# GEOLOGICAL AND GEOPHYSICAL FIELD INVESTIGATION

# DEER CREEK LAKE

*Plymouth County, Iowa*

prepared for

## IOWA DEPARTMENT OF NATURAL RESOURCES
## - LAKE RESTORATION SECTION -

September 6, 2012

Prepared by

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# 1.0 INTRODUCTION

A dam was constructed across Deer Creek in the mid 1990s and was intended to form Deer Creek Lake (DCL) located in Sioux Township, Plymouth County, Iowa. The intended purpose of the lake was for recreational activities such as fishing, boating, and swimming. After the dam was constructed, the lake did not reach its designed full pool level of 1,252 feet above sea level (asl). Subsequently, several engineering consulting firms and multiple sections of the Iowa Department of Natural Resources (IDNR) have collaborated in an effort to better understand the issue and find an economically viable remedy.

The following section provides a brief summary of the work performed relating to the design, construction, and subsequent lake level investigations of DCL. This summary is not intended to be comprehensive in nature and is limited to the information that was provided to the Iowa Geological and Water Survey (IGWS) prior to the issuance of this report. All previous reports should be reviewed to acquire a complete understanding of the efforts made by others in conjunction with this project.

## 1.1 Project History

In November 1986, Patzig Laboratories Company, Inc. (Patzig) conducted a Preliminary Geotechnical Investigation for the proposed DCL dam. The project included drilling three borings (BH-1, BH-2, and BH-3) to depths of 35.5 feet, 34.5 feet, and 45 feet below ground surface (bgs), respectively. Bedrock encountered in borings BH-1 and BH-3 was clay shale while boring BH-2 encountered weathered limestone and sandstone. Information from the Patzig 1986 report was included in a Feasibility Study that was conducted by Brice, Petrides-Donohue & Associates, Inc. (BPD&A) in 1987. The Feasibility Study investigated multiple aspects that would affect the presence of a lake at the proposed site such as: geology, geomorphology, watershed features, hydrologic setting, soil properties, and impacts to both natural and cultural resources. The report recommended that the proposed site for the dam was feasible and provided construction specifications for the proposed dam.

In August 1992, a Geotechnical Exploration was conducted by Patzig and included drilling nine borings to supplement the three borings they drilled in 1986. The purpose of the additional borings was to provide more detailed information during final planning stages of the proposed dam. Based on the location of the additional borings, it appears that the proposed location of the dam was moved slightly to the south. Six of the borings (BH-4 to BH-9) ranged in depth from 30 to 40 feet bgs and were focused in the area of the proposed dam. Borings BH-5, BH-6, and BH-7 encountered siltstone and clay shale bedrock while boring BH-4 encountered uncemented sandstone followed by clay shale. Boring BH-8 did not encounter bedrock. Borings BH-9 to BH-12 ranged in depth from 15 to 20 feet bgs and were located in upland areas for the purpose of identifying potential borrow sites. The report also stated that evidence of an apparent historic landslide was observed about 300 feet downstream of the existing siltation structure on the west bank of the creek valley.

In November 1992, Patzig issued an Addendum No. 1 to the Geotechnical Exploration report. This addendum addressed the identification of a historic landslide observed on the west abutment of the valley, in the vicinity of the proposed dam, and that additional remedial efforts would be required to avoid compromising the dam. According to the addendum, the dam was relocated approximately 400 feet north of the previous site. Seven additional borings (BH-13 to BH-19) were drilled to depths ranging from 30 to 40 feet bgs to investigate the subsurface conditions at the new site. Borings BH-13 to BH-18 were placed in the footprint of the proposed dam and all except BH-15 encountered siltstone/clay shale bedrock. Boring BH-15 encountered shale with interbedded limestone followed by limestone. Boring BH-19 was located near the top of the west-adjacent hill to identify potential borrow material for the dam.

In August 1996, Geotechnical Services, Inc. (GSI) conducted a Geological Investigation at the site. The investigation included five exploratory borings, however only three of the borings were located in the vicinity of the dam (BH-2, BH-3, and BH-4), which were drilled to depths of 54, 65, and 80 feet bgs, respectively. According to the GSI report, all three borings encountered limestone and shale bedrock. The report indicated that the limestone portions of the borings appeared to be highly weathered and fractured allowing significant loss of drilling fluid. The report concluded that the leakage of the lake was likely due to openings within the limestone layers of the Greenhorn Limestone, particularly through a zone at approximately 1,220 to 1,235 feet asl.

In September 1996, Advanced Engineering, Inc. (AEI) issued a report discussing the previous work performed at the site and presenting findings based on the recently completed GSI borings (described above). According to the report, an engineer from AEI and personnel with the IDNR visited the site in the spring of 1996 to inspect the lake and dam, when it was decided that placing dye in the lake away from the dam would be done. The report indicated that the dye testing revealed water leaking from the lake into the bedrock and flowing past the dam. According to the report, the AEI engineer conducted a visual inspection of the entire lake shore and did not identify bedrock exposed at the surface of the lake or dam. AEI hired GSI to perform borings (as described above), and according to the report, water was flowing too fast in the boreholes to install water level devices or to properly set monitoring well casings. The report states that dye was detected discharging from the seep almost instantly after being placed in the boreholes. The report concluded that the lake would not reach full capacity due to the presence of a fractured layer of limestone bedrock that is allowing lake water to flow underground and around the west side of the dam.

In March 2011, the Schemmer Associates, Inc. (Schemmer) conducted a Revised Geotechnical Exploration at DCL in response to the failure of previous attempts to remedy the lake level issue. According to the report, a grout curtain was installed by others in 1999 in an effort to stop the subsurface seepage of water from the lake around the west side of the dam, however, records indicate that the grout curtain did not have any effect on the seepage of the lake. As part of Schemmer's project, four additional borings were drilled in the upland areas west of the dam (BH-1 to BH-4) to depths of 100, 105, 45, and 70 feet bgs, respectively. According to the report, the bedrock encountered in each boring was clay shale. Furthermore, by comparing the top of bedrock elevation among the four borings, a bedrock low was identified in the vicinity of the power lines south of the western portion of the lake. The elevation of the bedrock at borings BH-1 and BH-4 is approximately 1,260 feet asl and at borings BH-2 and BH-3 is approximately 1,224. The report indicated that the bedrock low was likely due to faulting of the bedrock causing vertical displacement. Additionally, the report states that streams in the region occur in a dendritic pattern and that evidence of faulting was supported by the notion that dendritic stream patterns are often indicative of bedrock faulting. The report concluded that leakage from the lake was flowing through permeable sand layers that were deposited in the bedrock low and that the path of the leakage water was much further west of the dam than previously thought.

On March 21, 2011, IGWS staff members met with staff from the IDNR Lake Restoration and Water Quality Improvement Program, Fisheries, and Engineering Services to listen to a presentation by Schemmer, concerning their preliminary investigation to rehabilitate DCL. Schemmer was contracted to assess the continued leakage problem at DCL. Schemmer indicated that their preliminary study suggests that a second grout curtain should be installed in several phases in areas identified as bedrock anomalies (faults) as shown in their report. It was suggested by IGWS geologists that these anomalies most likely represent fractures in the limestone units within the Greenhorn Limestone rather than faults. In addition, comments were made at that time as to whether the IDNR could afford another grout curtain without some assurance that this remedial measure would be effective. It remained uncertain if the source of the ongoing leakage is located at a distance west of the dam, as suggested by Schemmer; immediately west of the dam, or underneath the dam.

The IGWS proposed a geophysical investigation as a more cost effective, efficient, and minimally-invasive approach to assess the subsurface geologic package at the site. The goal was to assist in the identification of potential pathways of leakage, as well as obtain a more complete geologic understanding of the site to aid in further discussions on remediation efforts.

Geophysical field work was completed on-site May 14 to 18, 2012, by IGWS geologists Jason Vogelgesang, Robert Rowden, and geologic field assistant Carolyn Koebel. In conjunction with the geophysical survey, IGWS geologists Robert McKay, Ryan Clark, and Section Supervisor Deborah Quade were on-site May 15, 2012, to conduct field observations.

# 2.0 GEOLOGIC HISTORY & SETTING

## 2.1 Surficial Geology & Geomorphology

The Deer Creek Lake (DCL) area lies on the western edge of the Northwest Iowa Plains landform region. This region is typified by a distinct branching drainage network providing broad valleys and gently rounded interstream divides. The uplands are characterized by thick Wisconsinan loess deposits underlain by Pre-Illinoian tills, with overall thicknesses exceeding 200 feet. Occasional alluvial deposits within the glacial sediments indicate periods of erosion between glacial advances and windblown loess deposition. The Pleistocene glacial deposits are not prone to yielding groundwater in significant quantities, however, interbedded alluvial deposits may host locally productive zones of perched groundwater. Stream valleys in the DCL area are characterized by a mixture of thinly bedded silty, sandy clay overlying till. Very few streams in the DCL area have the erosional strength to erode into bedrock; although, as seen in the project area, steep cutbank walls in some streams may expose bedrock upon slumping of the overburden onto the valley floor.

## 2.2 Bedrock Geology

Bedrock exposures in the DCL area are not common and are typically confined to the Big Sioux River valley located about 5 miles to the southwest. Much of what is known about the bedrock in the DCL area comes from drilling records. Borehole locations are provided in Appendix I. Due to the variability observed in the lithologic descriptions between the borings performed by different parties, correlation of geologic units in the DCL area is very difficult. Appendix II illustrates the lithologic variability among select boreholes.

Initial bedrock encountered at the DCL area belongs to the Cretaceous (~91 to 104 million years) Greenhorn Limestone. Underlying the Greenhorn Limestone in the DCL area is the Graneros Shale followed by the Dakota Formation.

***Greenhorn Limestone***

The Greenhorn Limestone is typified by limestone, in part argillaceous to shaly, with thin to medium bedded chalks and increasingly interbedded with clay shales near the base. The deposition of the Greenhorn Limestone took place in a shallow, near-shore shelf environment where pulses of terrigenous sediment from inland streams interrupted the carbonate/chalk deposition in the warm, shallow seaway. As the sea continued to advance inland (transgression), the terrigenous input dwindled allowing increased faunal occupation in the DCL area. The limestone of the Greenhorn Limestone is known to exhibit karst features, such as solution cavities, as noted by fluid loss during drilling of area wells. The limestone units of the Greenhorn Limestone hosts abundant pelecypod (*inoceramus sp.)* fossils and scattered fish fragments occurring sparsely throughout the formation. Microscopic foraminifera fossils occur throughout the limestone units of the Greenhorn Limestone and are the primary components of the chalk deposits.

The thickness of the Greenhorn Limestone in the DCL area varies; however, based on drilling records in and around the lake, it appears to reach a maximum thickness of about 20 feet in the area west of the dam. The limestone units of the Greenhorn Limestone in the DCL area are typically very fine grained to microcrystalline in texture commonly with a light gray to light brown color. Chalk layers within the formation are off-white to light gray in color and may appear as greasy residue in drilling samples. The thin to medium interbedded clay shales within the Greenhorn Limestone appear brown to olive green to gray and are generally calcareous and partly bentonitic, with sparse fish and plant fragments. The contact between the Greenhorn Limestone and the underlying Graneros Shale is typically gradational.

***Graneros Shale***

The Graneros Shale in the DCL area consists primarily of dark gray to black, calcareous, silty clay shale. Lime-rich streaks occur throughout the formation. Some beds within the Graneros Shale are fossiliferous with pelecypod (*inoceramus sp.),* fish, and plant fragments. The formation becomes less calcareous as it grades into the non-calcareous shales of the underlying Dakota Formation.

## 2.3 Deer Creek Lake Sample Description

On May 15, 2012, IGWS geologists visited the site to investigate the occurrence of water seeping from the valley wall downstream of the DCL dam. It was observed that the water seeping out of the valley wall was flowing from exposed bedrock that had been exhumed by historic slumping of the overlying unconsolidated material and vegetation. Using a hand shovel, IGWS geologists excavated an area that appeared to be discharging the most water. All of the rock dug from this part of the seep appeared to be limestone. One representative sample was collected from that area for petrographic analysis.

The rock sample collected from the seep was cut and slightly polished in order to gain the best cross sectional view of the rock (Figure 1). This rock is a tan-yellow, very fine grained to microcrystalline argillaceous limestone and part inoceramite packstone. This rock also exhibits up to approximately 30% porosity (Figure 2) as noted by abundant pore spaces between the grain boundaries.

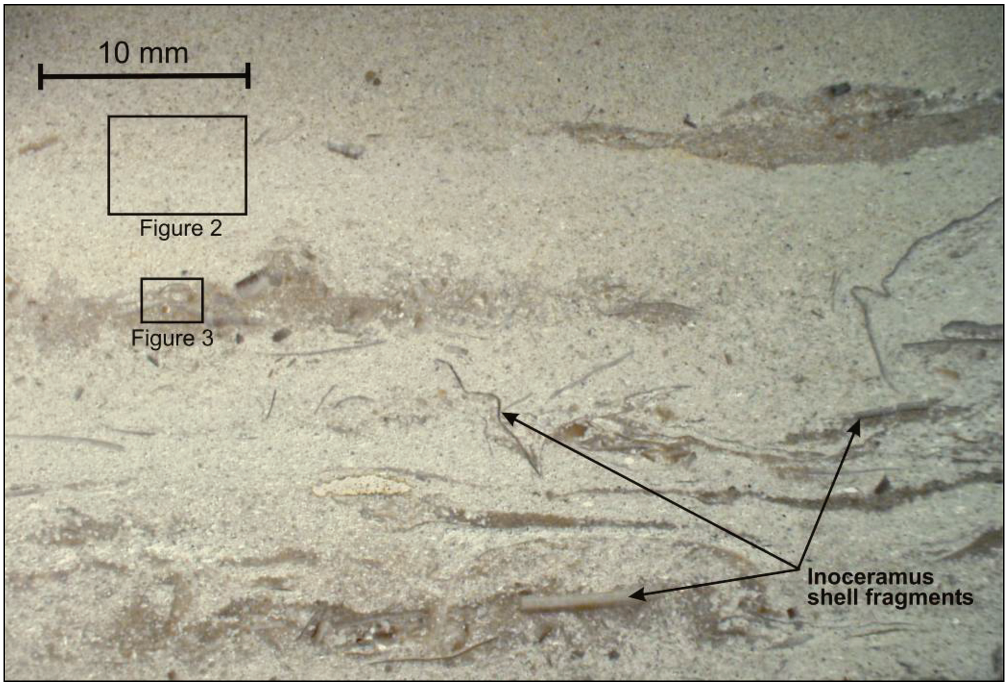


**Figure 1.** Slab cut from limestone sample collected at the mouth of the seep. Note distinct zones of inoceramus shell debris mixed with clay surrounded by fine grained matrix. The image is oriented such that up is toward the top of the page.

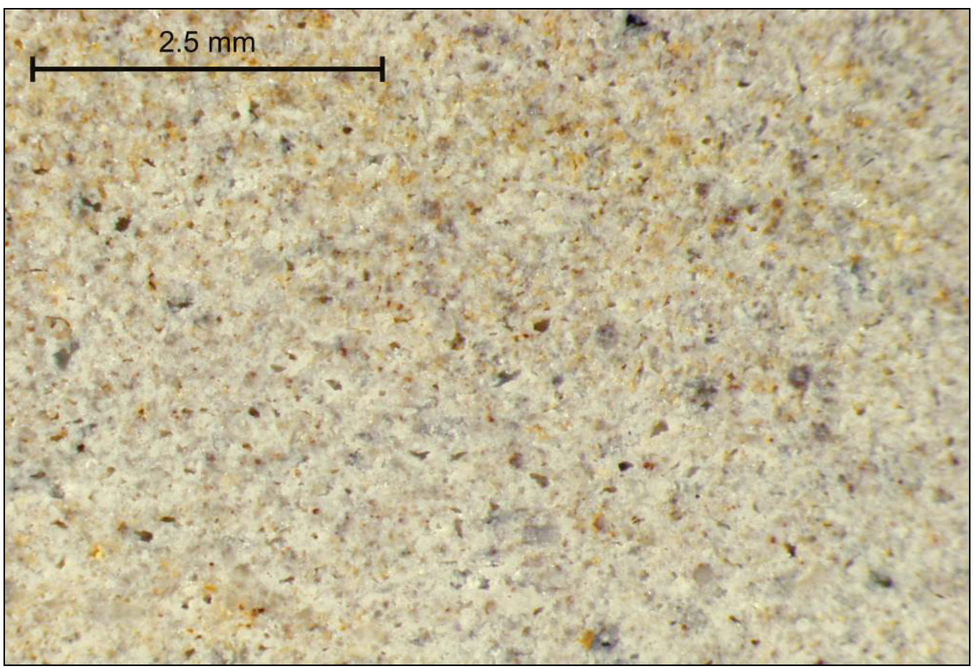


**Figure 2.** Close up view showing abundant pore spaces within the microcrystalline texture of the limestone sample. The primary component of this rock is minute shell fragments and calcite crystals.

Foraminifera are also abundant in this rock (Figure 3), primarily concentrated in zones where shell fragments have accumulated.

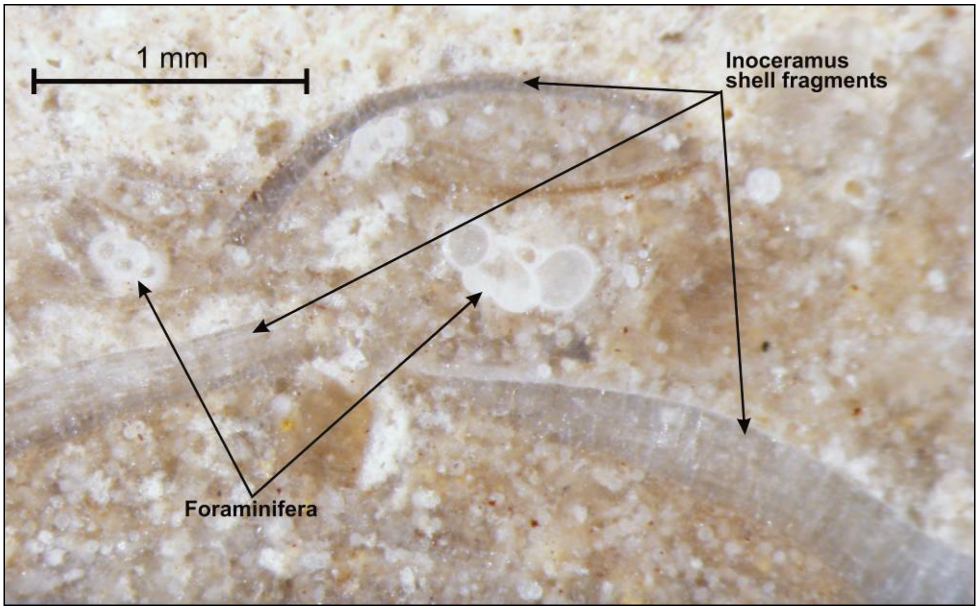


**Figure 3.** Close up view of accumulation zone of shell fragments and foraminifera fossils. These zones also show increased clay content versus the less fossiliferous zones.

Microscopic analysis of a thin section made from this rock sample reveals the true abundance of calcite crystal fragments, shell debris, and foraminifera fossils that make up the limestone unit of the Greenhorn Limestone in the area of the seep (Figure 4).

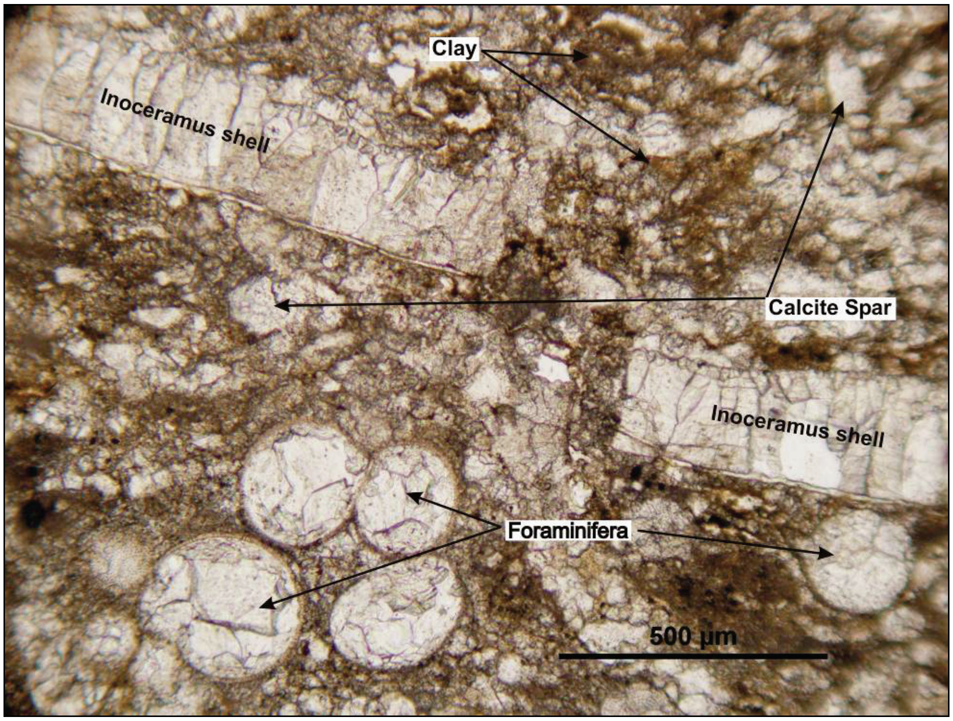


**Figure 4.** Photograph of thin section taken from same sample as Figure 1. The inoceramus shell fragments have been completely recrystallized with calcite as is the case with the foraminifera fossils (scale 500 µm = 0.5 mm).

## 3.0 HYDROGEOLOGIC SETTING AND FIELD OBSERVATIONS

Carbonates such as the limestone units of the Greenhorn Limestone encountered in the subsurface at DCL are susceptible to fracturing due to its physical nature. Fractures increase porosity and can greatly increase permeability within a limestone or dolomite formation. In addition to mechanical weathering processes that cause fractures, carbonate rock is also highly susceptible to chemical weathering. Slightly acidic rainfall and its associated runoff can cause dissolution in carbonate rocks. This dissolution usually starts occurring on the uppermost surface when vulnerable bedrock is near the land surface and/or along fracture sets. When chemical weathering occurs in the subsurface, “karst” or cave-like passages are created, and the potential for large volumes of water to be transmitted greatly increases.

Evidence of karst conditions is noted in two of the three borings performed at the site in 1996 by GSI. Borings BH-2 and BH-4 identified broken/fractured limestone within the first seven feet of bedrock. The borehole log for BH-4 noted loss of drilling fluid in a fractured zone at an approximate elevation of 1,234 feet asl.

**Figure 5.** IGWS geologist exposes and examines the seep south of the dam. Images to the right show the limestone hand samples collected from the seep.

Figure 5 shows the observed seep southwest of the dam (see Appendix I for location). After removing vegetation and exposing the seep, visible signs of chemical dissolution and fracturing were observed in the exposed Greenhorn Limestone. A probable scenario is that this near surface carbonate formation had fractures along natural bedding planes and/or joints that have been enlarged by shallow groundwater flow.

**Figure 6.** Image of sinkhole feature.

A closed depression that indicates a possible dissolution cavity, or sinkhole (Figure 6), was identified near the south-central shore of the lake (see Appendix I for location). This feature is lower in elevation than the high water line, and was within two feet of the lake level at the time of field work. A borehole log from GSI boring BH-2, located approximately 100 feet SSW of the sinkhole feature, indicates limestone from the Greenhorn Limestone occurring at an elevation of approximately 1,231 feet asl. Similarly, the Survey A electrical resistivity model (Appendix IV) indicates a bedrock high in that area (see discussion below). Additionally, nearby GSI boring BH-3 lists a bedrock elevation of 1,233 feet asl. Lake water surface has reached an elevation of at least 1,239 feet asl based on IDNR LiDAR data gathered from December 2008, and possibly higher based on shoreline observations. A cross-sectional view of the geologic units west of the DCL dam is given in Appendix III. It can be determined that limestone units of the Greenhorn Limestone are in close proximity to the lake, especially on the southern shore. There may be countless other pathways such as the observed sinkhole feature through which water may travel hidden beneath the shoreline and/or lake sediments. The hydraulic head pressure from the lake likely puts stress on these bedrock voids, allowing groundwater flow to increase dramatically during times of high water level until equilibrium is reached.

# 4.0 GEOPHYSICAL METHODS

## 4.1 Electrical Resistivity (ER) Field Data Collection

An eight-channel SuperSting R8 Resistivity and IP meter (Advanced Geosciences, Inc.) was used to collect all ER measurements for the study, using multi-core cables and stainless steel electrodes supplied by the manufacturer. Electrodes were spaced at 6 meters along the ground surface, following the surveys shown in Appendix IV, and driven into the surface such that approximately 1 foot of the ~0.5 inch diameter electrode was below the ground surface. Data were collected using 56 electrodes in 768 unique combinations of four electrodes (a current pair and potential pair), using both dipole-dipole and Wenner configurations. After these data were collected, 14 electrodes from the east of the line were relocated to the west end, and data collection repeated in a "roll along" fashion (resulting in a single data set along the entire transect length combining all observations).

Surveys A and B consist of 6,331 and 4,576 observations, respectively. To quantify error in the field, two measurements were stacked (i.e., averaged) for each electrical measurement. If the standard deviation was greater than 2% of the mean value, a third measurement was included in the average. If the standard deviation of the three measurements was greater than 2% of the mean value, the three measurements were repeated once. Average measurement errors quantified by repeatability of individual measurements were 0.18% and 0.32% for Survey A and B, respectively. Reciprocal data were not collected to quantify error, as this would have substantially increased collection time.

## 4.2 Electrical Resistivity Data Inversion

Data were inverted using an error-weighted, smoothness-constrained "Occam's type" inversion code (R2, v2.7, http://www.es.lancs.ac.uk/people/amb/Freeware/freeware.htm). The inversion mesh was 6 meters × 6 meters for the area encompassed by each transect, and was extended and coarsened laterally beyond the transects and vertically below the surface after 120 meter depth to provide appropriate boundary conditions while minimizing computational demands. Because the inversion problem is both ill-conditioned (small data errors can lead to large model errors) and ill-posed (solutions are non-unique), regularization in the form of a smoothing constraint was applied. We assumed an error model of 0.001 Ohm absolute error in field data and a relative error of 2% of the resistance value for all field measurements. We excluded measurements with apparent resistivities greater in magnitude than ±10,000 Ohm-m, as these are likely to be erroneous (typically having a low signal-to-noise ratio). We rejected 15 and 63 measurements for the A and B transects, respectively (the larger number for B owing to an electrode cable that was temporarily disconnected during data collection). Data were initially weighted equally in the inversion process, and individual weights were updated (decreased only) during subsequent iterations. Final inversions converged to root-mean square error of 1.36% for both the A and B transects.

After data inversions were complete, a resolution matrix was calculated for each transect. Values of the resolution matrix range from zero to unity, with values close to unity indicating perfect resolution and values close to zero indicating less certainty about the resistivity value assigned to a given pixel.

The results of the inversion process are spatial distributions of electrical resistivity in the subsurface, and represent the best-fit solution given the data collected. The images represent a physical parameter (electrical resistivity), that can be effected by a number of factors, including but not limited to material type, material compaction or cementation between grains, fluid content, dissolved ions in pore fluid, and biological species present in the pore spaces). Interpretation of these data must be in the context of additional information at the site (e.g., borehole logs, geologic history of the site and region).

## 4.3 Spontaneous Potential (SP) Field Data Collection

An eight-channel SuperSting R8 Resistivity and IP meter (Advanced Geosciences, Inc.) was used to collect all spontaneous potential (a.k.a., "self potential," "streaming potential") measurements for the study, using multi-core cables and non-polarizable Copper – Copper-sulfate electrodes supplied by the manufacturer. Data were collected by installing the electrodes in the shallow subsurface at a spacing of approximately 1 meter, with the electrode itself 4 to 6 inches below the ground surface. All observations were collected relative to an electrode located at the west edge of the dam. The same reference electrode was used for both the E-W and N-S observation sets. The difference in potential between the reference electrode and the observation electrodes was recorded.

Spontaneous potential surveys were designed to identify areas of preferential groundwater flow through the subsurface. Such locations would be identified in the data as a location of anomalously high or low spontaneous potential. Spontaneous potential can also be affected by temperature gradients, solute concentration gradients, redox gradients, telluric current fields, vegetation present, and buried metal objects. As with electrical resistivity, these data should be interpreted in the context of other information known about the site.

## 5.0 DATA SYNTHESIS AND FIELD OBSERVATIONS

Geophysical techniques were used in this field survey as a means of assessing site geology, as it relates to the inability of forming Deer Creek Lake at full pool. Electrical resistivity seeks to use direct current as a way of modeling the subsurface. The model provides a "best-case" look at how the subsurface variably responds to electrical influence. It is the hope of this technology to assist in "connecting the dots" when only point data are known. Due to the many factors that can influence the final models mentioned above, these images must be compared to existing borehole and site information. Borehole logs from previous site characterization efforts conducted by Schemmer, GSI, and Patzig were analyzed, and were used to help understand the electrical resistivity models.

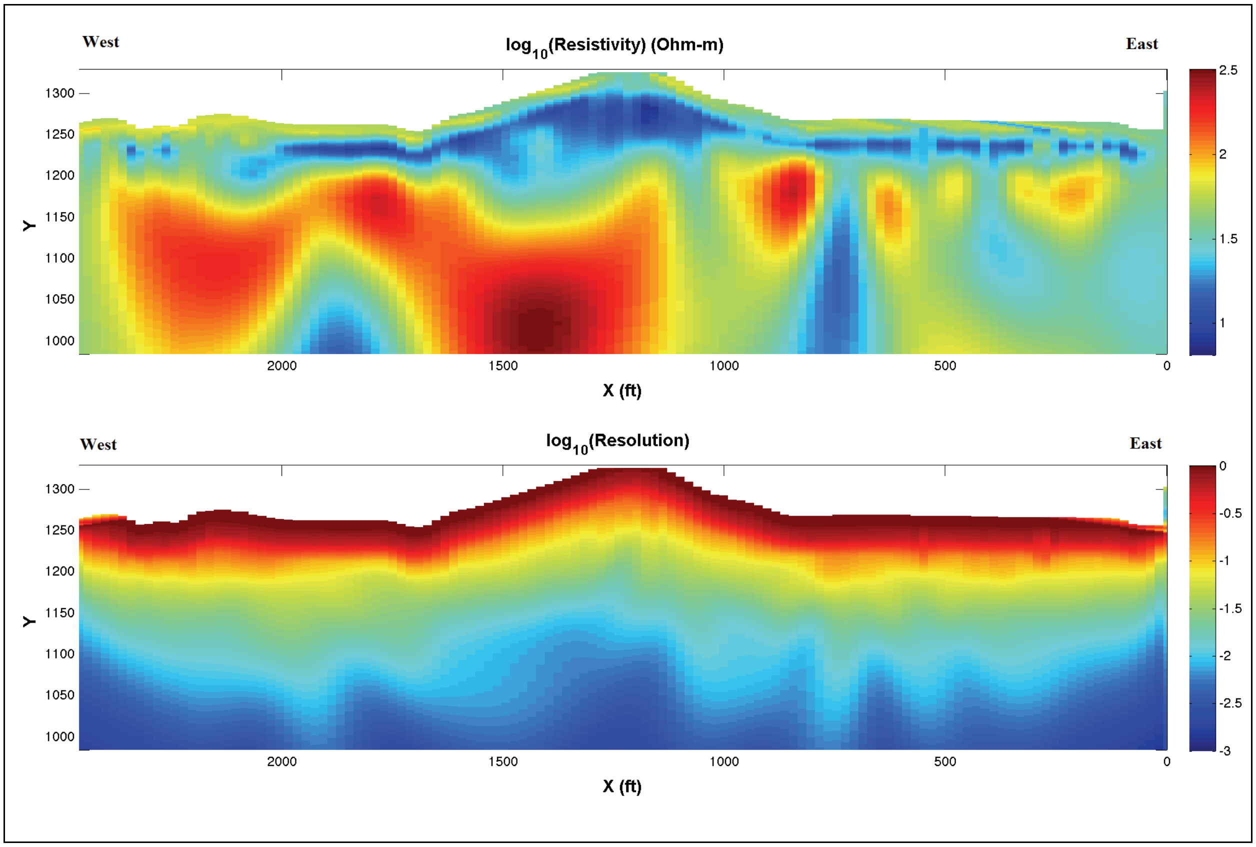


**Figure 7.** ER Survey A model (top) and associated resolution (bottom). X axis shows distance in feet. Y axis shows elevation in feet above sea level.

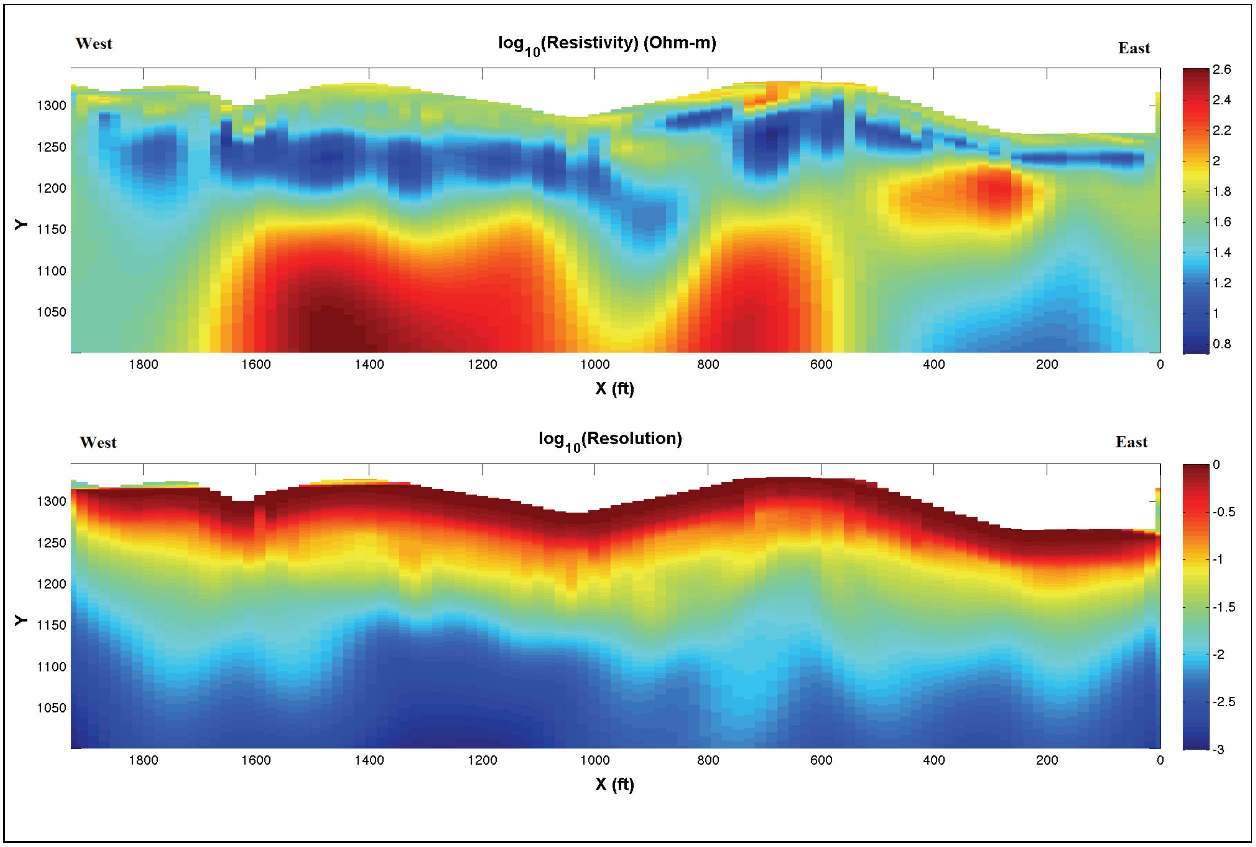


**Figure 8.** ER Survey B model (top) and associated resolution (bottom). X axis shows distance in feet. Y axis shows elevation in feet above sea level.

Figures 7 and 8 show resistivity models and associated resolution for Surveys A and B, respectively. Images are shown west to east, when viewed left to right. Pixels in model images containing resolution values less than -2.5 were not considered in this study to increase data confidence. The location for ER Surveys A and B are shown in Appendix IV. Models have been corrected for elevations at each electrode location to accurately depict topographic changes through the use of IDNR 3 meter LiDAR elevation data. Resistivity is shown on a logarithmic scale, with red representing high resistivity, and blue low resistivity.

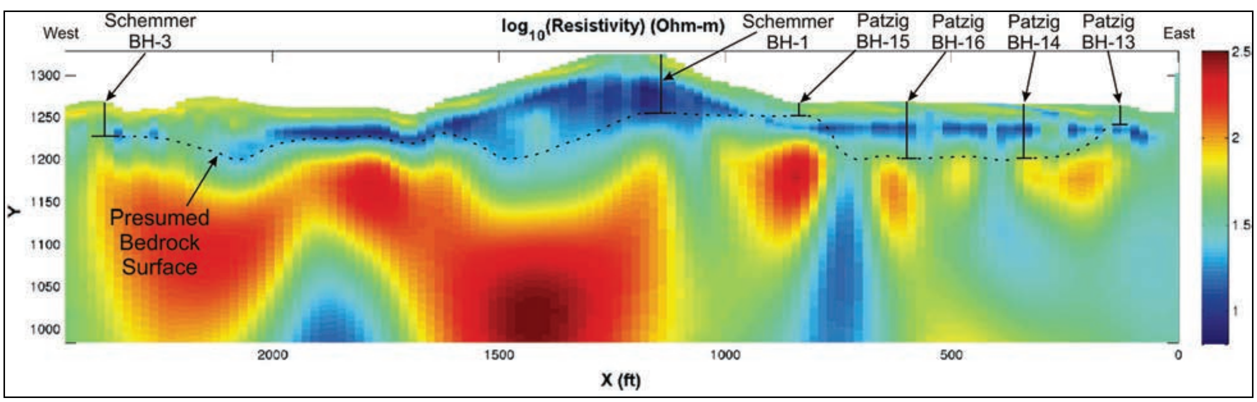


**Figure 9.** ER Survey A model with inferred bedrock surface interpretation.

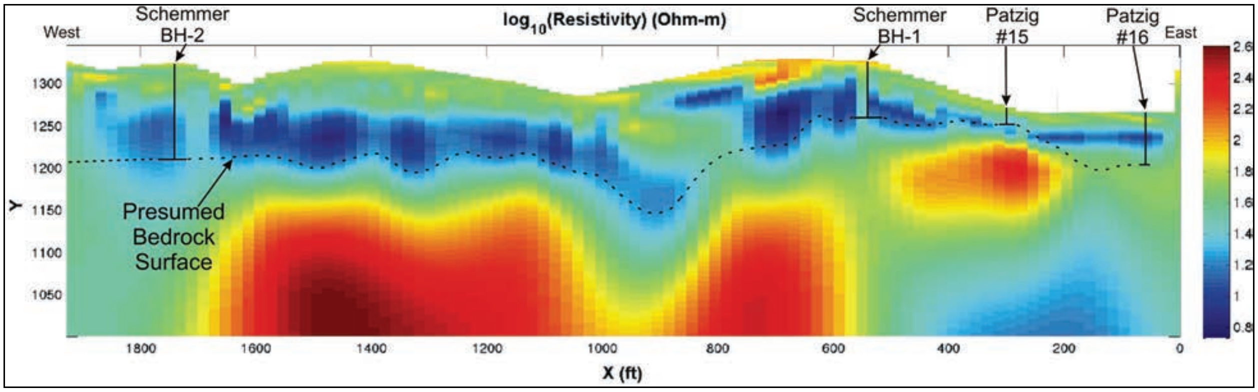


**Figure 10.** ER Survey B model with inferred bedrock surface interpretation.

Figures 9 and 10 show an interpreted bedrock surface overlaid on the ER Survey A and B models, respectively. Boreholes showing known bedrock depths used in correlation of the surface are noted above each occurrence. Although many factors can influence resistivity values, high values *generally* indicate course grained sediment or bedrock, while low values *generally* indicate fine grained sediments or water saturation (Burger, et. al., 2006). Through the use of electrical resistivity concepts, geologic interpretative techniques, lithologic borehole logs, and existing site information, an interpreted bedrock surface was indicated. Along both transects, this bedrock surface appears to be closest to the land surface near the observed seep. The bedrock surface appears to drop in elevation near the area of the power lines, possibly indicating an old stream channel. Models can be exaggerated, generalized, or otherwise variable, especially in areas of high resistivity or great depth. For this reason, it is difficult to make accurate interpretations at depth without data from boreholes that penetrate the entire model depth. The discontinuation of the highly resistive area generally below Schemmer boring BH-1 might represent a zone of voids with increased groundwater flow, variability in the bedrock surface, or model error. Prior to the geophysical survey, very little was known about the depth to bedrock in the area immediately around and near the power lines. Resistivity models have provided a look at how the bedrock surface depth may vary across the field area. Based on these models, it appears that the bedrock surface is closest to the land surface in an area immediately west of the dam, and east of the east parking lot.

SP was used at a location south of the dam (see Appendix IV for location). SP is useful as it seeks to identify areas with increased shallow groundwater movement. The goal for the SP surveys was to help determine if subsurface flow is occurring in areas hidden below the land surface. The seep was useful as it acted as a control, relating a value to a point where flow was physically observed at the land surface. Figure 11 shows the results from the SP survey. Data are plotted to show changes in voltages across SP Surveys A and B, with all values relative to a fixed location on the west edge of the dam. Abnormally high or low results could suggest increased groundwater flow in the subsurface. The seep seen at the surface correlates to approximately the 30-37 meter range noted along the X-axis of Figure 11. SP values in this range are higher relative to the reference electrode, but results do not conclusively identify other areas of increased flow. A possible area of increased groundwater flow could be on the west side of SP Survey B, but a more probable explanation would be that such flow would be related to the existing drainage pattern of the dam.

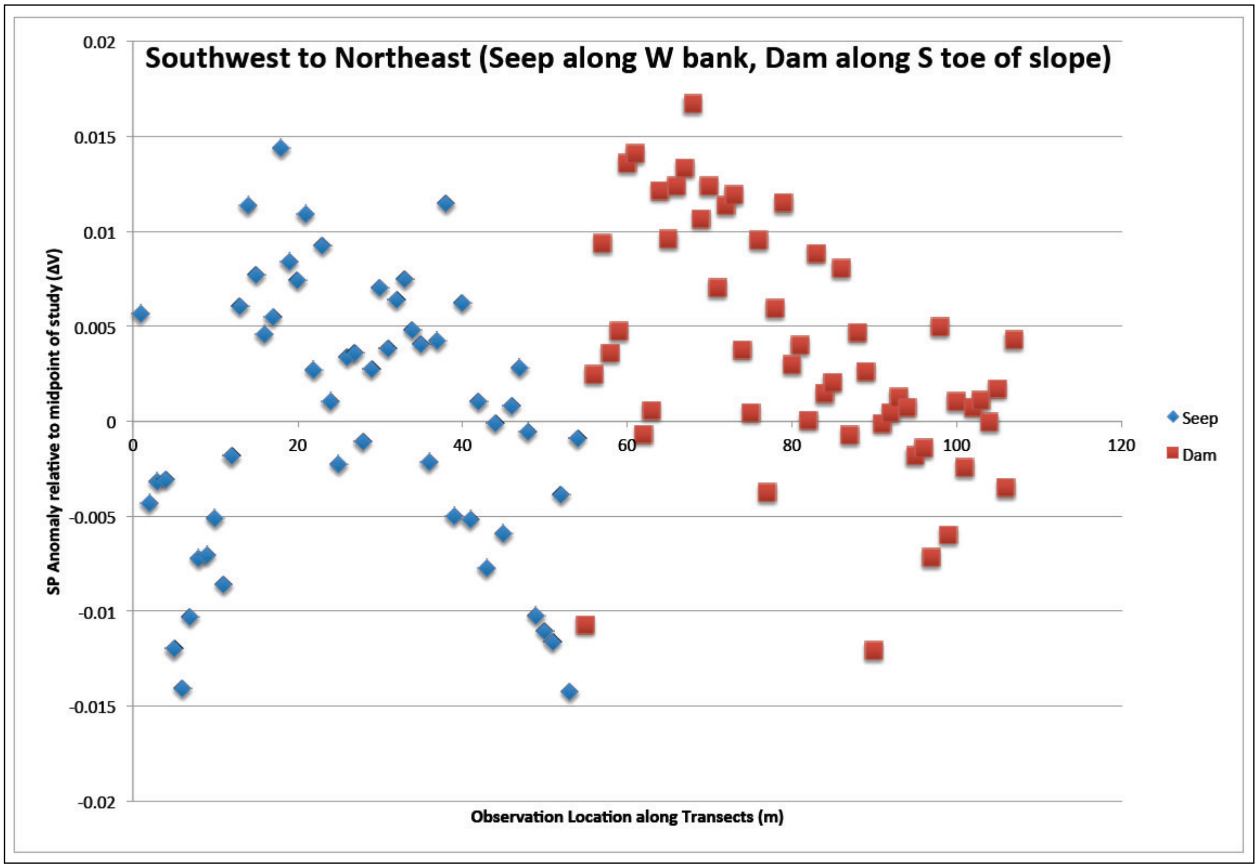


**Figure 11.** Scatter plot showing SP results for Surveys A and B, shown southwest to northeast.

## 6.0 CONCLUSIONS

After a dam constructed across Deer Creek in Plymouth County, Iowa, failed to create an intended full pool lake, many attempts to understand potential seepage pathways and remediation efforts were completed. A partial grout curtain was installed near the west end of the dam, with no effect in lake levels observed. A second grout curtain was recommended to be installed in an area generally under power lines that run through the site. IGWS staff proposed the use of electrical resistivity and spontaneous potential geophysics as a cost effective, efficient, and minimally invasive approach to assess the subsurface geologic package.

IGWS geologists completed a week of on-site field work, conducting geophysical surveys in pre-defined areas of interest (Appendix IV). Electrical resistivity models were produced representing interpreted subsurface models (Figures 7 and 8). In addition, a scatter plot showing spontaneous potential survey results was generated (Figure 11). The geophysical surveys, specifically the electrical resistivity models, improved geologic understanding of the site. The most useful outcome of the ER models was the ability to "connect the dots" from existing borehole data. An interpreted bedrock surface was identified, showing that bedrock appears to be closest to the land surface in an area immediately west of the dam, and east of the east parking lot. Before the ER model data, limited lithologic data existed, especially in the area near the power lines.

In addition to geophysics, IGWS geologists conducted a survey of the site to further examine the seep and lake shoreline. The seep was exposed and examined and it was found that water is discharging from voids in a limestone unit of the Greenhorn Limestone. Hand samples of the carbonate rock were examined in the field and collected for further analysis. During the site survey, a closed sinkhole feature was observed (Figure 6). The feature correlates to the GSI borehole BH-2 located approximately 100 feet SSW of the sinkhole feature, which indicates a limestone unit of the Greenhorn Limestone is likely within 10 feet of the feature. It is very probable that lake water is seeping though unconsolidated material into this and/or other hidden voids in the underlying limestone. While alluvial sands in the vicinity of the power lines cannot be discounted as a contributor of seepage, water moving through the limestone units of the Greenhorn Limestone by means of fracture sets, joints, bedding planes, dissolution cavities, or other void networks appears to be the main pathway for subsurface water loss from the lake.

## 7.0 RECOMMENDATIONS

Geologic knowledge has been gained about the DCL area through the use of geophysics and field observations. Additional methods of gathering site information exist, and might be considered to help pinpoint how and where subsurface flow is occurring. IGWS has access to the necessary equipment and services described below, if further work is desired.

Dye tracing would be an economical and potentially beneficial way to determine which part of the lake is more susceptible to seepage. For example, if dye was placed in or near the observed sinkhole feature, it could be determined whether that feature is contributing to seepage or not by measuring the concentration, if any, that is detected at the seep after a given time period. In addition, if time of travel could be determined it may provide insight on how large the void network is in the subsurface.

Since flow through carbonate voids is usually quick and relatively unfiltered, surface contaminants are often present in the outlet water. Water quality parameters collected at the seep compared to those collected from the lake could help determine whether the majority of seepage flow is occurring through bedrock voids or alluvial materials.

The most effective way to obtain more detailed knowledge of the subsurface in designated areas of interest would be to advance additional borings. Due to the variability in the lithologic descriptions among the boreholes at DCL, targeted borings examined by an IGWS geologist would provide a more detailed understanding of the geology at DCL. The borings should be completed into the Graneros Shale in order to gain access to the full extent of the Greenhorn Limestone. It is recommended that an IGWS geologist be present at the time of drilling to provide accurate lithologic descriptions. If requested, the IGWS could provide a preliminary boring location plan with estimated boring depths.

Additional geophysical work in areas of interest could aid remediation efforts. Further geophysical surveys would require additional borings along the transect surface for correlative purposes. If additional geophysics is not desired, the existing electrical resistivity models could be used to direct exploratory drilling in areas of interest that lack adequate geologic information.

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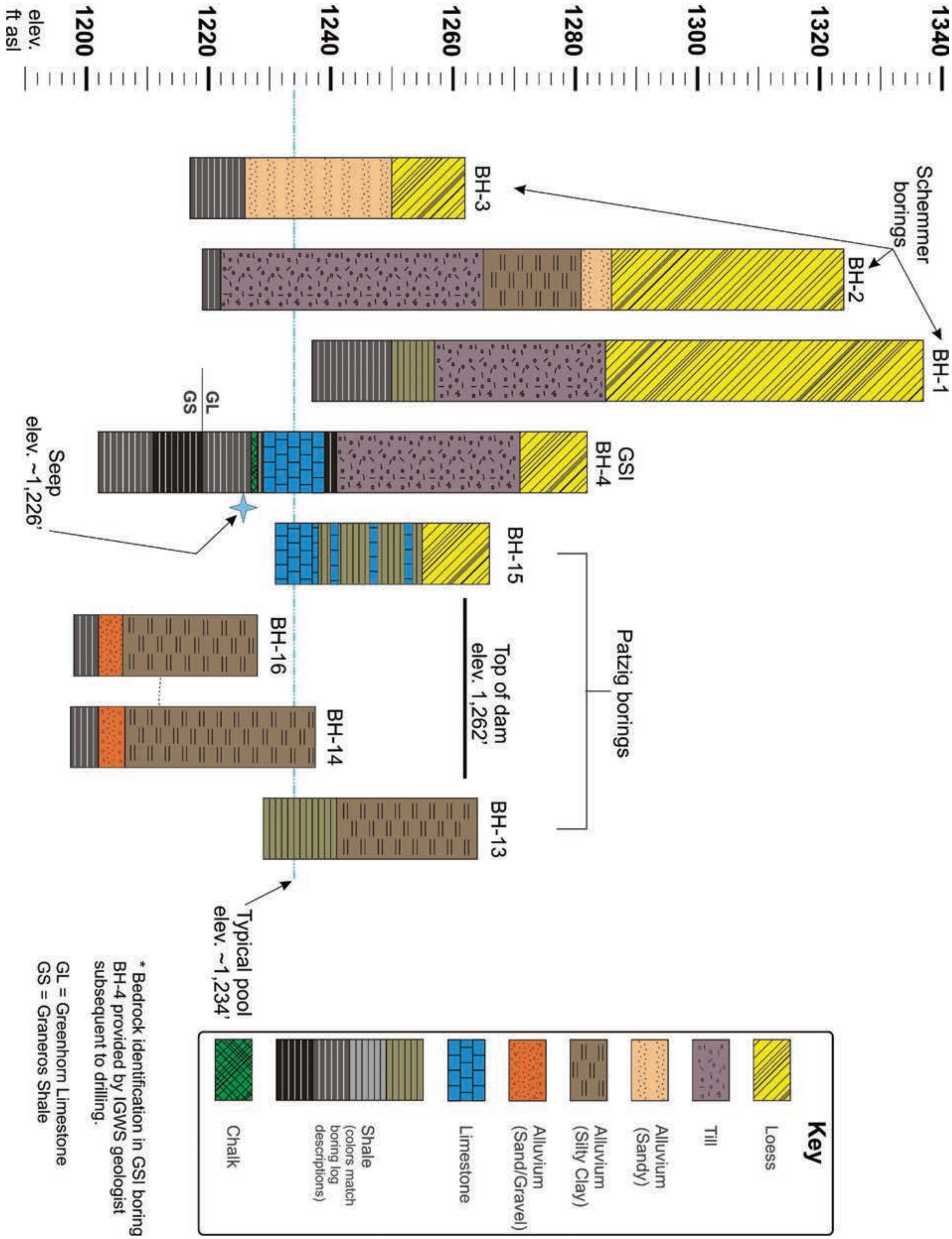
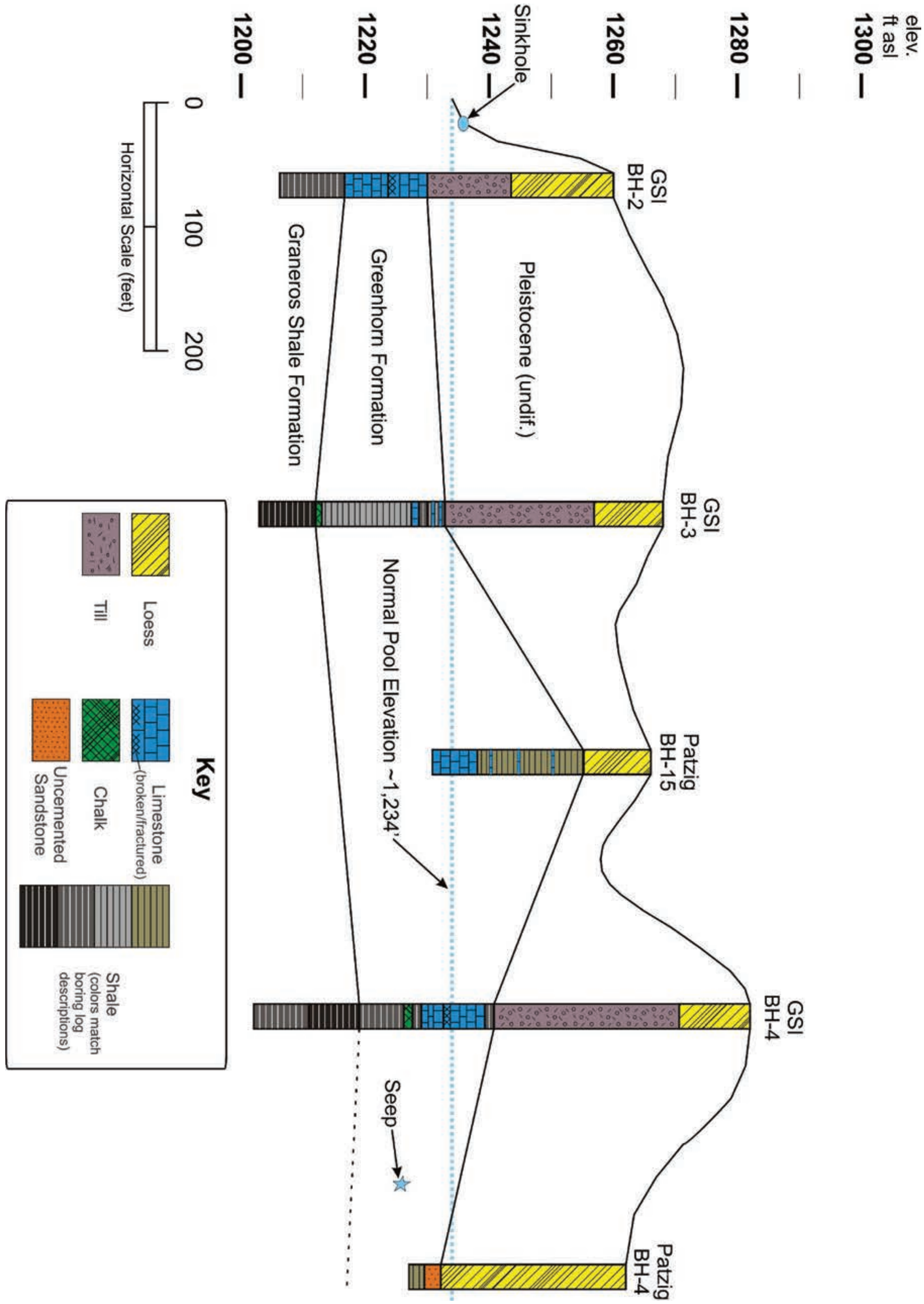
## APPENDICES

### *APPENDIX I – Site Plan*

*APPENDIX II – Borehole Record*



***APPENDIX III – North-South Cross Section***



*APPENDIX IV – Geophysical Survey Locations*