Ground-Water Exploration in the Worthington Area of Nobles County: Summary of Seismic Data and Recent Test Drilling Results

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Table of Contents

List of Figures

Appendix A

Appendix A List of Figures

1.0 Introduction

In 1996, the Minnesota Department of Natural Resources (DNR) and the City of Worthington drilled four deep test holes (725-979 feet) to hard rock (Sioux Quartzite or granitic basement) to help locate new aquifers for the city. The project was successful in locating several new aquifers at depths ranging approximately from 130 to 740 feet. The results of this test drilling project were summarized in "Southwestern Minnesota Groundwater Exploration Project, 1996-1997". The city and other potential appropriators in the area still faced the problem of defining the lateral extent of these aquifers so that the resources could be used in the most cost-effective manner. The quantity and distribution of existing well and test holes were not sufficient for defining most of the aquifers.

Therefore, in 1997, the DNR Geophysics Group began a project to help delineate one of these aquifers, the sub-Quaternary unit, with two-dimensional seismic technology. In June 1999, our interpretations from one of the seismic lines (WORE) were evaluated with a mud rotary test hole (616893 or 53-5) that was drilled through the base of the Cretaceous shale and sandstone section.

2.0 Project Objectives

An area map is shown in Figure 1. The trace of Cross Section B-B' (Figure 2) is shown on this map.

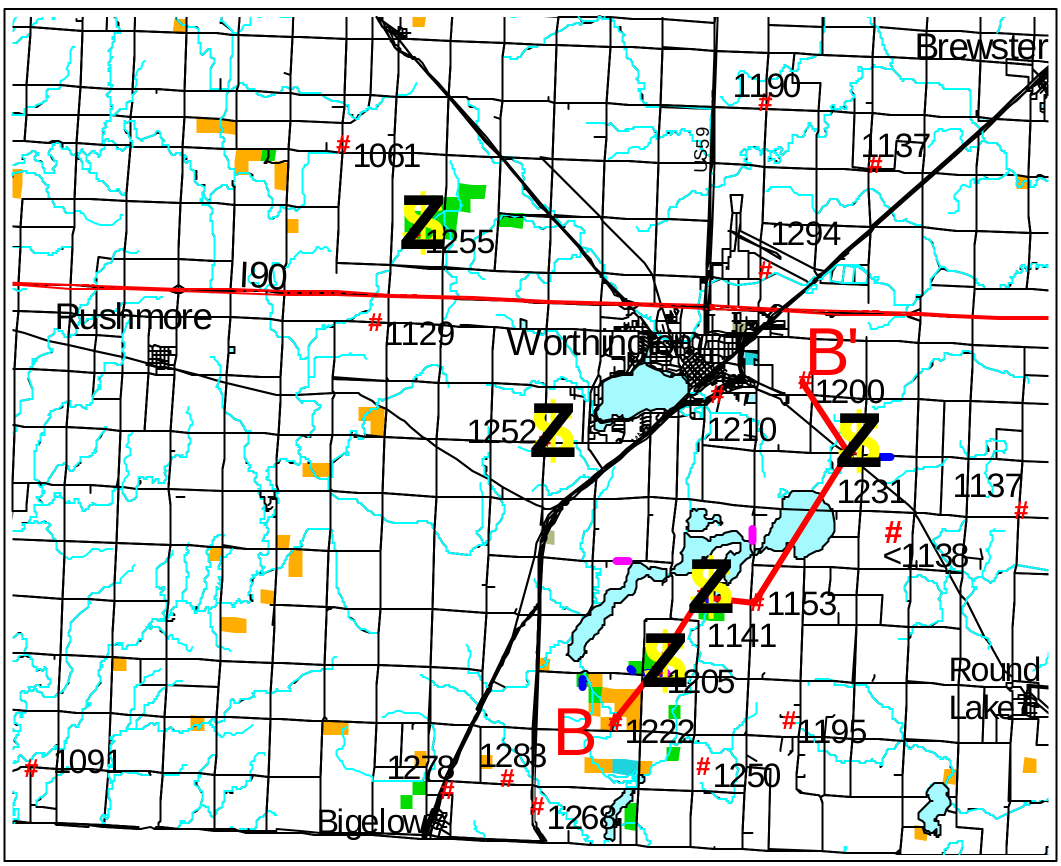

Figure 1. Worthington Area

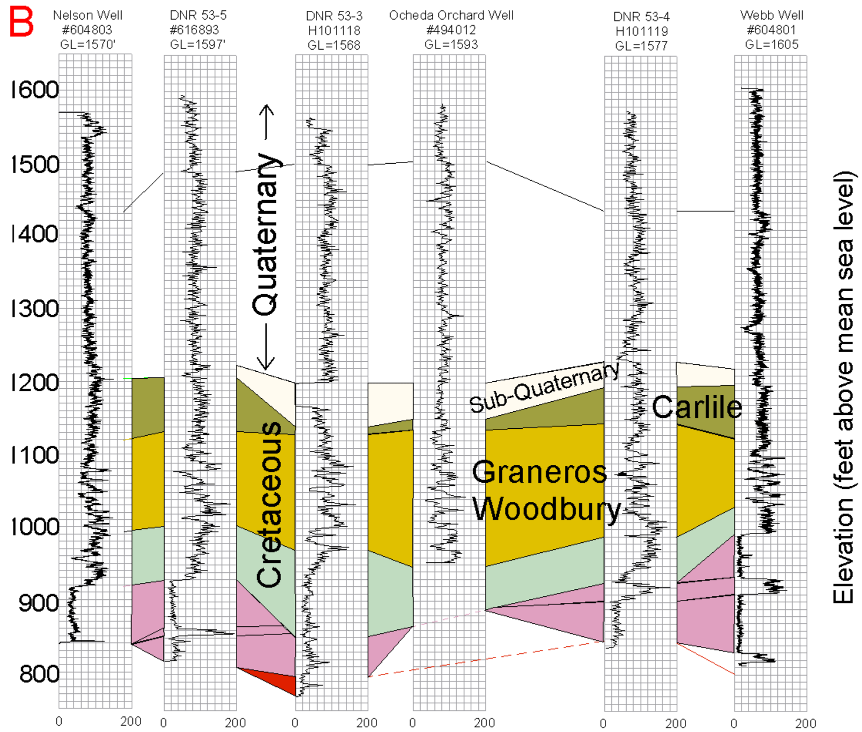

Figure 2. Cross Section B-B'

This cross section was made using gamma logs that were collected by the Minnesota Geological Survey, Minnesota DNR Waters, and Steffl Well Drilling. The left deflections of the curves (low gamma values) indicate the high quartz content of sand, sandstone, and weathered Sioux Quartzite (violet layer).

The area is underlain by a thick section of Quaternary glacial drift. This drift consists mostly of clay-rich till interbedded with layers of sandy outwash. Beneath the Quaternary section is a layer labeled sub-Quaternary. The primary objective of this latest exploration project was to define this layer. The sub-Quaternary layer is an accumulation of weathered sediments and fluvial sand from the Cretaceous and other bedrock that were exposed after the Cretaceous period but before the Quaternary period. Across the region, this unit may be one of the most prolific aquifers. Compared to shallower sand layers within the glacial drift it is generally thicker and more laterally continuous. Generally, the thickest and most prolific portions of this aquifer should occur where the top of the Cretaceous is deep (or low from an elevation point of view). Before we began the project we thought the top of the Cretaceous shale might appear as a reflector on a seismic reflection profile. Therefore, one project objective was to find a location where the top of Cretaceous shale exists at a relatively low elevation (1140 feet or below).

Other data needs included seismic velocity information of the entire sedimentary section. Seismic velocity is defined as the speed that sound waves travel through the sediment and rock layers. This information is required for calculating the actual depth to an acoustic reflector. In addition, reflections occur at significant velocity boundaries, so a velocity profile can be used to predict the occurrence of reflectors or analyze the actual depth of observed reflections. Therefore, a second project objective was to drill a test hole through the Quaternary sediments and Cretaceous sedimentary rocks and log their seismic velocities with a sonic log.

The third objective was to evaluate the lateral extent of the Dakota sandstone. The 1996 test-drilling project located a thick (approximately 100 feet) Dakota sandstone at the base of the Cretaceous shale section in test hole 53-3 (Figure 2). Little was known about the distribution of the sandstone and its relationship to weathered bedrock sand that has also been found in the area.

3.0 Two-Dimensional Seismic Reflection Survey

3.1 Refraction Feasibility Testing

Before the seismic reflection data was acquired we tested the feasibility of seismic refraction for determining the depth to Cretaceous shale. Three lines of refraction data were acquired at locations south of Worthington (Figure 3). The depth to hard Precambrian rock was relatively easy to determine with this data but the depth to Cretaceous shale could not be determined. An analysis of this problem is included in Appendix A along with other survey information. The limitation of the method in this instance is the thickness of the Cretaceous shale and sandstone in relation to depth. The Cretaceous section was too thin at a depth of approximately 400 feet to be detected by this method. Therefore, seismic refraction methods were abandoned in favor of seismic reflection.

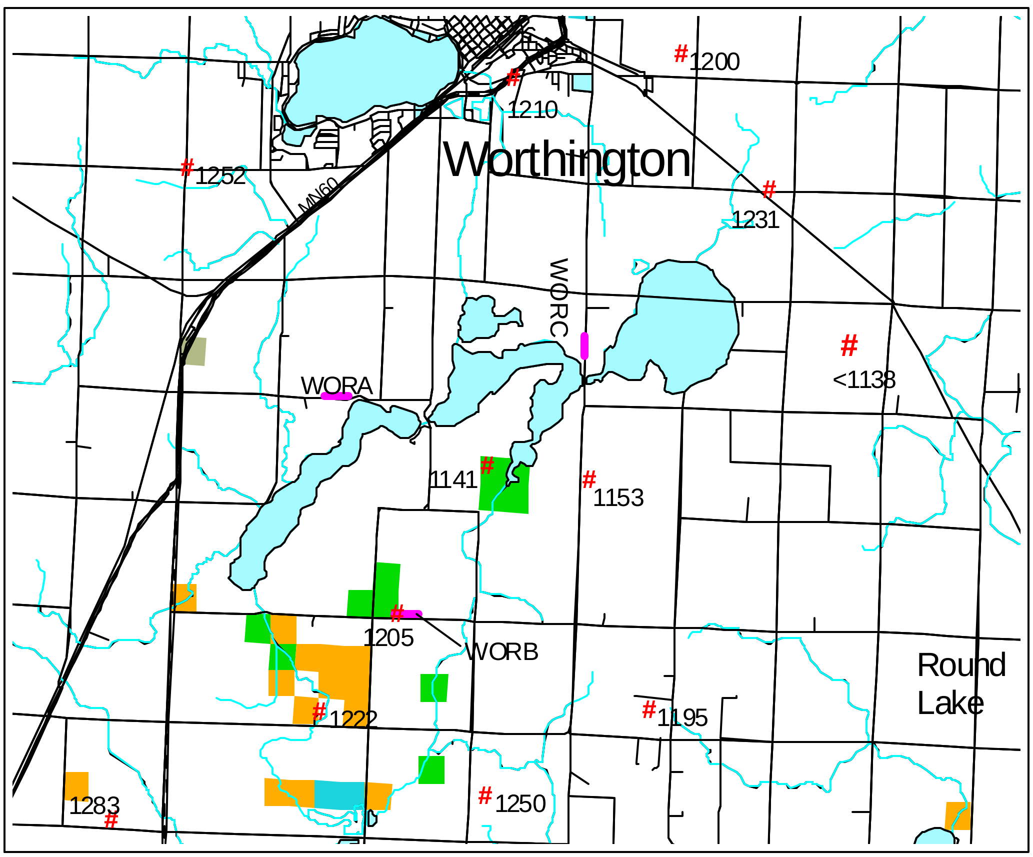

Figure 3. Seismic Refraction Line Locations

Seismic refraction line locations are shown as pink lines on the map. The red dots represent well log locations with reliable Cretaceous shale top information. The green squares and rectangles are DNR-owned land. The orange squares and rectangles are 1997 CRP land.

3.2 Seismic Reflection Line Placement and Acquisition Methods

Seismic lines WORD, WORE, WORG, and WORH (Figure 4) were placed in locations around test hole 53-3 location away from power lines. Power lines created significant interfering noise in this area.

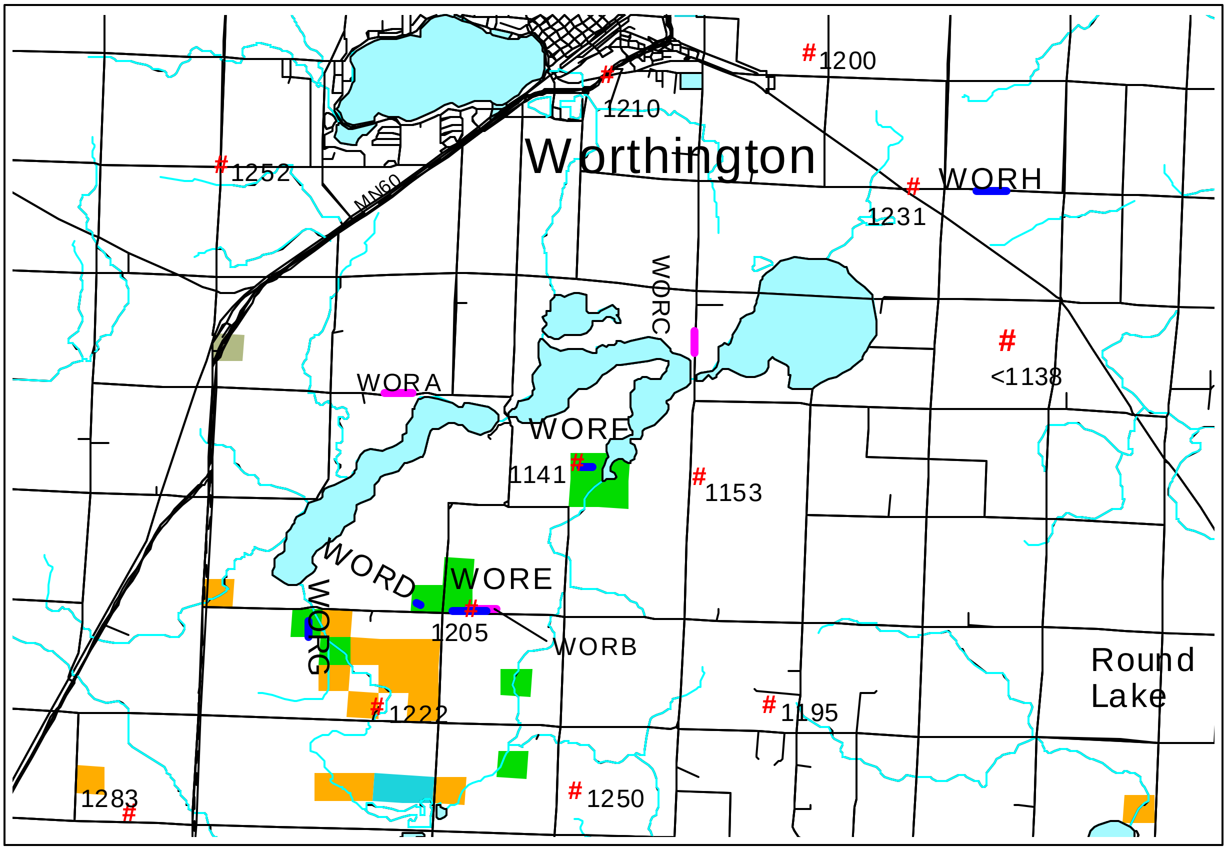

Figure 4. Seismic Reflection Line Locations

A 12-pound sledgehammer was used for the energy source for all the reflection lines. All the reflection data were acquired with the common depth point (CDP) method.

Line WORF was located adjacent to test hole 53-3 (Figure 4). Drilled in 1996, this test hole penetrated a 27-foot-thick sub-Quaternary unit sand layer (Figure 2) and encountered the top of Cretaceous shale at a relatively low elevation of 1141 feet above sea level. We completed seismic line WORF at this location to compare with other lines in the area (Figure 5).

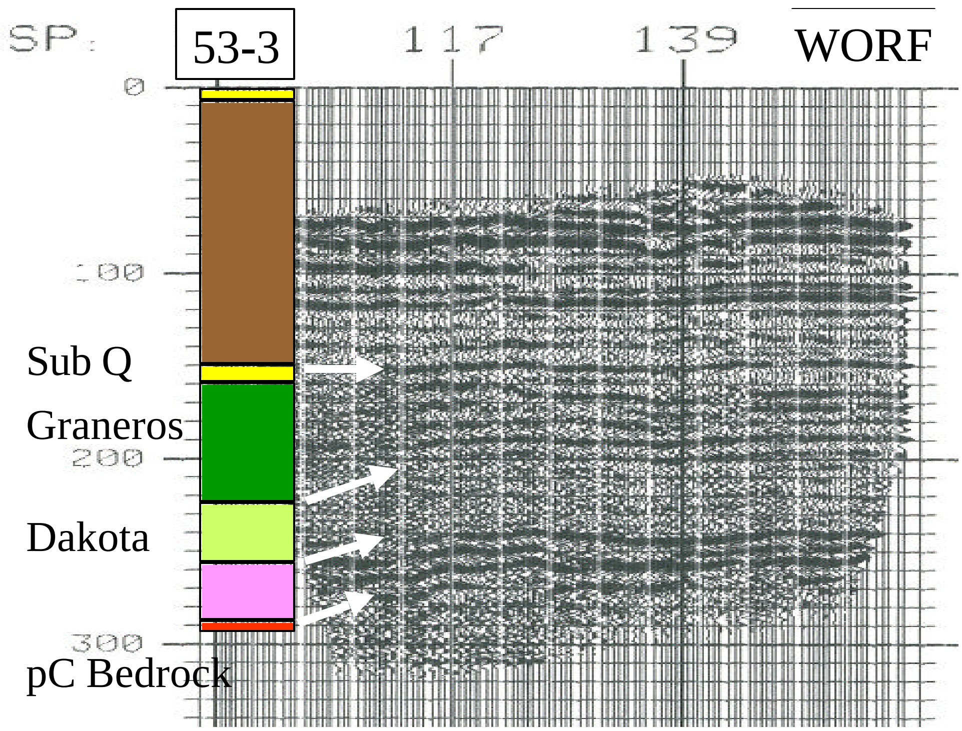

Figure 5. Seismic Reflection Line WORF at the Test Hole 53-3 Location

Seismic reflection data is compared with lithology and stratigraphy in this figure. The brown section represents glacial till, the yellow layers are sand, the green sections are Cretaceous formations, the violet section is weathered Precambrian bedrock, and the red section is Precambrian bedrock. Two-way travel time is shown along the left edge of the diagram in milliseconds. The numbers along the top of the figure are station locations. One station interval is 10 feet. Therefore, the distance between station 117 and 139 is 22 stations or 220 feet.

After collecting and processing our prospect line data (data collected in unknown areas), line WORE appeared interesting to us. The interpreted Cretaceous shale reflector on WORE appeared to be as deep as the Cretaceous shale reflector on seismic line WORF (Figure 6).

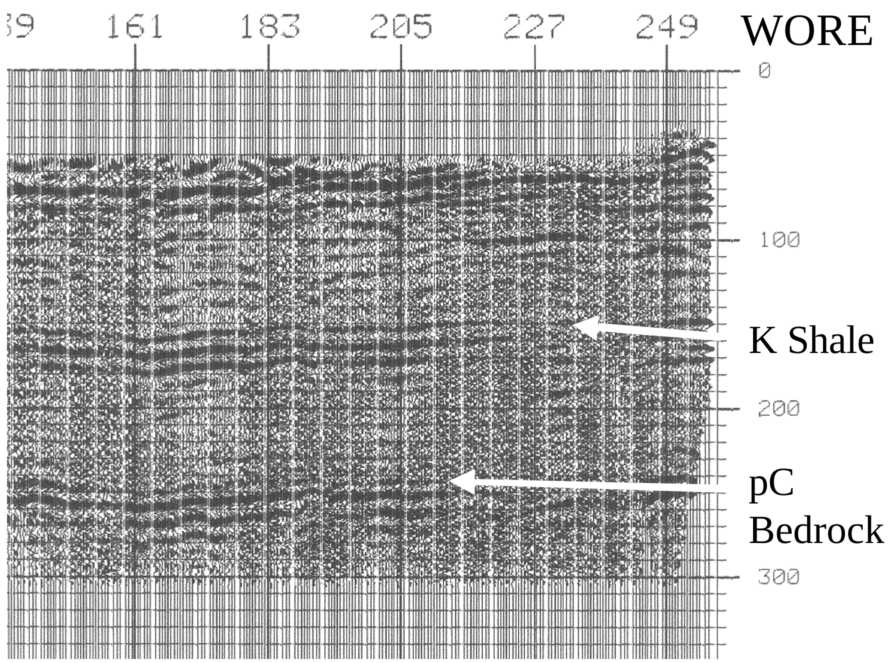

Figure 6. First Interpretation of Line WORE

The strong reflection labels on this figure were our best guesses prior to drilling a test hole at this location. This interpretation was not correct for reasons explained in the text. The final interpretation is shown in Figure 9.

Based on this relationship it seemed possible that the buried valley and sub-Quaternary sand found at test hole 53-3 might also exist at the WORE location.

4.0 Test Hole Drilling and Logging Results

4.1 Cretaceous Shale Top Elevation and Sonic Velocity Profile

Test hole 616893 (53-5) was drilled, in June 1999, at the WORE location to test for the sub-Quaternary unit sand and to determine the actual elevation of the Cretaceous shale top. In addition, the test hole was drilled through the Cretaceous shale into the weathered Precambrian bedrock. DNR geologists collected and logged the sample cuttings and the hole was logged with gamma and sonic tools.

The Cretaceous shale top in the test hole was found at a depth of 388 feet (1205-foot elevation) based on cuttings samples and the character of the gamma log. This elevation was much higher than the base of the buried valley that was found at test hole 53-3. The sub-Quaternary sand thickness was only 8-10 feet. This information indicated test hole 53-5 missed the buried valley that was found in test hole 53-3. This apparent discrepancy between the reflection profile and the actual Cretaceous shale elevation at that location can be explained with a portion of the sonic log from the test hole (Figure 7). The sonic log measures delta T, which is the refracted travel time through the formation of a sound impulse produced at one end of the sonic tool and received at the other end. Since the tool is a fixed length this value is expressed in time/distance. In Figure 7, the sonic log data has been converted to velocity expressed as distance/time, which is the inverse of delta T.

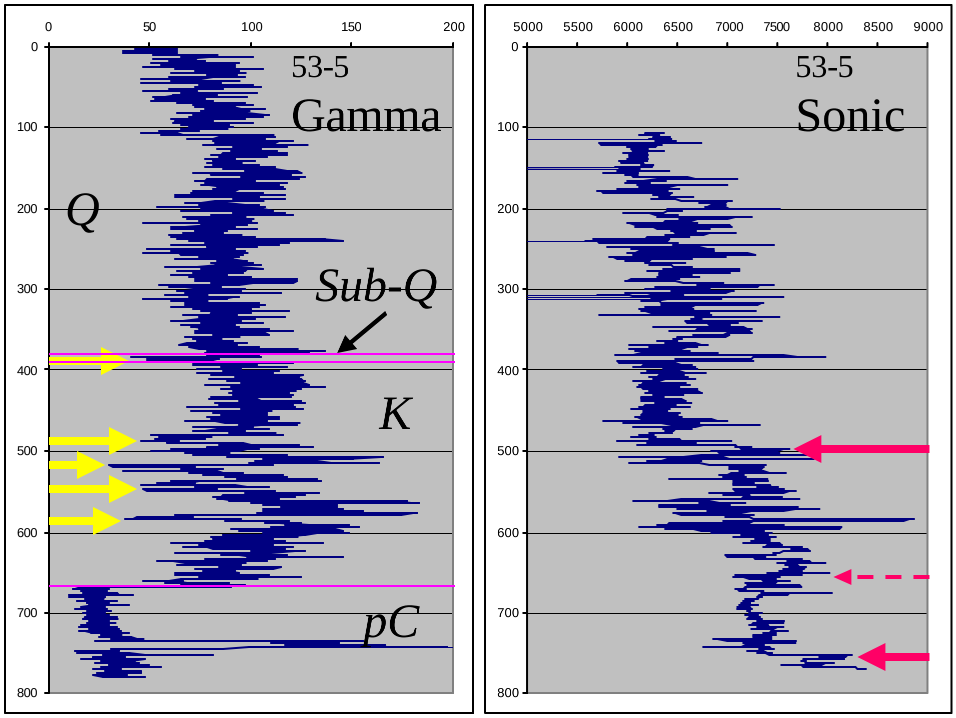

Figure 7. Gamma and Sonic Logs from Test Hole 53-5

The geologic stratigraphy of test hole 53-5 (left) is compared with a plot of seismic velocities calculated from a sonic log (right). Thin sand and sandstone layers are highlighted on the gamma log with yellow arrows. The red arrows on the sonic log indicate significant velocity changes and therefore horizons that will create reflections in a seismic survey. Note that the contact between the Quaternary sediments (Q) and Cretaceous shale (K) is not associated with a significant velocity change.

Most of the Quaternary till and the upper 100 feet of the Cretaceous shale have a velocity of approximately 6200 feet per second (ft/sec). A significant velocity increase occurs at approximately 490 feet. The velocity at this depth increases to approximately 7100 ft/sec. These data indicate the Cretaceous reflectors on line WORE are not from the top the Cretaceous shale but from a formation contact within the Cretaceous section.

These lithologic stratigraphy and seismic stratigraphy relationships are summarized in Figure 8.

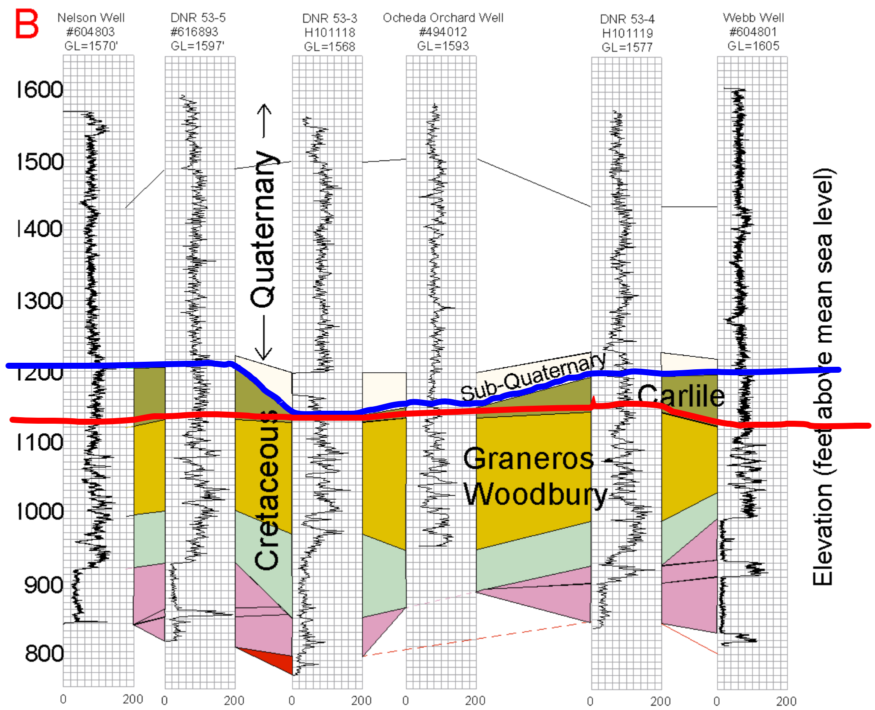

Figure 8. Lithology and Seismic Stratigraphic Relationships in the Worthington Area

The blue line represents the Cretaceous shale top. Along the cross section this line represents the top of the Carlile shale. Although we measured the Carlile Shale velocity only in this test hole and from a short segment from a Lincoln Pipestone Rural Water observation well in Yellow Medicine county (#633505), it appears that the Carlile Shale has the same seismic velocity as the overlying Quaternary till. Therefore, the Cretaceous shale top (blue line) that we had hoped we could image is not a strong reflector and cannot be surveyed with our seismic methods. We appear to be imaging the formation contact between the Carlile shale and the Graneros Formation represented by the red line shown on cross section B-B'.

The final interpretation of seismic line WORE is shown in Figure 9.

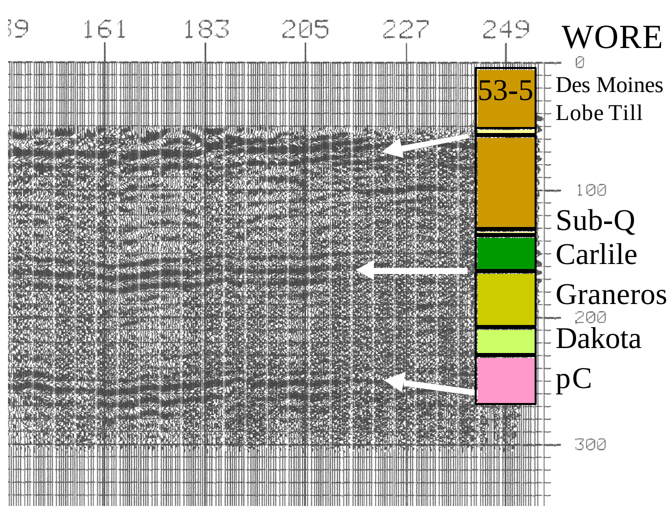

Figure 9. Final Interpretation of Line WORE

In this figure, the lithology at test hole 53-3 is compared with the strong reflections from line WORE. Note that the Quaternary/Cretaceous and Cretaceous/Precambrian contacts are not associated with strong reflections.

4.2 Dakota Sandstone

The third objective of the project was to help determine the extent of the Dakota Sandstone that was found in the 1996 test hole 53-3. In addition to new information from the recently drilled DNR test hole 53-5, three other deep holes have been drilled in the area that penetrated Precambrian bedrock. Geophysical logs from two of these holes (604803 – Nelson well and 604801 – Webb well) have been included in cross section B-B'. The other deep test hole, not included on the cross section, was drilled within the Worthington city limits by Worthington Utilities (130505 or W-4-97).

All four of these new test holes and wells (drilled after 1996) penetrated a unit that mostly has a low gamma response and a 10- to 20-foot thick interbedded layer with a high gamma response. This unit was encountered at depths ranging from 570 to 670 feet (elevations approximately 850 to 1000 feet). This unit is shown as the violet layer on cross section B-B'. Because this unit generally has a low gamma response, it is superficially similar to the Dakota sandstone of 53-3. However, the abrupt top and lower, more uniform gamma values suggest that it is a different unit. Cuttings recovery from this depth tend to be poor; however, some of the sample logs through this interval indicate fine crystalline quartz grains and quartzite chips. Therefore the unit is probably weathered Sioux quartzite.

The distinction between Dakota sandstone and weathered quartzite may be important for an appropriator that requires high volumes of ground water. The weathered quartzite has been proven as an adequate aquifer for domestic uses. Small-volume wells have been completed at the Webb and Nelson residences. However, the average grain size of the Dakota sandstone (fine to coarse) appears larger than grain sizes of the weathered quartzite (silt to fine). Therefore, the Dakota sandstone might prove to be a significantly better aquifer.

The distribution of the Dakota sandstone in the Worthington area is still unknown. Additional deep drilling in the area appears to be the only reliable exploration method.

5.0 Conclusions and Recommendations

Unfortunately the physical properties of the glacial and bedrock materials limit the usefulness of seismic surveys for aquifer delineation purposes in this area. However, continued test drilling and analysis of new data from reliable water well logs is helping to improve our understanding of the area's subsurface geology. Identification of geologic boundaries and units in this area is even difficult from borehole data but very important for understanding the area's subsurface geology. Good cuttings recovery, accurate cuttings descriptions, and modern downhole geophysical logs are all essential data.

Appendix A

Seismic Refraction Analysis

The seismic refraction method measures layers in the earth that have significant velocity differences, where the velocity of each layer increases with depth. If the velocity of a layer is lower than the one above it, or is "too thin", then it will not be visible using the seismic refraction method.

The seismic refraction method is typically used to map three layers of interest for water resources: the unsaturated/unconsolidated layer, the saturated/unconsolidated layer, and the top of bedrock. It measures the thickness and velocity of the top two of these layers, and the velocity of the third or bedrock layer. Sometimes intermediate layers can be seen. For example multiple unsaturated layers, or a second saturated till, and or a second bedrock layer have all been seen.

In the Worthington area, there are four layers that we hoped would be visible on a refraction section: the unsaturated Quaternary, the saturated Quaternary, the Cretaceous, and the Precambrian layers. The unsaturated Quaternary layer should have a velocity of approximately 1900 feet per second (ft/sec). The saturated Quaternary layer has a velocity of about 6100 ft/sec. The Cretaceous layer should have a velocity between 7200 and 7700 ft/sec (based on the sonic log velocities). The Precambrian layer should have a velocity of approximately 20,000 ft/sec. These velocity differences are great enough to produce refractions. The relative layer thicknesses are the potential problem.

Figure A1 shows the seismic waveform data from refraction line WORB. The X-axis represents distance. Each trace represents the ground motion from one geophone. The distance between geophones is 20 feet. The Y-axis represents the seismic travel time in milliseconds.

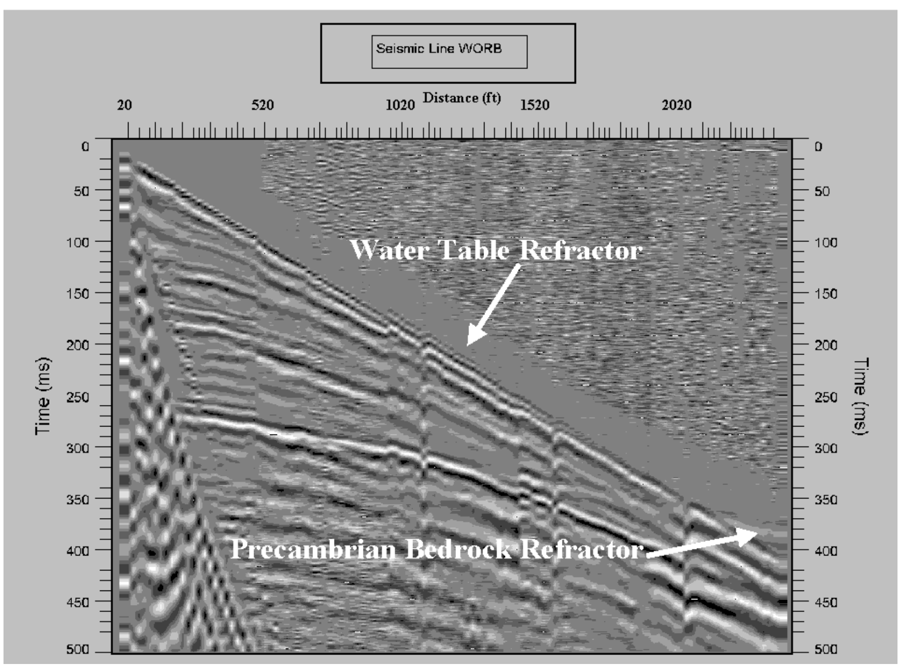

Figure A1. Typical Refraction Seismic Data in the Worthington Area

There are two refractions visible on Figure A1: the water table refraction and the Precambrian refraction. The slope of the refraction line represents the material velocity of the refracting layer. The water table refractor has a velocity of ~ 6100 ft/sec. The Precambrian bedrock refractor has a velocity of ~ 20,000 ft/sec. There is no Cretaceous refraction present.

The reason for this is that the Cretaceous layer is not thick enough, relative to the velocity contrast between it and the other layers and its depth below the land surface. To confirm the absence of a Cretaceous refraction, a forward model was run using an Excel spreadsheet.

Figure A2 is a model showing the expected seismic time versus distance plot for the Worthington Area. Velocities and thicknesses for four layers were put into the spreadsheet. The air wave, the direct arrival, and three refractions are plotted. The air wave is the sound wave that travels through the air from the seismic source to each of the geophones. It has a velocity of about 1100 ft/sec. The direct arrival is the sound wave that travels through the unsaturated Quaternary layer above the water table (about 1900 ft/sec in this case). The water table refraction is the sound wave that travels along the top of the water table. It has a velocity of about 6100 ft/sec. The Cretaceous layer has a velocity of 7200 ft/sec in the model. The Precambrian arrival is the sound wave that travels along the top of the unweathered Precambrian surface and has a velocity of 20,000 ft/sec.

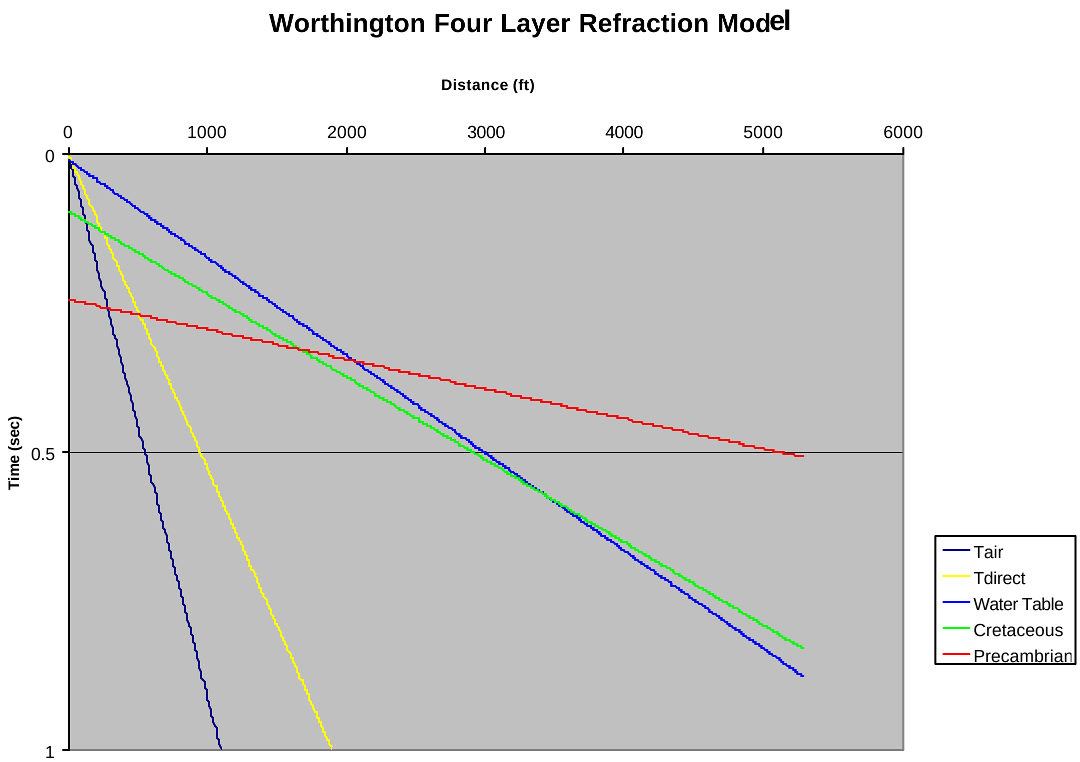

Figure A2. Refraction Model

Figure A2 shows the predicted time depth curves for the air wave, direct wave, and three refractions, using expected velocities and depths from the Worthington area. (The refractions are plotted as lines that extend across all distances. In reality, deeper refractions do not materialize until twice the distance of the critical angle. But, for the purposes of demonstrating which refractions are the first arrivals, these plots are accurate.)

On figure A2, the water table, Cretaceous, and Precambrian refractions plot very close to one another. Figure A3 is an enlargement of Figure A2, which was made to help distinguish the separation of the curves.

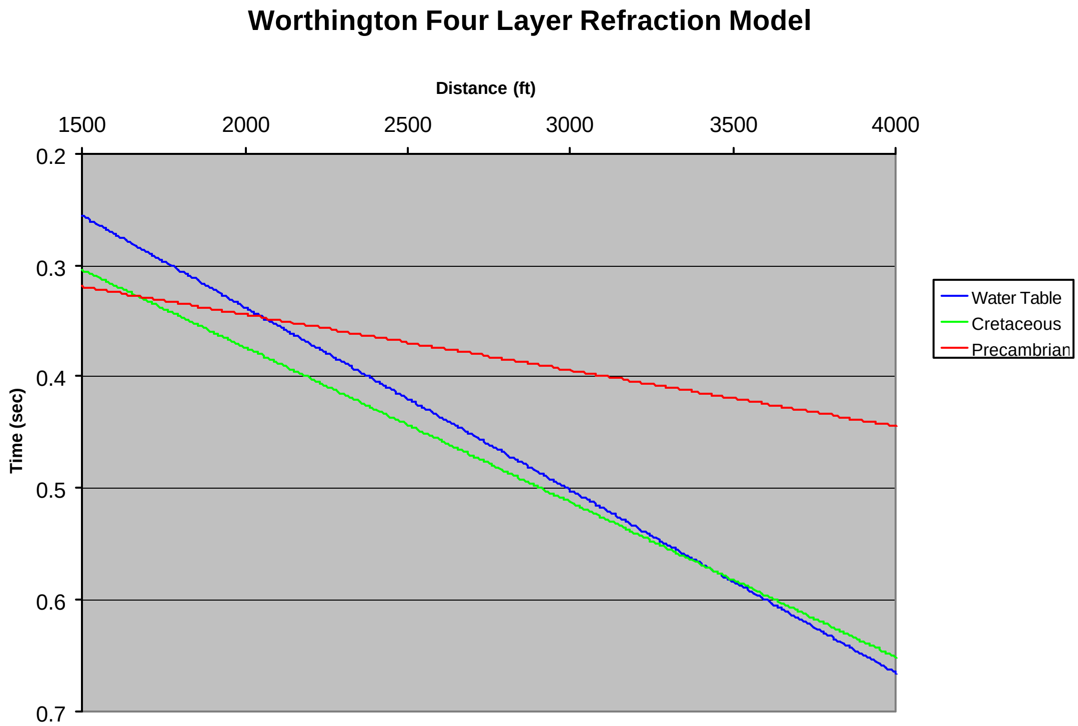

Figure A3. Detail of Refraction Model

The refraction technique only uses the first arrival of seismic energy to time a refraction. From figure A3, it is apparent that the water table refraction is the first arrival of seismic energy up to 2065 feet away from the source. Beyond 2065 feet, the Precambrian refraction becomes the first arrival. The Cretaceous refraction arrives late. The reason for this is that the Cretaceous velocity of 7200 ft/sec is not much different from the saturated Quaternary velocity of 6100 ft/sec. Because of this limited velocity contrast and the depth to the refractor, the Cretaceous layer is not visible as a first arrival on the refraction section.

This model shows that the Cretaceous shale is too thin, given its seismic velocity and depth, to appear as a first arrival on a refraction survey.