Determination of Aquitard and Crystalline Bedrock Depth

Using Time Domain Electromagnetics

by

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IV. Project Summary

Project Title Determination of Aquitard and Crystalline Bedrock Depth Using Time Domain Electromagnetics

Project Number R/UW-HDG-006

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Background/Need

As groundwater needs and concerns have increased, larger and more complex groundwater flow models have been developed to address the problems associated with the exploitation of this precious resource. One of the first steps in creating a useful groundwater flow simulation for the Wisconsin region is the development of a conceptual model that includes hydrostratigraphic units, e.g., shale aquitards, sandstone aquifers, and streambed deposits in tills. The depth, thickness, and extent of these units are usually determined from geologic logs, but in locations where the logs are sparse or nonexistent, the modeler is left with the difficult choice of deciding stratigraphic placement at depth. Time domain electromagnetics is a geophysical tool that showed promise in filling in the gaps in the geologic record so that better flow models and understanding of geology can be realized. However, this tool needed further analysis to determine its accuracy under Wisconsin geologic conditions. Guidelines were needed to set boundaries on what structures the method is capable of resolving.

Objectives

The objective of this study was to provide an assessment of the Time Domain Electromagnetic (TEM) method as a hydrostratigraphic mapping tool and to delineate the shaley facies of the Eau Claire Formation.

Methods

The shaley facies of the Eau Claire Formation, an important regional aquitard in southern and southwestern Wisconsin, served as the test case in this study. We used borehole geophysics to measure the thickness, depth, and resistivity of the Eau Claire shale at four locations. First, those measured values were employed in a forward modeling exercise to determine the theoretical limits of the thickness, depth and resistivity of a shale unit that might be resolved using TEM. Following the forward modeling, we conducted 16 TEM surveys in Dane, Sauk, La Crosse, and Trempealeau counties using a Zonge NT-20 transmitter with a loop size of 100 m. Five TEM surveys were conducted at locations where the Eau Claire shale is constrained by well logs and in areas where the method was challenged due to the shale being thin and/or deep. Multiple surveys were conducted at Pheasant Branch Conservatory, the location where the method was pushed to its limit of resolution with the shale depth and thickness. These surveys allowed us to calibrate and test the method. Finally, 11 additional surveys were conducted at locations where the presence of the Eau Claire shale was unknown. The data collected in the field surveys were analyzed using the WinGLink geophysical software package.

Results and Discussion

The method successfully detected the presence of the Eau Claire shale when the unit was thick and/or shallow, but the method did not always correctly delineate the depth and thickness of the shale. At sites where the Eau Claire shale was present along with a second conductor, e.g., conductive lake sediments, or the deep Mount Simon, the inversion results typically indicated the presence of the deeper conductor, the Mount Simon shale, as well as a second conductor that was sometimes too shallow to be the Eau Claire shale.

Conclusions and Implications

By comparing the geologic structure predicted by the TEM surveys with known geologic structure, this study was able to measure how well the TEM survey could reproduce the known geologic structures. The method is useful for determining whether or not a shale is present and can give a general indication of depth and thickness, but should not be used without a geologic control point. The reliability of the method is significantly lessened by the presence of a second conductor at depth. TEM surveys with different loop sizes might possibly reduce this error. A smaller loop could more accurately characterize the shallower conductor. That information could then be incorporated into the analysis of the data from the larger loop.

Related Publications

Anderson, M.L., D.J. Hart, and D.L. Alumbaugh, Use of the Time-Domain Electromagnetic Method for Determining the Presence and Depth of Aquitards, abstract in American Water Resources Association – Wisconsin Section, 27th Annual Meeting, 2003.

Anderson, M.L. Use of the Time-Domain Electromagnetic Method for Determining the Presence and Depth of Aquitards, Master's Thesis, University of Wisconsin, 2003. pp. 143.

Key Words

TEM surveys, electromagnetic, aquitard, Eau Claire shale, inversion, nonuniqueness

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University of Wisconsin – Water Resources Institute

V. Introduction

Hydrogeological investigations of flow systems typically involve the delineation of the horizontal and vertical extent of the aquifers and aquitards, the lithology and hydraulic parameters of the aquifers and aquitards, the vulnerability of the aquifers to contaminants, and water quality. Electromagnetic methods have been one of the primary geophysical methods used in these investigations because of their ability to distinguish between formations of different resistivity (Christensen and Sorensen, 1994). The electrical resistivity of formations can be linked to their porosity and hydraulic conductivity, and thus the flow pattern of groundwater. Due to the presence of clay minerals, shales typically have a much lower resistivity than sandstones.

The time domain electromagnetic method (TEM) has been used in several hydrogeological investigations because of its ability to detect good conductors, such as clay and shale units acting as aquitards (Auken et. al, 1994 and Pullan et. al 1994) and saline zones causing poor water quality (Jansen et. al, 2000). The goal of this study was to develop guidelines for the use of TEM for determining the presence and depth of aquitards in Wisconsin.

The Eau Claire shale, an important regional aquitard in southern and southwestern Wisconsin, was used as a test case in this study. TEM surveys were conducted at locations where the Eau Claire shale was well constrained by well logs, including areas where the method was challenged due to the shale being thin and/or deep. Additional surveys were conducted at two areas where the presence of the Eau Claire shale was uncertain. These areas were chosen because the presence or absence of the Eau Claire shale would have a significant impact on the groundwater flow systems in those two areas.

VI. Procedures and Methods

This study was completed in three parts: forward modeling based on borehole geophysics, TEM surveys at locations with known lithologies, and TEM surveys at locations where the presence of the shale was uncertain.

Borehole geophysics was conducted in three wells in Dane county and one in La Crosse county where the Eau Claire shale was present in the borehole. These locations are shown in Figure 1. Natural gamma and normal resistivity logs for the four wells resulted in a clear delineation of the Eau Claire shale with depth at a resolution of less than one foot. The data was collected using a Mount Sopris MGX II logger and a 2PEA-1000 combined natural gamma and normal resistivity downhole tool. The values from the borehole geophysics were then used to provide reasonable ranges for the forward modeling of a TEM response to the Eau Claire shale. The forward modeling exercises were conducted to determine limits of the thickness, depth, and resistivity for a shale unit that can be resolved using TEM. EMMA (ElectroMagnetic Model Analysis), a program developed for electromagnetic data and model analysis by the HydroGeophysics Group at the University of Aarhus, Denmark, was used in the forward modeling exercises. All geophysical models in EMMA are assumed to be 1D, and each layer is homogeneous and isotropic.

Field data were collected at the 16 locations in Dane, Sauk, Trempealeau, and La Crosse counties shown in Figure 1. A TEM system manufactured by Zonge Engineering and Research Organization was used to collect the data. The system consisted of the GDP32II geophysical data processor, an NT-20 transmitter, a solenoid receiver with a moment of 10,000 m^2, a 100m x 100m transmitter loop, and one NTEMBAT battery pack. The NT-20 transmitter, which operated in ZeroTEM mode, input 3 Amps of current supplied from the battery pack into the transmitter loop. The receiver measured the voltage induced by the H_z component of the secondary magnetic field while positioned at the center of the transmitter loop. Both the transmitter and the receiver were connected to the GDP32II, which controls the transmitter and records the data collected by the receiver.

At least one TEM sounding was conducted at each site, and the location of the transmitter loop and receiver were determined using GPS. Two to three sets of data were collected at each site using a frequency of 32 Hz with 8,192 cycles. The data generated by the 8,192 cycles were stacked to enhance the signal-to-noise ratio. Each set of data took approximately five minutes to collect. To reduce the effects of cultural noise, the surveys were set up at least one to two loop lengths away from power lines, railroad tracks, and metal fences.

In this study the TEM field data were inverted using both smoothest and simple layered model inversion schemes. The software WinGLink by Geosystem, employs the Occam's inversion method to invert for the smoothest model, as well as the Marquardt method to invert for the simple layered model. Occam's inversion method attempts to find the smoothest model that fits the observed data. The smoothest model departs from the simplest case only to the extent that is necessary to fit the data (Constable et al., 1987). Inverting for the smoothest model helps to decrease the likelihood of being misled by features in the model that are not necessary to fit the observed data. Additionally, unlike the simple layered model inversion schemes, the resulting smoothest model is independent of the initial guess. The smoothest model was produced in WinGLink using 18 layers, with a minimum depth of 5m and a maximum depth of 600m. The maximum number of iterations was set to 30, and the maximum RMS value was set at 0.050. The results of the Occam's inversion were then employed to constrain the Marquardt inversion.

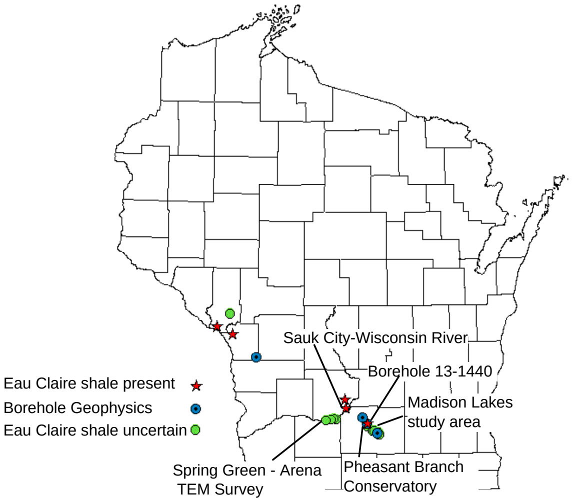


Figure 1. Locations of borehole geophysics and TEM surveys.

VII. Results and Discussion

Geophysical Borehole Logging

Figure 1 shows the locations of four geophysical borehole logs that include the Eau Claire shale. The natural gamma and borehole corrected normal resistivity values with depth for borehole 13-1440 are shown in Figure 2. This record seems to be typical of the shaley facies of the Eau Claire formation. The top of the shaley facies, seen here at a depth of 225 feet, often shows several small peaks in the gamma signal with corresponding valleys in the resistivity curves. The smaller peaks subsequently give rise to a more continuous peak in the gamma record and valley in the resistivity record with a thickness of 10 to 15 feet. The normal resistivity of the Eau Claire shale is between 25 and 50 ohm-meters in the four boreholes. The average resistivities of the Wonewoc sandstone above the shale and Mt Simon sandstone below the shale varies from 150 to 300 ohm-m in the four geophysical logs. These measured resistivities and thicknesses of the shale allowed us to conduct forward modeling based on measured values.

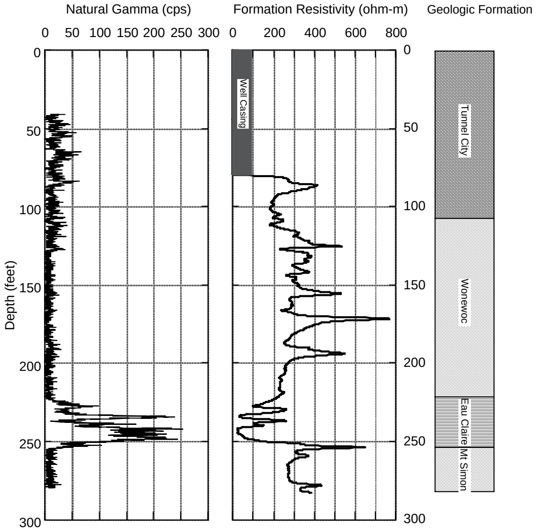


Figure 2. Gamma, normal resistivity, and lithology for the Pheasant Branch Conservancy (WGNHS well Id #13-1440).

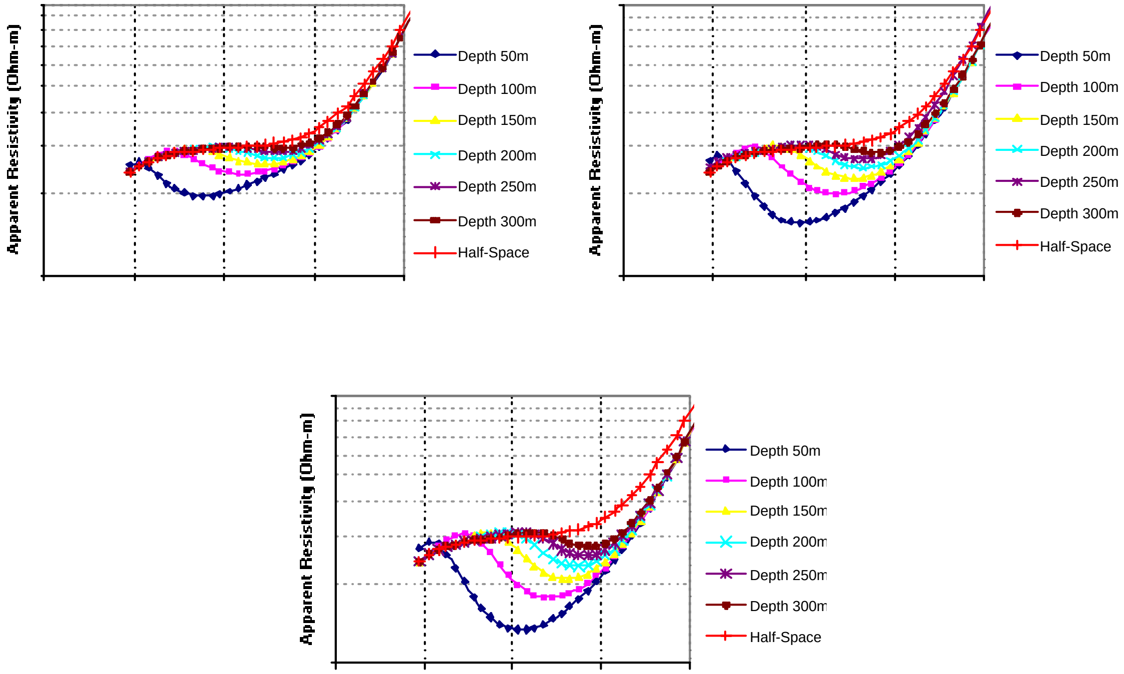
Forward Modeling

Simple three layer models consisting of a thin conductive layer between two resistive layers were used to simulate the thin, conductive Eau Claire shale unit between resistive sandstones. Homogeneous half-space models were also used for comparison to determine the strength of the response due to the conductor. Finally, two multilayer models were also constructed to simulate the response of the shale unit in a more realistic geologic setting.

Only one parameter was varied at a time in each set of modeling exercises. The parameters of interest included the depth to the conductor, the thickness of the conductor, and the resistivity of the conductor. Transmitter and receiver configurations were held constant for all models. To simulate the data acquisition, the configuration consisted of a 100m x 100m transmitter loop with a receiver located in the center of the loop. The depth of the conductor was limited to 300m because the maximum depth sensitivity of a TEM system is usually limited to two to three times the length of one side of the transmitter loop. Thus, a 100m x 100m transmitter loop is typically only sensitive down to depths of 200m to 300m.

Three sets of the 3 layers models were created. The resistivity of the shale was set to 25, 50 and 100 ohm-meters for the three sets. The depth and thickness of the shale was then varied as well. Here we report results from the second set which consisted of a 10m, 20m, and 30m thick conductor with a resistivity of 50 Ohm-m placed between two 300 Ohm-m layers. The initial depth of the conductor in each case was 50m, and the depth was increased by 50m each time.

The synthetic TEM responses for a 10m, 20m, and 30m thick conductor at varying depths are plotted in Figures 3 A, B, and C. The 10m thick conductor has a fairly strong response up until a depth of 250m. Once the conductor reaches a depth of 300m, the apparent resistivity curve plateaus at approximately 300 Ohm-m. The responses are fairly strong for all depths for the 20m and 30m thick conductors. A noticeable drop in apparent resistivity occurs at approximately 2.26 x 10^{-4} seconds when both the 20m and 30m thick conductors are placed at a depth of 300m. The apparent resistivity curves begin to overlap at approximately 2.26 x 10^{-3} seconds for the 10m thick conductor, 3.58 x 10^{-3} seconds for the 20m thick conductor, and 4.51 x 10^{-3} seconds for the 30m thick conductor.



Figures 3A, B, and C. Apparent resistivity curves for a (A) 10m, (B) 20m, and (C) 30m thick conductor with a resistivity of 50 Ohm-m with varying depth to the conductor.

Following initial TEM surveys at Pheasant Branch Conservatory in Middleton, Wis. we noticed that a second conductor seemed to be present beneath the Eau Claire shale. A survey of geologic logs in Dane county showed that the Mt Simon formation frequently has a shale unit near its base. We conducted forward modeling to understand how a second conductor might affect our results. Three-layer models and five-layer models were compared to determine how the response changes when two conductors are present. One three-layer model included a relatively shallow conductive layer located between two resistive layers to represent the Eau Claire shale surrounded by sandstone. The 9m thick conductive layer was placed at a depth of 70m and had a resistivity of 40 Ohm-m. The surrounding layers had resistivity values of 260 Ohm-m. The second three-layer model consisted of a relatively deep conductive layer situated between two resistive layers to simulate the shale unit in the Mount Simon Formation. The 12m thick conductor had a resistivity of 40 Ohm-m and was placed at a depth of 199m. The two resistive layers both had a resistivity of 260 Ohm-m. The five-layer model consisted of the two previously described thin conductors surrounded by resistive layers to simulate the Eau Claire shale and the Mount Simon shale. The resistive layers bounding the two-conductive layers each had a resistivity of 260 Ohm-m. A second 5-layer model was created in which the resistivity of the Mount Simon shale was increased to 75 Ohm-m. A homogeneous half-space model with a resistivity of 260 Ohm-m was used for comparison to determine the anomalous response due to the conductors.

The TEM responses for the homogeneous half-space, three-layer, and five-layer models are plotted in Figure 4. A decrease in apparent resistivity is seen almost immediately for the shallow conductor. The drop in resistivity starts at approximately 1.80 x 10^{-5} seconds, with the lowest resistivity value occurring at 1.13 x 10^{-4} seconds. The apparent resistivity curve for the three-layer model with a deep conductor starts out with a resistivity of approximately 260 Ohm-m and virtually overlaps the curve for the homogeneous half-space. However, the resistivity begins to decrease after 1.13 x 10^{-4} seconds. The five-layer model overlaps the shallow conductor model until approximately 1.13 x 10^{-4} seconds. The resistivity becomes fairly constant between 7.15 x 10^{-5} seconds and 4.51 x 10^{-4} seconds, with a very slight increase near 1.43 x 10^{-4} seconds. The five-layer model never exactly overlaps the responses of the homogeneous half-space or the three-layer model with a deep conductor. When the resistivity of the deep conductor is increased to 75 ohm-m in the second five-layer model, the response closely resembles the three-layer model with the shallow conductor during the late times. This result shows that differentiation between a one conductor and a two conductor model may not be possible.

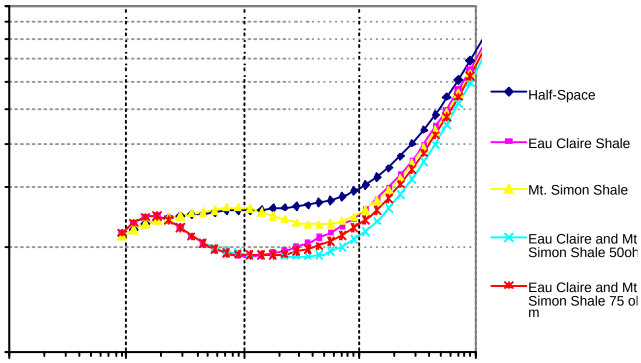


Figure 4. Comparison between 3-layer (1-conductor) and 5-layer (2-conductor) models.

TEM Surveys at locations with known geology

We conducted TEM surveys at five locations shown in Figure 1 where the Eau Claire shale was known to be present based on either geological or geophysical logs. The results of those surveys allowed us to set limits on the resolution of the method. Here we discuss results for two of those five sites. The data was inverted using a best initial starting guess corresponding to the geology (simple layered model) and also using a smoothest model. Root mean squared (RMS) errors, normalized by the data values, were used to determine misfit between the models and the data. A complete discussion of the limits of the TEM method can be found in Anderson (2003).

The first site is located immediately west of Sauk City near the Wisconsin River. This site is one where the shale was shallow and thick. Figure 5 shows the model results of the inverted data and the geology of this site based on a geologic log for WGNHS well 57-0010 located 2 miles to the east of this site. The smoothest model correctly predicts the depth and approximate thickness of the shale. The initial simple layered model layer thicknesses and resisitivities are shown in Figure 5, where the low resistivity layer corresponds to the Eau Claire shale. The layered model inversion with no fixed values resulted in a slight downward shift of the Eau Claire shale and a decrease in the resistivity of the upper layer. The RMS errors for the smoothest and the 6-layer models were 0.050 and 0.049, respectively.

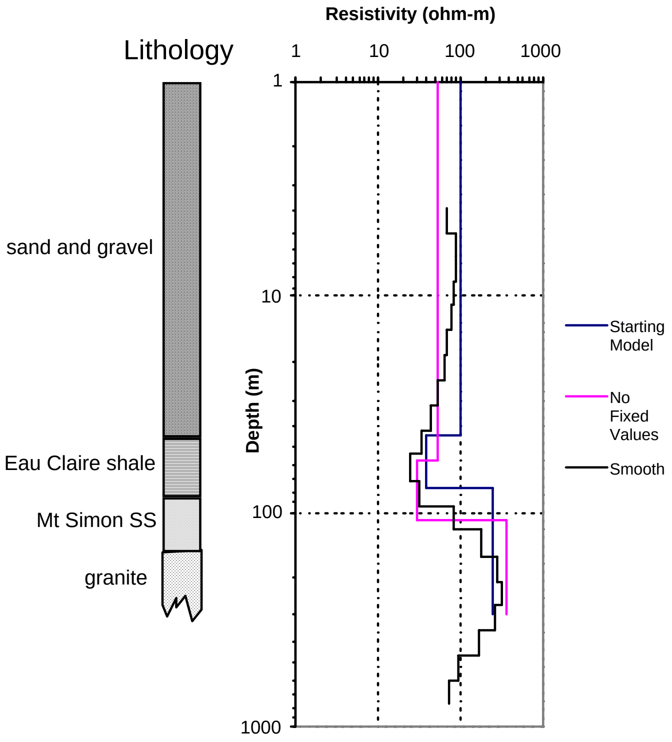


Figure 5. Results of TEM survey at Wisconsin River near Sauk City, Wis.

The second site discussed here was located north of Middleton, Wis. at the Pheasant Branch Conservatory. Figure 6 shows the model results for the inverted data and the geology of this site based on a geologic log for WGNHS well 13-1440 located 200 meters to the southeast of this sounding location. The smoothest model correctly predicts the approximate depths and thicknesses of the two shale units. The initial model layers and resisitivities are shown in Figure

6, where the upper low resistivity layer corresponds to the Eau Claire shale and the lower layer to the Mt Simon shale.

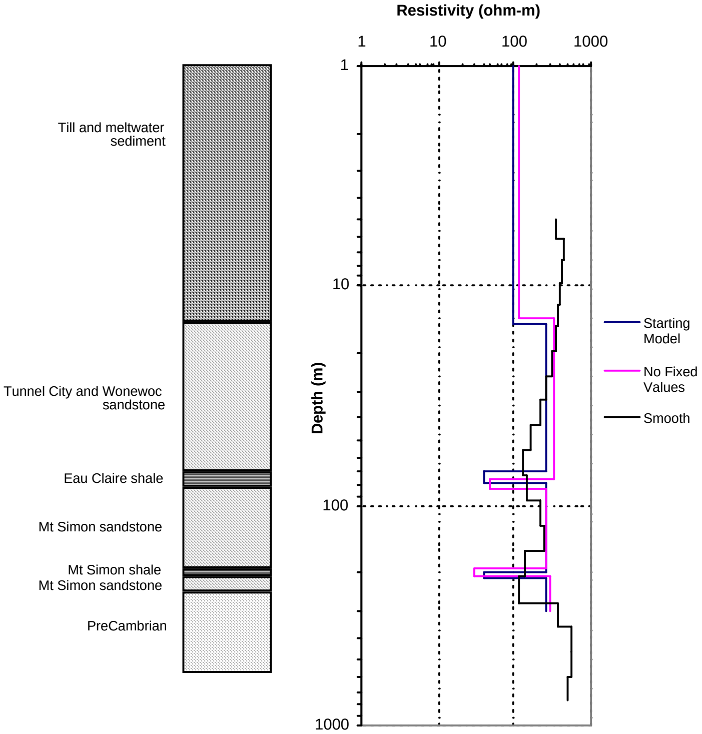


Figure 6. Results of TEM survey at the Pheasant Branch Conservatory, Middleton, Wis. for 6-layer model. The lower portion of the log is inferred from other Dane county wells that extend to the pre-Cambrian.

Because the forward modeling for this site suggested that TEM might not be able to distinguish between one- and two-conductor models, we attempted to fit the Pheasant Branch data to two four-layer models, one with only the Eau Claire shale and one with only the Mt Simon shale. The results of those inversions are shown in Figure 7. We can see that the model with the Eau Claire shale dramatically shifts the conductor downward, while the model with the Mt Simon shale does not dramatically alter the location or thickness of this lower conductor. The RMS errors for these two models is 0.069 for the Eau Claire shale only model and is 0.047 for the Mt Simon shale only. From this we conclude that although the Eau Claire shale is present because it was observed in the well log located 200 meters from the TEM sounding, the data do not require that it be present in the model. Thus we cannot use TEM to determine the presence or absence of the Eau Claire shale at these depth and thicknesses as the presence of the lower conductor, the Mt Simon shale, causes nonuniqueness in the inversion results. When using TEM to study a potential two-conductor system, it may not be possible to resolve whether the signal is due to the shallow, the deep, or both conductors.

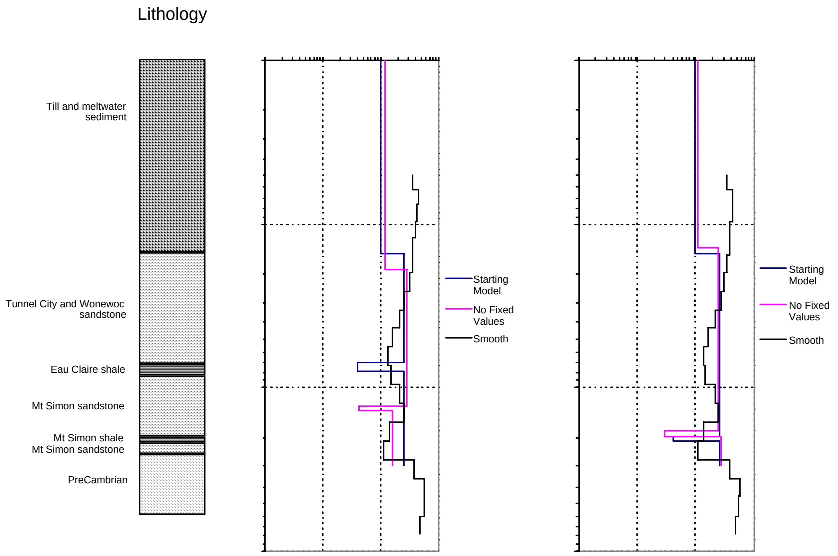


Figure 7. Comparison between models with only Eau Claire shale and only Mt Simon shale.

TEM Surveys at locations where the presence of the shale is uncertain

In addition to conducting TEM surveys at locations where the geology was known, we also attempted to use TEM to determine the presence or absence of the Eau Claire shale at two study areas where no other geologic information is available. The first study area was on the Madison chain of lakes. The locations of the surveys are shown in Figures 1 and 8. The Eau Claire shale is thought to be absent, eroded by glaciers, beneath the Madison chain of lakes, allowing groundwater flow from the shallow aquifer into the deeper aquifer. We conducted a series of TEM soundings on and near the lakes during the winter of 2002-2003 when they were frozen. The surveys on Lakes Mendota and Waubesa and the Beltline wetland weakly suggest that the Eau Claire shale is absent, while the survey on Monona Bay weakly suggests that the Eau Claire shale is present. The surveys on Lake Wingra and the Pheasant Branch wetland have too much noise for any inversion to determine presence or absence of the shale. These inversions all are subject to the nonuniqueness from two conductors discussed previously and so TEM is not able to resolve the Eau Claire shale with any certainty at any of these locations.

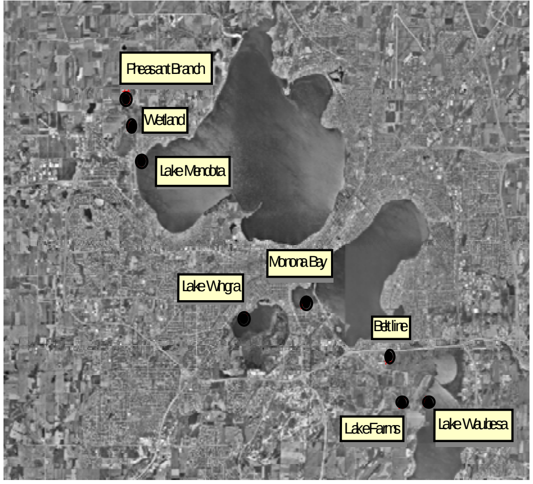


Figure 8. Locations of the TEM surveys to determine the presence of the Eau Claire shale beneath the lakes.

A second investigation was conducted in northeastern Iowa and southern Sauk counties. A geologic log in Arena, Wisconsin (WGNHS Well Id# 25-0003) shows 100 feet of Eau Claire shale at a depth of 200 feet while a geologic log in Spring Green, Wisconsin (WGNHS Well Id# 570018) shows no shale in the Eau Claire formation. Only 10 miles separate these two municipalities. We used TEM to determine whether the shale shows a sharp transition (erosional surface) or a gradual transition (a facies change or gradual thinning of the shale). The survey locations are shown in Figures 1 and 9.

Based on the geological logs from Arena and Spring Green, we set the depth and thickness of the Eau Claire shale to 200 and 100 feet, respectively, for each of the four surveys and allowed the inversion to adjust the resistivity of the Eau Claire shale to fit the model. The resulting resistivity of the shale is plotted on the map by its survey location. The resisitivity of the shale unit increases from 35 Ohm-m at the eastern most site, Hottman Farm, to 60 Ohm-m at Heck Farms approximately midway between Arena and Spring Green to 120 Ohm-m at the Frank Lloyd Wright estate (FLW) just east of Spring Green. The increase in resisitivity is likely due to either a gradual thinning of the shale or a gradual facies change from shale to sandstone. Based on the TEM results, there does not appear to be an abrupt change from the thick shale to sandstone.

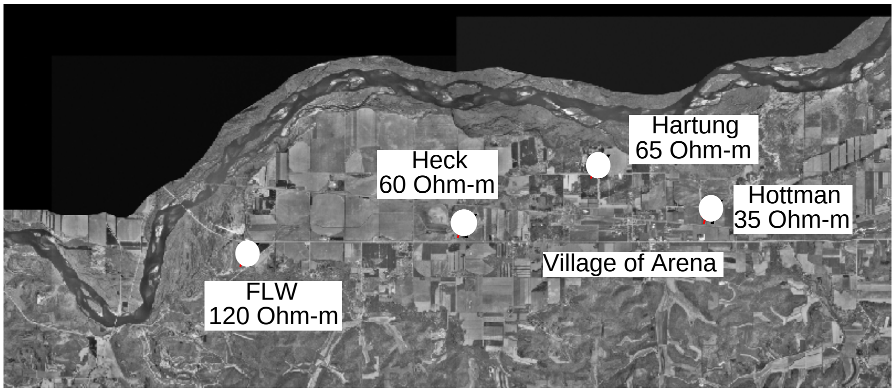


Figure 9. Locations and resistivities of the Eau Claire shale in northeastern Iowa county.

VIII. Conclusions and Recommendations

We found that the electrical resistivity structures suggested by the smooth models were generally consistent with the geology present at the sites, even without a-priori information. The smooth models were also found to be useful in establishing the least number of layers required by the simple layered models to fit the observed data.

The simple layered model inversion results indicated that the method was able to determine whether or not the Eau Claire shale was present when the shale was shallow and/or thick, as was the case for the Sauk City survey site. It was not always able to correctly delineate its depth and thickness.

However, where a second conductor was present, i.e., in the Madison area with the deep Mount Simon shale, conductive overburden, or conductive lake sediments, in addition to the thin and fairly deep Eau Claire shale unit, the method was unsuccessful in detecting the Eau Claire shale, or the results were somewhat inconclusive. The presence of the second conductor resulted in the ambiguity of the results. As shown in the forward modeling, the second conductor introduced greater uncertainty and nonuniqueness into the model results than a thinning and decrease in resistivity contrast between the units. The method can reliably detect a single conductor but in the case of two possible conductors, TEM cannot reliably determine whether the shallow, the deep, or both conductors are present.

The method was successful in mapping an increase in resistivity that may correspond to a facies change or thinning of the Eau Claire Formation from Arena, Wis. to Spring Green, Wis. This result corroborates a hydrogeologic interpretation of wells logs in Sauk County that was used to gradually vary the hydraulic conductivity of the Eau Claire Formation in a groundwater flow model for that county.

Recommendations

Care should be taken when inverting TEM data at locations where two conductors both might be present. A simple test for nonuniqueness is to create three models, one with the shallow conductor, one with the deeper conductor, and a third model that includes both conductors. Model fit, here we used RMS error, will then determine whether or not one or both layers are necessary to fit the data.

The nonuniqueness might be overcome by using several different sized transmitter loops that are "tuned" to different depths. Smaller loops will sense only the shallow but not the deeper conductor. In addition to using several transmitter loop sizes, measuring more than one component of the secondary magnetic field may help to verify whether 2D or 3D geology is present beneath the site.

IX. References

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X. Appendix A – Publications and Presentations

Publications

Anderson, M.L. Use of the Time-Domain Electromagnetic Method for Determining the Presence and Depth of Aquitards. Master's Thesis. University of Wisconsin. 2003. pp. 143. (Title Page and Abstract are attached)

Presentations

Anderson, M.L., D.J. Hart, and D.L. Alumbaugh. Use of the Time-Domain Electromagnetic Method for Determining the Presence and Depth of Aquitards, abstract in American Water Resources Association – Wisconsin Section, 27th Annual Meeting, 2003.