PIERSON RHEEMS LLC

RHEEMS QUARRY

30 ACRE EXPANSION HYDROGEOLOGIC STUDY

West Donegal & Mt. Joy Township
Lancaster County, PA

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EXECUTIVE SUMMARY

Akens Engineering Associates, Inc. (AKENS) has prepared the following document for Pierson Rheems LLC (PIERSON) for their Rheems, PA Quarry operation SMP 36080301. PIERSON currently operates a 102.64-acre (30 acres of mining) noncoal surface mine operation and is looking to expand the SMP by 30 acres and pit by approximately 20 acres. Currently, the mine floor is at ~200 feet Above Mean Sea Level (AMSL) with an ultimate depth of 126 feet AMSL. The site was previously operated by Union Quarries, then Donegal Rock before changing hands to PIERSON in 2008.

This report is a compilation of multiple decades worth of previously completed studies, as well as more recent site work. The site already has a Module 8 and hydrogeologic study on file at the Pennsylvania Department of Environmental Protection (PADEP). This has enabled the completion of a three-dimensional groundwater model, establishment of a Zone of Influence (ZOI), and a proposed future monitoring network to assess current and future impacts caused by the dewatering activities associated with mining. This report will detail all the work performed at this quarry and will highlight all pertinent hydrogeologic data necessary to evaluate any impacts from the expansion of this mining operation and provide information to the PADEP that would allow for the pit expansion of the requested 20 acres (30 acres total, 20 additional for mining).

For mining to occur at the Rheems Quarry, dewatering of the pit will be required. Dewatering can be accomplished through the installation of a sump, with pumps installed, to remove the water from the pit area. As water is removed from the pit, this dewatering will also impact the area surrounding the pit. To assess the impacts of the necessary pumping, a series of four groundwater monitoring wells equipped with pressure transducers were installed around the perimeter of the quarry. Data loggers were also installed in three of the previously installed monitoring wells at the site, along with a permanent flow meter with data logger. These wells served as a source for water level monitoring during aquifer testing and will function as future groundwater monitoring wells. The data collected from these wells was used to develop the three-dimensional groundwater model and associated ZOI. The data also helped establish groundwater contour mapping, groundwater flow direction, and gradient.

Contained herein is a comprehensive and detailed report explaining all of the items addressed in this Executive Summary, focusing on the hydrogeologic data in and around the Pierson Rheems Quarry. The interaction between quarry dewatering and the surrounding aquifer is understood, and predictions for future pumping have been calculated. The quarry pumping will have minimal impact to the surrounding aquifer and a sinkhole mitigation plan has been prepared deal with future sinkholes that may occur. The overall results of this study have determined that mining to the permitted depth of 126 feet AMSL, including the 20-acre expansion, will not cause any deleterious impacts to the surrounding aquifer and/or environment.

This document was prepared by Charles Brown and Rick Caranfa, under the supervision of Mark Forester, P.G, and of Mr. James Rumbaugh, P.G., for groundwater modeling and accompanies the PADEP Surface Mine Module 8.

Geology:

The Rheems Quarry is located within the Piedmont Lowland Section near the boundary with the Piedmont Upland Section of the Piedmont Physiographic Province. The Piedmont Lowland Section consists of broad, moderately dissected valleys separated by broad low hills. The Section is developed primarily on limestone and dolomite rock. Karst topography is common. Local relief in the Section is generally less than 100 feet but may be as much as 300 feet. Elevations in the Section range from 60 feet to 700 feet. Drainage is basically dendritic in pattern, but some areas have virtually no pattern because of the well-developed subsurface drainage. The limestone and dolomite bedrock in and around the Limestone Quarry generally have a strike to the East/West and dip to the North at 45˚.

The Village of Rheems lies in the carbonate valley of northern Lancaster County, in southeastern Pennsylvania. Rheems is two miles east of Elizabethtown, shown on the 7-minute quadrangle bearing that town's name. The quarry is a short distance west of the village, adjacent to Harrisburg Avenue in West Donegal Township.

We have attached two publications of detailed structural geology of the Rheems Quarry by Wise, 1958 and Faill & Geyer, 1983.

The quarry exposes only the Lower Ordovician Epler Formation, an approximately 2,500 feet thick carbonate unit within the Beekmantown Group (Meisler and Becher, 1971) present throughout the entire Lebanon Valley nappe from Reading to Harrisburg. Perhaps the most distinctive aspect of the Epler is the interbedding of limestone and dolomite, which on weathered surfaces provides striking displays of mesoscale structures. The limestone is mostly medium to medium-light gray (locally light pinkish gray) and weather to a light olive-gray or light gray. The finely crystalline beds contain very fine dark gray laminations. The medium crystalline dolomite beds are medium gray in color, and weather to a yellowish gray. The dolomite is also laminated, and both lithologies tend to be medium to thick bedded. Chert, occurring as dark gray to black nodules, lenses, and stringers, is scattered throughout the Epler Formation.

The quarry highwalls provide excellent exposures of the mesoscale structures that comprise the local tectonic grain. The north and south highwalls approximately parallel the 75-azimuth trend of the folds and display the change along the grain; the east and west walls exhibit good cross sections of the structures.

The dominant tectonic factor was the northward transport of the nappe; all other Taconian structures in this quarry are derived from this fundamental movement (Wise, 1958, 1960). A consequence of this movement is that most of the rocks in this underlying limb have undergone, to varying degrees, an extension in the north-south direction. Most of the mesostructures in the quarry amply demonstrate this strain.

The two most dramatic structures are the two recumbent folds in the east wall. No evidence of depositional tops of beds has been found in this quarry, so which fold is the anticline, and which is the syncline cannot be determined from the sedimentary criteria. However, because the quarry is in the lower limb of the nappe, one can presume that the stratigraphic section is probably inverted. If so, then the upper fold, the one that is concave toward the north, has younger beds in the core, and thus it is the syncline. Similarly, the lower fold, the one that is convex toward the north, should have older beds in the core, and so it is the anticline. The axial surfaces of both the anticline and the higher syncline persist across the east wall with a 15 to 25 feet separation, extending horizontally though at least 650 feet of rock. This is an average dip of 3˚, not quite a perfect recumbent fold. This exposure also enables one to see that the folds possess a similar geometry.

The highwall exposure in the west wall at is in distinct contrast to the east wall; no recumbent folds disturb the gentle south dip of the (presumably) overturned beds, The relation between the different structures displayed in the two walls can be determined from the folds in the north highwall. The 5˚ to 15˚ plunge of the folds at the entrance ramp to the east-northeast demonstrate that the western highwall exposure is structurally below the folds in the eastern wall, This can be verified by examining the east highwall. No folds are present; only the fairly constant gentle south dip is present, similar to that in western part of the quarry.

The important faults present in this quarry occur in two orientations - parallel and transverse to the fold trends (Faill. 1983). Both types of faults, a steeply north-dipping parallel fault and a steeply west-dipping transverse fault, are present at the south wall. They are both post folding because they offset parts of a fold. Another steeply west-dipping transverse fault along the southeast wall has an apparent offset of 6 feet down on the west, but its gently south-plunging slickenslides indicate strike-slip movement. This fault extends northward across the quarry to the northeast wall where the slickenslides plunge steeply (obliquely) to the northwest. These complex fault movements may represent a late stage of the Taconian deformation, effects of the late Paleozoic Alleghenian orogeny, or they may even be of Jurassic age and be a consequence of the Mesozoic rifting and opening of the Atlantic Ocean.

It is evident from published literature and numerous field views that Rheems Quarry is so intensely folded and faulted that a single strike and dip reading could not adequately describe the attitude of the rock units exposed here.

Regional Geologic Structure:

The Piedmont Province where Rheems Quarry is located is an extensive, gently undulating province which in general slopes southeastward. It has undergone prolonged erosion so that much of its former plateau-like appearance has been modified to slopes and gently rounded hills. It comprises a southeastern belt, adjacent to the Coastal Plain, which is underlain chiefly by Precambrian crystalline rocks but in some places by Ordovician limestone.

The Taconian Orogeny during the Ordovician Period produced the alpine-style Lebanon Valley nappe in south-central Pennsylvania. Weathering and erosion have reduced this enormous recumbent anticlinorium to a humble topography, with complexities and grandeur.

The sedimentary rocks at Rheems Quarry were deposited on the carbonate shelf on the edge of the Laurentian continent, the Precambrian core of what is now North America. During the Middle and Late Ordovician, the continental convergence and closing of the proto-Atlantic Ocean created the Taconian orogeny. During this diastrophism, enormous blocks of the sedimentary shelf and large fragments of the underlying Precambrian rocks were forced up and into a younger shale basin to the (then?) northwest, which contained sediments of the present

Martinsburg Formation. In the course of this (presently) northward movement, some of the blocks overrode their leading edge, forming recumbent anticlinoria of considerable complexity. The Lebanon Valley nappe is one of these thrust blocks.

The Lebanon Valley nappe contains rocks of Precambrian, Cambrian, and Ordovician age. The nappe is more than 60 miles in width and extends across the regional trend for at least 30 miles from the Great Valley north of Lebanon well into the Piedmont terrane south of Lancaster. Although the nappe was modified, mostly by faulting, during the late Paleozoic Alleghenian deformation, the structures in the quarry are almost entirely of Taconian age. The southeastern edge of the Mesozoic basin lies only 1,000 feet to the north of the quarry, but the extent to which the quarry was affected by the Jurassic (?) Deformation, if at all, is unknown.

Hydrogeology:

The climate of Lancaster County is considered humid continental. On average, there is approximately 44 inches of precipitation throughout the year, most of which falls in the form of rainfall. May-August is typically the period of the highest precipitation. Average snowfall is 27 inches per winter. Of the 44 inches of annual precipitation, on average, 10 inches goes to surface runoff, 11 inches to groundwater discharge and 23 inches to evapotranspiration (Royer 1983).

Surface Water:

The Rheems Quarry discharges into an Unnamed Tributary to Donegal Creek (East UNT). This Unnamed Tributary's headwaters are not far from the quarry and during most times has very little flow, less than 75 gallons per minute (gpm). We have attached StreamStats report for this UNT. The upstream drainage area as shown on the attached Drainage Area Map is approximately 245.83 acres. The total drainage area to Monitoring Point #6 which is at the downstream NPDES 002 discharge point is 350 acres. This Unnamed Tributary is located to the east of the operation. The quarry discharge is the main component of flow for the Unnamed Tributary immediately downstream from the quarry. Water sampling analysis demonstrates that quarry dewatering activities are having no deleterious impact to this Unnamed Tributary and the added discharge to the creek is an overall benefit.

There is a mapped Unnamed Tributary (West UNT) west of the quarry operation. This Unnamed Tributary no longer exists at the surface over the extent of the mining project. Many years ago, the farmer that owns the land installed an underground piping system that carries this water across the property. *This piping system keeps the surface dry and will not allow for this water to enter the quarry dewatering system.* We have also attached the Streamstats report for this area. The upstream drainage area to Monitoring Point #3 is 21.84 acres. The contributing drainage includes runoff from 7 residential houses. The contributing flow to the piping is mainly from the pond across the street from MP#3, two industrial sites from runoff, and surrounding agricultural farms. The volume of upstream flow was not measurable during background sampling. We have attached photos for reference. The total drainage to Monitoring Point #7 is 525.21 acres. The surface flow at this point was not measurable during background sampling. The minimal upstream contributing drainage areas and measured volumes of stream limit the possibility of the quarry pulling outside contaminants into the pit sump. The discharge of the quarry would be identical to the background water quality of the existing aquifer.

Groundwater:

The Epler Formation is also considered an excellent source of water. It is capable of producing an adequate water supply for industrial and municipal needs. Reported yields from the Epler Formation range from 3 to 1,800 gpm with a non-domestic median yield of 265 gpm. Specific Capacity values also vary greatly, but the median is around 9 gpm. As is the case with the other carbonate rocks, the water is very hard with a median hardness of 291 mg/L. In addition, the unit has a high median specific conductance, which means that there is an abundance of dissolved solids.

The Stonehenge Formation is also an excellent source of groundwater. The formation has a high permeability and well-developed secondary porosity. Nondomestic well yields range from 10 to 225 gpm with a median yield of 20 gpm. Specific capacities range from 0.03 to 250 gpm/foot. The water in the Stonehenge Formation is also hard and nitrates can be an issue. This formation is geographically south of the quarry.

The Annville Formation is generally not considered an important aquifer because it has a limited areal extent due to the fact that the formation usually is found in thin bands. However, reported yields in the Annville Formation range from 28 to 200 gpm with a median reported yield of 30 gpm. The median specific capacity calculated for a limited number of wells is 0.21 gpm/foot. The water is considered very hard.

As part of the previously submitted Hydrogeologic Study, a comprehensive water well inventory was performed. While some of the homeowner names may have changed, this data is still valuable and therefore included in this report. This report gives the details of approximately 50 wells within the vicinity of the quarry.

The quarry is a relatively dry quarry, which is to say that there is not a lot of discharge associated with the mining activities. Also, there are not a lot of water inflows within the quarry. The one notable inflow is what the quarry operators refer to as the “red bed”. This is a thin band of red clay that appears within the quarry. It is 6-18 inches in thickness and has some associated flow. This is a bedding feature and is relatively small. While there is not any current visible flow from this zone, quarry personnel reported that there was some flow from this feature in the past. This red bed is visible and dips to the south. It was also encountered in Wells MW22-2 and MW22-3.

Site Specific Data:

In order to better assess the effects of the dewatering activities associated with the Rheems Quarry, a series of monitoring wells were installed at the site. As stated previously, this site already has a previous Module 8 and Hydrogeologic Study prepared. As part of that study, a series of wells were installed around the then active pit. Of those wells previously installed, three were used as part of the permanent monitoring system. These wells, in addition to the newly installed wells, are detailed below.

To function properly, monitoring wells need to be adequately connected to the underlying aquifer. The best way to ensure that these wells are connected to the aquifer is to have them drilled on a secondary porosity feature, such as a fracture. Akens used fracture trace analysis (FTA) to aid in the location of the wells. FTA involves analyzing paired stereoscopic photographs to locate potential fractures on the land surface. The stereoscopic photographs appear 3-dimensional when viewed through stereographic glasses. The surface expressions of the fractures are identified on the photos. In addition to FTA, fractures were also located by identifying them in the quarry high walls, surveying them and projecting them out from the quarry.

In January 2022, a series of four groundwater monitoring wells were installed around the Rheems Quarry. The monitoring wells were installed by Myers Brothers Well Drilling, from Salunga, Pennsylvania. The wells were installed using an 8-foot stabilizer was used to assure the wells stayed properly aligned. All wells were properly cased and sealed with bentonite pellets. All wells were drilled using a nominal 6-inch (6 5/8”) drilling bit with the top hole being drilled with a nominal 10-inch bit. Each well was properly developed by using water injection and air lift. An estimated blown yield for each well was determined using air lift and a weir, at the completion of development. Well logs for each well are included.

Monitoring well MW22-1 was drilled on the southeast corner of the site. The well was installed with 40 feet of casing and was drilled to a total depth of 350 feet. The well encountered water bearing zones at depths of 168 and 240 and yielded a total of 4-5 gpm. This well provides information on the aquifer to the southeast of the operation.

MW22-2 was installed along the south side of the active pit. It was drilled to a total depth of 350 feet, with 20 feet of casing. The water bearing zone was located at 330 feet and the total yield was 4 gpm.

MW22-3 was drilled at the southern extent of the permit line. This well was drilled to a total depth of 350 feet, with 40 feet of casing and encountered no discernable water bearing zones and yielded a total of 1 gpm. This well was located in this direction to give detail as the drawdown gradient to the south.

MW22-4 was installed near the Wolgemuth farmhouse, to the west of the proposed expansion operation. This well was drilled to a total depth of 350 feet, with 40 feet of casing and encountered water bearing zones at 290 and 295 depth and yielded a total of 1 gpm. This well has a static water level less than 20 feet from the ground surface and will be an excellent monitoring point as mining proceeds to the west.

All well drilling activities were completed by the end of January 2022 with permanent pressure transducers installed within each well, along with a flow meter and datalogger installed at the site. The pressure transducers collect continuous data and allow this data to be compared to precipitation and quarry pumping data. In addition, data loggers were installed in three of the previously drilled wells (Wells A, B, and D).

The well logs are attached for Wells A, B, C and D. Monitoring Well C has been mined through and no longer exists. Wells A and D were converted to multi-level piezometers after they were drilled in the 1990’s. For our monitoring purposes, the data loggers were installed into the deep monitoring point. All referenced data within this report pertains to the deep monitoring point within these two wells.

As part of the background data, water quality samples were obtained on the Unnamed Tributary to Donegal Creek, the quarry discharge, and numerous homeowner wells around the quarry that were willing to participate in the study. It should be noted that well sampling was also done as part of the previously submitted Module 8. Again, all sampling is in line with expected groundwater quality. Also, every home that participated in this study has some form of filtration system installed. These systems are for sediment and not any chemical analyte. This water quality data is attached and detailed in Module 8: Hydrology, which is also attached to this report.

Quarry Pumping and Discharge:

In June of 2022, a permanent flow meter was installed on the discharge line from the Rheems Quarry to the Unnamed Tributary. This meter is a Seametrics EX253B-127 Mag Meter and collects continuous discharge data. This discharge data is included in the application.

Akens was able to obtain discharge records, collected by quarry personnel from 2010 through 2017. This data was based upon rating curves and hours pumped. Starting in June 2022, the data should be considered much more accurate and was collected with the aforementioned flow meter. Interestingly, the data shows a slight decrease in quarry discharge over the 12-year period. While this is likely due to the accuracy of the equipment, what we can discern is that quarry discharge likely remained the same over this 12-year period. This indicates stabilization of the aquifer in relationship to the quarry activities. The stabilized conditions around the site would mean that the data acquired would be excellent for calibrating a groundwater model.

Overall, quarry discharge averages just over one million gallons per day. Monthly fluctuations will be dependent upon precipitation, with maximum monthly discharge of 2.8 MGD to not needing to pump during drought conditions.

The quarry discharge operates on a 2-stage discharge system. This means that water is pumped from a "lower" sump, which is located on the floor of the active mining level (~200 AMSL), and is temporarily discharged to "transfer" sump, which is located at the ~250 AMSL bench. This system improves the quality of the discharge water by allowing solids to settle. It also offers the quarry more control and stability over the discharge.

Permanent Monitoring Network:

To help assess any future impacts the mining and associated dewatering may have, an extensive permanent monitoring network was established around the quarry. The monitoring network should include the following wells:

Well A	Monitoring
Well B	Monitoring
Well D	Monitoring
MW22-1	Monitoring
MW22-2	Monitoring
MW22-3	Monitoring
MW22-4	Monitoring

These wells are located on the attached 6.2 Environmental Resources Map. These wells have permanent data loggers installed, which collect data daily. This extensive list of monitoring wells will provide an indication as to how the various aquifers/formations are responding to the dewatering activities of the quarry. These wells also help to protect the surrounding environment from any negative impacts. If the water level within any of these wells takes a sudden drop, the incident will be investigated. The water level readings should also help to protect the quarry from unnecessary liability for problems that may arise that were not caused by dewatering activities.

In addition to the groundwater monitoring network, a series of two surface water monitoring points have been established on the Unnamed Tributary to Donegal Creek. These surface water points are also labeled on the 6.2 Environmental Resources Map as SW-1 and SW-2. These monitoring points will be sampled on a quarterly basis and stream flow monitored.

The six groundwater monitoring wells and two surface water monitoring points will adequately detail any potential quarry impacts to the surrounding aquifer system. In addition to these monitoring points, a permanent flow meter has been installed.

Groundwater Model and Zone of Influence:

To properly calibrate a groundwater model, representative hydraulic conductivity values need to be entered for the various formations across the project area. This is done so that the model can more accurately predict future impacts from the quarry dewatering activities. The calculation of these parameters can be achieved in various ways. There is currently an active pit sump established at the Rheems site. This pit sump is used on an "as-needed" basis to keep the mining operation dry.

To assess the quarry's impact on the surrounding aquifer, permanent data loggers were installed in monitoring wells MW22-1, MW22-2, MW22-3, MW22-4, MW-A, MW-B, and MW-D. Data was collected over a 6-month period from these wells. The correlation between pumping and water level fluctuations within the monitoring wells provides excellent data on the surrounding aquifers. This data was analyzed by Environmental Simulations, Inc. (ESI), of Reinholds, Pennsylvania. The data from the testing is summarized below:

Formation	Horizontal K	Vertical K
Epler	0.5	0.2
Stonehenge	0.5	0.05
Millbach	5.0	0.5
Annville	2.0	0.2
Hershey	2.0	0.2
Cocalico	2.0	0.2
New Oxford	1.0	0.1
New Oxford Congl	0.2	0.02

A groundwater model was constructed and calibrated for the Rheems Quarry by Environmental Simulations, Inc. (ESI), of Reinholds, Pennsylvania. The purpose of the model is to help predict any future impacts caused by mining and the associated dewatering activities. The model was constructed using the MODFLOW2000 model (Harbaugh et al, 2000) developed by the United States Geological Survey (USGS). The model was designed using Groundwater Vistas software developed by ESI.

Model parameters required by MODFLOW2000 for the model include horizontal and vertical hydraulic conductivity values (K) for each cell in the model. Hydraulic conductivity determines the ease with which groundwater flows through the aquifer. To calculate the K values for each boundary or zone, data was used from the onsite sump testing explained previously. The modeling parameters are explained in great detail in the attached modeling report. Because the geologic formations around the quarry have such varying values for K, the geologic units were divided into different hydraulic conductivity zones. The data is summarized in *TABLE 2.1* of the attached Model report.

Model calibration is the process of adjusting parameters in the model so that the model-computed water levels match water levels measured in the wells. During calibration, the model-computed water levels are compared to those water levels measured in wells. These measured water levels are called calibration targets or just targets. The targets represent water levels measured at a particular time during the simulation or they can represent steady-state conditions. In the case of the current model, steady-state conditions represent average water levels measured in 2022 for the seven monitoring wells and three additional homeowner wells, coupled with the long-term average pumping from the quarry. The computer model then compares predicted water levels to the actual readings and the calibration was complete.

Typically, a groundwater model is used to predict a Zone of Influence (ZOI) as well as future impacts from the quarry. This model predicts the current mining operation, expansion, and future mining at deeper levels. This quarry has a geologic setting in which the geologic formation being mined is somewhat pinched on all sides, and small in extent to the North and South. Because of this geologic setting, one would predict the ZOI for this operation to be relatively small. The model predicts exactly this, and the impacts expected from mining will be limited to a small area. The 10’ drawdown line acts as the ultimate ZOI and is shown on several maps found herein. It should be noted that in the case of well replacement, the 25’ drawdown line is more indicative of wells that could potentially be impacted by mining. The attached well survey indicates depths of wells and should be taken into consideration.

The ZOI for the current mining pit, as shown delineated on the attached 6.2 Environmental Resources Map, was predicted to be a total of 346 acres. The computer modeling for the site over-predicted the current pumping by 25%, resulting in a ZOI too large for actual site conditions. Akens adapted the ZOI based on specific site conditions (geologic formations and structure, groundwater levels, quarry pumping and discharge, etc.) as represented on the map.

The quarry discharge happens to be lower than the model capabilities to calibrate this difference is in the conservative direction.

The model also predicted the ZOI at complete buildout of the quarry. This includes the western expansion and the deepening to level 126 AMSL. The ZOI almost doubles in size to ~680 acres. Again, because the original calibration was overpredicting the flow, the predicted future model is likely overpredicting the size of the ZOI. The ZOI was slightly adjusted from the original computer model to account for this factor, as well as the geology in the area.

The ZOI predicts some impacts of at least 25 feet of drawdown for 15 private wells surrounding the quarry. These fifteen wells and predicted impact are listed below:

Private Well	Predicted Impact
PW-1	~25 feet
PW-2	~100 feet
PW-3	~50 feet
PW-4	~70 feet
PW-5	~25 feet
PW-7	~25 feet
PW-9	~25 feet
PW-14	~25 feet
PW-15	~25 feet
PW-16	~25 feet
PW-17	~25 feet
PW-18	~50 feet
PW-20	~100 feet
PW-21	~100 feet
PW-22	~100 feet

It should be noted that Well PW-20 was previously replaced (paid for by Pierson) and deepened with a new pump installed. This occurred during this study and therefore the associated cost of replacement is known (~$11,000). There was significantly more casing installed than was required, resulting in a slightly increased cost. The well was originally ~118 feet deep as drilled, with the pump set at ~100 feet. It is known that mining activities did impact this well due to its shallow nature.

PW-22 was deepened to bring the bottom of the well below the proposed ultimate quarry depth. PW-21 was investigated and is shown to be below the bottom the ultimate quarry depth. The

Wells that are predicted to be impacted by a drawdown of 25 feet or less are not expected to need deepening or replaced. PW-4 is reported to be significantly lower than the proposed ultimate quarry depth.

The predicted ZOI, at final buildout shows a potential 100-foot impact to Well PW-2 located at the Sweigart Farm. This impact is NOT associated with the expansion to the west but is associated with mining deeper. It is Akens' recommendation that this well be replaced prior to any advancement in depth of the quarry. Again, moving to the west will not impact this well, as that is moving further away than the current mining activities. However, if this well has any issues, they will be investigated immediately and well replacement will occur as needed.

The model has overpredicted flow, which in turn will overpredict the ZOI. We know that the geologic contact to the north between the Epler Formation and the New Oxford Formation will limit the extent of the real ZOI in that direction. The proposed monitoring network will allow for early detection of impacts to the aquifer.

The Epler Formation is known to be susceptible to sinkhole development, there are only two mapped historic sinkholes in the vicinity of the operation. These are shown on the 6.2 Environmental Resources Map and are located on the Wolgemuth farm. There is a sinkhole mitigation plan at the end of this document in the event that any sinkhole activity occurs.

Quarries are unique in their water handling operations. When there are drought conditions, quarries pumping rates are reduced in response to the drought conditions. Conversely, if rainfall is above average, then pumping rates will tend to be above average. Quarry pumping in general will usually be maintained at a steady rate with only modifications to coincide with precipitation amounts. Discharge data shows stable pumping rates for many years. The measured pumping rates indicate a very steady consistent pumping rate of around 1 MGD. Continued monitoring of this parameter, along with the continuous logging of the monitoring wells will provide adequate information to monitor the effects of the quarry on the karst features. No changes are required to the NPDES Permit discharge rate.

Conclusions:

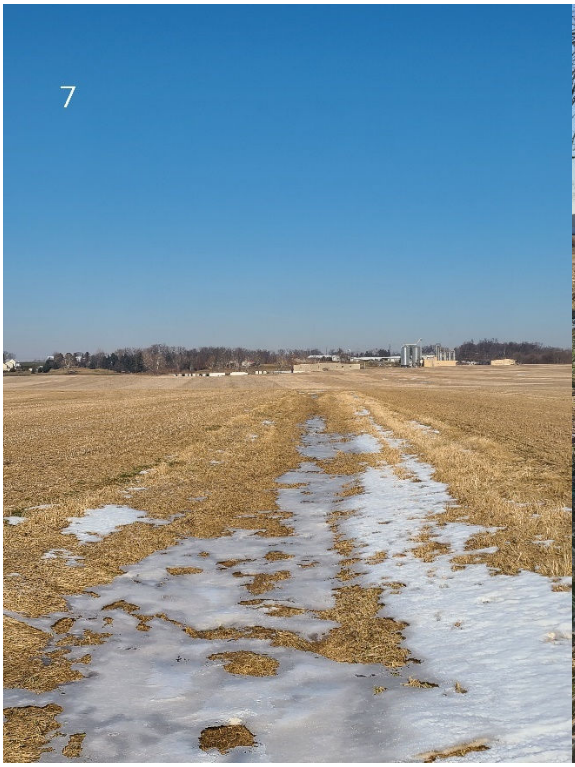
This report has detailed the hydrogeologic data collected in the field and published in and around the Rheems Quarry. Quarry operations have been determined to have caused minimal impact to the surrounding aquifer through drawdown associated with quarry dewatering. Listed below is a summary of findings:

- Mining operations began at this site over 85 years ago. The mine has progressed to its current size and depth with no major reported impacts to the surrounding environment. The mining operations discharge helps supplement the Unnamed Tributary to Donegal Creek with water of good quality.
- An excellent groundwater monitoring network, surrounding the quarry, has been established. This network is comprised of seven strategically placed wells, all of which are equipped with pressure transducers. In addition, a permanent flow meter, with data logger was installed at the site. The flow data combined with the water level monitoring network will serve as an early detection system for any potential off-site impacts. This monitoring network will take daily readings of the groundwater system and they will be reviewed and submitted to PADEP on a quarterly basis. The flow monitoring will also serve as an early alert to any potential increase in pumping, which could indicate a migration of the ZOI. This system will ensure protection to the surrounding aquifer and associated homeowner wells.
- The eight private wells listed as potential to be impacted can be further investigated. Also, the Sweigart well should be replaced prior to any deepening activities.
- The surrounding geology will limit the size, shape, and extent of the ZOI. The quarry is mining the Epler Formation, which is limited in extent to the north and south.
- Current pumping averages just over 1 million gallons per day (mgpd) and is predicted to double to 2.1 mgpd at maximum buildout. Again, the expansion to the west will not increase the ZOI or discharge much as this area has already been dewatered to some

extent. Also, the fact that the surface water feature in this area is now piped underground will limit the amount of recharge. This requested expansion does not require any increase in the NPDES discharge permit.

- Discharge from the quarry has remained stable since 2010 and is expected to continue as mining progresses.
- Sinkholes have been minimal surrounding the site for the last ~85 years. However, the Epler Formation is known to be prone to sinkhole development. Therefore, a Sinkhole Mitigation Plan is at the end of this document and should be followed in the event that a sinkhole develops and is associated with the mining activities.

This hydrogeologic study incorporated new data as well as historical reports to form the aforementioned conclusions. Predictive three-dimensional groundwater modeling indicates that minimal impacts have been exhibited on the surrounding aquifer and that this minimal impact trend will continue as mining progresses. Proper monitoring of the groundwater and surface water will ensure against any future impacts. This report and accompanying groundwater model have assessed conditions to the 126 AMSL lift, however, after the completion of each lift, or if there is any drastic deviation, the model should be reviewed and updated, as necessary.



Monitoring Point #7 January 27, 2022 Monitoring Point #3

Monitoring Point #7 February 23, 2022 Monitoring Point #3

Monitoring Point #7 March 16, 2022 Monitoring Point #3

Monitoring Point #7 April 27, 2022 Monitoring Point #3

May 16, 2022 Monitoring Point #3

Monitoring Point #7 June 30, 2022 Monitoring Point #3

Groundwater Flow Model for the Pierson Rheems Quarry, Lancaster County, Pennsylvania

March 17, 2023

Prepared for

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1.0 Introduction

A groundwater model was constructed and calibrated for the Pierson Rheems Quarry in Lancaster County, Pennsylvania. The quarry is operated under mining permit 36080301. The model was created to predict future impacts as quarry development continues and is being submitted to Pennsylvania Department of Environmental Protection as a file update.

The model was calibrated to steady-state conditions assumed to be prevailing currently at the site. Both water levels measured in wells and discharges from quarry dewatering were matched during model calibration. The calibrated model was then used to predict the impacts and inflows to the quarry from the last lift at an elevation of 126 ft above mean sea level (msl).

The construction and calibration of the model is documented in Chapters 2 and 3. Predictions of future impacts from mining are presented in Chapter 4.

2.0 Model Construction

2.1 Code Selection

The groundwater model for the Pierson Rheems Quarry was constructed using the MODFLOW-USG model (Panday et al, 2013) developed by the United States Geological Survey (USGS). The MODFLOW family of models (MODFLOW88, MODFLOW96, MODFLOW2000, MODFLOW2005, MODFLOW-NWT, and MODFLOW-USG) is the most popular groundwater flow model used in the U.S. and has become the standard for groundwater flow modeling in the country. The model was designed using Environmental Simulations' Groundwater Vistas software (ESI, 2007), which creates the MODFLOW-USG input files and allows for analysis of the results. MODFLOW-USG is the latest version of MODFLOW from the USGS and was chosen for this project primarily for its capability of simulating subsurface conduits and fractures.

MODFLOW is capable of simulating steady-state or transient groundwater flow in one, two, or three dimensions. A wide variety of boundary conditions may be simulated, including constant head, constant flux (wells, recharge), and head-dependent flux (evapotranspiration, drains, rivers, streams, and general head) boundaries. The types of boundaries used in this model will be described below. MODFLOW can simulate aquifer systems that are unconfined, confined, or a combination of confined and unconfined.

MODFLOW was chosen for this study because it has most of the requisite capabilities to simulate flow in the Pierson Rheems Quarry. MODFLOW is also thoroughly documented (McDonald and Harbaugh, 1988, Harbaugh et al. 2000, and Panday et al. 2013), and has been extensively tested (see for example Andersen, 1993).

MODFLOW is not specifically designed to simulate flow in fractured rock. However, MODFLOW-USG does have the capability of simulating discrete fracture and conduit features through the use of its Connected Linear Network (CLN) Package. CLNs were used to simulate inflow to the Pierson Rheems pit from an inferred fracture zone south of the pit. For the rest of the model area, a fundamental assumption in the current modeling is that the fractures behave as a porous medium at the scale of a model grid block. This is a common assumption in groundwater modeling.

2.2 The Model Grid

The flow of groundwater can be described using mathematical equations that form the basis for all computer models used in the field of hydrogeology. Computer models may be subdivided into two broad categories, called numerical and analytical models. Analytical models are exact solutions of the groundwater flow equations, and numerical models are approximate solutions. Given the choice between an exact solution and an approximate one, it seems logical that one would choose an analytical model over a numerical model. However, analytical models are limited to ideal aquifers that are homogeneous with simple boundaries. Most real world aquifers are not that simple. Consequently, numerical models are used most often in practice.

Because numerical models are approximate, they typically compute hydraulic head (water levels) at fixed points within the aquifer. These points are called nodes, and are often arranged in a rectangular pattern called a grid. There are many different types of numerical techniques that are used to solve the groundwater flow equations. MODFLOW-USG uses a technique called the control volume finite-difference method.

The finite-difference technique requires that the aquifer system be divided into a set of discrete blocks or cells. These blocks are rectangular in shape in the current model and form the model grid. The process of creating the grid is call discretization. Water levels computed for a block represent the average water level over that rectangular region of the aquifer. Thus, adequate discretization is required to resolve features of interest, such as the location of the wells, faults, and hydrologic boundaries in the vicinity of the quarry.

An algebraic equation that describes groundwater flow is written for each block in terms of the surrounding blocks, and the complete set of linear equations is iteratively solved until the change in head between iterations meets a set criterion. An iterative solution is required because the model is an approximate solution to the groundwater flow equations.

The model grid developed for the Pierson Rheems Quarry covers approximately 16 square miles. The model domain measures approximately 5 miles from west to east and 4 miles from north to south. The southwest corner of the model grid is located at Easting 2,279,174 ft and Northing 279,583 ft. These coordinates are in Pennsylvania State Plane Coordinate System South, NAD 1983, in units of US survey feet.

The model grid spacings vary from 40 feet to 200 ft. The model grid was finer in the vicinity of the quarry. The model grid contains 111 rows, 147 columns, and 5 layers. Some of the cells in the new pit area were further subdivided into a nested grid with 40 ft grid spacings. This allows an area of refinement only where needed (in this case the pit) and is a more efficient gridding technique. A total of 134,385 cells were used in the final model. There are 108,885 active cells. The model area is shown in Figure 2-1.

The model was divided into 5 layers to facilitate making predictions down to an elevation of -600 ft relative to mean sea level. The proposed lifts for this permit are contained in the upper 2 model layers. Additional layers were added below the active quarry so that vertical flows into the pit can be computed. The base of the model in the vicinity of the quarry is at an elevation of -600 ft msl.

2.3 Boundary Conditions

Once the aquifer system has been discretized, it is implicitly assumed that groundwater outside the model grid can be ignored. The model, however, must account for areas where groundwater enters or leaves the system. These effects are included in a model using boundary conditions. Ideally, boundary conditions should represent identifiable regional hydrologic features at which some characteristic of groundwater flow is easily described (Franke et al. 1984).

In the case of the current model, the hydrologic boundaries for the model were inferred from surface watershed boundaries. The main assumption is that any activity at the quarry will not affect the location of these small water shed divides. Based on observed patterns of drawdown at the quarry, this appears to be a reasonable assumption. However, by simulating these divides as no-flow boundaries, any drawdown that might be computed at these locations will be greater than if the boundaries were further away. Thus, these are conservative with respect to quarry impact predictions.

The outer edges of the active model thus consist of groundwater divides and river or drain cells where the outer boundary coincides with a stream as shown in Figure 2-2. Cells outside these boundaries are considered inactive and shown as no-flow cells on Figure 2-2.

Numerical groundwater models, such as MODFLOW, use three types of boundary conditions to model ways in which water may enter or leave the model domain. These include the specified-head, specified-flux, and head-dependent flux boundaries. A description of each type is given below as applied in the current model. Boundary conditions are shown in Figure 2-2 for Layer 1 of the entire model domain.

The specified-head boundary condition is called a constant head in MODFLOW. The head or water level at a constant head boundary is specified independently of the simulation results and is fixed at the specified elevation throughout the simulation. Constant head boundaries were not used in the current model.

Specified flux boundary conditions are implemented in MODFLOW to represent wells, recharge, or no-flow (i.e., flux equals zero) cells. Constant flux boundary conditions were used in the model to simulate infiltration of recharge from precipitation. The recharge rate in this model was assumed to be 5.7 inches per year (0.0013 ft/d). This value was determined through calibration to quarry sump pumping rates.

No-flow boundaries are placed in a model where the aquifer is not present or where leakage of water into the model is negligible. No-flow boundaries were placed at the outer edges of the model outside the flowlines and divides, as described above and shown on Figure 2-2. Also, implicit in the model construction is that the base of the model is no-flow. That is, groundwater inflow and outflow below an elevation of about -600 ft msl is considered negligible.

Head-dependent flux boundary conditions are a hybrid between the specified head and specified flux boundary conditions. In a head-dependent flux boundary, the flux (flow rate) of water into or out of the cell is computed by the model based upon the head calculated for the cell, the head specified for the boundary, and a conductance term. The flow rate into or out of a head-dependent flux boundary cell is computed by multiplying the difference in head between the boundary and the cell times the conductance term.

MODFLOW offers many different types of head-dependent flux boundary conditions, including the drain, river, stream, general-head, and evapotranspiration packages. Each type is slightly different. River and drain boundary conditions were used in the current model and are described below.

Drain boundary conditions were used to simulate quarry dewatering and also were placed along the western edge of the model to keep water levels from going above land surface. Since no data exist in this area and it is far from the quarry, these drain locations would not effect the model predictions.

River boundary conditions are similar to drains except that rivers can recharge the aquifer if the water level in the aquifer is lower than the river water level. Creeks in the vicinity of the quarry were simulated using this type of boundary condition.

Drain and river elevations were obtained from topographic maps of the area for the streams. The conductance value assigned to each drain and river boundary cell is computed using the following equation:

$$C = (K\ W\ L)/T$$

Where C is the conductance value in units of ft^2/d, K is the hydraulic conductivity of the stream bed, or quarry interface in units of ft/d, W is the width of the hydrologic feature (or width of cell for the quarry drains), L is the length of the hydrologic feature within the cell (or cell length for quarry drains), and T is the thickness of the bed or interface material (ft). The width and length terms were defined from a Geographic Information System (GIS) for each grid cell containing a river or drain. The thickness of the bed material was assigned a uniform value of 1 ft because no direct measurements were made in the area. The hydraulic conductivity was generally assigned a value of 1.0 ft/d. Since most of these boundary conditions were located far from quarry impacts, the boundary conductance was not a sensitive parameter during calibration.

2.4 Model Parameters

Model parameters required by MODFLOW for the model include horizontal and vertical hydraulic conductivity values for each cell in the model. Hydraulic conductivity determines the ease with which groundwater flows through the aquifer. This section describes the final distribution of parameters in the model derived during calibration. The calibration process will be described in the next chapter.

The usual philosophy in model construction and calibration is to start with a simple distribution of parameters and add complexity (heterogeneity) as required during calibration. In calibrating the model, the hydraulic conductivity distribution was homogeneous by geologic formation.

A digital version of the Pennsylvania geologic map was obtained from the Pennsylvania Geologic Survey and overlain on the model grid. The area was divided into eight main hydraulic conductivity zones representing the Epler Formation (zone 1), Stonehenge Formation (zone 2), Millbach Formation (zone 3), Annville Formation Formation (zone 4), Hershey Formation (zone 5), Cocalico Formation (zone 6), New Oxford Formation (zone 7), and New Oxford Conglomerate (zone 8). Another zone (10) was added to represent an inferred fractured zone trending to the south from the current pit location. This area was interpreted to have a higher hydraulic conductivity because of the very flat gradient in this direction.

Representative values of hydraulic conductivity were obtained from other models created in the area and these values were further adjusted during model calibration. Table 2-1 shows the final hydraulic conductivity values for each formation. Each layer in the model was assigned the same hydraulic conductivity values.

2.5 Fracture Zones in the Model

Connected linear networks (CLNs) were added to the model in the area south of the current pit. These are shown in Figure 2-1. These were used because it was not possible to obtain a flat enough gradient using hydraulic conductivity increases alone. The CLNs can be thought of as discrete fractures or fracture zones.

3.0 Model Calibration

3.1 Calibration Concepts

Calibration is the process of adjusting parameters in the model so that the model-computed water levels match water levels measured in wells. Calibrating a groundwater model is difficult because there is relatively little information on subsurface conditions in most groundwater models. Most of the parameters in a model, such as hydraulic conductivity, are only known at a few points where measurements have been taken. Even at those “known” points, the measurement of subsurface properties is an inexact science. Thus, calibration is a necessary part of groundwater modeling where the initial estimates of aquifer properties, entered when the model is first created, are changed so that the model computes more realistic water level elevations and, in the current model, quarry inflow rates.

During calibration, the model-computed water levels are compared to those water levels measured in wells. These measured water levels are called calibration targets or just targets. The targets represent water levels measured at a particular time during the simulation or they can represent steady-state conditions. In the case of the current model, steady-state conditions represent average water levels measured in 2022 for the seven monitoring wells and two home-owner wells. Table 3-1 shows the wells used in the calibration of the Pierson Rheems Quarry model.

In addition to water level measurements, the model was also calibrated to the long-term average discharge rate for the quarry in 2022. The 2022 average pumping rate from the quarry is about 1 million gallons per day.

During calibration, the target water levels are compared to model-computed water levels. The model-computed water levels are subtracted from the field measurements to produce a residual. Positive residuals represent computed water levels that are lower than those measured in the field. Conversely, negative residuals are those where the model is computing water levels higher than the measured ones.

A statistical analysis is performed on the collection of residuals from all targets used in the model (Konikow 1978). Simple statistics such as the mean, standard deviation (sometimes called root-mean-square or RMS error), and absolute mean are commonly used. The mean residual should be close to zero, indicating that the positive and negative residuals are balanced. The absolute mean is computed by making all residuals positive and thus represents the average error in the calibration. These statistical measures are used to determine the quality of the calibration. Goals should be established for acceptable values of the mean, standard deviation, and absolute mean residual. These goals are discussed later in this chapter.

In addition to statistics computed for residuals, the distribution of residuals should be analyzed during calibration. It is desirable to have positive and negative residuals randomly scattered throughout the model. Clustering of positive or negative residuals over large areas is called spatial bias. One goal of calibration is to reduce spatial bias as much as possible. It is virtually impossible, however, to eliminate spatial bias because of the lack of subsurface data.

3.2 Calibration Results

There are many ways to assess the quality of a calibration. The Pierson Rheems Quarry model calibration was assessed by comparing the calibration statistics to the goals used by ESI in all company modeling projects. In addition, the degree of spatial bias was assessed.

What constitutes an acceptable calibration is very subjective. Woessner and Anderson (1992) suggest that goals should be established before the calibration starts. However, no standards have ever been put forth by ASTM or in the scientific literature that describe what these goals should be. Goals were established in the protocol for this model, and are based on goals used by ESI in all models and which have undergone peer review from U.S. Environmental Protection Agency and many state government agencies. These goals are summarized as follows:

- Residual standard deviation divided by range in head for all targets should be less than 0.10 (10%)

- Absolute residual mean divided by range in head for all targets should be less than 0.10 (10%)
- Residual mean divided by range in head for all targets should be less than 0.05 (5 %)
- There will be limited spatial bias in the distribution of residuals.

As previously discussed, a residual is the difference between a measured water level and the model-computed water level. The residual is calculated as the observed head minus the model-computed head. Thus, a negative residual occurs where the model-computed head is too high and a positive residual is where the model-computed head is too low.

The statistical analysis of the regional calibration is provided in Table 3-2 for the steady-state calibration. The table shows the residual mean, residual standard deviation and absolute residual mean. The residual mean uses both positive and negative residuals and thus should be close to zero if the positive and negative residuals balance each other. The absolute residual mean is computed after all residuals are made positive and is thus an average error in the model.

The statistics for the current model calibration meet the calibration goals described above. The residual mean, residual standard deviation, and absolute residual mean were -4.39 ft, 8.82 ft, and 7.94 ft, respectively. The residual mean divided by range in head is 3.3%, well below the goal of 5%. The standard deviation divided by range in head was 6.6%, again well below the goal of 10%. The absolute residual mean divided by range in head was 6.0%, significantly less than the goal of 10%. Therefore, all of these statistical measures are substantially better than the established goals.

Another aspect of the calibration compared the model-computed flow rate of the quarry discharge. As mentioned previously, the average flow is about 1 million gallons per day. The predicted flow rate of the quarry is 1.2 million gallons per day in the model. This rate is about 20% higher than current pumping.

3.3 Groundwater Flow in Quarry Area

Monitoring well locations are shown in Figure 3-1 and the water table map computed by the model is shown in Figure 3-2. This simulation also has a global mass balance error of 0.00%.

The calibrated water table map for the quarry shows a cone of depression caused by quarry dewatering around the current sump. This cone of depression is elongated to the south following the fracture zones inferred for that area. Away from the quarry, groundwater flows from topographic highs to the streams surrounding the quarry property.

4.0 Predictions of Future Impacts

The mine plan calls for mining to an elevation of 126 ft above sea level. Drains were set in the model in layer 1 to simulate mine dewatering. Drawdown contours were produced for these simulations, along with a prediction of quarry inflow rate. The drawdown contours are provided in Figures 4-1 for the current operations and in Figure 4-2 for the 126 ft elevation. The model predicts that drawdown will expand as the quarry is mined to deeper levels as one might expect. The 10 ft drawdown contour shown in these figures equates to the new zone of influence for the quarry at these depths. The 10 ft contour was chosen because an impact of 10 ft is unlikely to cause significant harm to local well owners.

Predicted quarry inflow rates are predicted to increase to 2.1 million gallons per day at the 126 ft level. Since the calibration over-predicted the inflow rate, this new rate is also likely on the high side.

5.0 References

ASTM, 1993, Standard Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem, Standard D5447-93, American Society for Testing and Materials, Philadelphia, Pennsylvania, 15 p.

Anderson, M.P. and W.W. Woessner, 1992, Applied Groundwater Modeling; Simulation of Flow and Advective Transport, Academic Press, San Diego, California, 381 p.

Andersen, P.F., 1993, A manual of instructional problems for the USGS MODFLOW model, U.S. EPA, EPA/600/R-93/010.

Environmental Simulations, Inc., 2007, Groundwater Vistas Version 5 User's Guide.

Franke, O.L., T.E. Reilly, and G.D. Bennett, 1984. Definition of boundary and initial conditions in the analysis of saturated groundwater flow systems - an introduction, U.S. Geological Survey Open-File Report 84-458, Reston, Virginia.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald, 2000, MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model – User Guide to Modularization Concepts and the Ground-Water Flow Process, USGS Open File Report 00-92.

Konikow, L.F., 1978. Calibration of groundwater models, in Proceedings of the Specialty Conferences on Verification of Mathematical and Physical Models in Hydraulic Engineering, College Park, Maryland, August 9-11, 1978.

McDonald, M.G. and A.W. Harbaugh, 1988, A modular three-dimensional finite-difference ground-water flow model, U.S. Geological Survey TWRI, Book 6, Chapter A1.

Panday, S., C.D. Langevin, R.G. Niswonger, M. Ibaraki, and J.D. Hughes, 2013, MODFLOW-USG Version 1: An Unstructured Grid Version of MODFLOW for Simulating Groundwater Flow and Tightly Coupled Processes Using a Control Volume Finite-Difference Formulation, USGS Techniques and Methods 6-A45.

Risser, D.W., R.W. Conger, J.E. Ulrich, and M.P. Asmussen, 2005, Estimates of Ground-Water Recharge Based on Streamflow-Hydrograph Methods: Pennsylvania, USGS Open-File Report 2005-1333.

Woessner, W.W. and M.P. Anderson, 1992. Selecting calibration values and formulating calibration targets for groundwater flow simulations, Proceedings of the NWWA Conference on Solving Ground-Water Problems with Models.

Table 2-1. Hydraulic Conductivity Zones in the Calibrated Model.

Formation	*Location*	*Zone*	*Horizontal Hydraulic Conductivity (ft/d)*	*Vertical Hydraulic Conductivity (ft/d)*
Epler Fm	Regional	1	0.5	0.2
Stonehenge Fm	Regional	2	0.50	0.05
Millbach Fm	Regional	3	5.0	0.5
Annville Fm	Regional	4	2.0	0.2
Hershey Fm	Regional	5	2.0	0.2
Cocalico Fm	Regional	6	2.0	0.2
New Oxford Fm	Regional	7	1.0	0.1
New Oxford Conglomerate	Regional	8	0.2	0.02
Epler Fm	Quarry	10	5.0	0.5

Table 3-1. Monitoring Well Locations for the Pierson Rheems Model.

Name	X	Y	Layer	Water Level (ft msl)
A	2,295,327	292,742	1	385.90
B	2,296,765	292,430	1	349.40
D	2,295,241	291,761	1	366.68
22-1	2,296,913	291,513	1	300.00
22-2	2,295,992	290,929	1	308.50
22-3	2,296,335	290,040	1	304.90
22-4	2,294,307	288,983	1	386.80
North	2,293,244	291,886	1	433.00
Bossler	2,297,245	289,122	1	315.00

Table 3-2. Calibration Results for the Pierson Rheems Model.

Name	X	Y	Layer	Observed	Computed	Residual
A	2,295,327	292,742	1	385.90	387.24	-1.34
B	2,296,765	292,430	1	349.40	355.19	-5.79
D	2,295,241	291,761	1	366.68	362.17	4.51
22-1	2,296,913	291,513	1	300.00	320.44	-20.44
22-2	2,295,992	290,929	1	308.50	312.55	-4.05
22-3	2,296,335	290,040	1	304.90	314.83	-9.93
22-4	2,294,307	288,983	1	386.80	388.47	-1.67
North	2,293,244	291,886	1	433.00	421.53	11.47
Bossler	2,297,245	289,122	1	315.00	327.29	-12.29

Statistical Analysis:

Residual Mean	-4.39
Absolute Residual Mean	7.94
Residual Std. Deviation	9.36
Range in Observations	133.00
Scaled Residual Std. Deviation	7.0%
Scaled Absolute Residual Mean	6.0%
Scaled Residual Mean	-3.3%

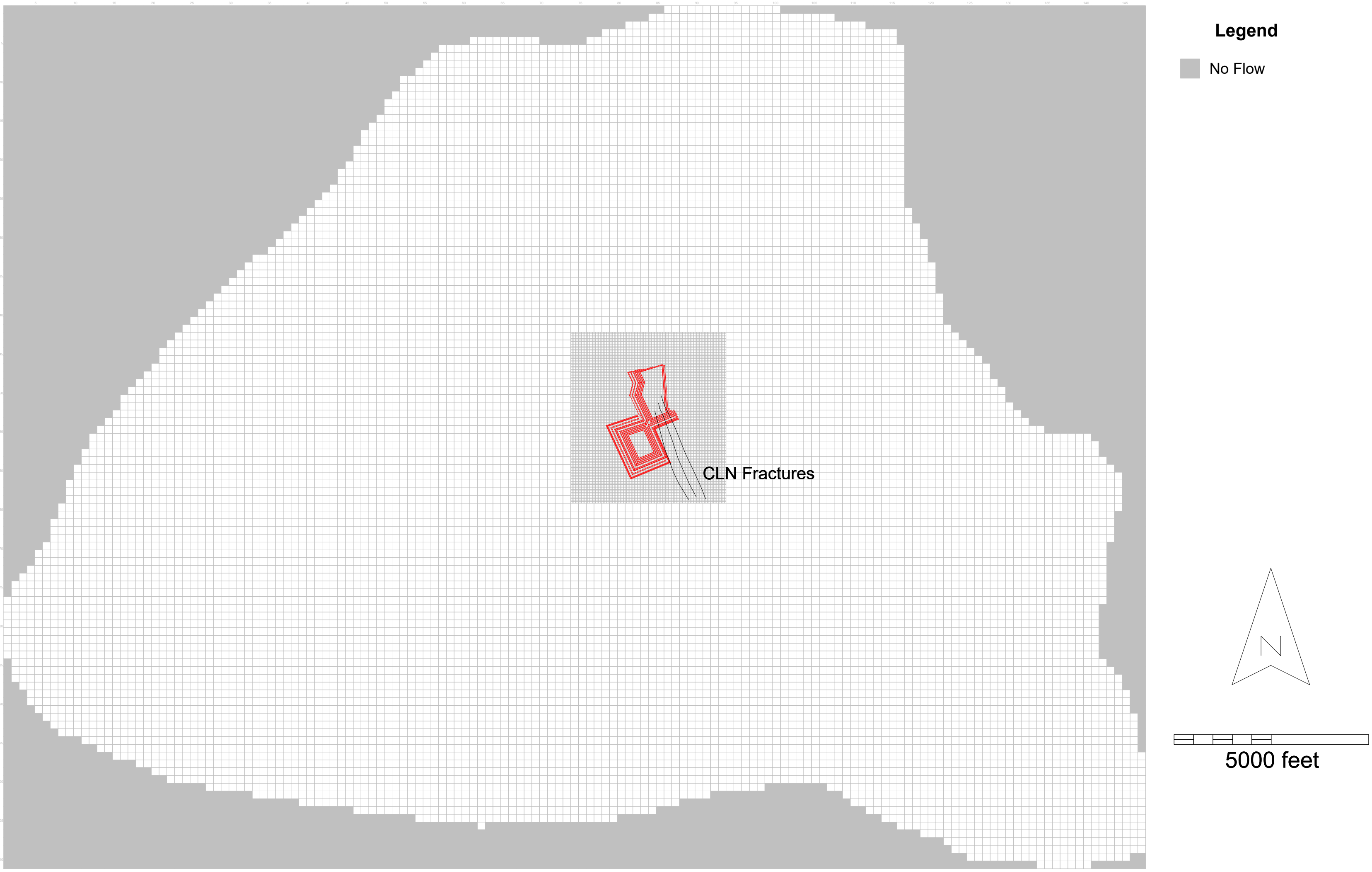


Figure 2-1 Model Grid for the Pierson Rheems Groundwater Model.

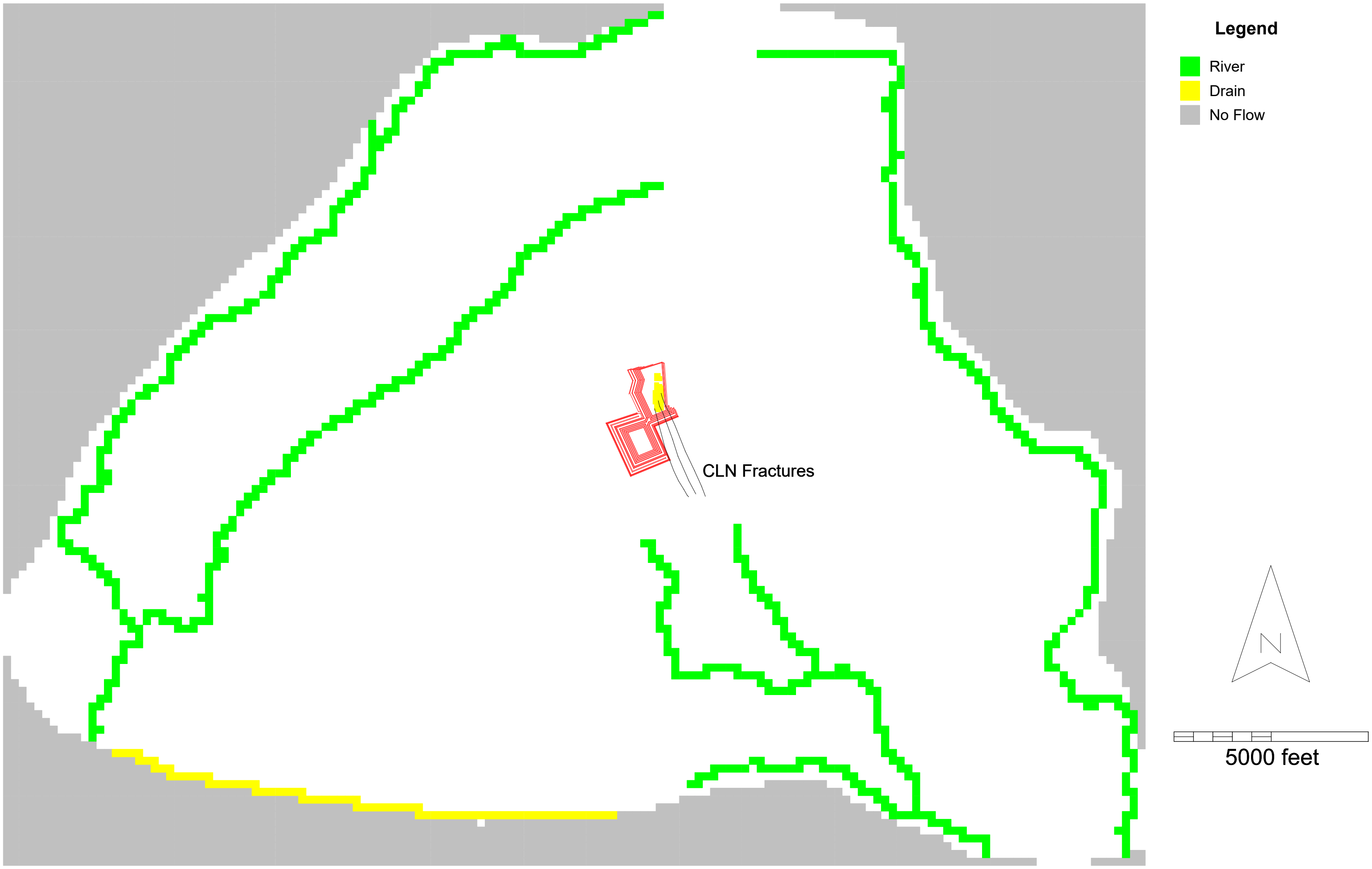


Figure 2-2 Boundary Conditions for the Pierson Rheems Groundwater Model.

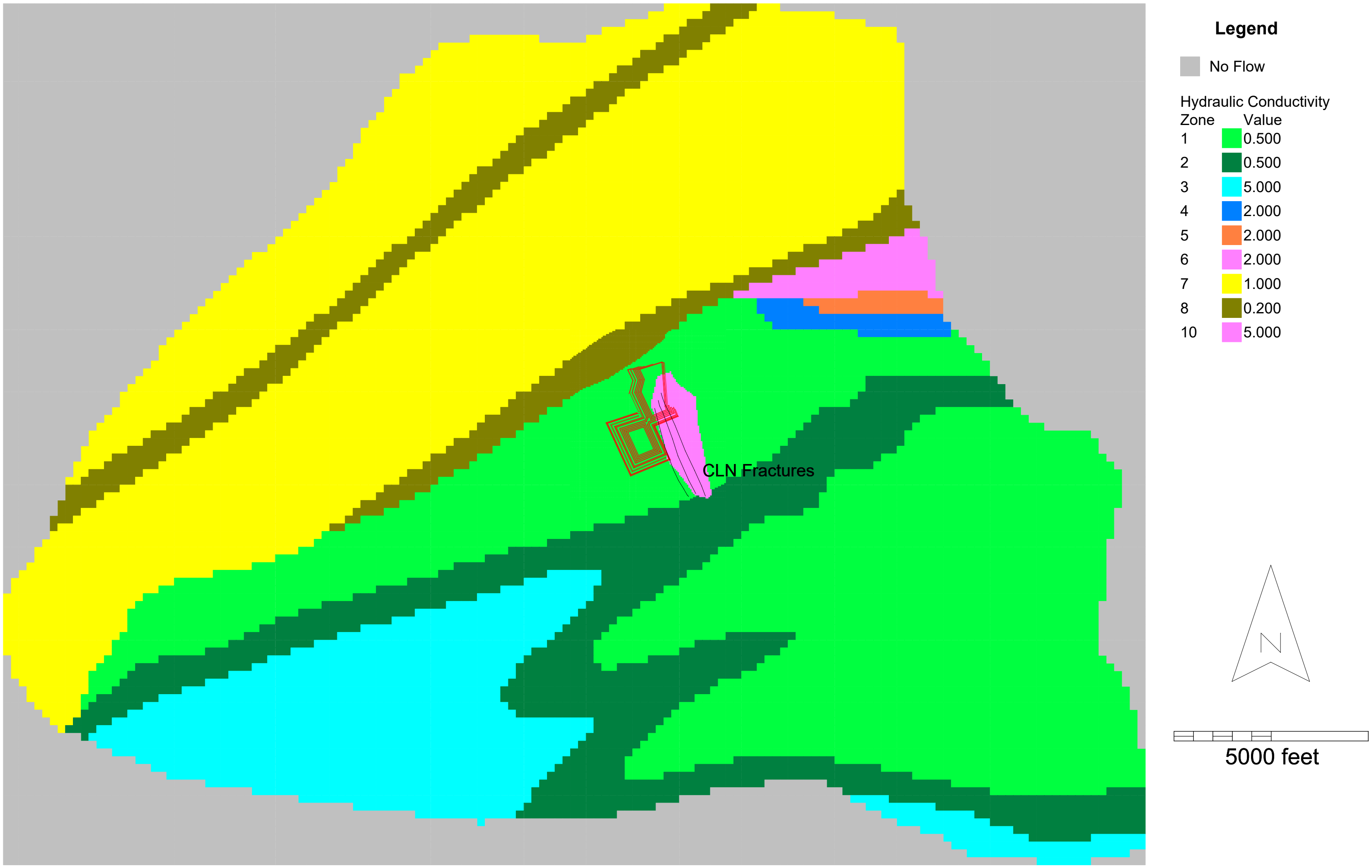


Figure 2-3 Hydraulic Conductivity Zones for the Pierson Rheems Groundwater Model.

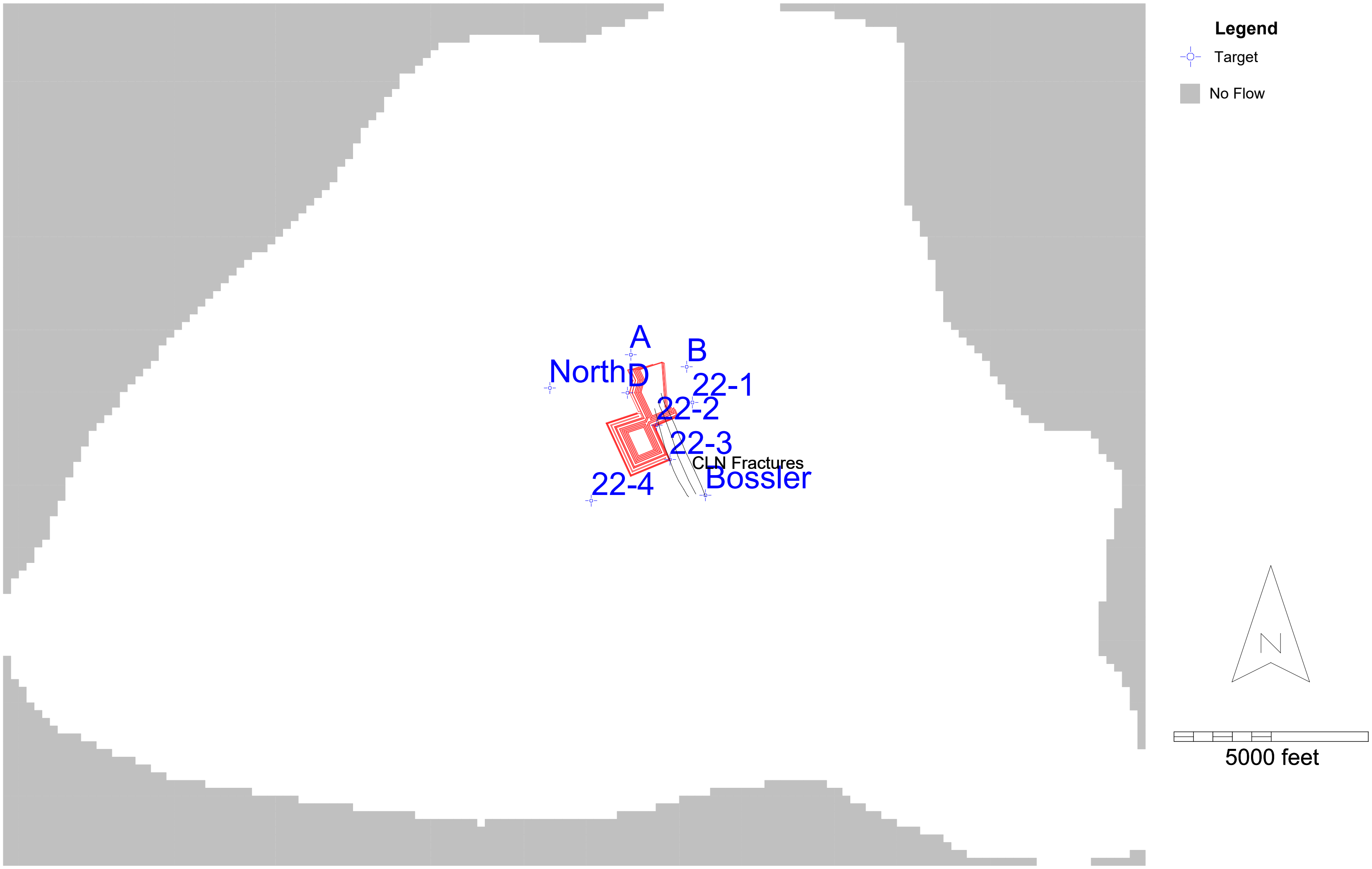


Figure 3-1 Monitoring Well Locations in the Pierson Rheems Groundwater Model.

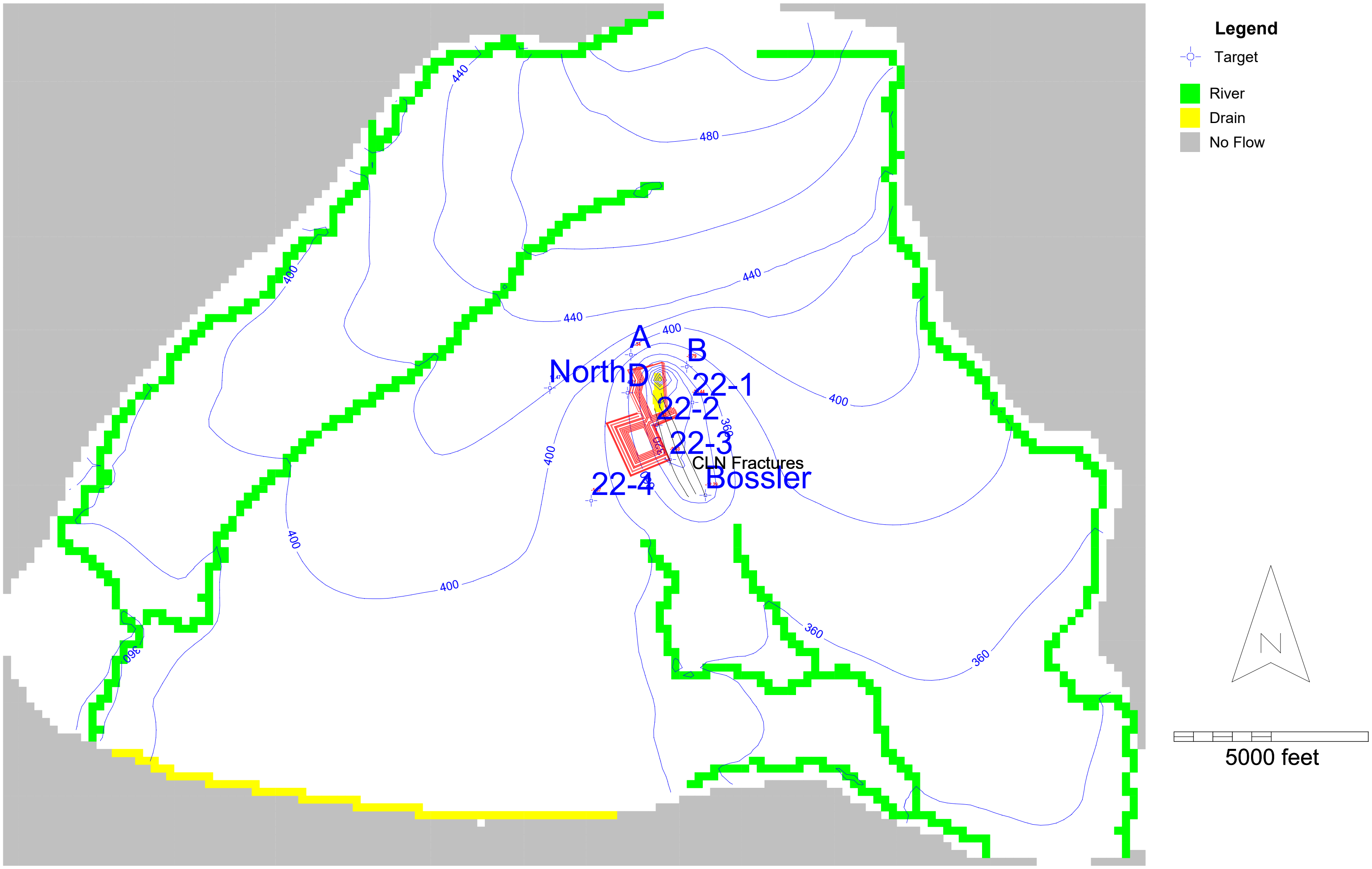


Figure 3-2 Calibrated Water Table in the Pierson Rheems Groundwater Model.

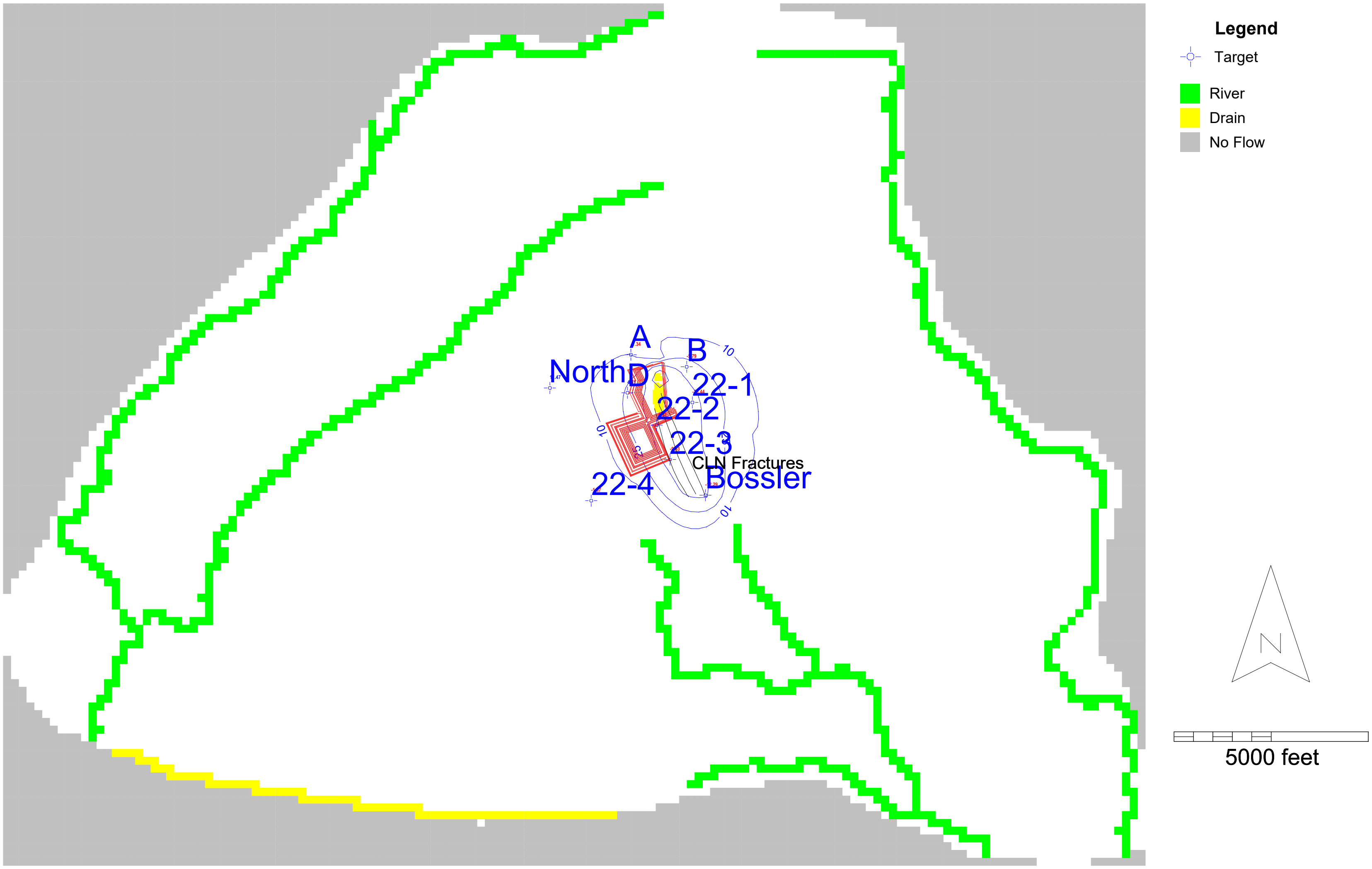


Figure 4-1 Zone of Influence Under Current Conditions.

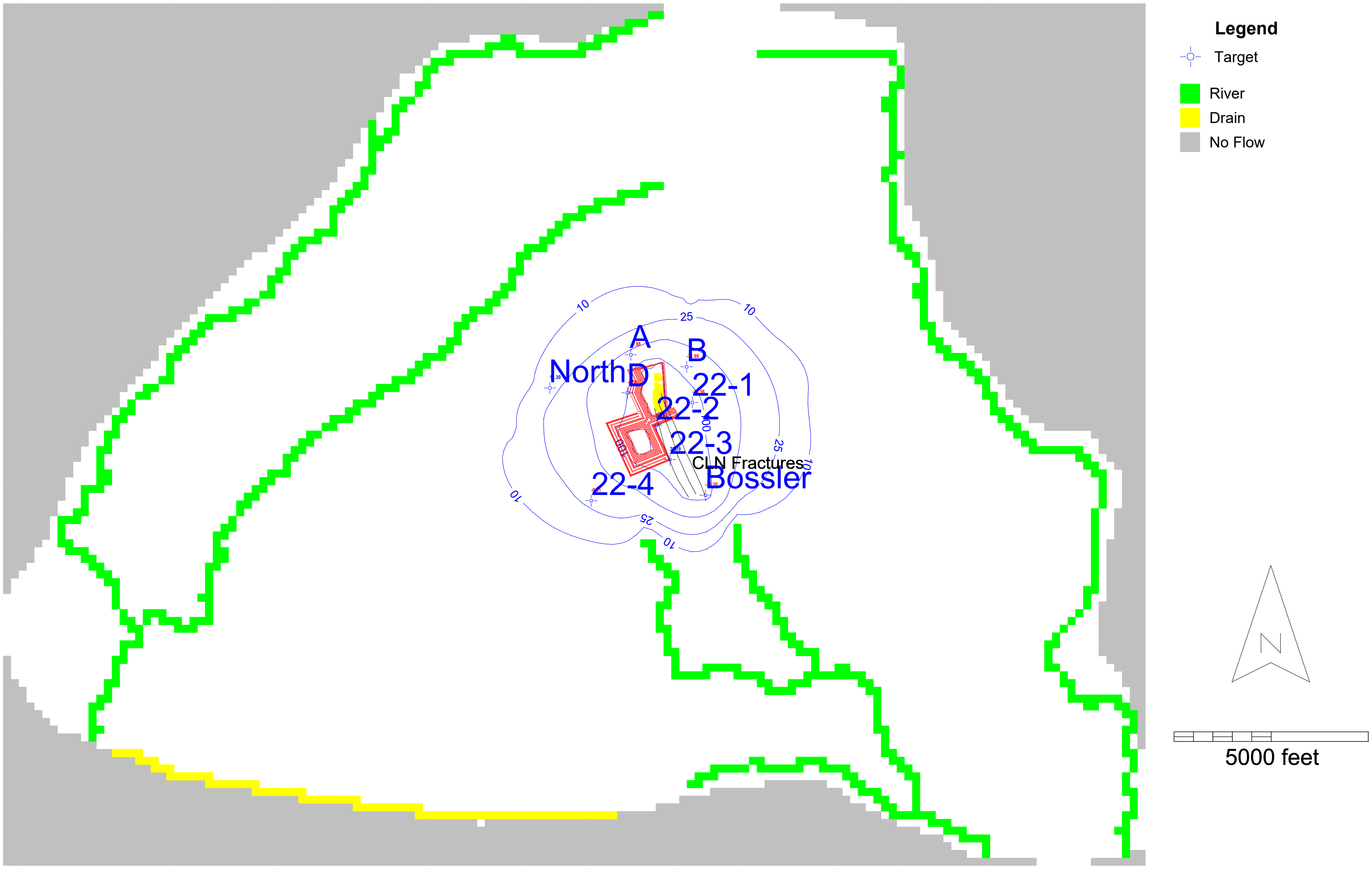


Figure 4-1 Zone of Influence with Pit Floor at 126 Ft. msl.

SINKHOLE MITIGATION PLAN

The area generally south of Heisey Quarry Road near the Rheems Quarry is karstic and prone to sinkhole development. In the event of an active sinkhole located within the zone of influence (a noticeable surface depression caused by the collapse of soil or rock material below it, where, due to its particular location, directly threatens public health or safety, a private dwelling, structure or the environment) the Quarry shall take action to repair it, unless it can be shown that the sinkhole(s) is/are related to some other factor, a man-made feature or activity, or significant overlap of the hydrologic zones of influence of adjacent water withdrawal sources. The quarry shall report to the PADEP within 24 hours of any known sinkhole or reported sinkhole. The PADEP will be notified with a schedule for repair within three (3) business days of identification of the problem. Repair of the sinkhole shall begin immediately upon Department approval after meeting any other governmental permitting requirements, if applicable, and after obtaining required third-party access needed to affect the work. The permitee will notify the Department of any problems it is experiencing in its efforts to obtain access to private property. The department will consider any disputes or alternative plans with regards to the permitee fulfilling obligations of this condition, including any arrangement between the permitee and the third-party property owner with respect to the disposition of the sinkhole in question. A third-party utility contact list is included in this report.

Any sinkholes that occur within 100 feet of a stream channel including within the stream channel shall follow the emergency permit conditions listed below:

Emergency Permit Conditions

1. No change in the proposed work shall be made except with the written consent of the Department. Minor field adjustments or additions to the erosion and sediment pollution controls shall be made, as necessary, to ensure that runoff from all affected, unstabilized areas passes through an adequate erosion and sediment pollution control device prior to exiting the site; that runoff from off-site, unaffected areas is properly diverted around or through the site without coming into contact with sediment-laden on-site runoff, and drainage areas to controls or other facilities, as designed, are maintained.

2. The permittee shall notify the Surface Mine Conservation Inspector when work is commenced to implement the plan and after completion of work.

3. All disturbed areas not draining to some type of sediment-removal facility shall be stabilized within twenty (20) days of affecting these areas, weather permitting.

4. Within thirty (30) days after completion of work authorized in the approved plan, permittee shall file with the Department a statement certifying that work has been performed in accordance with the approved plan.

5. The erosion and sediment pollution controls must be properly implemented, closely monitored and revised, as conditions warrant, to minimize erosion and to prevent excessive sedimentation in the receiving stream channel.

6. The Pennsylvania Fish and Boat Commission and the local County Conservation District shall be notified prior to beginning of construction.

7. The permitee shall exercise caution during the proposed work to eliminate excessive turbidity and sedimentation of the stream channel downstream and shall immediately stabilize all excavated areas by seeding and mulching or other approved means.

8. All material and debris removed from the stream bed shall be moved entirely out of the flood plain area.

9. Care shall be taken so as not to discharge construction materials or sediment into stream waters. No waste construction materials or pollutants may be disposed of into the waters of the Commonwealth (i.e., concrete, gravel, washings, sediment, etc.).

10. The proposed work shall be timed, if possible, during low-flow periods. Any flow during construction must be diverted around the work area. Work within the stream must be minimized (i.e., from the top of bank whenever possible) and completed as quickly as possible, but in no case extending for more than 24 hours.

11. All material and equipment necessary to construct, complete and stabilize work areas and channel must be readily available or on-site prior to beginning of work to avoid unnecessary delays. All disturbed areas within or flowing into the relocated channel shall be stabilized prior to diverting flow into the channel.

12. Any area which is disturbed during this operation shall be stabilized within three (3) weeks of the most recent earth-moving activity in that area, or as soon as weather or seasonal constraints permit. Individual erosion and sediment pollution controls must be maintained until the areas draining to each control are permanently stabilized.

13. Prior to repairing any sinkhole which involves digging a Pennsylvania One Call must be made to 811. The Pennsylvania One Call is how sinkhole repair shall be coordinated with adjacent utilities.

We have made a “Design” One Call and the Utility Contact List has been developed:

Company: Elizabethtown Area Water Authority
Address: 211 W Hummelstown Street
Elizabethtown, Pa. 17022
Contact: Del Becker

Company: Elizabethtown Regional Sewer Authority
Address: 235 Ersa Dr
Elizabethtown, Pa. 17022
Contact: Steven Rettew
Email: Steve@Ersapa.Com

Company: First Energy Penelec
Address: 21 S Main St
Akron, Oh. 44308
Contact: Cara Warren
Email: Carawarren@Firstenergycorp.Com

Company: Ppl Electric Utilities Corporation
Address: 434 Susquehanna Trl
Northumberland, Pa. 17857
Contact: Doug Haupt
Email: Dlhaupt@Pplweb.Com

Company: Lumen/Centurylink
Address: 200 Technology Drive
Pittsburgh, Pa. 15219
Contact: Dan Shento
Email: Dan.Shento@Lumen.Com

Company: David Miller Associates Inc.
Address: 1076 Centerville Road
Lancaster, Pa. 17601
Contact: Scott Hain
Email: Shain@Dmai.Com

Company: UGI Utilities Inc
Address: 1301 AIP DR
Middletown, PA 17057-5987
Contact: Stephen Bateman
Email: sbateman@ugi.com

In Addition to the One Call List we have added the following relevant contact information

West Donegal Township
John O. Yoder III, RA
Township Manager
One Municipal Drive
Elizabethtown, PA 17022
717-367-7178
jyoder@wdtwp.com
www.wdtwp.com

Mount Joy Township
Justin S. Evans, AICP
Township Manager/Zoning Officer
8853 Elizabethtown Road
Elizabethtown, PA 17022
717-367-8917 x.207 (office)
717-719-2089 (cell)
www.mtjoytwp.org

Pennsylvania Department of Transportation
District 8 Office
2140 Herr Street
Harrisburg, PA 17103
Main Phone 717-787-6653
Highway Occupancy Permits 717-787-8789
Mazhar Malik 717-787-8789
Email: mmalik@pa.gov

Amtrak
Krista Keene, Senior Manager
30th Street Station
2955 Market Street, Box 25
Philadelphia, Pennsylvania 19104
Office: (215) 349-3446
Fax: (215) 349-1983
Email: krista.keene@amtrak.com

Utility & Right-of-Way, Occupations, Policies and Procedures, dated 9/30/2020 or latest version should be followed for any work within the Amtrak Right of Way.

Entering any railroad right-of-way or other railroad property without the written permission of the railroad is trespassing and illegal. Violators will be prosecuted, and they risk the possibility of serious, even fatal, injury.

GENERAL SINKHOLE REMEDIATION

When sinkholes require repairs all construction techniques should be in accordance with a geotechnical engineer's report and specifications or as per the attached Chapter 17 of the Erosion and Sedimentation Pollution Control Manual March 2012. Figures 17.1 through 17.4 which provide guidance based on varying conditions that may be encountered in completing the repairs.

If any conditions are encountered that are not specified in these figures, a geotechnical engineer should review the conditions and develop alternative remediation.

SINKHOLE REPAIR

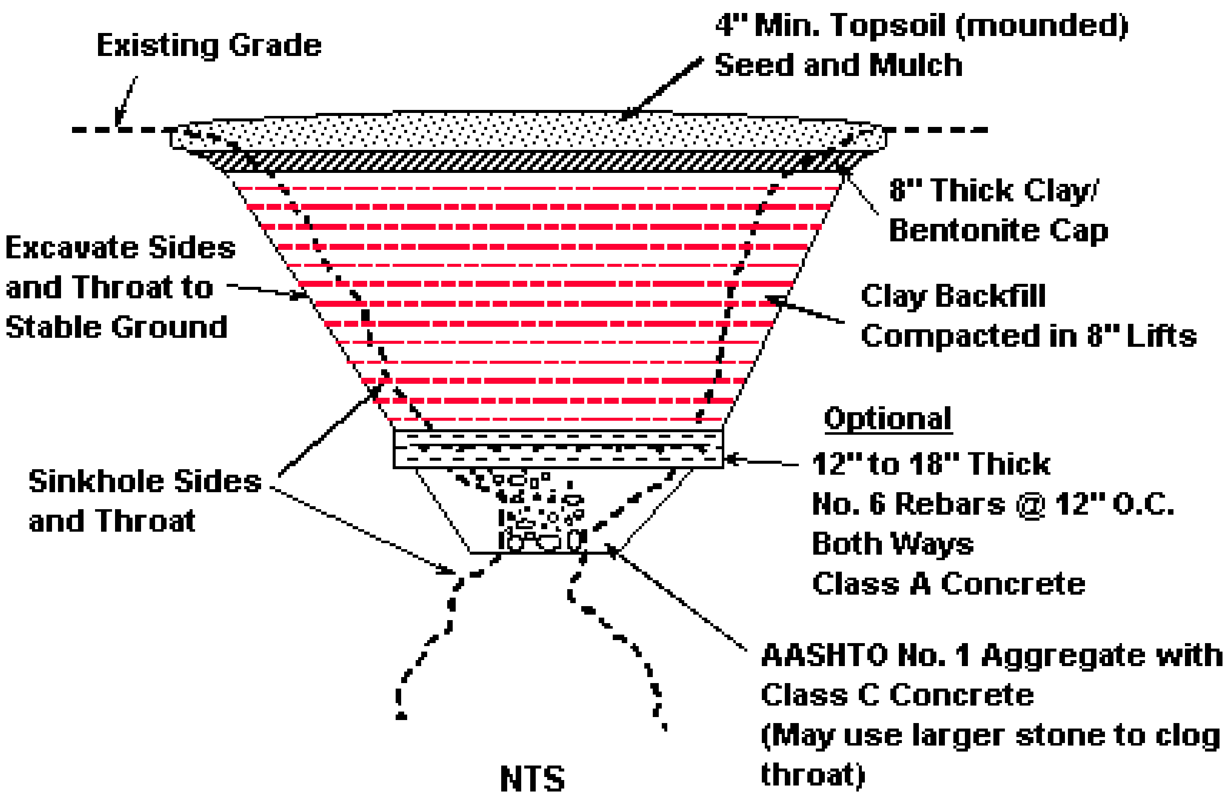
Source Unknown

Sinkholes vary greatly in size and nature. Therefore, specific methods of repairing sinkholes will depend on site conditions including but not necessarily limited to:

- Sinkhole diameter and depth
- Surface slope
- Presence or absence of surface runoff
- Soil type
- Connectivity to public or private water supplies
- Proximity of surface waters
- Ease of access by construction equipment
- Potential danger to the public or damage to structures

Due to the variable nature of sinkholes, they should be repaired under the direct observation and supervision of a professional geologist or licensed geotechnical engineer. Figures 17.1 through 17.4 are provided as general guidelines for the repair of sinkholes. They may be modified as necessary to accommodate specific site conditions. Site specific sinkhole repair plans will be reviewed on a case-by-case basis.

FIGURE 17.1
Sinkhole Repair with a Bentonite Cap

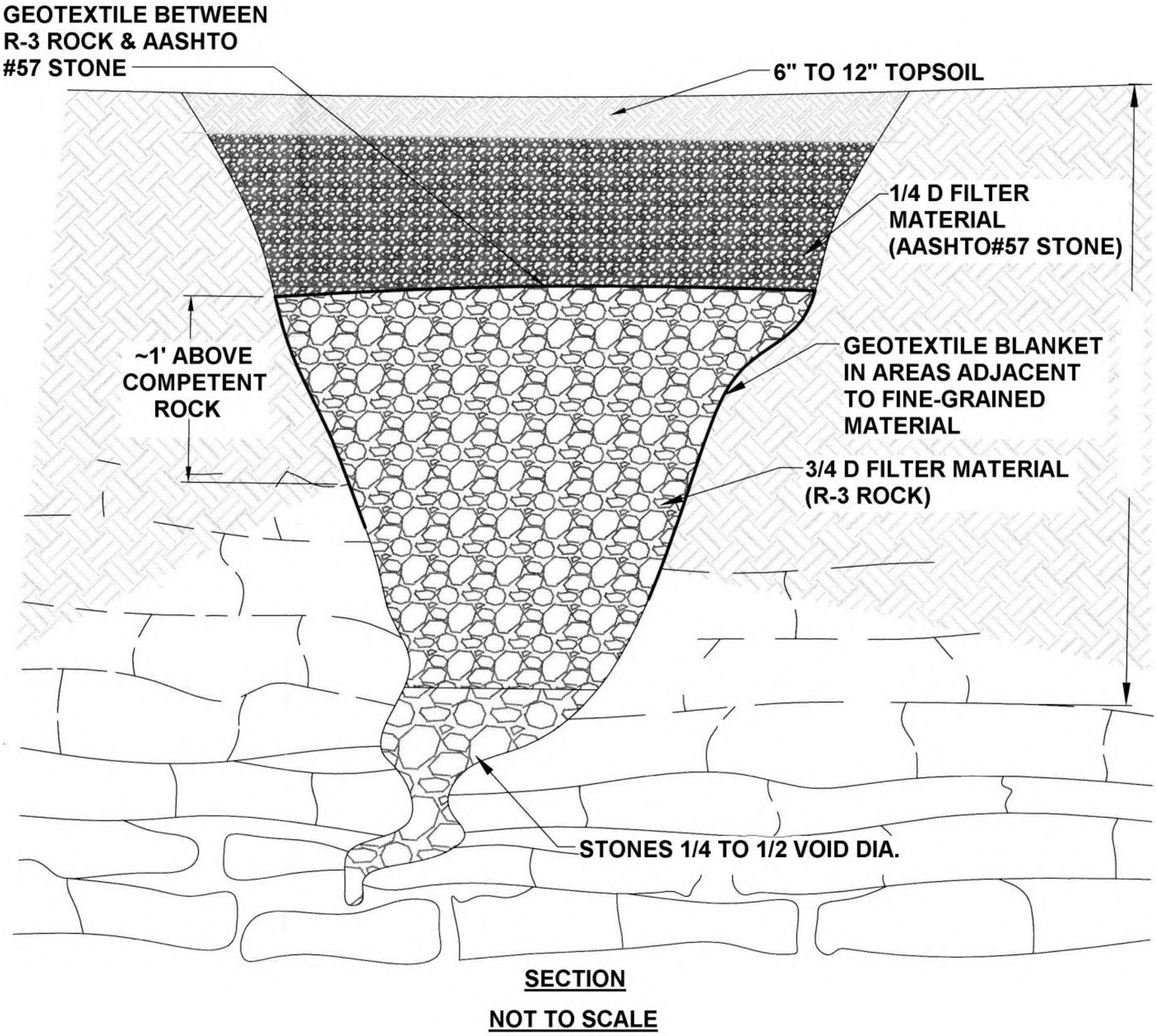


PA DEP

Loose material shall be excavated from the sinkhole and expose solution void(s) if possible. Enlarge sinkhole if necessary to allow for installation of filter materials. Occupational Safety and Health Administration (OSHA) regulations must be followed at all times during excavation.

Stones used for the “bridge” and filters shall have a moderately hard rock strength and be resistant to abrasion and degradation. Shale and similar soft and/or non-durable rock are not acceptable.

FIGURE 17.2
Sinkhole Repair with a Pervious Cover

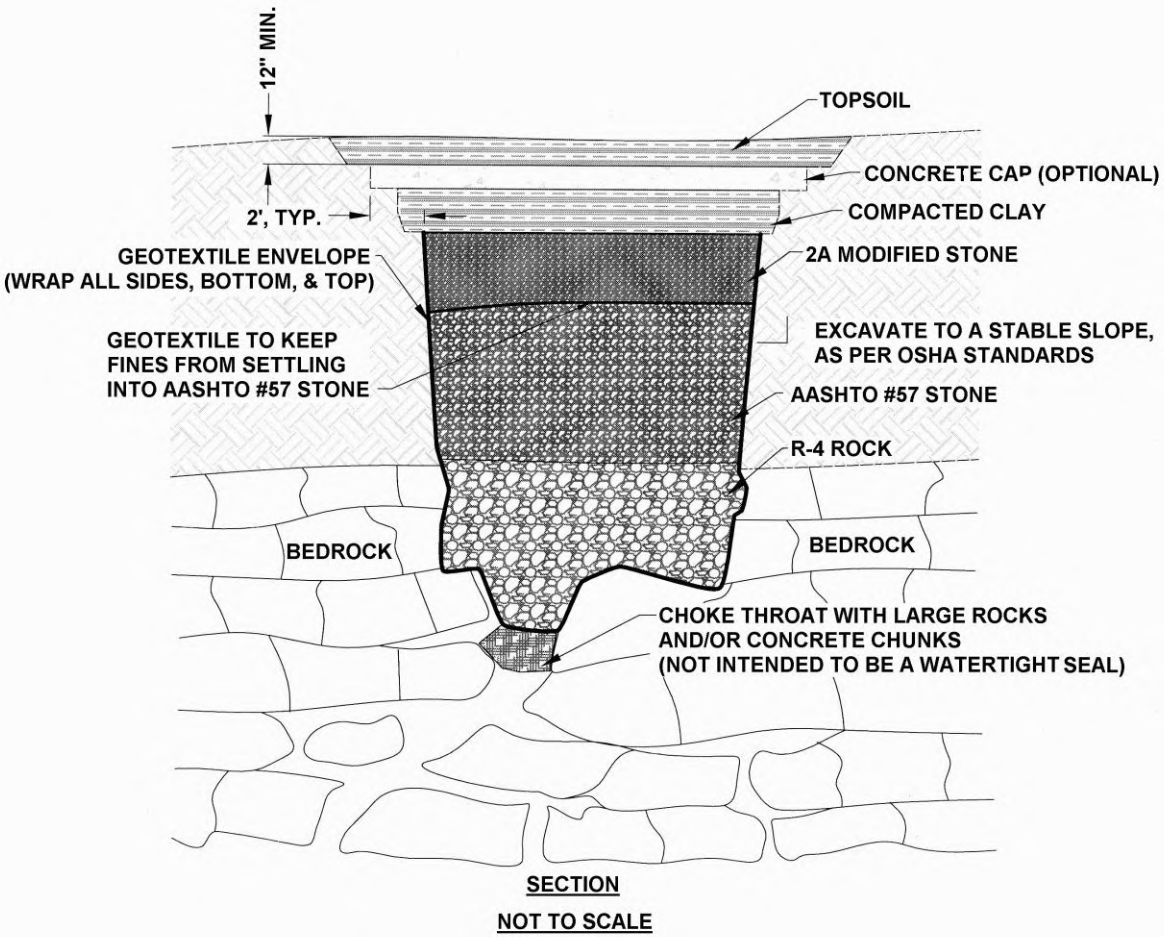


Adapted from USDA NRCS

Loose material shall be excavated from the sinkhole and expose solution void(s) if possible. Enlarge sinkhole if necessary to allow for installation of filter materials. OSHA regulations must be followed at all times during excavation.

Stones used for the "bridge" and filters shall have a moderately hard rock strength and be resistant to abrasion and degradation. Shale and similar soft and/or non-durable rock are not acceptable.

FIGURE 17.3
Sinkhole Repair with an Impervious Cover



Adapted from USDA NRCS

Loose material shall be excavated from the sinkhole and expose solution void(s) if possible. Enlarge sinkhole if necessary to allow for installation of filter materials. OSHA regulations must be followed at all times during excavation.

Geotextile shall be non-woven with a burst strength between 100 and 200 psi.

Select field stone(s) about 1.5 times larger than solution void(s) to form “bridge.” Place rock(s) so no large openings exist along the sides. Stones used for the “bridge” and filters shall have a moderately hard rock strength and be resistant to abrasion and degradation. Shale and similar soft and/or non-durable rock are not acceptable.

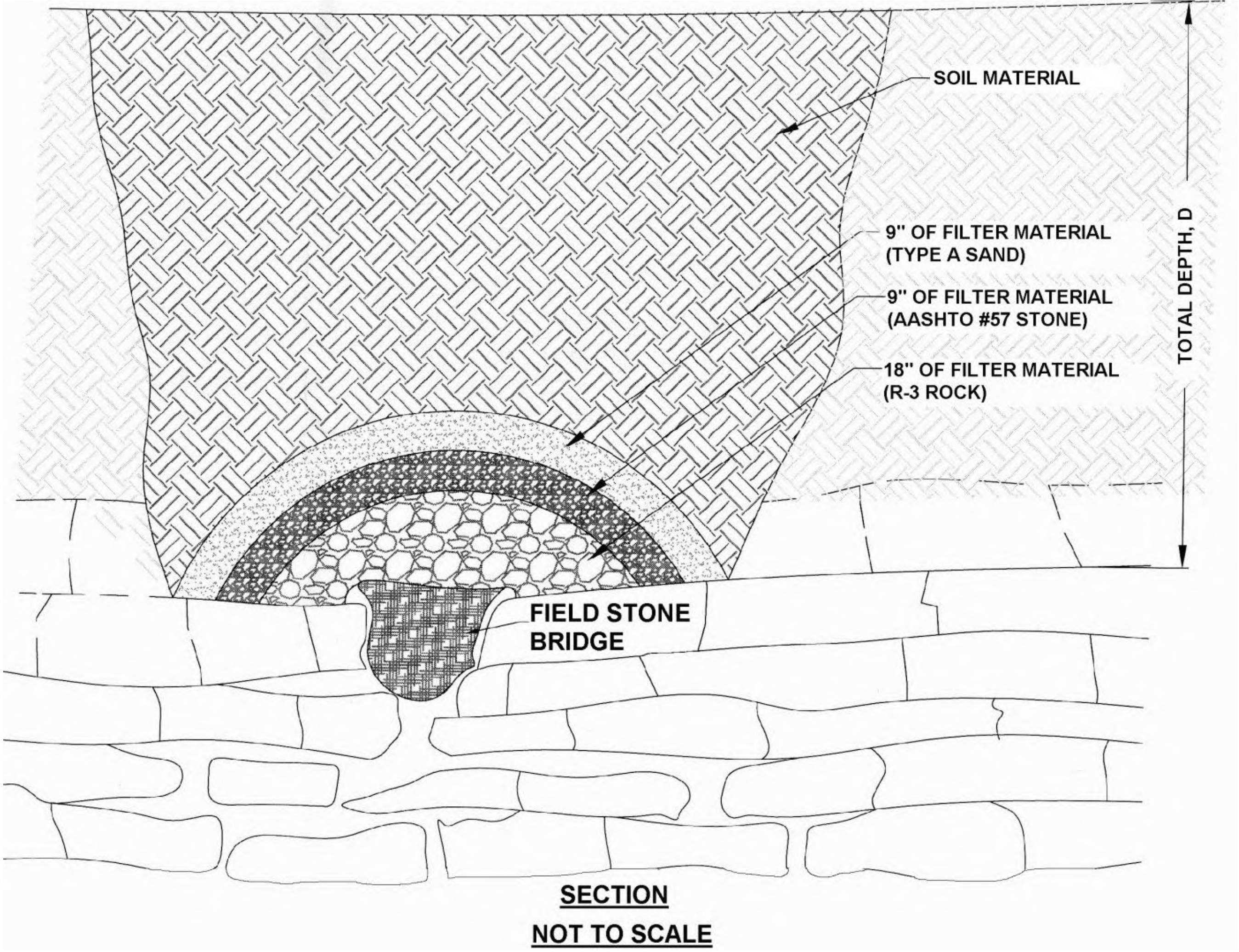
Minimum thickness of R-4 rock is 18.” AASHTO #57 stone thickness shall be ¼ to ½ that of the R-4 rock. Minimum thickness of 2A modified crushed stone shall be 9”. AASHTO #57 stone and 2A modified crushed stone shall be compacted after each placement.

Compacted clay seal shall be a minimum of 12” thick. Clay shall be placed in 6” to 9” lifts and thoroughly compacted.

Concrete cap, which is optional, shall be a minimum of 8” thick. Use 4,000 psi concrete with 6” X 6” - 6 gauge welded wire fabric, or # 3 rebar on 18” O.C. both ways.

Topsoil shall be a minimum of 12” thick. Grade for positive drainage away from sinkhole area.

FIGURE 17.4
Sinkhole Repair with Soil Cover



Adapted from USDA NRCS

Loose material shall be excavated from the sinkhole and expose solution void(s) if possible. Enlarge sinkhole if necessary to allow for installation of filter materials. OSHA regulations must be followed at all times during excavation.

Select field stone(s) about 1.5 times larger than solution void(s) to form “bridge.” Place rock(s) so no large openings exist along the sides. Stones used for the “bridge” and filters shall have a moderately hard rock strength and be resistant to abrasion and degradation. Shale and similar soft and/or non-durable rock are not acceptable.

Minimum thickness of R-3 rock is 18.” AASHTO #57 stone thickness shall be a minimum of 9” thick. Minimum thickness of type A sand shall be 9”. NOTE: A non-woven geotextile with a burst strength between 100 and 200 psi may be substituted for the AASHTO#57 stone and type A sand.

Soil shall be mineral soil with at least 12 % fines and overfilled by 5% to allow for settlement. Suitable soil from the excavation may be used. Any available topsoil shall be placed on top surface.

AN EXAMPLE OF RECUMBENT FOLDING SOUTH OF THE GREAT VALLEY OF PENNSYLVANIA

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Franklin and Marshall College, Lancaster, Pennsylvania

ABSTRACT

In the Beekmantown limestone, at Rheems, Lancaster County, Pennsylvania, quarry operations have revealed an example of a style of folding common in the Great Valley to the north. Flow folds, indicative of considerable tectonic transport, show closely spaced axial planes traceable for 700 feet across the strike with an average dip of only 3 degrees. The pattern of these folds is presented and some of the differential pressure effects during flow are discussed.

INTRODUCTION

Recumbent folding, widespread overturning and other evidences of large tectonic transport have been reported in the Great Valley area by Gray (1) and others. On the southern border of the Great Valley this belt of recumbent folding is sharply interrupted by the Triassic Basins so that its extension southward toward the source area is poorly known.

Just south of the Triassic Basins, at Rheems, near Elizabethtown, Pennsylvania, very complex recumbent folding is exposed in a quarry operated by Heisey Brothers, Inc. The folding (like much of that in the Great Valley) is in the Ordovician Beekmantown limestone and appears to be an extension of the Great Valley zone of tectonic transport. Recent excavation in the quarry has revealed the interrelations of many of the complex folds exposed in its walls. Three dimensional pictures of these structures have been provided as work proceeded down the eastward plunge of the fold axes. The quarry operation has progressively destroyed some of these structures as it revealed them.

The purpose of the present paper is threefold: to describe for the record a fine example of recumbent folding which is now partly destroyed; to point out that the Great Valley zone of intense horizontal tectonic transport exists to the south of the Triassic Basins; and third, to discuss some of the internal mechanics of this type of deformation as shown in Rheems quarry.

THE FOLD PATTERN

In this area of Pennsylvania, fold axes trend nearly east-west with tectonic transport toward the north. These structures show a 5 to 15 degree eastward plunge through the irregularly shaped quarry workings. Hence some of the quarry faces represent cross-sections through the fold pattern at a number of different levels. Other faces trending parallel to

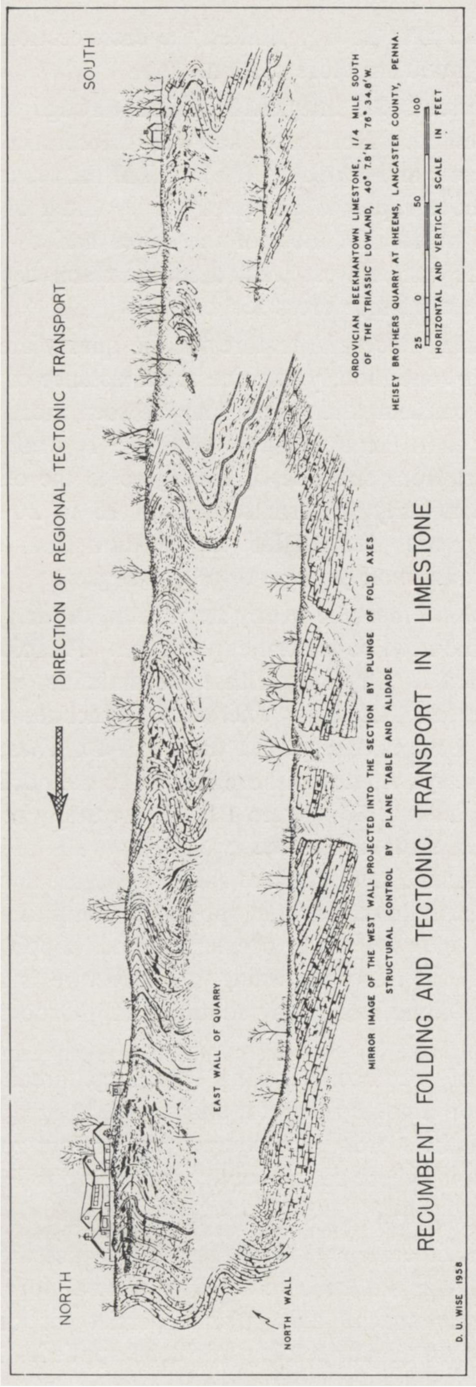
SOUTH
DIRECTION OF REGIONAL TECTONIC TRANSPORT
NORTH
EAST WALL OF QUARRY
NORTH WALL
MIRROR IMAGE OF THE WEST WALL PROJECTED INTO THE SECTION BY PLUNGE OF FOLD AXES
STRUCTURAL CONTROL BY PLANE TABLE AND ALIDADE
ORDOVICIAN BEEKMANTOWN LIMESTONE, 1/4 MILE SOUTH
OF THE TRIASSIC LOWLAND, 40° 7.8'N 76° 34.8'W.
HEISEY BROTHERS QUARRY AT RHEEMS, LANCASTER COUNTY, PENNA.
25
0
50
100
HORIZONTAL AND VERTICAL SCALE IN FEET
RECUMBENT FOLDING AND TECTONIC TRANSPORT IN LIMESTONE
D. U. WISE 1958

Figure 1

the strike of the fold axes have permitted the cross-sections to be tied together into an integrated structure section.

Figure 1 represents the integrated section through the quarry, constructed by this method. Horizontal and vertical control for the projecions was by plane table and alidade. The detail of the section was sketched from a series of photographs of the quarry faces taken over the past five years. It is to be noted that most of the lower half of the section is a mirror image of the visible west wall, a modification necessary to combine all the views into a single cross section.

The most striking structural features of the quarry are the nearly flat axial planes of folds continuously exposed for a distance of 700 feet across the strike. One prominent axial plane may be seen most readily just below the ground level in the upper part of figure 1, where similar curvatures of beds persist from one side of the figure to the other. A second axial plane retains a fairly uniform separation 15 to 20 feet below this plane. The axial planes rise 35 feet in elevation from one end of the quarry to the other, an average slope of only 3 degrees.

Where axial planes become nearly horizontal, ordinary terms such as anticline and syncline need additional explanation. As folds become more and more overturned it can be seen that the anticlines will be advanced farther in the direction of transport whereas the synclines will be retarded. Thus with regional tectonic transport to the north-northwest, the folds concave to the north are synclines and those convex to the north are anticlines. Accordingly the topmost fold in figure 1 is a structurally retarded syncline.

The contrast in structure of the two major walls of the quarry is a puzzling feature until the interrelations shown in figure 1 are noted. The west wall, a structurally lower section, shows the complex recumbent folds passing with depth into uniformly overturned beds dipping about 20 degrees to the south. In this overturning, the structure is almost identical to the miles of overturned and gently south-dipping Ordovician limestones in the Great Valley.

This pattern of recumbent folding with large areas of overturning is indicative of major tectonic transport and can be termed alpine structure in the true sense of the word. The source area or root zone of the moving mass must lie somewhere to the south, deeper in the Piedmont.

MECHANICS OF DEFORMATION

The mechanics of deformation of these limestones are those of complex flowage of a huge viscous mass. The general forms of folds and the individual closely spaced axial planes persist for considerable distances so that the term similar folding might be applied. Any single persistent axial plane represents a mass of rock that has either moved forward or been slightly retarded with respect to the adjacent axial planes. This pattern of folding by slight differential movements in the direction of transport is characteristic of the flowage of viscous fluids, as pointed out by Carey (2). Carey would probably regard the flow pattern at Rheems quarry as the result of horizontal slip on widely spaced planes of laminar flow in a viscous mass, a view which the present author favors.

To permit the overall flow pattern to take place, many complex internal flow movements must occur to absorb the local changes in volume between beds. This must be accompanied by some flexural slip between adjacent beds, a process which has resulted in bedding-plane slickensides throughout the quarry.

Some units are capable of flowing easily under the local differential pressures generated in the moving mass. These units now occupy much of the thickened axial portions of the folds. One bed is 14 feet thick on the axis but only four feet thick on the adjacent limb of the fold. The prominent flow feature at the top center of figure 1 is the result of "pumping" material into the closely-spaced axial regions of an adjacent syncline and anticline. This caused these thickened areas to merge and eliminate the limb between them. Local excessive flow of this nature causes minor alteration of the larger flow pattern. The result is minor warping of the axial planes in the zones of most intense flow. The zones of most intense flow, a combination of the tightest foldling and maximum shear, facilitate the development of a prominent axial plane jointing or cleavage.

In distinct contrast to the limestone beds undergoing intense flowage are other less viscous dolomitic beds which must make the volume adjustments to folding by a completely different mechanism. These beds show little thickening or thining and instead make the adjustments by filling of extension fractures with calcite veins. The openings formed by extension represent low pressure zones into which interstitial fluids move from adjacent areas, redepositing fresh calcite according to Riecke's principle. The relations of the extension veins to the folds are of two types: one set of veins fans the folds with strike parallel to the fold axes, the other set lies in planes perpendicular to the fold axes.

Where the more viscous beds suffer extreme elongation they neck down into boudins. The necked areas represent local areas of extreme lowering of pressure and may consist of almost pure vein calcite. The overall pressure forces adjacent beds into the potential opening created on either side of the neck to produce an hour-glass fold.

Of the approximately fifteen boudins visible in the quarry, all occur in one structural position, the strongly overturned limb of the fold. In a folding mass the overturned limb represents the plane of most active stretching as shown by some of the Alpine studies and by Cloos' work on oőlites (3). In Rheems quarry, the boudins indicate the pitfalls of measuring true stratigraphic thickness in strongly overturned and stretched beds. All of the beds have been stretched an equal distance and have undergone thinning in the process. It is only in the more viscous beds that the extent of the stretching and stratigraphic thinning may be evaluated by means of boudins and extension veins.

CONCLUSION

In spite of partial destruction, the exposures of recumbent folding in the quarry at Rheems, Pennsylvania, afford a concentrated lesson in the mechanics of viscous deformation. The pattern is one of great hoizontal transport and flow with countless local pressure and volume adjustments to accommodate the overall flow process. The exposure at Rheems Quarry is only a sample of a style of deformation common in a much larger region of tectonic flow in the Great Valley to the north.

LITERATURE CITED

1. Gray, C. 1954. Recumbent folding in the Great Valley, Proc. Penna. Acad. Sci. 28:96-101.
2. Cloos, E. 1947. Oolite deformation in the South Mountain Fold, Maryland, Bull, Geol. Soc. America. 58:843-918.
3. Carey, S. W. 1954. The rheid concept in geotectonics, Journal Geol. Soc. of Australia. 1:65-117.

Rheems quarry; The underside of a Taconian nappe in Lancaster County, Pennsylvania

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Alan R. Geyer, *5334 Huntingwood Court, Sarasota, Florida 33580*

LOCATION

The village of Rheems lies in the carbonate valley of northern Lancaster County, in southeastern Pennsylvania, at the edge of the Appalachian Piedmont Province (Fig. 1). Rheems is 2 mi (3.2 km) east of Elizabethtown, in the 7½-minute quadrangle bearing that town's name. The quarry is a short distance west of the village, adjacent to East Harrisburg Avenue in West Donegal Township. If you are arriving from some distance, the quarry can be most easily approached from the Rheems/Elizabethtown exit of Pennsylvania 283 (Fig. 2).

Rheems quarry is currently active; it is accessible only on weekends and after work ceases at 3:30 P.M. on weekdays. Permission to enter may be obtained by letter, phone, or in person from Union Quarries, Incorporated, Old Harrisburg Pike, Rheems, Pennsylvania 17570 (717-367-1080). Permission may also be obtained from the present superintendent, Denny Dupler, whose phone number is 367-4515. The quarry maybe entered by foot or by car. Because the quarry is active, hard hats, safety glasses, and hard-toed shoes are necessary.

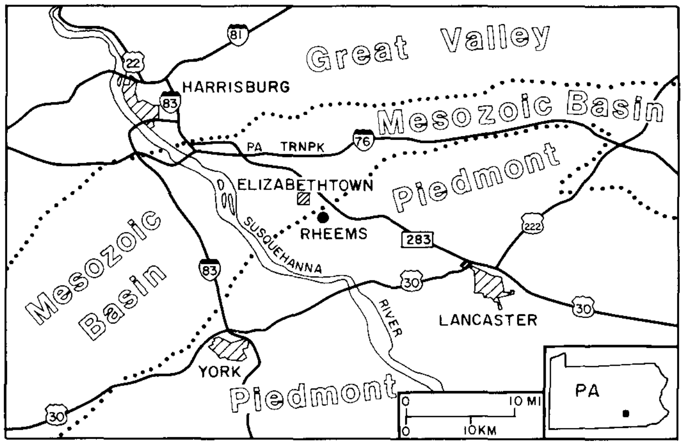

Figure 1. Roadmap of southcentral Pennsylvania, showing the major highways in the Rheems vicinity.

SIGNIFICANCE

The Taconian orogeny produced the alpine-style Lebanon Valley nappe in south-central Pennsylvania. Weathering and erosion have reduced this enormous recumbent anticlinorium to a humble topography, but a few glimpses here and there provide clues to its complexities and grandeur. The quarry at Rheems exhibits recumbent folds, rock flowage, boudinage, faults and fractures, cleavage, and transport indicators in the overturned carbonate beds of the lower limb of the nappe.

SITE INFORMATION

The rocks. Rheems Quarry was opened in the 1920s to supply stone for building purposes, the use that continues to this day. The quarry exposes only the Lower Ordovician Epler Formation, an approximately 2,500 ft (750 m) thick carbonate unit within the Beekmantown Group (Meisler and Becher, 1971) present throughout the entire Lebanon Valley nappe from Reading to Harrisburg.

Perhaps the most distinctive aspect of the Epler is the interbedding of limestone and dolomite, which on weathered surfaces provides striking displays of mesoscale structures. The limestones are mostly medium to medium-light gray (locally light pinkish gray) and weather to a light olive-gray or light gray. The finely crystalline beds contain very fine dark gray laminations.

The medium crystalline dolomite beds are medium gray in color, and weather to a yellowish gray. The dolomites are also laminated, and both lithologies tend to be medium to thick-bedded. Chert, occurring as dark gray to black nodules, lenses, and stringers, is scattered throughout the Epler Formation.

Regional setting. The sedimentary rocks at Rheems quarry were deposited on the carbonate shelf on the edge of the Laurentian continent, the Precambrian core of what is now North America. During the Middle and Late Ordovician, the continental convergence and closing of the proto-Atlantic Ocean created the Taconian orogeny. During this diastrophism, enormous blocks of the sedimentary shelf and large fragments of the underlying Precambrian rocks were forced up and into a younger shale basin to the (then?) northwest, which contained sediments of the present Martinsburg Formation. In the course of this (presently) northward movement, some of the blocks overrode their leading edge, forming recumbent anticlinoria of considerable complexity. The Lebanon Valley nappe is one of these thrust blocks.

The Lebanon Valley nappe contains rocks of Precambrian, Cambrian, and Ordovician age. The nappe is more than 60 mi (100 km) in width, and extends across the regional trend for at least 30 mi (50 km), from the Great Valley north of Lebanon well into the Piedmont terrane south of Lancaster. Although the nappe was modified, mostly by faulting, during the late Paleozoic Alleghanian deformation, the structures in the quarry are almost entirely of Taconian age. The southeastern edge of the Mesozoic basin lies only 1000 ft (300 m) to the north of the quarry, but the extent to which the quarry was affected by the Jurassic(?) deformation, if at all, is unknown.

The quarry exposures. The quarry highwalls provide ex-

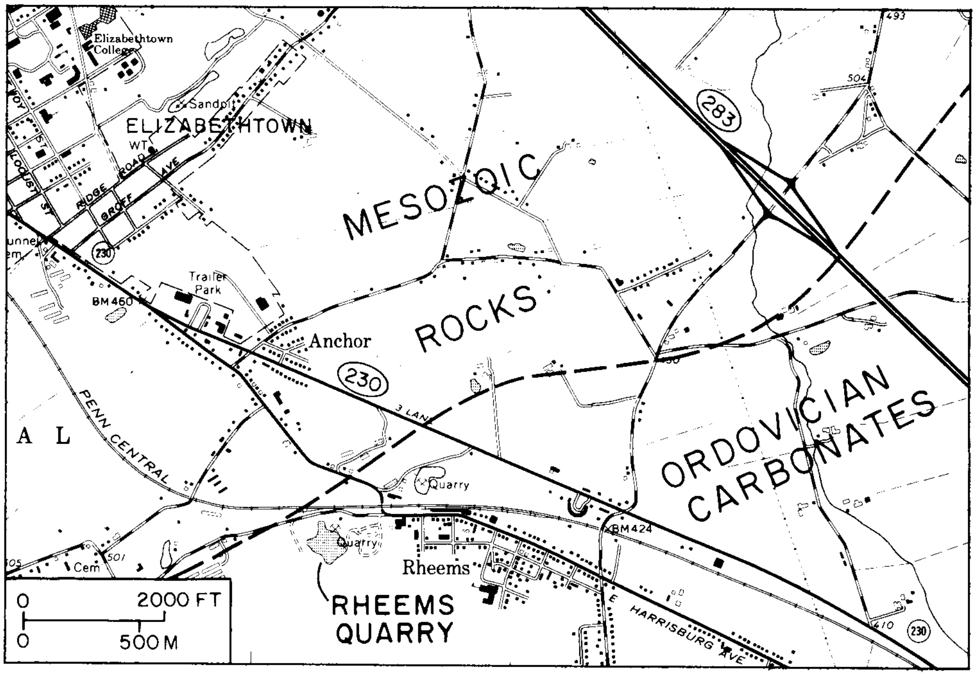

Figure 2. Local roadmap showing the Rheems-Elizabethtown exit from Pennsylvania 283, and the quarry just west of the village of Rheems.

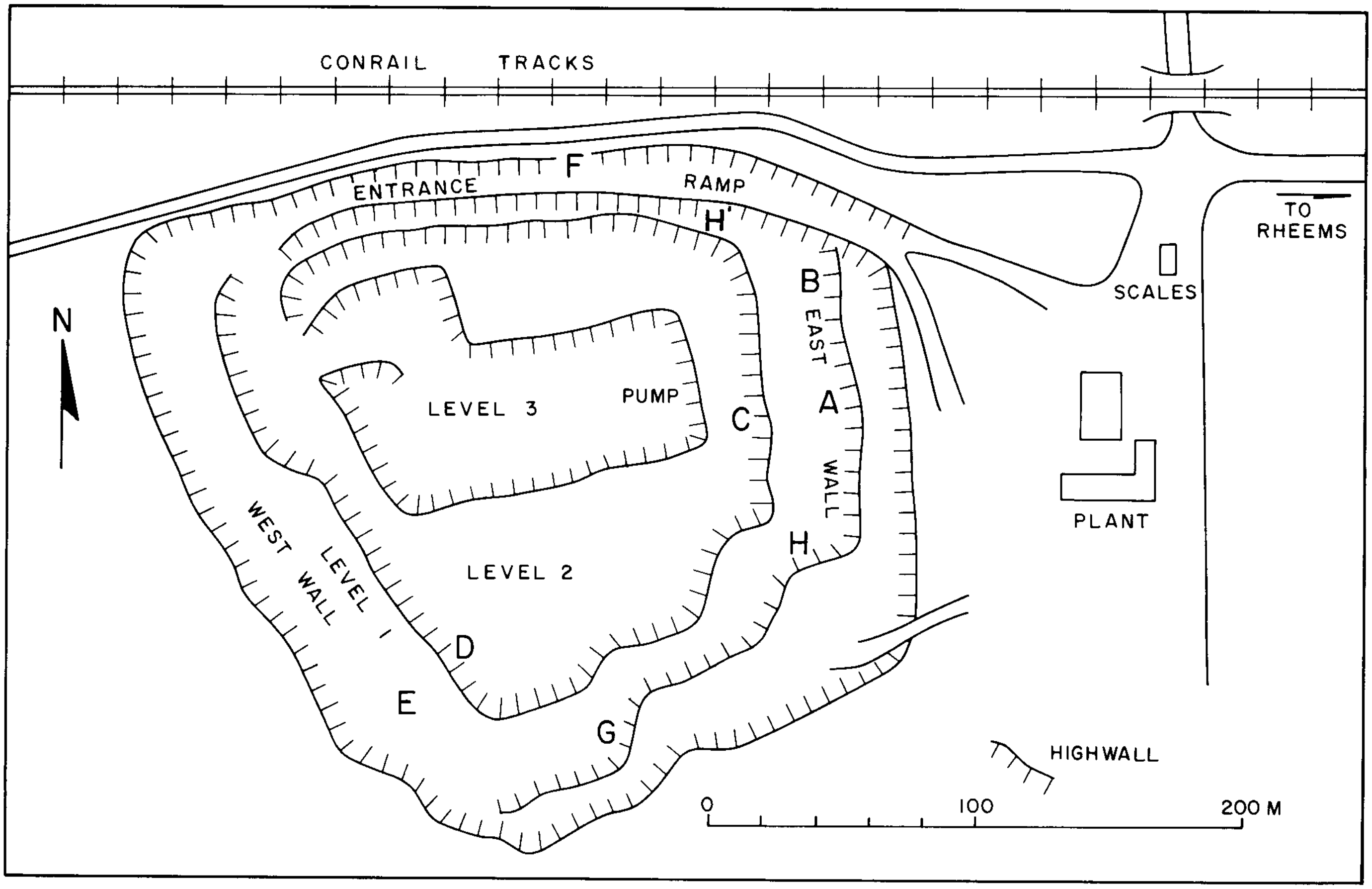

Figure 3. Generalized map of Rheems Quarry, which currently has three levels. Letters indicate the Stations where features described in the text may be seen.

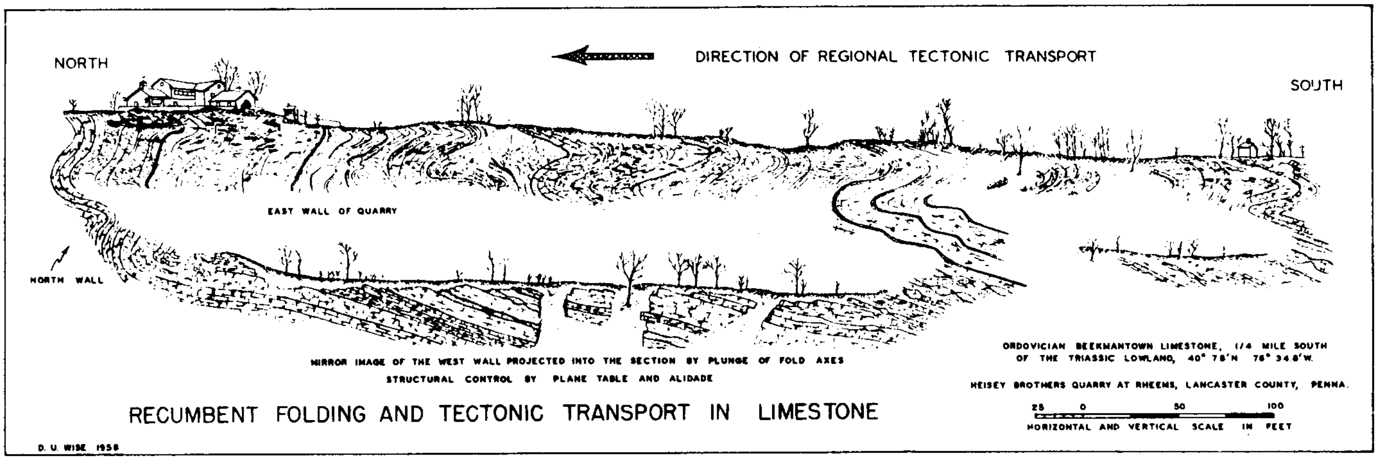

Figure 4. Diagram of the east and west (mirror image) highwalls of level 1 (from Wise, 1958). The 6° northeastward plunge of the structures in the quarry indicates that the west wall is structurally below the folds in the east wall. See text for discussion.

cellent exposures of the mesoscale structures that comprise the local tectonic grain. The north and south highwalls approximately parallel the 075 azimuth trend of the folds and display the changes along the grain; the east and west walls exhibit good cross sections of the structures (Fig. 3).

The dominant tectonic factor was the northward transport of the nappe; all the other Taconian structures in this quarry are derivative from this fundamental movement (Wise, 1958, 1960). A consequence of this movement is that most of the rocks in this underlying limb have undergone, to varying degrees, an extension in the north-south direction. Most of the mesostructures in the quarry amply demonstrate this strain.

The two most dramatic structures are the two recumbent folds in the east wall at Level 1 (Fig. 4). No evidence of depositional tops of beds has been found in this quarry, so which fold is the anticline and which is the syncline cannot be determined from sedimentary criteria. However, because the quarry is in the lower limb of the nappe, one can presume that the stratigraphic section is probably inverted. If so, then the upper fold, the one that is concave toward the north, has younger beds in the core, and thus it is the syncline. Similarly, the lower fold, the one that is convex toward the north, should have older beds in the core, and so it is the anticline. The axial surfaces of both the anticline and the higher syncline persist across the east wall with a 15 to 25 ft (5 to 8 m) separation, extending horizontally through at least 650 ft (200 m) of rock. This exposure also enables one to see that the folds possess a similar geometry.

The highwall exposure in the west wall at Level 1 is in distinct contrast to the east wall; no recumbent folds disturb the gentle south dip of the (presumably) overturned beds (Fig. 4). The relation between the different structures displayed in the two walls can be determined from the folds in the north highwall, above the entrance ramp (Station F in Fig. 3). The 5° to 15° plunge of the folds at Station F to the east-northeast demonstrate that the western highwall exposure is structurally below the folds in the eastern wall (Fig. 4). This can be verified by examining the east highwalls at Levels 2 and 3. No folds are present at these levels; only the fairly constant gentle south dip is present, similar to that in all three levels in the western part of the quarry.

The smaller mesostructures. Calcite crystals possess several slip systems that are not present in dolomite crystals. As a consequence, calcite deforms ductilely at low stress levels, whereas dolomite deforms in a brittle fashion at much higher stresses. This difference in reformational behavior shows up in several ways in Rheems quarry.

The dolomite beds tend to preserve a constant bed-normal thickness around fold hinges because of their greater strength and brittle behavior. The more ductile limestones flowed into the hinges increasing the bed normal thickness there, in some instances by large amounts, and greatly changing the fold profile (e.g., at Station A and southward, Fig. 3). Other types of profile distortion are also present. At Station B (Fig. 3), just north of the beds expressing a concentric fold geometry, the beds in the middle limb (between the syncline and anticline hinges) appear to be anomalously thickened, either by ductile flow or faulting. Nearby, several small recumbent folds in dolomite beds are detached from one another and surrounded by limestone. Although cleavage is not a strongly developed structure in this quarry, a weak axial-plane cleavage is present in many of the limestones in the fold hinges, representing a certain amount of flattening of the folds.

Boudinage, the "necking" or separation of beds, is common in many of the "overturned" layers (particularly at Stations C, D, and E, Fig. 3). The boudins trend 075 azimuth, parallel to the fold axes, suggesting that the boudins and folds are coeval. Again, the contrast in behavior of the rocks led to the boudinage. The stronger, less ductile dolomite beds developed "necks" of enhanced extension during the northward transport. The more duc-

Figure 5. Boudins in a dolomite embedded between limestone beds (at Station D in Fig. 3). The northward tectonic transport pinched and fractured the more brittle dolomite beds; the more ductile limestones extended by flow, and expanded into the boudin necks as well. The fractures in the dolomite were filled with white vein calcite. The white notebook on the left side is 8.3 in (21 cm) long.

tile limestones adjacent to the dolomites "flowed" into the necks between the dolomite boudins, producing the "hour glass" structure typical of boudins (Fig. 5). Interestingly, this boudinage does not occur in the "right-side-up" beds above the anticlinal hinge, because these beds were carried along as a unit by the northward transport of the nappe and did not experience extension.

Fractures filled with white vein calcite (Fig. 5) are another aspect of the brittle extension produced in the dolomite beds. These fractures parallel the east-trending fold axes, tend to be perpendicular to bedding, and are far more common in the overturned beds than in the upright ones. This, in addition to their association with boudin necks (as at Stations D and E, Fig. 3), and their absence in the more ductile limestones indicates that they formed, opened, and were filled during the later part of the northward transport and extension.

Ductile flow was an important, if not dominant, mode of deformation in these rocks, but it was not the only mode. Abundant slickensides on bedding surfaces attest to flexural slip folding being a significant process that contributed to the total deformation. Slickensides are particularly well exposed in the folds above the entrance ramp along the north wall (at Station Fin Fig. 3).

The important faults present in this quarry occur in two orientations-parallel and transverse to the fold trends (Fain, 1983). Both types of faults, a steeply north-dipping parallel fault and a steeply west-dipping transverse fault, are present at Station G (Fig. 3). They are both postfolding because they offset parts of a fold. Another steeply west-dipping transverse fault (Station H in Fig. 3) has an apparent offset of 6 ft (2 m) down on the west, but its gently south-plunging slickenlines indicate strike-slip movement. This fault extends northward across the quarry (to Station H in Fig. 3), but at Station H the slickenlines plunge steeply (obliquely) to the northwest. These complex fault movements may represent a late stage of the Taconian deformation, effects of the late Paleozoic Alleghanian orogeny, or they may even be of Jurassic age and be a consequence of the Mesozoic rifting and opening of the Atlantic Ocean,

It is only in the past few decades that the regional nappe structure of this part of the Appalachians has been unraveled by Gray (1954), Wise (1958, 1960), and others, using the few excellent exposures provided by quarries such as the one at Rheems. However, the complexity of this terrane was recognized as early as the late nineteenth century by geologists, such as J. Peter Lesley, of the Second Pennsylvania Geological Survey. Lesley (1883, p. 54) wrote "Level as the general surface may be, it is the planed-off section of as gnarled and twisted a piece of the earth's crust as can be found in any country. Although these placations are comparatively small, they are of the same nature as the gigantic overthrown anticlinals of the Alps and Apennines"

REFERENCES CITED

Fain, R. T., 1983, Rheems quarry, *in* Mowery, J. R., ed., Geology along the Susquehanna River, southcentral Pennsylvania: Guidebook, 2nd Annual Field Trip of the Harrisburg Area Geological Society, p. 47-52.

Gray, C., 1954, Recumbent folding in the Great Valley: Pennsylvania Academy of Science Proceedings, v. 28, p. 96-101.

Lesley, J. P., 1883, Introductory *in* Prime, F. P., cd., The Geology of Lehigh and Northampton counties Pennsylvania Geological Survey, 2nd ser., Report of Progress DDD, vol. 1, p. 1-82.

Wise, D. U., 1958, An example of recumbent folding south of the Great Valley of Pennsylvania Pennsylvania Academy of Science Proceedings, v. 32, p. 172-176.

— , 1960, Rheems quarry, *in* Wise, D. U., and Kauffman, M. E., eds., Some tectonic and structural problems of the Appalachian Piedmont along the Susquehanna River: Guidebook, 25th Annual Field Conference of Pennsylvania Geologists, p. 76–83.