information about site hydrostratigraphy. These approaches, however, are limited in their ability to resolve fine-scale features. Although the quality of geologic logs varies greatly with drilling technology and logging personnel, small-scale features are difficult to detect without the collection of continuous cores. High-resolution wellbore geophysical methods (e.g., microresistivity logging) have been developed for use in consolidated materials. Most logging tools for unconsolidated formations, however, have large averaging volumes and thus are of limited effectiveness for the detection of fine-scale features. In addition, data from high-resolution wellbore logging methods are often biased by irregular borehole diameter and drilling fluids. Moreover, cost considerations typically result in a well spacing that is inadequate for the detailed characterization of heterogeneous systems. Surface-based geophysical methods overcome the restrictions imposed by well spacing, but are rarely capable of high-resolution characterization of heterogeneous sequences in a nonresearch context. Cone penetrometer technology (CPT) provides high-resolution records of geotechnical properties of unconsolidated materials that can be related to sediment type through empirical relationships (Lunne et al. 1997). Although CPT equipment has been augmented in recent years with a variety of sensors for contaminant transport investigations (Lieberman 2000; Shinn 2000; Kram et al. 2001), operating costs hinder its widespread use. Thus, as Huggenberger and Aigner (1999), among others, have pointed out, many features of hydrostratigraphic relevance continue to remain unrecognized in the vast majority of contaminant-transport investigations.

The approach described in this paper uses a direct-push electrical conductivity (EC) probe to characterize hydrostratigraphic features in unconsolidated formations at a scale of relevance for contaminant transport investigations. This probe, which was developed in the mid-1990s (Christy et al. 1994), allows information to be obtained at a vertical resolution (0.02 m; Geoprobe Systems 1998) that has not been possible using most conventional methods in unconsolidated formations. By coupling the EC probe with a mobile direct-push unit, information can be obtained at a lateral spacing that is not feasible in most investigations using methods that require wells or core holes. Several recent applications (McCall 1996; Johnson et al. 1999; Beck et al. 2000; McCall and Zimmerman 2000; Einarson et al. 2000) and technology assessments (U.S. EPA 2000) have demonstrated the utility of this approach for investigations at sites of ground water contamination. Although many of these studies have used logs of electrical conductivity to enhance understanding of subsurface stratigraphy, none have focused on the resolution and quality of the information that may be obtained using EC logging. The investigation of that issue was the major objective of the work described here.

This paper will focus on the use of direct-push EC logging to resolve fine-scale hydrostratigraphic features in saturated unconsolidated formations. The paper begins with a short discussion of factors that control the electrical conductivity of unconsolidated sediments. The details of the direct-push EC sensor are then briefly discussed, after which the field area that was the site of the majority of the work is described. The quality and resolution of information obtained from direct-push EC logging is assessed using geologic and hydrologic data, logs obtained with conventional geophysical tools, and results of particle-size analyses. The potential of the approach for developing significant new insights into ground water flow at a site is then demonstrated. The paper concludes with a discussion of some important considerations for direct-push EC logging and a summary of the major findings of the investigation.

## Background

### Electrical Conductivity in Unconsolidated Sediments

The electrical conductivity of unconsolidated materials is a function of the moisture content of the material and the conducting properties of the pore fluids and sediments (Schon 1996). In the saturated zone, where variations in moisture content are small, fluid and matrix properties are the major factors. In formations where variations in ground water chemistry are small, differences in sediment size and type are the dominant control on electrical conductivity (Keys 1990). The electrical conductivity associated with sedimentary materials varies with particle size and mineral species. Silt- and sand-sized particles of covalently bonded minerals, such as quartz, mica, and feldspar, are generally nonconductive. For this reason, electrical conductivity in sand and gravel aquifers primarily reflects variations in concentrations of dissolved constituents. Clay-sized particles, such as phyllosilicates, humic substances, and iron and manganese oxides and oxyhydroxides, tend to be highly conductive due to their extremely small size, relatively high surface area per unit volume, and charge characteristics (Langmuir 1997). Thus, in formations where clay-sized particles are present, both lateral and vertical variations in lithology may be assessed using EC logs. The direct-push implementation of this principle is a major theme of this paper.

### Direct-Push EC Logging

Direct-push EC logging is similar to other electrical logging methods in which the apparent electrical conductivity of an interval is calculated as an imposed current passes through it. However, the direct-push method does not require a preexisting well or borehole. Thus, high-resolution information can be obtained without the bias produced by borehole fluids or changes in borehole diameter. In direct-push EC logging, a sensor attached to the end of a steel pipe is driven into the subsurface using a percussion hammer and a hydraulic slide (Figure 1). The sensor configuration evaluated in this study consists of a four-electrode Wenner array with an inner-electrode spacing of 0.02 m (Figure 1). As the EC probe is advanced, a current is applied to the two outer electrodes and voltage is measured across the two inner electrodes. Given the applied current and the measured voltage, electrical conductivity is calculated to produce a log of electrical conductivity versus depth. The small electrode spacing allows the sensor to resolve thin units and sample a small lateral radius (5 to 10 cm; Beck et al. 2000). Data are collected every 0.015 m and a potentiometer mounted on the mast of the direct-push unit tracks the depth and speed of advancement of the probe. Upon retrieval of the EC tool and rods, the uncollapsed portion of the probe hole is grouted by injecting a bentonite slurry. In this study, a two-person team routinely completed EC logs to depths of 20 to 30 m within two hours (time includes grouting).

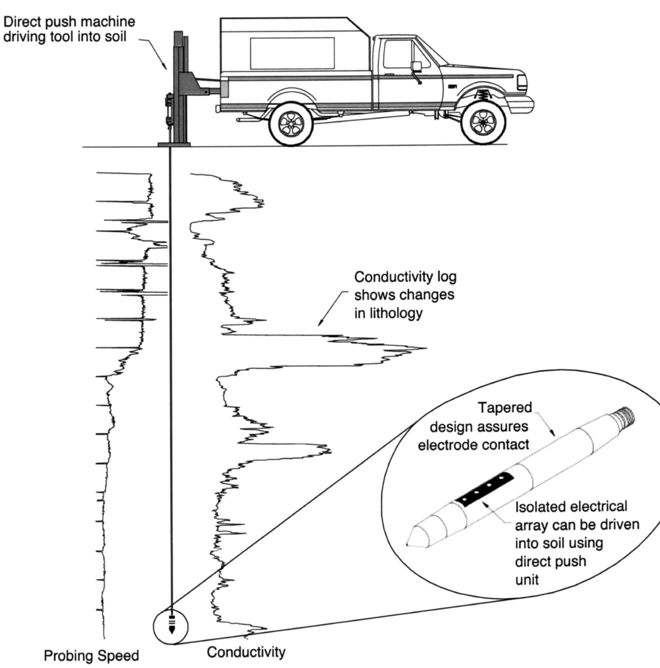

**Figure 1. Schematic of direct-push electrical conductivity logging (after Geoprobe Systems 1998).**

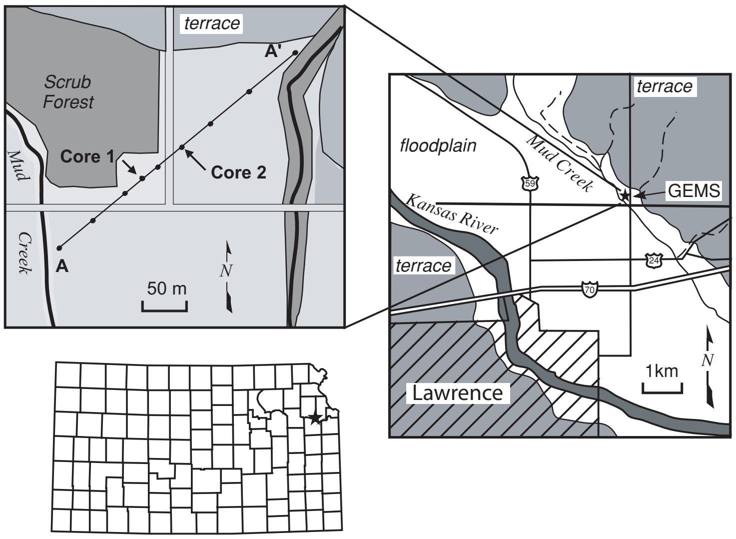


**Figure 2. Location of the Geohydrologic Experimental and Monitoring Site (GEMS). Locations of EC logs indicated by black dots.**

## Study Site

This direct-push approach was evaluated at a Kansas Geological Survey (KGS) research site at which hydrostratigraphic features are known to exert an important influence on ground water flow and solute transport (Butler et al. 1998, 2002; Bohling 1999; Schulmeister 2000). This site, the Geohydrologic Experimental and Monitoring Site (GEMS), is on the Kansas River floodplain, northeast of Lawrence, Kansas (Figure 2). The unconsolidated sequence underlying GEMS consists of ~22 m of alluvial sediments (Figure 3). The upper 11 m are predominantly silt and clay, with discontinuous layers of fine to medium sand at several depths. The lower 11 m contain a fining-upward sequence of pebbles to fine sand, with less permeable material distributed as discontinuous lenses. The specific conductance of ground water is between 70 and 90 mS/m in the silt and clay, and 50 and 80 mS/m in the sand and gravel (Schulmeister 2000; Schulmeister et al. 2001). Assuming an aquifer porosity of 30%, this small range in fluid conductivity would cause minimal variations in electrical conductivity, and thus can be ignored for purposes of this investigation. Relatively uniform fluid conductivity combined with the highly stratified nature of the alluvium make GEMS an ideal site for evaluating the resolution of direct-push EC logging.

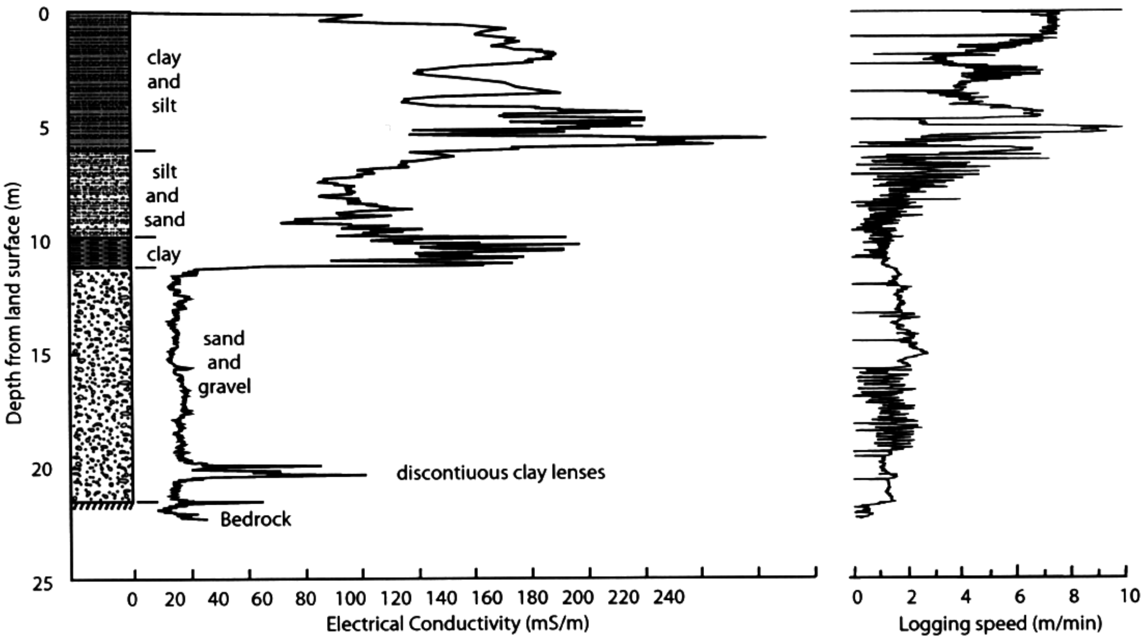


**Figure 3. Generalized geologic description of the unconsolidated sequence at GEMS and typical EC and drive-speed logs. Variations in the EC log are consistent with geologic interpretations made from previously collected core and logging data (Jiang 1991; McElwee and Butler 1995; Butler et al. 1999). Note that a reduction in logging speed occurs near the bedrock boundary (spikes to zero on speed log mark points at which logging was stopped to add pipe, etc.).**

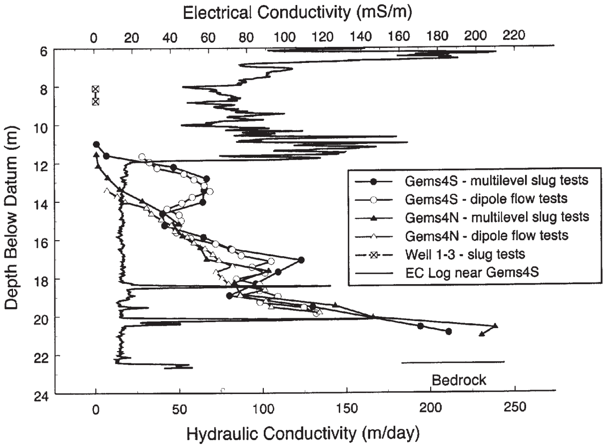


**Figure 4. EC log and hydraulic conductivity estimates based on multilevel slug tests and dipole flow tests conducted in the sand and gravel interval (Butler et al. 1998) and slug tests in the silt-sand interval at GEMS (Butler et al. 2002).**

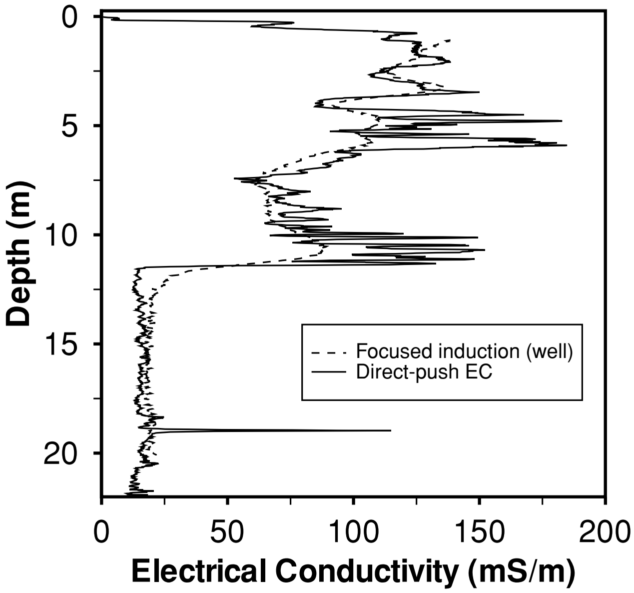


**Figure 5. Conventional focused-induction log and direct-push EC log collected from well and push locations, respectively, separated by less than 1.2 m. The smoothed nature of the induction log is a result of the larger sampling volume of that tool.**

## Evaluation of Direct-Push EC Data

### Comparison to Geologic and Hydrologic Data

The relevance of information obtained with direct-push EC logs can be assessed by comparing them to geologic data collected previously at GEMS. An example direct-push EC log taken near the center of GEMS is in general agreement with previous geologic interpretations for the site (Figure 3). The higher EC values in the upper 11 m of the profile are consistent with observations of silt and clay in that section of the alluvium (McElwee and Butler 1995). Sharp lithologic contrasts at ~7 and 11 m are denoted by abrupt changes in EC. The jagged profile in the upper 11 m implies the presence of sedimentary layers with differing amounts of electrically conductive material. The lower magnitude and variability of the EC log below 11 m suggests an absence of electrically conductive material, as would be expected in a sand and gravel interval. The high EC spikes observed near 20 m coincide with core intervals in which sieve analyses yielded higher proportions of fine-grained sediments (Jiang 1991).

The direct-push EC logs are also consistent with previously collected hydrologic data at GEMS. For example, the high EC interval indicated between 10 and 11 m in Figure 3 coincides with a zone over which a vertical head difference of >0.9 m occurs, and which has been identified as clay in core samples. In addition, hydraulic conductivity estimates from slug tests in the interval between 8 and 9 m (0.6 m/day) are consistent with the finer-textured lithology implied by the EC log, and are lower than hydraulic conductivity estimates from slug tests in the underlying sand and gravel (25 to >200 m/day) (Figure 4). Although vertical profiles of hydraulic conductivity from tests in the sand and gravel interval are consistent with the pronounced fining-upward grain size observed in core data (Jiang 1991), EC logs do not reflect such variations, demonstrating the inability of EC logging to resolve textural variations within coarse-grained units. Despite this limitation, direct-push EC logging does allow differentiation between sand and clay intervals, and thus can provide relevant information for geologic and hydrologic investigations in unconsolidated formations.

### Comparison to Other Geophysical Logs

Focused-induction and natural-gamma logging are two widely used conventional geophysical logging techniques for differentiating sand and clay intervals (Keys 1990). Further insight into the value of direct-push EC logging can therefore be obtained by comparing EC logs to focused-induction and natural-gamma logs from wells adjacent to direct-push locations. Although the direct-push EC and focused-induction tools are expected to respond in a similar manner to the presence of electrically conductive materials, differences were observed in the logs produced with these tools due to dissimilar volumes of investigations. Because the volume of investigation for an induction tool is dependent on the coil spacing, only those layers with a thickness greater than the coil spacing will be fully resolved by the tool. The induction tool used in this study, which is typical of those commonly used in ground water investigations, has a coil spacing of 1.52 m and focuses on the zone between 0.25 and 1.27 m from the center of the well (Century Geophysical Corp. 2001). This greater averaging volume causes the induction log to appear as a smoothed replica of the direct-push EC log at GEMS (Figure 5). The lithologic boundary at 11 m, which is seen as a sharp change in the direct-push log, appears as a gradual change in the induction log. High-conductivity zones observed at 2, 3, 5, and 10 m in the direct-push EC profile appear in the induction log as subdued peaks. The thin conductive layer at 19 m was observed in the direct-push log, but not in the induction log. The highest conductivity recorded in the direct-push log is between 4 and 6 m, while the highest values are in the upper 3 m for the induction log. Based on the focused-induction log, one might assume that the clay content of the upper 11 m of the formation decreases with depth and not recognize the importance of the clay unit between 10 and 11 m. Such potential misinterpretations and oversights are a direct result of the larger averaging volume used in the induction tool.

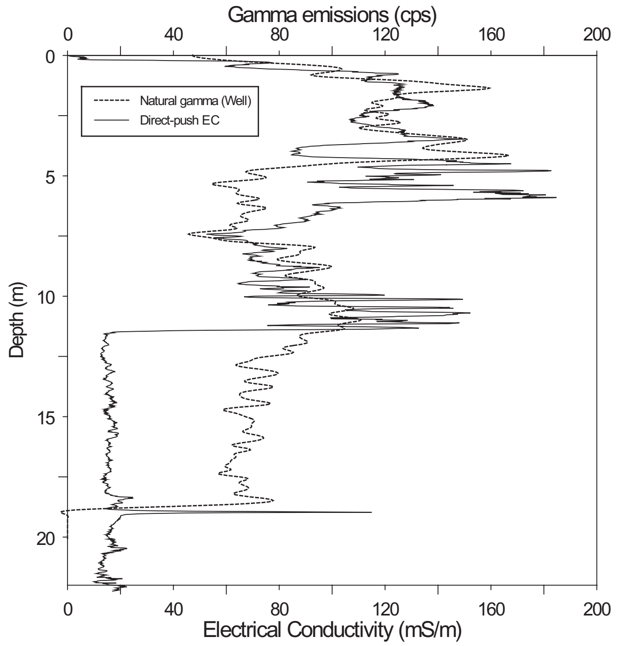


**Figure 6. Natural-gamma and direct-push EC logs from well and push locations, respectively, separated by 1.2 m. The natural-gamma log was filtered using a polynomial regression with a nine-point average that was applied five times (Savitsky and Golay 1964), and was conducted at a speed of ~6 m/min. Placement of gamma detector near top of tool resulted in no information being obtained from the lower portion of the well. Note that the natural-gamma and focused-induction (Figure 5) logs were obtained in the same well.**

Natural-gamma and electrical logging methods measure different properties of clay minerals and are commonly used in tandem to provide independent measures of the distribution of clay in a formation. In natural-gamma logging, radioactivity from gamma-emitting minerals is detected by a scintillation crystal (Keys 1990). As with the induction log, the natural-gamma log shows the effects of a larger averaging volume when compared to the direct-push EC record at GEMS (Figure 6). The logging tool used in this study counts emissions from a spherical sampling zone with a radius of 0.46 m (Century Geophysical Corp. 2001). In general, the natural-gamma log is in agreement with the EC log at GEMS, confirming interpretations regarding the distribution of clay layers at the site. High-level gamma emissions at 1.5, 3.0, and 10.5 m overlap with high EC zones observed at the same depths, but the transitions between these zones tend to be more gradual in the natural-gamma profile. Although the lithologic boundary at 11 m is observed in the natural-gamma log, it is much more gradual than that observed in the EC log. The EC peaks between 5 and 7 m were not observed in the natural-gamma log, whereas the peak at 19 m was below the maximum depth reached with the gamma tool. During visual inspection of cores taken adjacent to the direct-push log, oxide and oxyhydroxide materials, which are believed to be an artifact of previous water-table fluctuations, were noted between depths of ~2 and 6 m. Because these materials do not emit gamma radiation but can be electrically conductive, they would not be detected by natural-gamma logs but could appear as peaks in EC logs. The discrepancy between the natural-gamma and EC logs observed at 5 m in Figure 6 may therefore be caused by the presence of appreciable oxides and oxyhydroxides at that depth. Statistical variations in natural-gamma emissions can introduce considerable noise into a log, so care must be used to avoid interpreting statistical artifacts as variations in formation properties. Spatial smoothing algorithms, such as that of Savitsky and Golay (1964), are designed to reduce such artifacts, but they also diminish the vertical resolution of the log. Although natural-gamma logs can be run at a very low speed (<0.3 m/min) to help suppress statistical noise and thus reduce the need for spatial smoothing, this is rarely done in practice.

## Comparison to Sediment Cores

### *EC Logs as Indicators of Vertical Variations in Grain Size*

The resolution of direct-push EC logging was further evaluated by assessing the significance of the small-scale variations observed in direct-push logs (e.g., Figure 5). In this assessment, the clay content of core materials from the upper 11 m of alluvium was compared to adjacent EC logs at two locations at GEMS (Figure 7). Two continuous cores were subdivided into 116 layers (thickness ranged from 2.5 to 79 cm) based on visual differences in texture, color, and composition. Clay (<2 µm), silt (2 to 50 µm), and sand (>50 µm) percentages were determined for 100 samples using standard sieve and pipette methods (USDA 1996). A comparison of these data with the direct-push logs revealed a general agreement between peaks in the EC profiles and relative increases in the clay content of the sampled layers. A series of sharp EC peaks are observed in both logs from 4 to 6 m and 9 to 12 m, suggesting the occurrence of a series of thin layers with different clay contents. Clay-rich layers as thin as 2.5 cm correlate with peaks at several locations within these intervals, verifying that interpretation. An EC minimum that occurs in the vicinity of 9 m in both cores is coincident with those samples containing the least clay and most sand. The association of prominent layers and EC peaks at common depths in both sets of cores and logs suggests that certain layers are laterally continuous and may be correlated across the site using EC logs. A demonstration of the use of direct-push EC logging for the site-wide correlation of fine-scale hydrostratigraphic features is presented in a later section.

### *EC Logs as Predictors of Clay Content*

The relationship between grain-size distribution and EC logs illustrated in Figure 7 implies that it may be possible to quantitatively predict differences in the clay content of sediments using EC logs. The strength of this relationship was investigated by performing a linear regression on the average EC value and clay content of each sampled layer (Figure 8). The greater scatter at higher EC values suggests that some factor other than the amount of clay influences the electrical conductivity of certain layers. Because clay-sized particles of different compositions can have different electrical conductivities, a possible cause for the unexplained variability in the EC-clay regression may be variations in the mineralogy or composition of the clay-size fraction. The ratio of the cation exchange capacity (CEC) of a sample to its percent clay can be used to predict the proportions of various clay-sized mate-

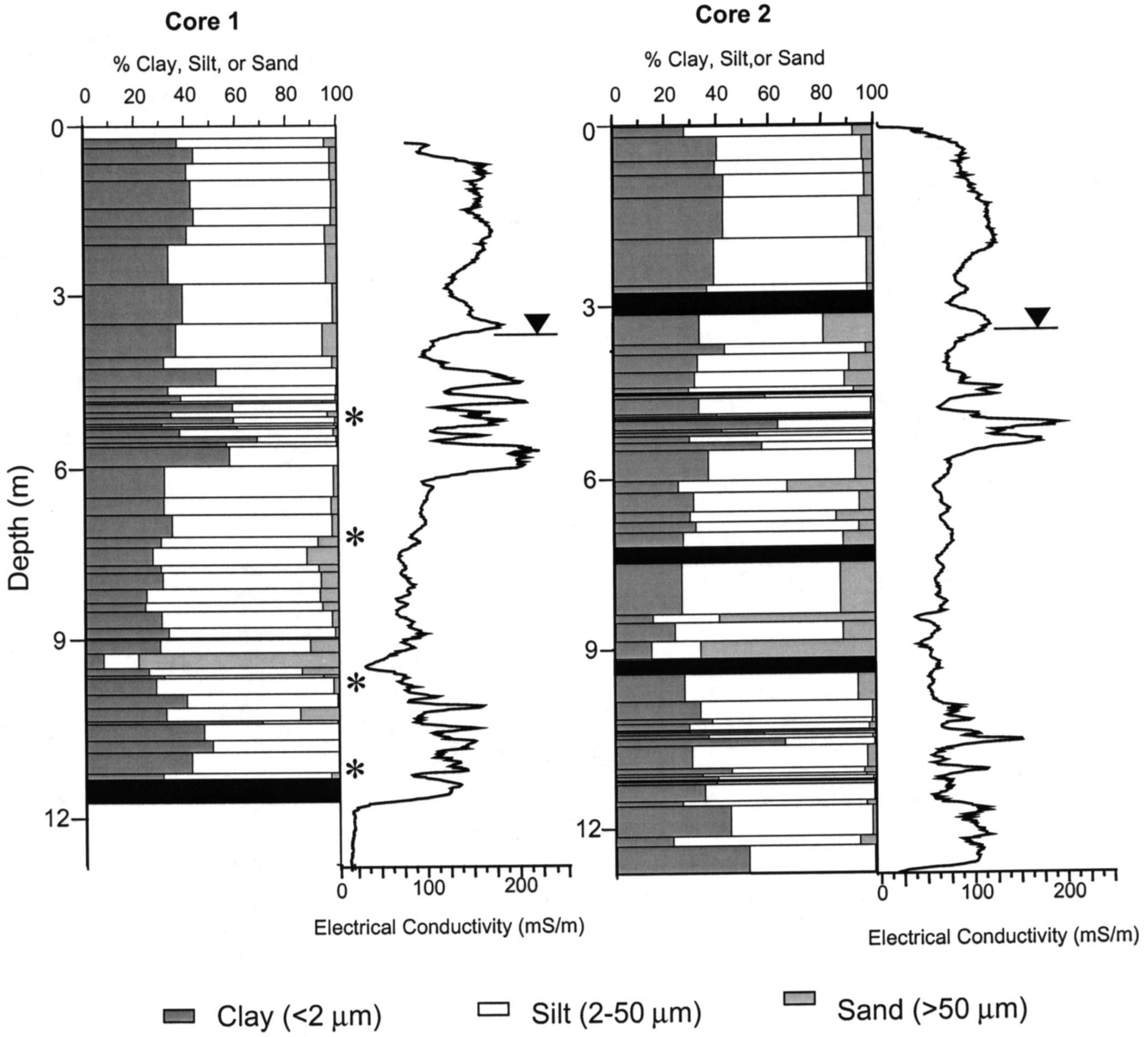


**Figure 7. Vertical variations in clay content and electrical conductivity in continuous cores and EC logs separated by less than 1 m. Blackened layers represent intervals for which particle-size analyses were not conducted. Clay mineral analysis was performed on samples marked by asterisks. The water table is denoted by the inverted triangles. Core locations are given in Figure 2.**

rials that may be present (USDA 1996). When the CEC/percent-clay ratio is below 0.5, vermiculite and chlorite dominate the clay fraction. When the ratio is between 0.5 and 0.7, the clay fraction is a mixture of clays in which smectite dominates. Above a ratio of 0.7, the clay fraction consists of smectite and nonlayered materials, such as organic matter or oxyhydroxides. The ratio of CEC to percent clay was calculated for a subset of samples from GEMS (Figure 9). The ratio for those samples varies between 0.5 and 0.9, implying the dominance of smectite and possible presence of organic matter or oxyhydroxides in the sampled intervals. X-ray diffraction analyses of four samples from Core 1 verify that smectite is the most prevalent clay mineral, with lesser amounts of kaolinite, mica, and vermiculite (Table 1). The presence of oxide and oxyhydroxide materials observed in core materials between ~2 and 6 m is also in agreement with this assessment. Clearly, the vertical variations in clay type shown in Figure 9 can have an important effect on the relationship between EC and clay content, and may be partly responsible for the scatter in Figure 8. These results illustrate the importance of considering potential variations in the composition of clay-size materials when interpreting EC logs.

### *EC Logs as Predictors of Hydraulic Conductivity*

The electrical conductivity of porous media is a function of physical properties of the media, such as porosity, pore geometry, and tortuosity, that also serve as major controls on hydraulic conductivity ($K$). Thus, it is plausible to assume that a relationship exists between EC and $K$. An extensive body of literature describes the prediction of hydraulic conductivity (permeability) from electrical logs or some factor derived from them (for a recent review, see Purvance and Andricevic 2000). Although a clear relationship exists between EC and $K$ at GEMS on the scale of the major units at the site (clay-silt, silt-sand, clay, and sand-gravel units of Figure 3), the relationship weakens on the scale of a single unit, particularly in the absence of a significant clay fraction. As Figure 4 indicates, there is no apparent relationship between the hydraulic conductivity profiles obtained from well tests in the sand and gravel interval and the electrical conductivity record from adjacent direct-push logs, except where thin clay layers are present. As would be expected from Figure 4, attempts to identify a possible correlation between EC and $K$ based on relationships given by Croft (1971), Hutchinson et al. (1961), and Jorgensen (1988) were not successful (Schulmeister et al. 2000). This lack of correlation between EC and $K$

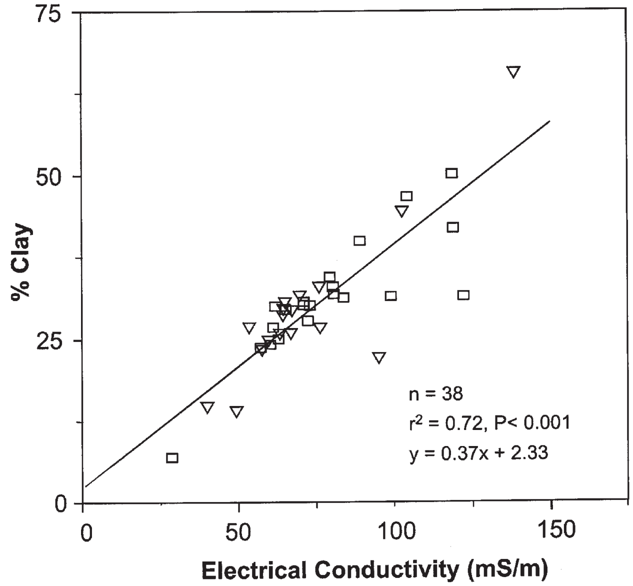


Figure 8. Percent clay and average EC values for samples from Core 1 (squares) and Core 2 (inverted triangles). Because EC data from the upper and lower 3 cm of sample interval reflect the transition between intervals, only those samples >6 cm in thickness were included in the regression. Similarly, EC data from the upper and lower 3 cm of a sample interval were not used to compute the average EC value for that interval.

is undoubtedly due to the insensitivity of the EC sensor to the grain-size variations that control $K$ in the sand and gravel section. Thus, it is doubtful that information on variations in $K$ within sand and gravel units can be obtained from the current generation of direct-push EC logging probes.

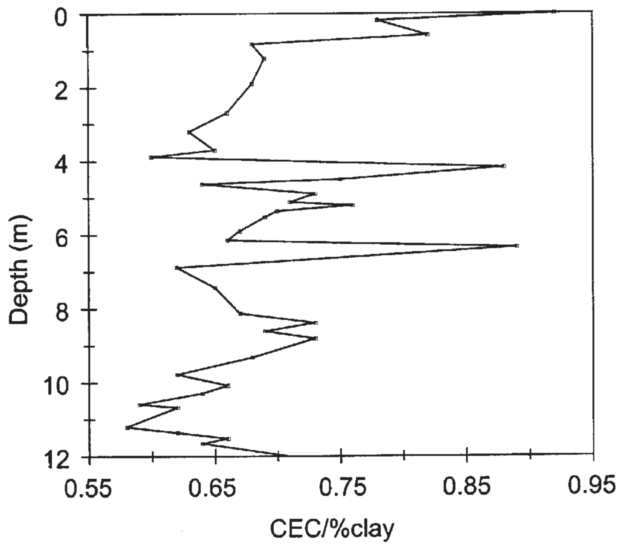


Figure 9. Ratio of cation exchange capacity (CEC) to percent clay in samples from Core 2. Values between 0.5 to 0.7 are typical of a clay fraction consisting of a mixture of clay minerals dominated by smectite. Values greater than 0.7 represent a clay fraction composed almost entirely of smectite with small amounts of clay-sized exchangeable materials such as organic carbon or oxides (USDA 1996).

## Lateral Correlation of Logs and Hydrostratigraphic Facies Mapping

The results of the previous sections indicate that direct-push EC logging has considerable potential for mapping the lateral continuity of layers with nonnegligible clay content. A series of EC profiles were obtained along a traverse across GEMS and were contoured to compile an EC cross section to

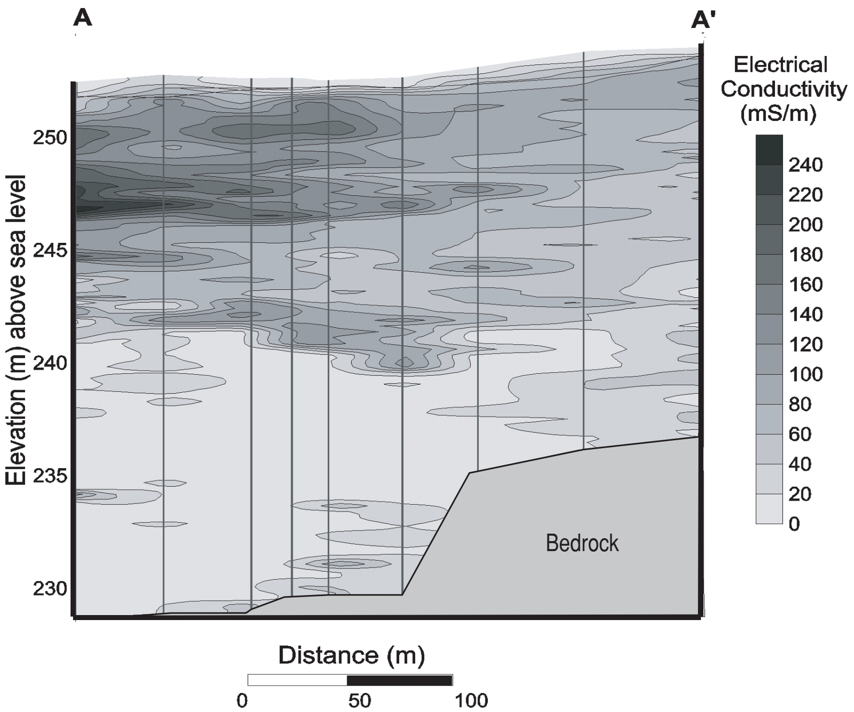


Figure 10. An electrical conductivity cross section along line A-A′ on Figure 2 (transect oriented perpendicular to the margin of the Kansas River floodplain near the mouth of a tributary creek). Vertical lines indicate locations of direct-push EC logs.

**Table 1**
**Mineral Content of the Clay-Size Fraction of Four Samples from Core 1 as Determined by X-ray Diffraction (sample locations shown in Figure 7)**

| | Mineral and Peak Height | | | | |
|---|---|---|---|---|---|
| Depth (m) | Smectite | Kaolinite | Mica | Vermiculite | Quartz |
| 5.3 | 3 | 2 | 2 | 1 | 1 |
| 7.0 | 3 | 3 | 2 | | 1 |
| 9.5 | 2 | 2 | 2 | 2 | 1 |
| 11.0 | 3 | 2 | 2 | | 1 |

Peak Size
5 = Very large
4 = Large
3 = Medium
2 = Small
1 = Very small
Peak sizes indicate the relative abundances of minerals present in each sample.

further evaluate this potential (Figure 10). Lithologic features inferred from EC logs, such as the clay-rich layer at an elevation of 247 m, the silty sand at 243 to 246 m, and the abrupt boundary between the clay-rich materials and underlying sands at 241 to 242 m, appear to persist laterally across most of the site. The presence of isolated clay layers in the sand and gravel interval, which had been noted in previous work (Butler et al. 2002), is indicated by intermittent zones of relatively high EC. In addition to documenting these known features, the EC cross section also reveals important lateral differences in hydrostratigraphy that had not been previously recognized. The transect clearly shows that the electrical conductivity of the upper 10–12 m of sediments decreases (sediments coarsen) as the margin of the floodplain is approached, and that the fine-grained cap that exists above the alluvial aquifer may be truncated by, or interfingered with, coarser materials near the floodplain margin. An increase in the clay content of the sand and gravel interval is also indicated near the floodplain margin. These lateral changes in the character of the sedimentary sequence could have significant ramifications for ground water flow and transport, and may explain previously observed lateral trends in ground water chemistry at GEMS (Schulmeister 2000). Preliminary results of a ground water sampling study based on the EC transect are in agreement with this finding (Schulmeister et al. 2002).

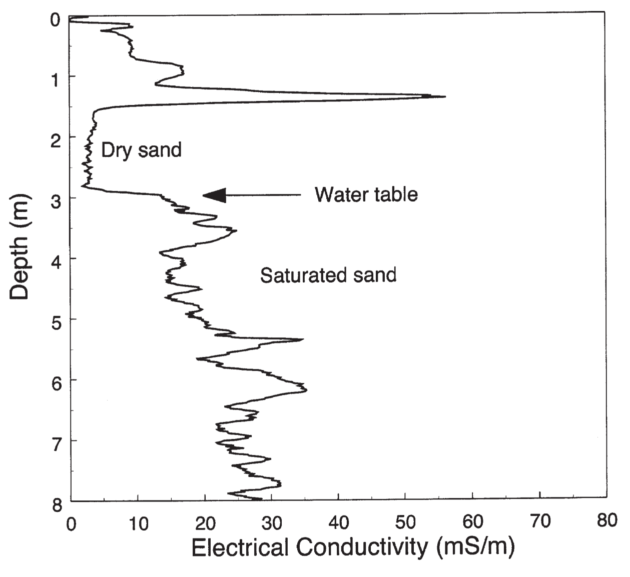


Figure 11. Direct-push EC log from the east bank of the Arkansas River near Kinsley, Kansas.

## Additional Considerations

The work discussed in the previous sections was conducted in conditions that are typical of many floodplain sequences. However, additional factors must be taken into account at sites where these conditions may not all apply. The most significant of these and other considerations are discussed in the following paragraphs.

### Moisture Content

Moisture content can have an important influence on electrical conductivity in some situations. For example, Figure 11 is a record of EC versus depth, obtained at a KGS research site along the Arkansas River in west-central Kansas (Healey et al. 2001), in which a step increase of more than 10 mS/m occurs at the water table. This step is the result of an abrupt change from the very low moisture content of the overlying dry sand to the saturated sand below the water table. In finer-grained materials, the transition from unsaturated to saturated conditions would be more gradual and an abrupt increase in electrical conductivity would not occur. The presence of any clay in the finer-grained materials would further mask the change in electrical conductivity produced by an increase in moisture content. Clearly, EC variations produced by changes in moisture content can be misinterpreted as variations in clay or other electrically conductive

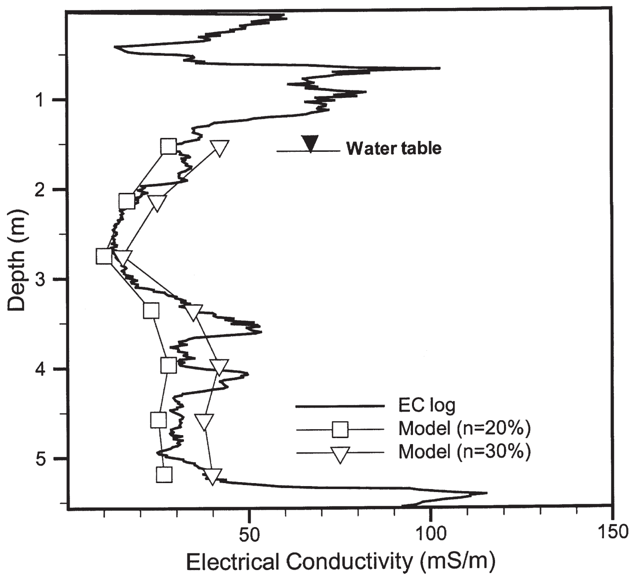


Figure 12. Direct-push EC log and modeled EC values from the east bank of the Arkansas River near Larned, Kansas. Modeled values were calculated using fluid conductivity measurements taken at depths denoted by symbols, and assuming that the EC value is solely a function of fluid conductivity. A uniform ground water temperature was assumed in making these estimates. Porosity ($n$) values were chosen that span the range expected in a sand aquifer

matrix materials if the hydrologic conditions at the site are ignored.

### Fluid Conductivity

The influence of fluid chemistry on EC logs was not examined in detail in this paper since there was little variation in the specific conductance of ground water at GEMS. In general, the use of EC logs for hydrostratigraphic delineation requires some knowledge of the relative importance of fluid and sediment contributions to electrical conductivity at a site. At sites where prior information about ground water chemistry or lithology is not available, variations in electrical conductivity caused by differences in specific conductance of the ground water could be misinterpreted as variations in matrix materials. For example, the 80 mS/m EC peak observed at 20 m in Figure 3 could represent a high-conductivity fluid instead of a thin clay layer if 30% porosity is assumed for the coarse sand, and ground water with a high specific conductance (267 mS/m) were present at that depth. Although such high specific conductance values have not been observed at GEMS, they do occur in other areas, either naturally (e.g., where saline surface waters or deep brines enter fresh-water formations), or as a result of ground water contamination (Schon 1996). Preliminary work at a second KGS research site along the Arkansas River in west-central Kansas further illustrates the importance of variations in fluid chemistry on interpretations of direct-push EC logs (Schulmeister et al. 2001). As shown in Figure 12, the specific conductance of ground water samples collected from seven depths appears to have a major influence on the EC log for the shallow aquifer at the site. The comparison indicates that the large-scale variations observed in the direct-push EC log below the water table are primarily caused by variations in fluid chemistry (specific conductance between 50 and 180 mS/m). Without monitoring ground water chemistry and collecting sediment samples, it is impossible to determine whether variations in electrical conductivity are caused by variations in fluid chemistry, clay content, or a combination of both. Direct-push methods that allow EC logging, geochemical sampling, and hydraulic testing to be done concurrently are currently being developed (Sellwood et al. 2001). Such methods would enable significant variations in fluid chemistry to be recognized at the time the log is obtained.

### Bedrock Boundaries

When a direct-push probe encounters competent bedrock, abrupt probe refusal occurs. However, weathered bedrock surfaces are often soft enough to penetrate with direct-push equipment and may be mistaken for clay or sand if a significant change in electrical conductivity is observed. Fortunately, logging speed will usually diminish in weathered bedrock, allowing a reduction in drive speed to be used as a diagnostic tool for identifying bedrock boundaries. For example, the surface of the weathered bedrock at GEMS often appears as a peak on the EC log at ~22 m. When logging speed is plotted along with EC values, the sudden decrease in speed at this depth provides an indication of the change in lithology (Figure 3). By simultaneously monitoring electrical conductivity and logging speed, the possibility of mistaking the bedrock surface for a lithologic change within an unconsolidated sequence is significantly reduced.

## Conclusions

Direct-push EC logging can provide information about the hydrostratigraphic framework of unconsolidated materials at a level of detail that is difficult to obtain with conventional drilling- and geophysics-based approaches. This unprecedented level of detail allows site-specific stratigraphic controls on ground water flow and transport to be identified without the need for wells. The direct-push EC approach is especially useful for lithofacies mapping where small-scale lithologic features may be indicative of a particular type of geologic deposit. Identification of fine-scale variations in such deposits may be important for applications ranging from studies of depositional history to investigations of ground water contamination. Because this high-resolution information can be obtained rapidly prior to any drilling or sampling, direct-push EC logging is well suited for guiding subsequent investigation activities.

The findings of this paper show that direct-push EC logging is a powerful tool for high-resolution characterization of hydrostratigraphic features when variations in electrical conductivity are primarily a function of variations in sediment type. Comparison of the direct-push EC logs with various types of hydrogeologic data demonstrates that higher EC values generally reflect fine-grained material, whereas lower values indicate coarser sediments. Logs of electrical conductivity, however, can be significantly affected by a variety of additional factors, most notably fluid chemistry and moisture content. Supplementary information, such as cores and water samples, must therefore be used to help interpret EC logs at a particular site. The coupling of direct-push EC logs with conventional natural-gamma logs, which are not sensitive to the effects of fluid chemistry or degree of saturation, can be helpful in this regard. Small-diameter natural-gamma tools have recently been developed for use in direct-push equipment (Viellenave and Fontana 1999).

A series of direct-push EC logs, such as that shown in Figure 10, can be rapidly obtained and can provide important insights into flow and transport within an area. Interpretations of such transects, however, must recognize that conditions between EC log locations are estimated using various interpolation schemes. If the continuity of a structure is of great importance, an attempt should be made to combine direct-push logging with surface geophysical methods. The control of high-resolution direct-push logging combined with the continuity of surface geophysical surveys should yield an image of the subsurface at a level of detail that has rarely been possible. At many sites in unconsolidated settings, such detailed views of the subsurface could vastly improve the efficacy of remediation activities and the quality of contaminant-transport predictions.

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