AN ANALYSIS OF THE DESIGN REQUIREMENTS AFFECTING WATER DISCHARGES THROUGH STRATA FROM BELOW DRAINAGE ABANDONED MINES

by

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The mining industry is required to prevent post-mining discharges through appropriate design and engineering considerations. The state and federal governments are responsible for making sure standards are maintained and followed. In recent years, both the mining industry and the government regulators have focused on the ability of strata barriers to prevent discharges from mine pools into surface waters. Strata barriers comprise the rock layers between the coal mine pool and the overlying stream; however, in Northern Appalachia, the strata can contain iron and acid producing geochemistries. As a result, water that comes into contact with these rocks has the potential to become impaired. The strata beneath stream valleys are also generally known to have increased frequencies of fractures in this region (Ferguson, 1967). The hydraulic head that is produced by the mine pool provides a discharge potential through surrounding layers of rock. When the mine pool elevation is greater than the lowest elevations on the surface, a “net head” is placed on the barrier which creates discharge potential. As a result, it is important to understand the movement of mine pool water through the strata above abandoned mine workings and establish design factors to prevent potential discharges into streams.

Several below drainage strata barriers were analyzed in this study. The primary objective is to determine how geology, overburden properties, hydraulic head, and mine layout impact the ability of abandoned mine workings below drainage to contain a mine pool and prevent discharges after production has concluded. Specific conditions are monitored to distinguish the primary design differences between barriers that discharge water through overlying strata and successful ones that prevent discharges to the surface or into streams. Multiple case studies in western Pennsylvania are analyzed, providing examples of situations where strata barriers are involved in post-mining drainage potential where mine pool elevations exceed the lowest elevations at the surface. Many factors are examined to determine the conditions associated with successful design properties that minimize discharges. Standards for optimal mine design are presented via analysis of design characteristics and associated potential discharges. Ultimately, this work clarifies the factors responsible for successful and unsuccessful designs of strata barriers that prevent a discharge to surface waters.

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1.0 INTRODUCTION

Underground coal mining operations have played an important role in the history of Pennsylvania. Mining practices and operations have changed immensely throughout the years as technology and environmental awareness have progressed. Due to the significance of the industry, much research has examined the environmental impacts of underground coal mining (Iannacchione et al., 2013a). This paper will examine the mining practices, geologic and hydraulic properties of several below-drainage strata barriers and examine their effectiveness in preventing post-mining discharges. By studying the natural factors and mining induced characteristics such as mining methods and properties of these western Pennsylvania mining operations, design criteria necessary for effective and efficient mining practices are defined.

The mining industry is required to prevent post-mining discharges through appropriate design and engineering considerations. The state and federal governments are responsible for making sure standards are maintained and followed. In recent years, both the mining industry and the government regulators have focused on the ability of strata barriers to prevent discharges from mine pools into surface waters. As opposed to coal barriers which prevent flow laterally within the coal seam, strata barriers comprise the rock layers between the coal mine pool and the overlying stream (Figure 1.1). In Pennsylvania, the strata beneath stream valleys are known to have increased frequencies of fractures (Ferguson, 1967). The strata within these barriers must resist the movement of potentially contaminated mine pool water to the surface. The hydraulic head acting on these strata is produced by the filling of mine workings with water. As a result, it is important to understand the movement of mine pool water through the strata surrounding abandoned mine workings and establish design factors in order to prevent potential discharges into streams.

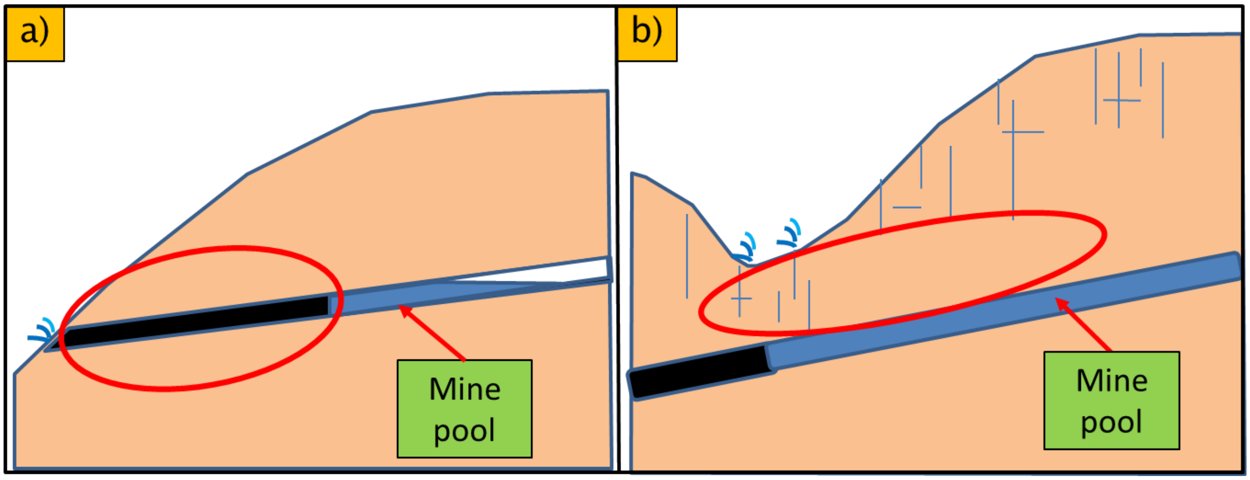

Figure 1.1: a) Coal (above drainage) barrier representation with possible discharge location. b) Strata (below drainage) barrier area of interest and possible discharge location in the overlying valley.

The primary objective of this study is to determine how geology, overburden characteristics, hydraulic head, and mine layout impact the ability of abandoned mine workings below drainage to contain a mine pool and prevent discharges after production has concluded. Several below drainage strata barriers were analyzed in this study. Specific conditions were examined to distinguish the primary design differences between barriers that discharge water through overlying strata and successful ones that prevent discharges into streams. Multiple case studies in the western Pennsylvania region were analyzed: Genesis No. 17, Grove No. 1, Keystone East, Urling No. 1, 2, and 3, Barbara No. 1 and 2, and Little Toby mines are examples of areas where strata barriers were involved in post-mining drainage. Many factors were examined to determine the appropriate conditions for the most successful design properties in minimizing discharges. The hydraulic conductivity at these case study mines is estimated and compared to site-specific factors such as overburden, hydraulic head, mine layout, and geologic characteristics. Standards for optimal mine design are presented.

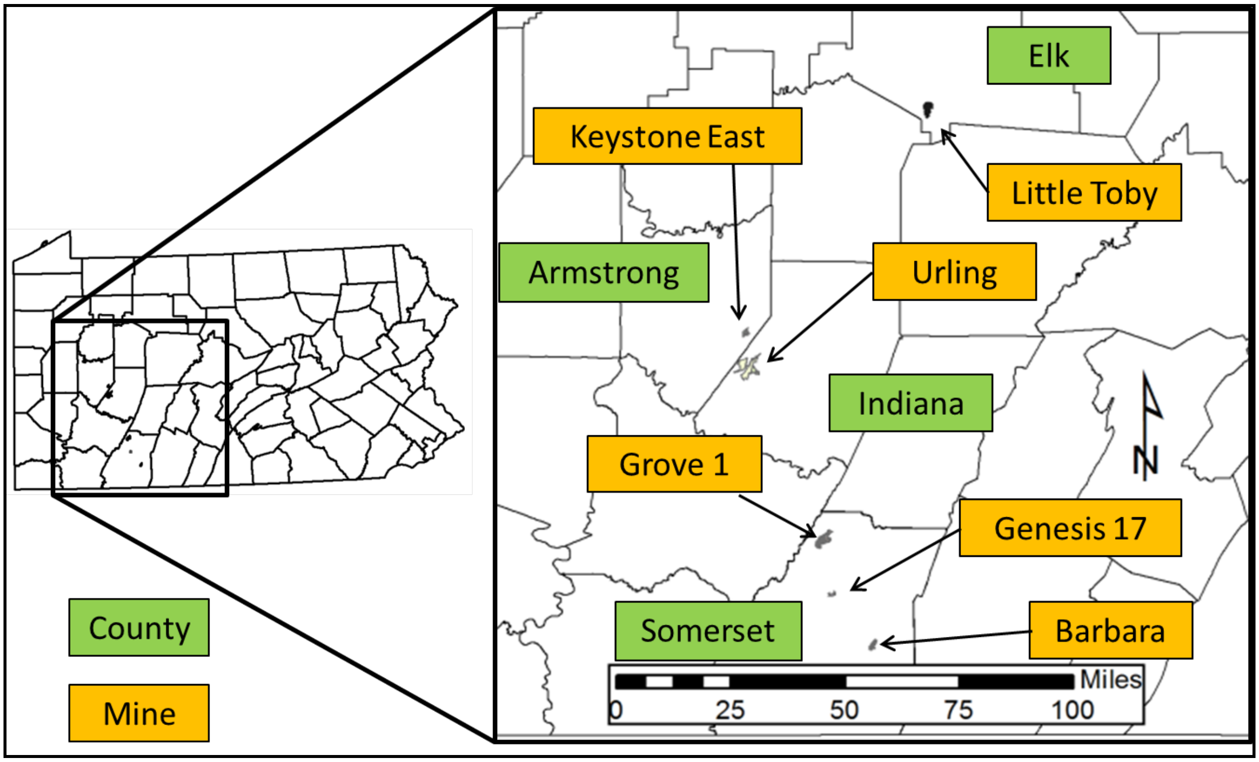

Figure 1.2: Case study area and mining operations.

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2.0 REVIEW OF LITERATURE

The mining of bituminous coal in western Pennsylvania spans several disciplines and industries. Engineers, geologists, hydrologists, and environmental scientists are responsible for determining permitting, production, maintenance, and reclamation techniques from pre- to post-mining operations. As a result, a variety of research and literature has been published pertaining to ensuring the mining industry's continued success. This chapter focuses on examining the background of the coal mining industry including mining techniques, geologic features, and the flow of groundwater.

2.1 BACKGROUND

This section contains background information about the case studies, characteristics about the region, and the regulations that led to the barrier designs that are used today. This material will provide context for the mining methods that were chosen as well as physical attributes of the geology within the case studies that were analyzed.

2.1.1 Room-and-Pillar Mining

Mineral extraction is carried out through many different methods. The type of deposit, geologic, geographic, and historical factors influence the manner in which it is mined. As far as underground coal mining, one of the oldest and most recognized methods is the room-and-pillar mining method. This style of mining is designed to recover mineral deposits of limited thickness that are oriented in relatively flat beds (Hustrulid and Bullock, 2001). As the name implies, a "room" is mined out for production while "pillars" are left in place to support the overlying strata and overburden rock above (Figure 2.1). From a production standpoint, pillars are designed to be as small as possible in order to maximize coal recovery while still supporting the overburden.

To recover the coal, a variety of machinery is used. The production process begins with the establishment of development entries. These entries are created using a continuous miner which cuts the coal away with rotating drums with blades attached. The roof is then immediately supported with a roof bolter where the coal has just been extracted and then it is hauled out of the mine on a series of belts.

The primary advantages to room-and-pillar mining are outlined by Paschedag (2014):

- Flexibility in terms of mining patterns or difficult shapes,

- lower cost than some other forms of mining such as longwall mining which requires more space and equipment per section,
- and transition of production to a different section is quick and inexpensive.

The primary disadvantages include:

- The degree of dip of the coal seam can be problematic (generally requires a dip of 8° or less with a maximum of 12° possible),
- competent rock conditions for the roof and floor are required,
- lower production rates than longwall mining which is 100% extraction.

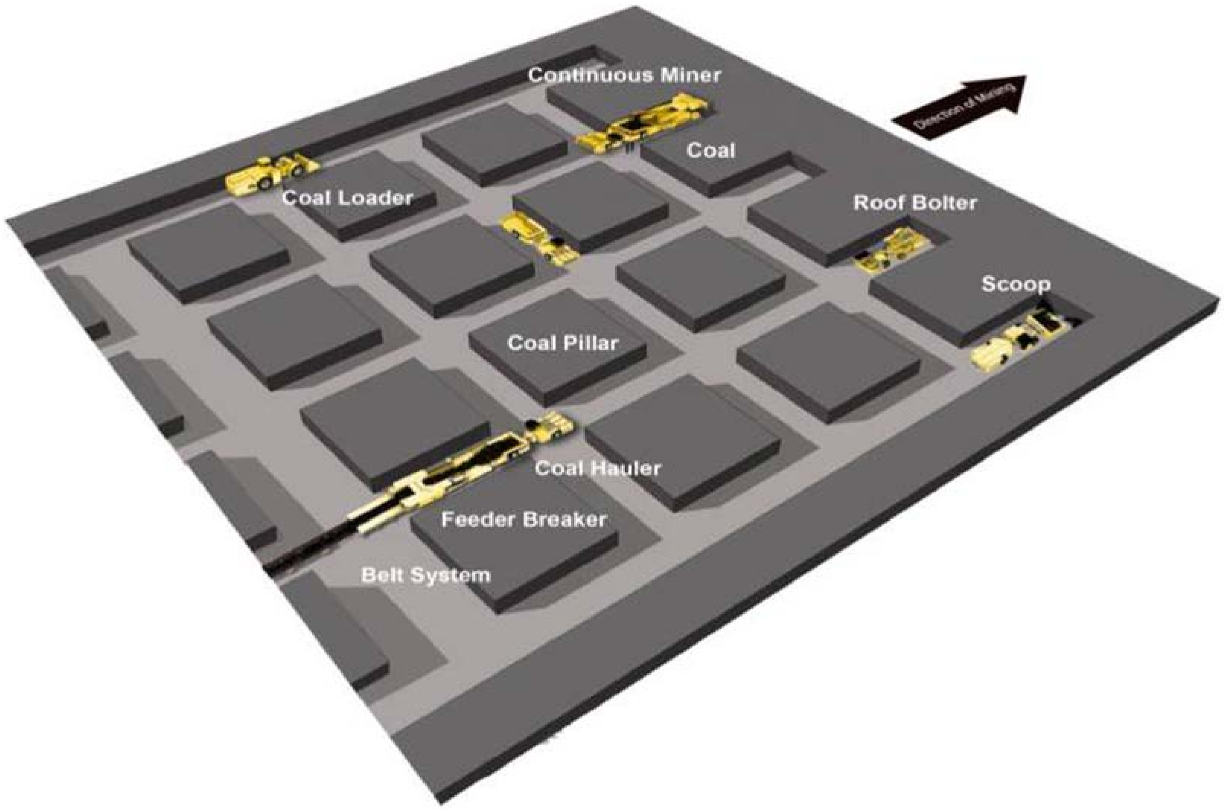


Figure 2.1: Room-and-pillar mining method (Paschedag, 2014).

In order to maximize coal recovery, in some cases a higher extraction ratio is used. In thin development pillar procedures, a higher percentage of coal is mined resulting in smaller pillar sizes (Iannacchione, 2013a). Room-and-pillar methods also may choose to employ retreat mining practices or pillar recovery. As described by Peng (2008), retreat mining takes place once development stages have reached the limits of the permit boundary. Mining then ensues backward from the end of the section toward the main entries or submains. The pillars are extracted while the roof is supported. Once the pillar or pillars are removed, the supports are shifted and the roof is permitted to collapse. Once again, collapsing of the roof often results in surface effects in the form of deformation and increased fracturing throughout the strata contained in the overburden.

Throughout the mining process, ground control procedures are carried out to ensure safe, efficient, and effective mineral recovery. The United States Department of Labor's Mine Safety and Health Administration (MSHA) is responsible for regulating all mining operations in the country. Title 30 of the Code of Regulations specifies roof support requirements for underground mining procedures (Code of Regulations, 1988). Roof bolts, free-standing supports, mesh and a variety of other methods are used to reinforce rock strata in the roof and the mine walls known as the rib. Keeping the roof and rib intact is essential to ensure worker safety and also to prevent slowing of production. In addition, these methods of reinforcement prevent rock failures that generate fracturing of surrounding stratigraphic layers and cause damage to the overburden.

The method of accessing the coal and developing the portal entries is important when implementing a new mine. Two of the basic entry developments are slopes and box-cuts. A slope mine involves utilizing an inclined opening to access the mineral (Speight, 1994). A box cut is an engineered excavation that involves cutting down to the seam to access the coal. Parker (2002) defines a box cut as “the first cut which results in a long pit with a highwall on both sides of the cut.” Slone et al. (2001) discusses the process of utilizing a box-cut; overburden removal, storage, and reclamation are the key components. Since the overburden is an important factor in preserving the mine workings below, consideration is taken so that there are no environmental impacts of altering the overburden. After it is removed and stored, the mine progresses through the production phase. Once the operation is complete, the box-cut void will be filled with the material that was removed (Figure 2.2). As expected, this material is loosely packed and contains a much higher hydraulic conductivity which provides conduits for fluid flow. In some cases, piezometer data reveals that water elevations return to and surpass pre-mining elevations. The properties of the box-cut could provide a method of increased water flow around mine workings once the operation has been completed and the box-cut has been backfilled. Figure 2.3 demonstrates the box-cut used at the Little Toby mining operation by Rosebud Mining Co.

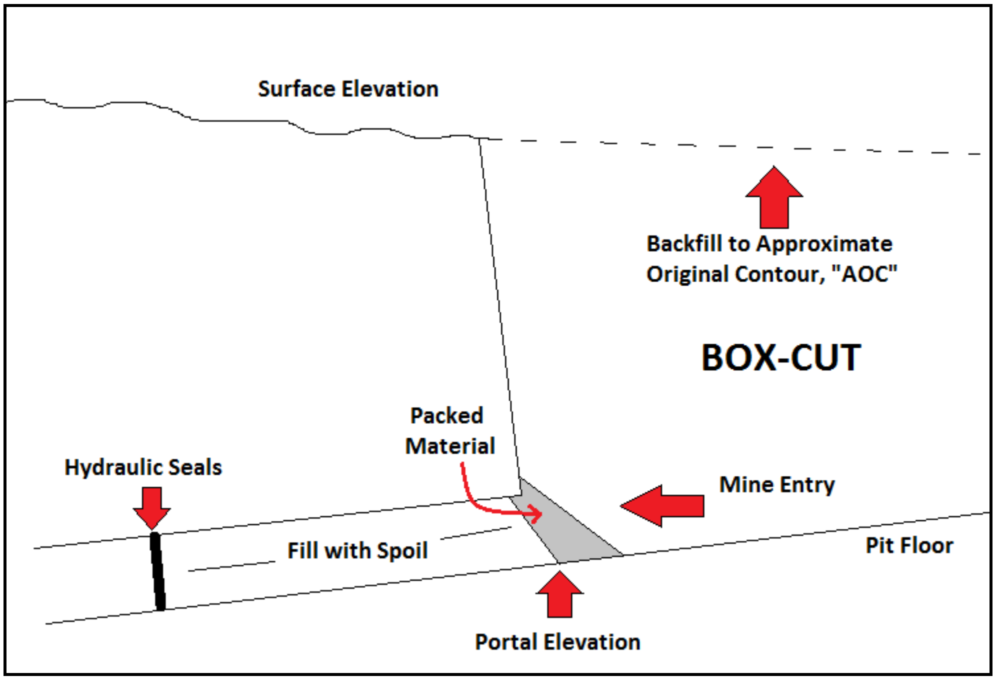


Figure 2.2: Box-cut representation (Mine Seal Design for Roxcoal, Inc. Barbara No. 2, PA DEP, Exhibit 23.3).

Figure 2.3: Box-cut development at the portal entries of Little Toby in Elk County, PA (Rosebud Mining 2006).

2.1.2 Surface Topography

Pennsylvania's surface topography plays an important role in the surface and subsurface mining operations. Landforms such as mountains and waterways dictate mining procedures and techniques. The region contains a wide range of physiography from the plains and valleys in the eastern part of the state to the mountains and lakes throughout central and western Pennsylvania. The Appalachian Mountains which is composed of the Allegheny High Plateau and several curving streams and valleys makes up the region of the northern Appalachian coal basin. This area to the eastern part of the state is drained primarily by the Susquehanna River and its tributaries while western Pennsylvania is drained by the Allegheny and Monongahela Rivers. These rivers join in Pittsburgh creating the Ohio River and along with the Beaver, Clarion, and Youghiogheny compose the primary sources of drainage in western Pennsylvania. Historically, geologically, the eastern part of the state was comprised of the mountainous regions while the west was sea. The prevalent coal which is mined today was developed by the interweaving of layers of vegetation along with the sandstone and shale as the bodies of water expanded and contracted over time (Pennsylvania Topography, 2010). As a result surface topography plays a critical role in the quality of subsurface strata and mining procedures that take place in a particular region.

2.1.3 Regulatory Background

The mining industry has seen an increase in regulatory actions over the past forty years. The Surface Mining Control and Reclamation Act of 1977 (SMCRA) increased awareness of the environmental impacts by making more stringent requirements for industry. These regulations are the responsibility of the state to monitor, the Pennsylvania Department of Environmental Protection (PA DEP) in this case. The Office of Surface Mining (OSM) monitors each state's progress and proficiency in upholding the law. Through the establishment of SMCRA, post-mining discharges were to be predicted, minimized, and prevented outside the permit boundary. Brent Means (2009) reported several permitting techniques used to prevent post-mining discharges. He cited five specific articles of SMCRA and related them to similar state and federal counterparts:

- a determination of probable hydraulic consequences,
- a detailed reclamation plan,
- permit approval requirements,
- environmental standards for surface effects,
- and prevention of gravity discharges are all requirements that apply to the prevention of post-mining discharges (Means, 2009).

After SMCRA was introduced, mine layout and barrier design became a critical component in the establishment of mining operations and permitting. Barriers are designed based on the location of mine workings relative to water sources. Coal (above drainage) barriers are made up of horizontal strata in order to prevent lateral flow within the coalbed while vertical and horizontal strata (below drainage) barriers are designed to prevent flow through the layers of strata comprising the overburden (Iannacchione et al., 2013a). While all barriers are unique to each mine, data was collected to demonstrate the resistance of hydraulic movement to the surface and the prevention of post-mining discharges in the case study mines in this investigation (Figure 2.4).

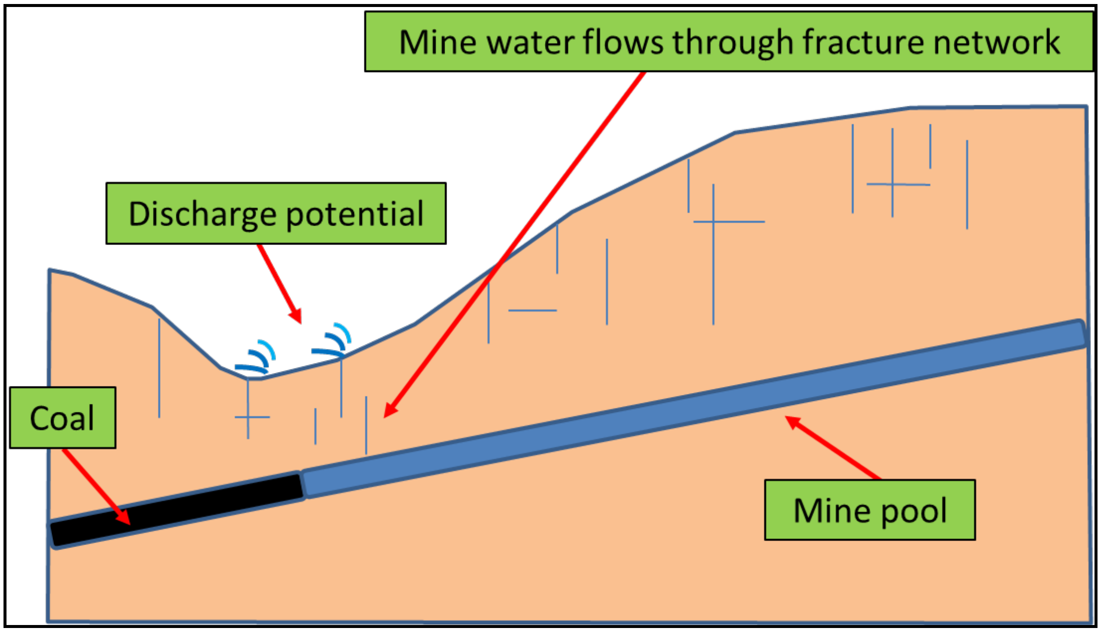


Figure 2.4: Vertical strata barrier illustration demonstrating discharge potential through fractures in the stream valley.

Flow through strata barriers is not limited to vertical movement. In some cases, as seen in the Grove 1 operation, mine pool water moved along bedding planes located in the strata above the mined out region. Iannacchione et al. (2013b) refer to this is as a horizontal strata barrier as seen in Figure 2.5.

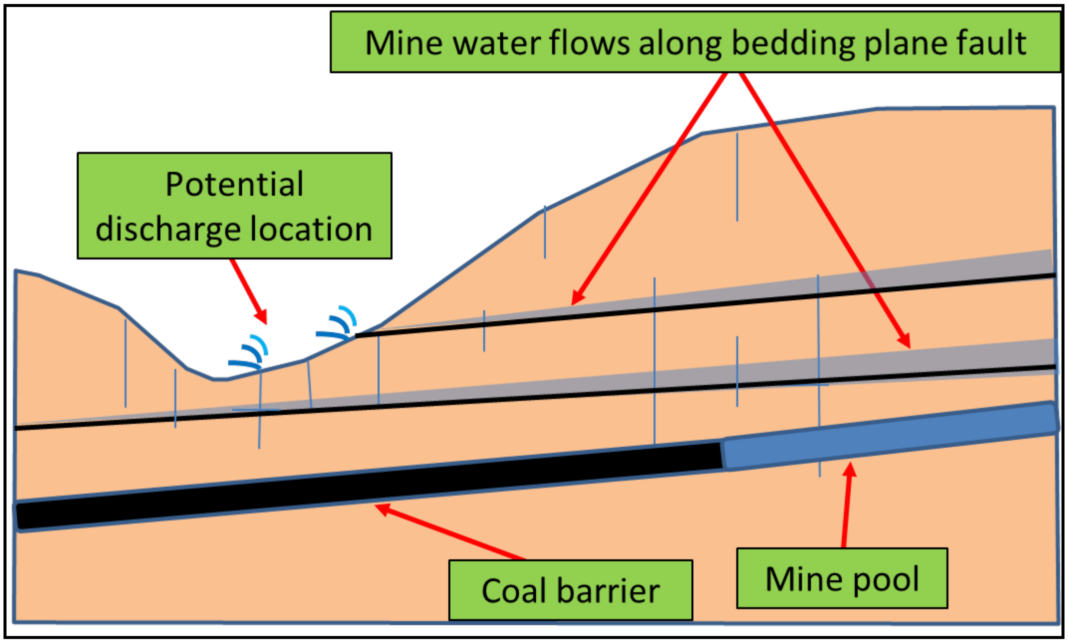


Figure 2.5: Horizontal strata barrier illustration demonstrating flow movement of mine pool, dominated primarily through fractures and along bedding planes.

2.2 RELATED STUDIES

The following section contains information and theory relating to groundwater movement and the influence that geology has on subsurface flow. Naturally occurring and mining induced conditions have an impact on rock quality and will be examined to determine the performance of strata barriers to prevent mine pool discharges to the surface.

2.2.1 Effects of Underground Coal Mining

Underground mining has the potential to impact the surface. One of the primary physical effects is deformation of the surface topography. Many underground coal mining operations employ extraction ratios greater than 50%. Partial or full extraction mining involves removing a large piece of coal such as in high extraction room and pillar mining. The result is a caving event which causes fracturing and surface deformation. This surface deformation is the vertical movement of the surface due to collapsed strata from high extraction mining and is known as surface subsidence (Peng, 2008). Figure 2.6 depicts a strata barrier with total extraction mining below it. The caved zone is composed of the strata immediately above the coal seam which contains the highest concentration of fractures and therefore the highest hydraulic conductivity.

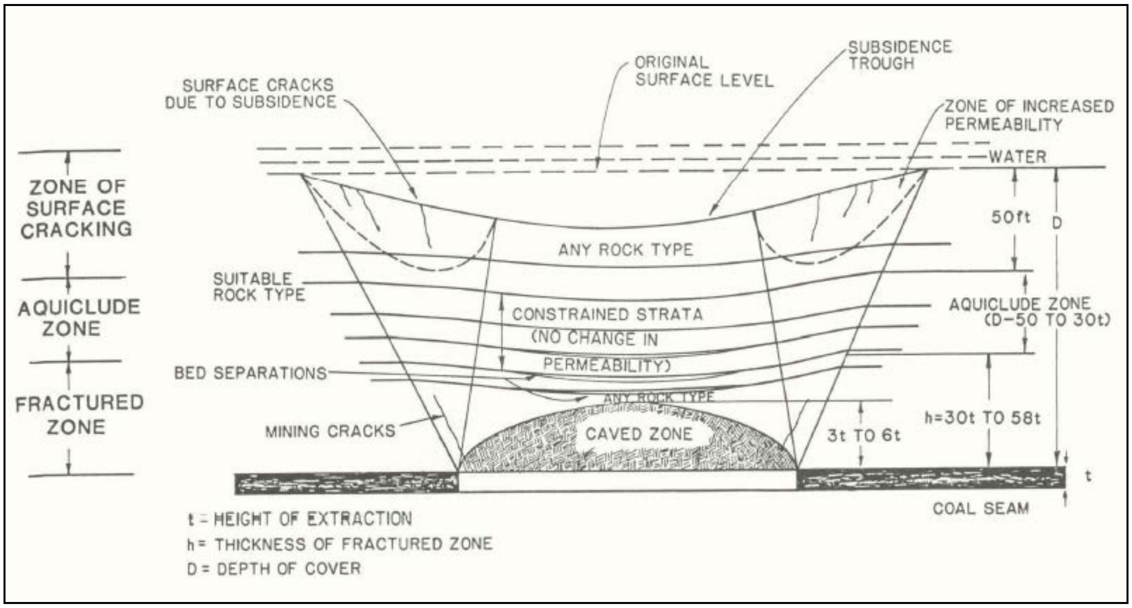


Figure 2.6: Strata barrier representation with total extraction mining (Singh and Kendorski, 1981).

According to subsidence theory, a subsidence basin will develop when mining impacts can be seen extending upward 30 to 60 times the height of mining (Kendorski, 1993). Many studies in western Pennsylvania room-and-pillar mining operations report the average approximate mining height to be 4 feet (Iannacchione et. al, 2013). Using this method, fracturing may extend 120 to 240 feet above mining operations. As a result, there is an increase in the potential for a surface discharge as fracture networks increase, particularly in areas of low overburden (less than 250 feet), as hydraulic head drives water through these fractures.

While full extraction mining provides a method of efficient coal recovery, geologic failures, intensified fracturing, and seismicity have been associated with high extraction operations for many years. Events have been known to occur after pillar failure known as coal bumps. Peng (2008) defines a coal bump as “sudden, violent bursts of coal from a pillar or pillars or a block of coal, resulting in a section, the whole pillar, or the solid block of coal being thrown into an open entry with shattered coal stacking up to the roof line.” These bumps are of interest because of their potential to disrupt strata in proximity of high extraction mining and the increased presence of fracture networks which increases hydraulic conductivity. Bumps have the potential to occur under three primary conditions (Iannacchione and Zelanko, 1994):

- Specific geologic conditions (i.e. high overburden thickness greater than 500-700 ft, the presence of stiff overlying strata, strong and brittle coal, strong floor),
- mining practices that promote high localized concentrations of stress, and
- the presence of geologic anomalies or faults.

While coal bumps are often the cause of events, smaller seismic events may be observed around full extraction pillar recovery methods under planned collapsing resulting in effects felt at the surface and increased fracturing of strata below the surface.

In some cases multiple seams are accessed within the same region. Multiple seam mining refers to the process of extracting coal from overlying coal seams within the same stratigraphic column. Peng (2008) describes undermining as the process where the upper seam is mined before the lower seam and conversely, overmining is when the lower seam is mined out before the upper seam. Despite achieving higher coal extraction, many ground control problems are introduced from multiple seam interactions. Fracturing in the surrounding strata is also amplified throughout the interburden between the mines and overburden above the upper mine.

Mining operations have the potential to interfere with geologic features that are unstable. Tectonic stresses are oriented in the horizontal direction and, in many cases, are larger than vertical stresses caused by the weight of the overburden. These horizontal stress features are felt dramatically in stream valleys due to their shape, which creates intensified fracturing below the streams. Several case studies in this report contain mining operations which are located in valleys where these conditions are expected to exist. Horizontal stress is caused by structural geological events such as continental drift (Peng, 2008). A cause of tectonic activity that is currently the most active in the Appalachian region is the mountain building process. The mountains experience high horizontal stresses and the orientation may be approximated in the east-west direction. Mining operations or geographic features such as streams oriented perpendicular to the horizontal stress field will experience the greatest stress concentration. Figure 2.7 portrays a study performed by Zoback and Zoback (1989) demonstrates the regional stress fields in the United States.

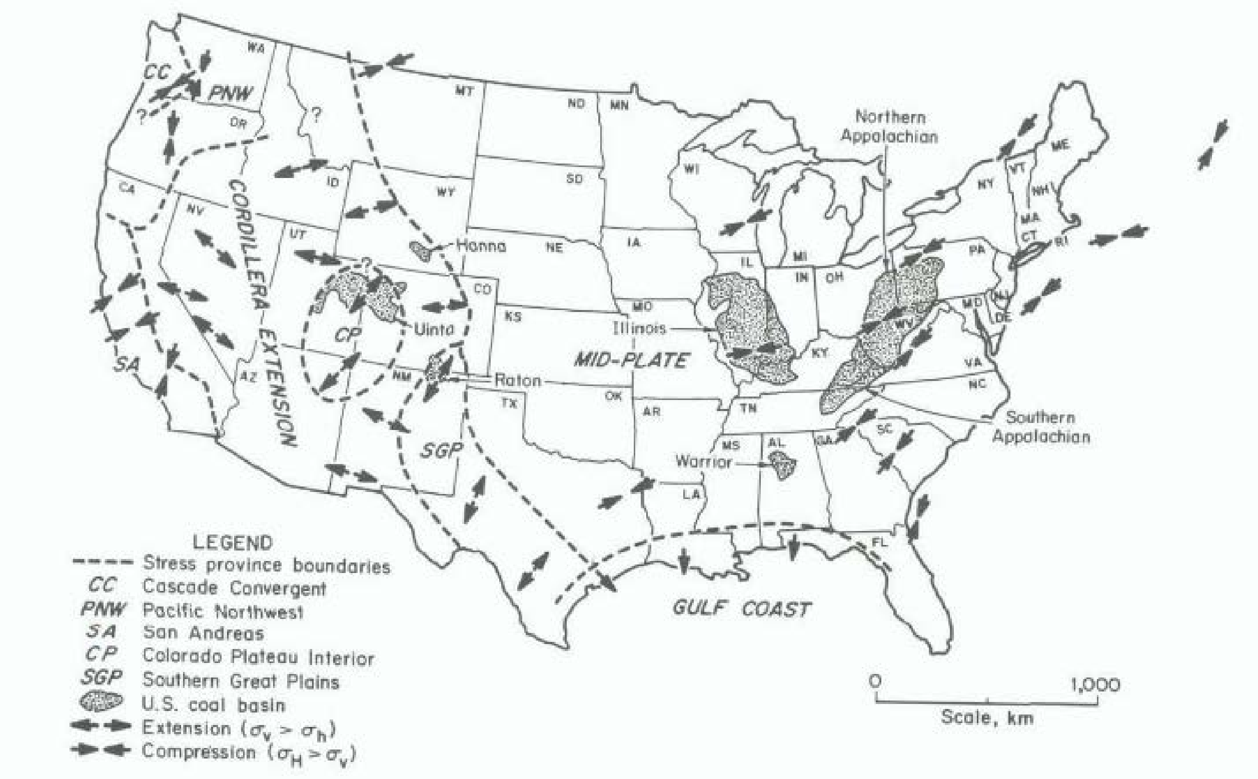


Figure 2.7: Stress Provinces in the United States (Zoback and Zoback, 1989).

2.2.2 Geology

Geologic features are critical when examining the effects of underground coal mining. Western Pennsylvania includes a variety of rock types and overburden depths. The more massive rock types such as sandstone and limestone are more competent whereas the less massive shales, claystones, and siltstones are more brittle and easily fractured (Iannacchione et al., 2013a). As overburden depth increases, higher stresses are placed on the underlying coal seam. This could result in lower extraction ratios based on the need to provide additional support. In contrast, as overburden depth becomes more shallow, there is a greater potential for water to discharge though it vertically. The PA DEP currently has additional requirements where overburden depths are less than 250 feet. Limited and no-mining zones, installation of hydraulic seals or grout curtains, or even relocating the entries are some of the controls as suggested by OSM (Means, 2009).

There are many discontinuities and anomalies in geologic strata. These unique features can be problematic throughout the mining process because of their unpredictability. Some of these discontinuities are outlined by Peng (2008):

- Sandstone channels – Massive deposits of sandstone may be in close proximity of the coal seam. They can create poor roof conditions by causing other, more brittle strata to become unstable stable after the region has been mined. Veins of pyrite are also often associtated with these channels. Since they are rich in sulfur they contribute to poor water quality which becomes problematic if the water reaches the surface.
- Faults – Faults are characterized by discontinuites or fractures in the subsurface strata. If movement or slipping occurs along a fracture plane, the anomolie is

known as a fault as opposed to a simple fracture. Local stresses cause faults to become more prevelant. This effects of faults are seen particularly well in stream valleys where fracture networks are amplified; hydraulic conductivity is increased in these zones due to the discontinuity which provides channels for fluid flow between layers of strata, shown in Figure 2.8.

- Bedding planes – Bedding planes are a separation within a layer of strata caused when similar sediments are deposited with a gap of time between or two different sediments are deposited back to back. This causes structural instability throughout the strata which could create unsafe mining conditions. It also provides a channel for fluid to flow through which dramatically increases the hydraulic conductivity and allows water to travel great distances over a short amount of time (Iannacchione, 2013b).

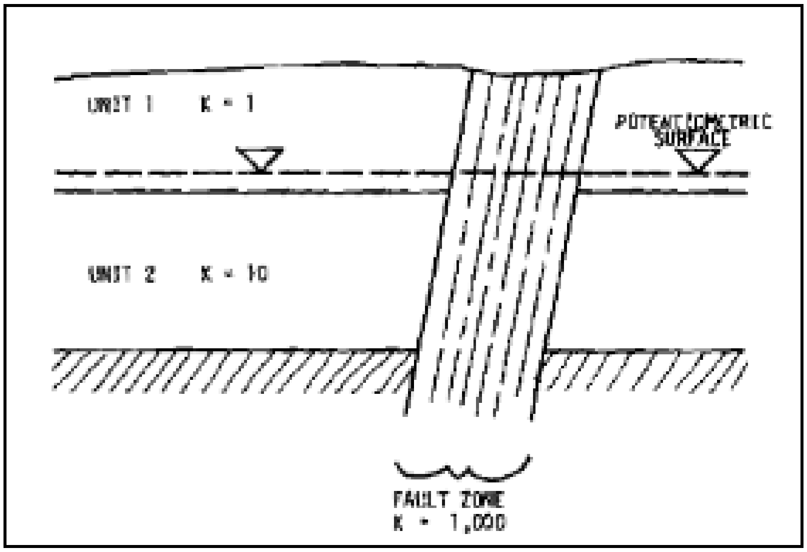


Figure 2.8: The effect of faults on hydraulic conductivity below the surface (Williams et al., 1986).

2.2.3 Hydrology

Groundwater movement is a primary consideration when preparing for mining operations and after production has completed. Water from aquifers pass from layers of strata and often times fill abandoned mines forming mine pools. These mine pools are a primary concern because they contribute to the post-mining discharge potential. As a result, several studies have been performed to better understand hydraulic conductivities of varying rock types.

Hydraulic conductivity refers to the measurement of a material's ability to transmit water. Using Darcy's Law, the hydraulic conductivity constant relates the capability of a porous medium to discharge under a unit hydraulic gradient (Duffield, 1998). Darcy's Law represents one relationship of barrier size, flow, and hydraulic conductivity and may be observed in Equation 1 (Iannacchione et al., 2013c). In the case of barrier analysis, the equation is defined as follows:

$$Q = K_h t L_b \left(\frac{dH}{w_b}\right) \qquad (Eq. 1)$$

This equation relates flow to the hydraulic conductivity, area that the material passes through, and the hydraulic gradient. Keener (2014) simplifies Darcy's Law by demonstrating the linear flow rate as it relates to hydraulic conductivity and hydraulic gradient, shown in Equation 2:

$$q = K\frac{dh}{dl} \qquad (Eqn.\ 2)$$

Where:

q = linear flow rate (ft/s),

K = hydraulic conductivity (ft/s),

dH = change in hydraulic head (ft),

dl = change in length (ft).

Darcy's law relies on many assumptions, including the assumption that flow is laminar. If flow velocities are too high and turbulent or nonlinear flow develops, Darcy theory does not apply. Where there are extremely fine grained materials under very low gradients, the law also may not apply (Williams et al., 1986). Darcy's law is used here because it is applicable to most bound water flow situations that are found within mining operations. Temperature is also a factor when considering Darcy’s Law because hydraulic conductivity is a function of water viscosity and density; however, Duffield mentions that temperature dependence is neglected more often than not because of the minimal temperature variance associated with most groundwater systems as well as the invariability of water.

Hydraulic head is critical to the movement of groundwater. Mine water is pumped out if groundwater enters the void during production, but after mining the abandoned mines are permitted to flood which forms mine pools. As water elevations within the mine rise, hydraulic head increases on the surrounding strata and coal. Using the principles of Darcy’s Law which dictate flow, general theory demonstrates that if the head reaches an elevation that is greater than the lowest surface elevation, the mine pool has the potential to discharge through the rock mass. Mine pool measurements are taken using piezometers, devices that record the height of water in a column as it rises against gravity. In this way, the piezometric head or pressure head of groundwater is determined (Dunnicliff, 1988). Studies done by Iannacchione et al. (2013a) analyzed the potential to discharge through coal and strata where hydraulic head exceeded land surface elevations in multiple cases. Several factors contributing to discharge potential, where a net positive hydraulic head is placed on the barrier, were identified. They consisted of high extraction ratios due to pillar extraction and barrier properties such as thickness and fracture presence (Iannacchione et al. 2013a).

Because of the importance of understanding water transmission through porous media, hydraulic conductivity values are determined through many methods. Aquifer tests such as pumping tests, slug tests, and constant-head tests are used to estimate values for hydraulic properties of aquifers. McCoy et al. (2006) and Islam et al. (2013) have published values of hydraulic conductivity of coal ranging from 0.03 to 14 ft/day. Table 1 demonstrates a more detailed description of McCoy's findings from 2006.

Table 2.1: Hydraulic Conductivity of Coal (McCoy et al., 2006).

Authors	K_{min}	K_{max}	K_{median}	Seam	Depth (ft)	Method	State
McCoy et. al (2004)	0.1	0.49	0.3	Pittsburgh	900-1500	modeling	WV
Luo et. al (2001)		0.23			1200	modeling	
Minns et. al (1995)	2.90E-04	1.20E-02	8.60E-04	Fireclay	300-900	packer tests	KY
Harper and Olyphant (1993)	0.2	11	4.9	Mariah Hill	69-90	slug tests	IN
Harlow and LeCain (1993)	1.10E-04	6.6	0.017		0-900	packer tests	VA
Aljoe and Hawkins (1992)			0.36			well tests	WV, PA
McCord et. al (1992)	3.3	0.033			2250	heat flux	CO, NM
Hobba (1991)	11	14		Upper Freeport	60	well tests	WV
Dames and Moore (1981)	1	4.9			300-600	modeling	
Rehm et. al (1980)			2.8			aquifer tests	ND, WY, MT
Rehm et. al (1978)			1.1			aquifer tests	ND
Dabbous et. al (1974)	2.90E-03	0.036		Pittsburgh		laboratory	PA
Miller and Thompson (1974)	0.72	3.1	0.98	Upper Freeport, Lower Kittanning	30-90	packer tests	PA

Domenico and Schwartz (1990) examined hydraulic conductivity for other types of rock. There are both vertical and horizontal components of hydraulic conductivity. Vertical and horizontal hydraulic conductivities are compared using an anisotropy ratio. K_z/K_r represents the vertical to horizontal ratio where K_z is the vertical component and K_r or K radial is the horizontal component. Domenico and Schwartz (1990) infer that K_x/K_y is approximately equal to 1, which assumes uniform flow in the horizontal plane. As reported by Carlson (2008) vertical conductivity is less frequently determined; the flow is often higher in the horizontal direction (an order of magnitude or more) as opposed to the vertical direction. Hawkins and Smoyer (2011) calculated vertical hydraulic conductivity values of the Middle Kittanning coal seam in western Pennsylvania. The median K_v was determined to be 0.028 ft/d. Todd (1980) reports Kz/Kr values that range anywhere from 0.1 to 0.5 for unconsolidated alluvium and as low as 0.01 in the presence of clay.

2.2.4 Hydrogeology

Fracture flow provides an even more rapid transmission of water as opposed to layers of strata which are not fractured. Fracture networks are of particular interest because of the associated increase in flow. They have the potential to greatly increase the hydraulic conductivity of water bearing strata. By viewing the fracture network on a macroscopic scale, flow equations such as Darcy’s Law may be applied to it (Parsons, 1966). Hydraulic conductivities of fracture networks are predicted based on aperture sizes and joint spacing (Snow, 1969). Because it is difficult to determine these values accurately and on an accepted scale, hydraulic conductivities associated with fracture networks are problematic to determine (Williams et al., 1986). While individual units of strata contain their own values of hydraulic conductivity, the vertical fracturing present throughout the region will likely dominate the ability of strata to conduct water (Wyrick and Borchers, 1981). As overburden depths increase, fracture or aperture prevalence decreases due to the increasing stress from the overburden which closes the openings and minimizes fracture network apertures (Callaghan, 1998). While hydraulic conductivities have been reported as high as 2.8-ft/d for shallow overburden (less than 150 feet), they've been reported as low as $3x10^{-4}$-ft/d beyond 300 feet of cover (Bruhn, 1985).

Because of the unpredictability of fracture networks, many methods are employed to determine the quality or competence of subsurface strata. Originally used to determine the favorability of tunneling underground, drilling core samples have become the staple in formulating the layout for underground mines and structural needs for stability. Cores are extracted by drilling into the earth and the geologic composition is determined. The gas concentration released from the strata is also monitored and then the competency of the rock is determined. The mass classification of quality of these rock layers is done using Rock Quality Designation (RQD). RQD values are assigned to segments of the core sample based on the presence of fractures in the rock (Deere and Deere, 1988). Equation 2 demonstrates the procedure for calculating RQD.

$$RQD = \frac{\sum Length\ of\ core\ pieces > 4\ in}{Total\ core\ length} \times 100\% \qquad (Eq.2)$$

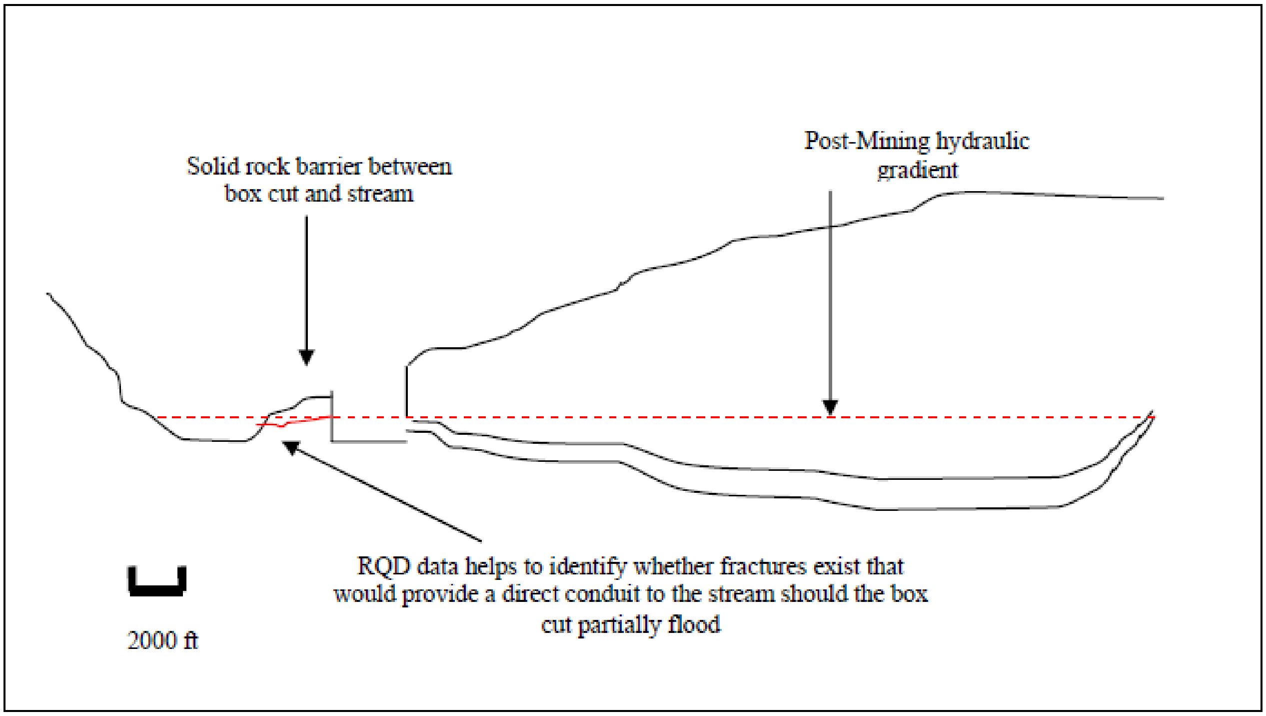


Figure 2.9: RQD portrays fracture networks in the strata (Means, 2009).

The PA DEP requires that rock quality data be acquired when permitting for mining operations (Means, 2009). RQD is advantageous when examining strata barriers because the quality of the strata may be understood in greater detail. Figure 2.9 displays a critical area where RQD values are important in determining the presence of fracture networks surrounding mining operations and streams. A majority of fracturing is located within fifty feet of mining and in the top fifty feet of overburden above the seam (Singh, Kendorski). However, stream valleys are of particular interest because of potential for increased fracturing due to tectonic stresses and stress relief fracturing. Keener (2014) discusses stress relief fracturing and how it results after the creation of valleys due to erosion. This eroded material is longer able to confine rock mass and the pressure release creates fracturing, mostly where tensile forces are present within the rock.

3.0 METHOD OF STUDY

This study aims to determine factors responsible for effectively preventing post-mining discharges in underground coal mines in western Pennsylvania. From May 2013 to spring 2014, several below drainage strata barriers were examined. Case studies were selected based on the presence of strata barriers with the potential to discharge. Potential to discharge refers specifically to scenarios where total head at the strata barrier was approximately equal to or greater than the lowest surface elevation within the mining region resulting in a “net positive head” acting on the barrier. The abandoned mines chosen in western Pennsylvania include Genesis No. 17, Grove No. 1, Keystone East, Urling No. 1, 2, and 3, Barbara No. 1 and 2, and Little Toby.

3.1 METHOD OVERVIEW

Analysis of strata barriers began with compilation of data from state government and industry. Examination of mine design, location, geography, and local hydraulic properties allowed determination of discharge potential. Computer software programs such as ArcGIS and AutoCAD were used to observe individual factors responsible for preventing or allowing an illicit post-mining discharge through strata barriers. This method provided information toward answering the following questions:

1) How does total hydraulic head impact strata barrier performance?
2) How do barrier conditions (i.e. thickness, fracture intensity as determined by RQD, geology) affect the success rate of strata barriers?
3) What mine designs are more effective in preventing post-mining discharges?

The methods used in this study consisted of data collection, data analysis, and field research. As a result, performance characteristics of strata barriers were able to be better understood.

3.2 DATA COLLECTION

Data collection included gathering of several distinct bodies of information. Six-month mining maps, which display mining locations and types, locations of hydrologic monitoring points, geologic logs, roads, and landmarks, as well as coal structure elevations within the mine were collected from the PA DEP California District Mining Office (CDMO). These maps were imported into ArcMAP 10.1, a Geographic Information Systems (GIS) computer program, and geo-referenced. Mining operations, monitoring and core locations, and surface and coal elevations were digitized from the rectified maps.

Geologic data was also gathered from the CDMO. Core logs, documenting strata type and proficiency in test holes, were compiled and organized in Microsoft Excel, including spatial coordinates. Strata quality at the case study mines was quantified using the Rock Quality Designation (RQD) collected from the PA DEP.

Hydrologic monitoring reports were obtained from both state and industry sources. Hydrologic monitoring reports contain piezometer and well water elevations allowing estimation of mine pool elevation and groundwater flow patterns. The well locations are mapped in GIS.

3.3 DATA ANALYSIS

After compiling strata barrier case study data, data were analyzed. Using GIS, contour maps were generated. Coal structure contour maps indicate coal dip direction and likely water flow direction through the abandoned mine. From these contours, overburden maps were created by subtracting the coal elevations from the surface and interburden maps were generated by subtracting the coal elevation from the elevation of the strata of interest such as an overlying coal seam. The overburden maps are used to locate coal outcrops and determine strata barrier thicknesses at the lowest surface elevations, locations where discharges are most likely to occur. Once the maps are created, the strata barrier locations are identified by taking the lowest surface elevation and shallow overburden areas into consideration. Discharge potential is then evaluated where the mine pool elevation is greater than the lowest surface elevation. Using the piezometer and monitoring well data, the mine pool height is reconstructed over time. The highest mine pool elevations are compared with the lowest surface elevations.

Case study overburden compositions were used to approximate hydraulic conductivities for the strata. From these estimates, fracture network permeability was inferred. The arrangement of the geology, which also plays an important role in strata resistance, is then analyzed. The groundwater movement through a variety of layers of strata was simulated using Darcy’s Law and the Romm Equation by inputting the hydrogeological properties (e.g., hydraulic conductivity, porosity, thickness). Overall hydraulic conductivity weighted averages were generated to simulate possible flow patterns through the overburden. Modeling the hydrogeological characteristics throughout a region and can be used to explain strata resistance along with the RQD data.

3.4 FIELD RESEARCH

Field visits were made following initial barrier analyses. Using the maps generated in GIS and mine pool data obtained from monitoring points and piezometers, case study locations were examined. Discharge locations were verified and photographed. Flow rates, temperatures, pH, and conductivity measurements were taken with all discharges. Mine pool elevations were also measured to obtain the total hydraulic head acting on the strata barriers during the visit. Professionals who operated or monitored the sites were present during visits, providing valuable knowledge and data as well as explanations of the events that occurred before, during, and after production. The field visits involving the case studies within this report consisted of:

- March 2013 – Genesis No. 17, Grove No. 1; Somerset County, PA: Visited discharge location at Grove No. 1 and Genesis No. 17 piezometers and surface reclamation with Brent Means of OSM.
- July 2013 – Little Toby; Elk County, PA: We visited the Brandycamp discharge site in the Shawmut region and monitored Mead Run water quality with Jay Hawkins of OSM.
- August 2013 – Keystone East; Armstrong County, PA: We took mine pool and piezometer measurements with Dennis Foster and Matt Morgan of Rosebud Mining Company.

3.5 LIMITATIONS

Throughout this study there were a number of limitations. In some cases, pre-mining data was difficult to obtain. Particularly in older abandoned mines before such reports were required by law, piezometer and core samples are more challenging to acquire. Discharge data can also be difficult to obtain because of the changes in the law and the procedures surrounding the investigation of discharges. Whereas three detailed reports were completed, the supplemental case studies within this report were limited based on data availability so an in depth analysis was unable to be performed and conclusions were restricted.

4.0 CASE STUDIES

The contents of this chapter reflect several case studies in western Pennsylvania. The mines represented are room-and-pillar mining operations in which vertical and horizontal strata barriers are evaluated for their effectiveness in preventing post-mining discharges. Each case study involves unique geologic and hydrologic features which were analyzed and modelled to determine the design factors associated with the prevention of discharges and containment of mine pool water. Three detailed case study evaluations are presented as well as three supplemental cases to examine barrier performance and hydrogeology in western Pennsylvania.

4.1 GENESIS NO. 17

The Genesis No. 17 coal mine (MSHA ID 3608980) is located in in Somerset County, Pennsylvania. The region has seen extensive mining and Genesis 17 is located in the Upper Kittanning coal seam, one of the area's more productive coalbeds. Now owned by Rosebud Mining Company, this operation was started in 2001 by Genesis Inc. and continued until its closure in 2005 due to difficult mining conditions. The location of the vertical strata barrier is shown in Figure 4.1 and is located above the main entries in the northern region of the mine below Beaverdam Creek.

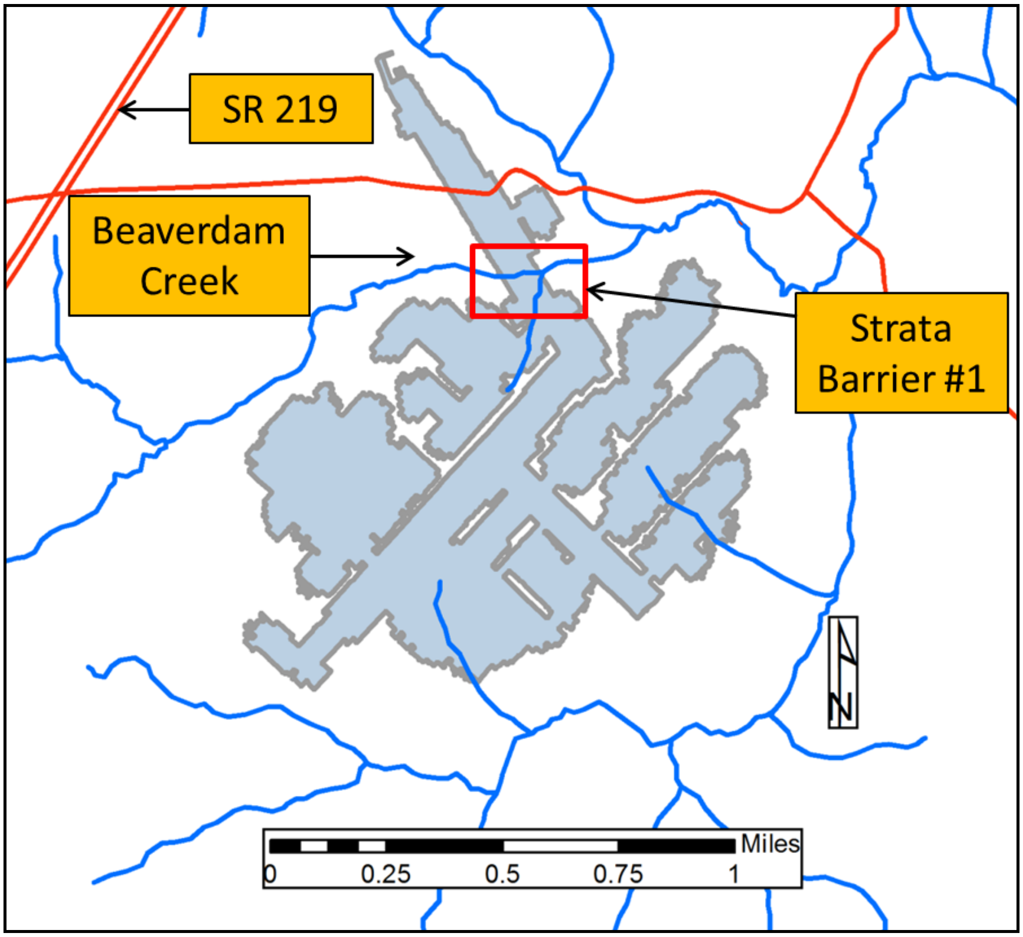


Figure 4.1: Genesis No. 17 Mine Outline and Strata Barrier #1 location above Beaverdam Creek.

4.1.1 Mining Methods

Genesis 17 was mined using room-and-pillar mining techniques. A box-cut was developed at the portal entries and coal extraction commenced in the third quarter of 2001. The mine registered its most productive year in 2003 producing almost 750 tons of coal. Thin pillar mining took place in some of the eastern and western flanks as well as the northwestern section of the mine to maximize coal recovery. Core logs recovered from the Pennsylvania Department of Environmental Protection (PA DEP) demonstrated that coal anomalies such as insufficient mining thicknesses, less than 23 inches, were present in the northern and southern areas of the permitted region, preventing expansion of the mining operation in these locations.

The presence of streams and shallow depth of cover dictated careful scrutiny of mining operations around Beaverdam Creek. The stream valley is at most 220 feet above the Upper Kittanning seam with some areas under 200 feet. As a result, preventative measures were taken by the state dictating the operator to cross under Beaverdam Creek at one location and with specific stipulations. Only 50% extraction was permitted in the crossing to provide stability.

Coal extraction ratio is an important factor when examining mine stability and post-mining environmental impacts. Iannacchione et al. (2013a) identified the presence of post-mining discharges as a direct result of high extraction mining. Extraction ratios were calculated in two specific locations within the Genesis 17 mine. The main entries were chosen because of their importance to mining operations and proximity to the critical strata barrier. Using average values for pillar length and width in the main entries below Beaverdam Creek, an extraction ratio of 43.85% was determined. This value was confirmed using the Analysis of Retreat Mining Pillar Stability (ARMPS) software developed by the National Institute for Occupational Safety and Health (NIOSH) and displayed in Table 2 (Mining Product, 2013). The second examined area was in one of the production panels in the western section of the mine. At this location, development pillars were designed and the maximum overburden of 505 feet was present. An extraction ratio of 53.65% was calculated in this development section.

Table 4.1: Genesis No. 17 Analysis of Retreat Mining Pillar Stability Input Values.

Genesis 17 ARMPS Analysis	
Input Values	
Overburden	240 feet
# Entries	7
Pillar Length (Average)	58.3 feet
Pillar Width	40 feet
Entry Width	16 feet
Entry Height	4 feet
Results	
Average Extraction Ratio	43.60%
Development Stability Factor	9.1

4.1.2 Geology

The permitted area for the Genesis 17 mining operations is located in the Appalachian Plateau which known for its smooth anticlines and synclines (Richardson, 1934). The southern part of the Somerset syncline begins within the permitted boundaries and trends northeast until bending north in northern Somerset county. While strata on the eastern side of the syncline dip regularly and carry the Johnstown Limestone below the Upper Kittanning coal seam, the region to the west follows a more irregular pattern. The strata rise due to the Boswell Dome which is located between the Somerset and Johnstown synclines (Richardson, 1934). The Upper Kittanning dips by approximately 3.2° in the Southeast direction over the permitted area (Means, 2009).

The Upper Kittanning coalbed is one of the county's most valuable sources of coal. The Somerset region's most recognized structure, the Johnstown Limestone, is located just below the coal, generally separated by only a few inches of shale. The Upper Kittanning coal is considered to be relatively harder when compared to the softer Freeport and other Kittanning coals.

Stratigraphic properties were carefully considered in the permitting of the Genesis No. 17 mine. The results from MSHA's lineament analysis were compiled by the PA DEP to discuss fracturing in the permit area. Lineaments may be defined as features on the Earth's surface that are represented as ridges or depressions topographically (Shake and McHone. 1985). While nine lineaments were identified, only five cross the permit and subsidence boundary and only two lineament intersections are within the subsidence boundary. Caution was used while approaching these intersections and no lineaments are present near the crossing of Beaverdam Creek (Genesis No. 17 Application, Module 7).

A number of bore holes were made during the permitting of mining operations. Core sample G-6 is located in the vertical strata barrier (Figure 4.2). The stratigraphy contains predominantly shale and sandstone. Rock quality designations (RQD) were assigned throughout the boring. RQD was measured because of the shallow overburden and the proximity of the Beaverdam Creek valley. The more competent rock layers, the sandstone and limestone, ranged from 81% - 100% and the less competent shales, clays and siltstones ranged from 63% - 100% of the stratigraphic column.

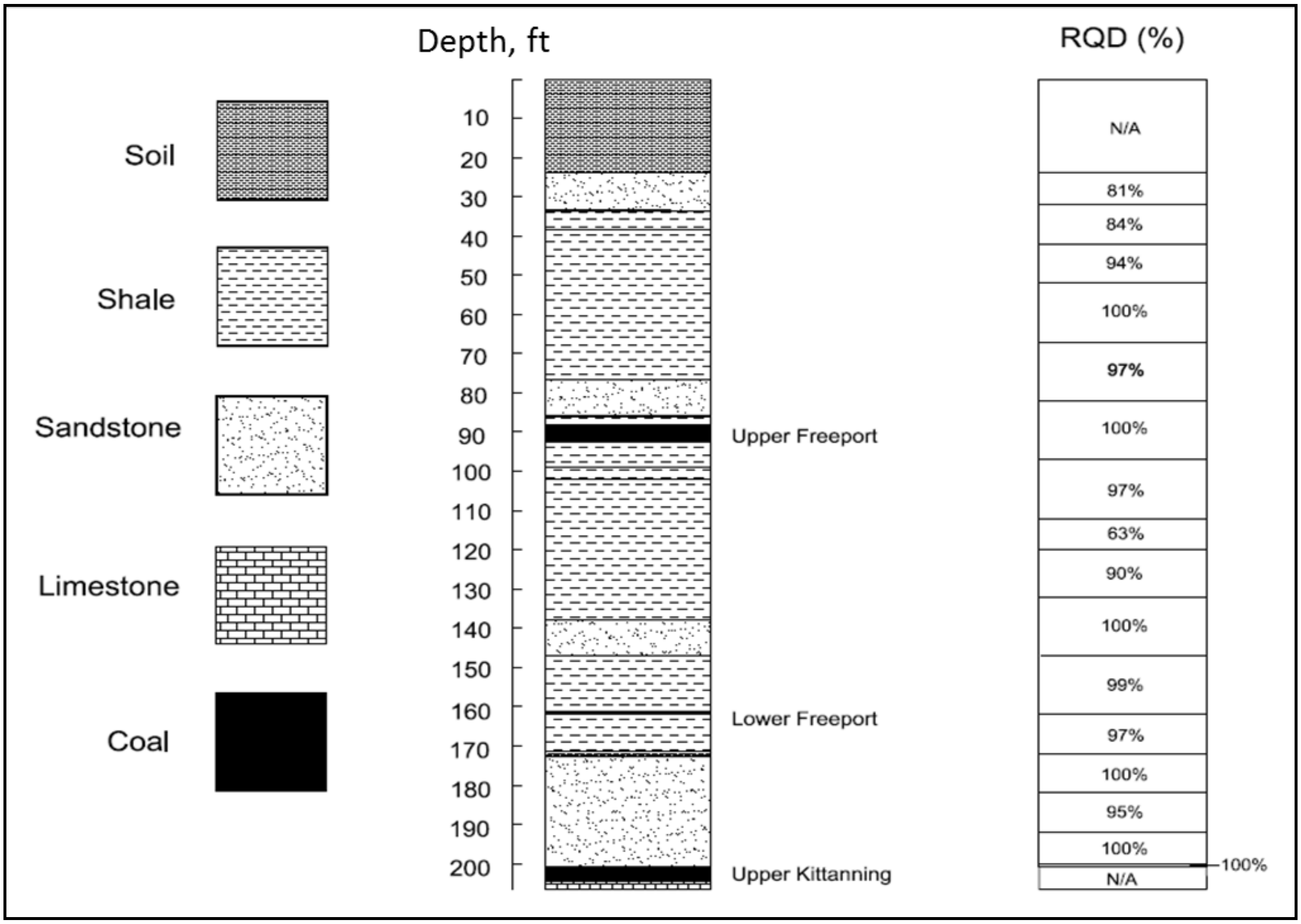


Figure 4.2: Genesis No. 17 core sample, G-6 with stratigraphic components and associated RQD values (Iannacchione et al. 2013a).

4.1.3 Hydrology

The Genesis No. 17 permit area contains three streams within its boundary: Beaverdam Creek, South Fork of Beaverdam Creek, and an unnamed tributary to Beaverdam Creek. Beaverdam Creek is the primary water source of interest in this case, as mining operations pass below the valley at the vertical strata barrier. The creek is known for its high water quality and abundance of aquatic life according to Dave Leiford (2013) of the PA DEP Ebensburg office. As a result an extensive hydrologic report was completed by the Department of Environmental Protection and discharge potential was also investigated by Brent Means in his 2009 study. Pre-mining and post-mining evaluations were performed on each of the water sources and mining impacts on groundwater dynamics reported.

Pre-mining evaluation data is essential to determine baseline hydrogeological conditions. The hydraulic gradient was monitored by installing piezometers at three locations. By monitoring groundwater flow before mining, a mine pool prediction height could be formulated based on the water levels in the Upper Kittanning coal seam. PZ-1, which is located in the strata barrier above the mains below Beaverdam Creek, was determined to contain approximately 204 feet of overburden strata. A shallow piezometer was installed here to monitor the shallow groundwater elevation and water was reported by Means (2009) to be 31 feet down as determined by the PA DEP.

Two additional nests of piezometers were installed in the established 700 foot barrier of South Fork Beaverdam Creek which runs along the eastern side of the mine. PZ-3 extended 213 feet below the surface and monitored the Upper Kittanning coal and PZ-4, a shallow piezometer that recorded water elevations in the Upper Freeport 57 feet down. The final set was installed in the South Fork Beaverdam Creek stream valley. A deep, intermediate, and shallow piezometer, PZ-5 (305 feet deep), PZ-6 (depth of 196 feet), and PZ-7 (depth of 113 feet), were located there, respectively. The intermediate monitors the Upper Freeport coal while the shallow piezometer reflects the Brush Creek water. The DEP required the installation of piezometers in the stream valleys where overburden depths were minimal. Along with core logs and fracture analysis using RQD, the potential to discharge due to hydraulic head could be analyzed at each of these locations. Figure 4.3 displays the change in water elevations throughout the pre-mining, operational, and post-mining stages as recorded in each series of piezometers.

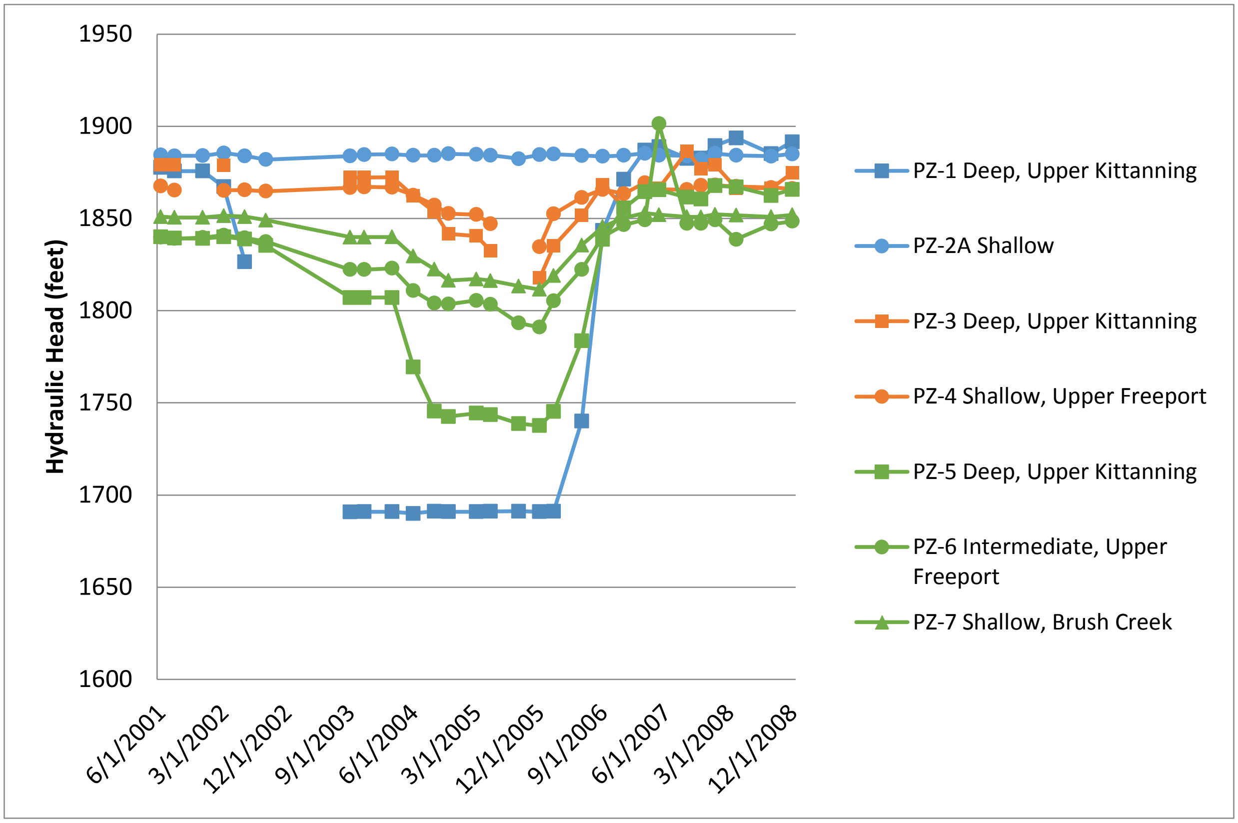


Figure 4.3: Genesis No. 17 piezometer data throughout mining. Mine pool elevations are represented by "PZ-1 Deep."

Following the closure of mining operations in 2005, a post-mining discharge evaluation took place to determine any hydrological effects after production. The potentiometric surface or piezometric surface was noted in the cases of PZ-1 and PZ-2A. Piezometric surface refers to the level that a reservoir of fluid will rise to if it is permitted to rise freely (Younger, 2007). These water levels can be used to predict long term post-mining elevations. The original maximum mine pool level was approximated to rise to 1810 feet which is the maximum elevation within the mine at the portal. The piezometric surfaces, elevations of the hydraulic gradient in the region, are approximately 1877 feet and 1884 feet for PZ-1 and PZ-2A, respectively, reported by Means (2009) and the PA DEP. The box-cut's lowest point is still above these surfaces, however, located at an elevation of 1910 feet.

4.1.4 Analysis

The Genesis No. 17 mine site is an example of a successful strata barrier design. There have been no reported discharges to the surface waters in any of the three surrounding streams. The location of the main entries below Beaverdam Creek is critical in terms of environmental concerns and regulations. With less than 200 feet of overburden separating the mine workings from the stream above, the strata has succeeded in containing the water from the mine pool despite being subjected to approximately 200 feet of head. The original mine pool prediction was the maximum elevation of coal within the mine, 1810 feet; however, the mine pool has risen to as high as 1892 feet, exceeding the heads observed in the pre-mining piezometer data. The piezometric surface of PZ-1 predicted that the mine pool would reach as high as 1877 feet. Although it is difficult to determine the exact cause of post-mining coal seam water hydraulic head, one theory developed throughout research suggests that coal extraction causes this change. Before any coal is mined, the water elevations in the piezometers in the Upper Kittanning reflect the height of the seam. However, after coal is extracted, it's possible that the coal seam will not behave as uniformly as the pre-mining hydraulic gradient and piezometer levels will be affected.

Those piezometers monitoring the higher coal elevations could potentially be lower whereas the piezometers that are located further down-dip have the potential to rise higher.

4.2 GROVE NO. 1

The Grove No. 1 coal mine (MSHA ID 3602398) is located in Somerset County, Pennsylvania (Figure 4.4). Throughout the life of the mine (1969 to 2001), the operation had many owners including GM&W Coal Company, Carbolith Extraction Inc., Grove Resources, and finally Lion Mining Company. As a result of mining, a discharge occurred north of the mine from mine pool water passing along bedding planes in the strata. The characteristics surrounding the horizontal strata barrier will be analyzed to determine the causes of the post-mining discharge and the factors associated with the effective vertical barrier will be identified.

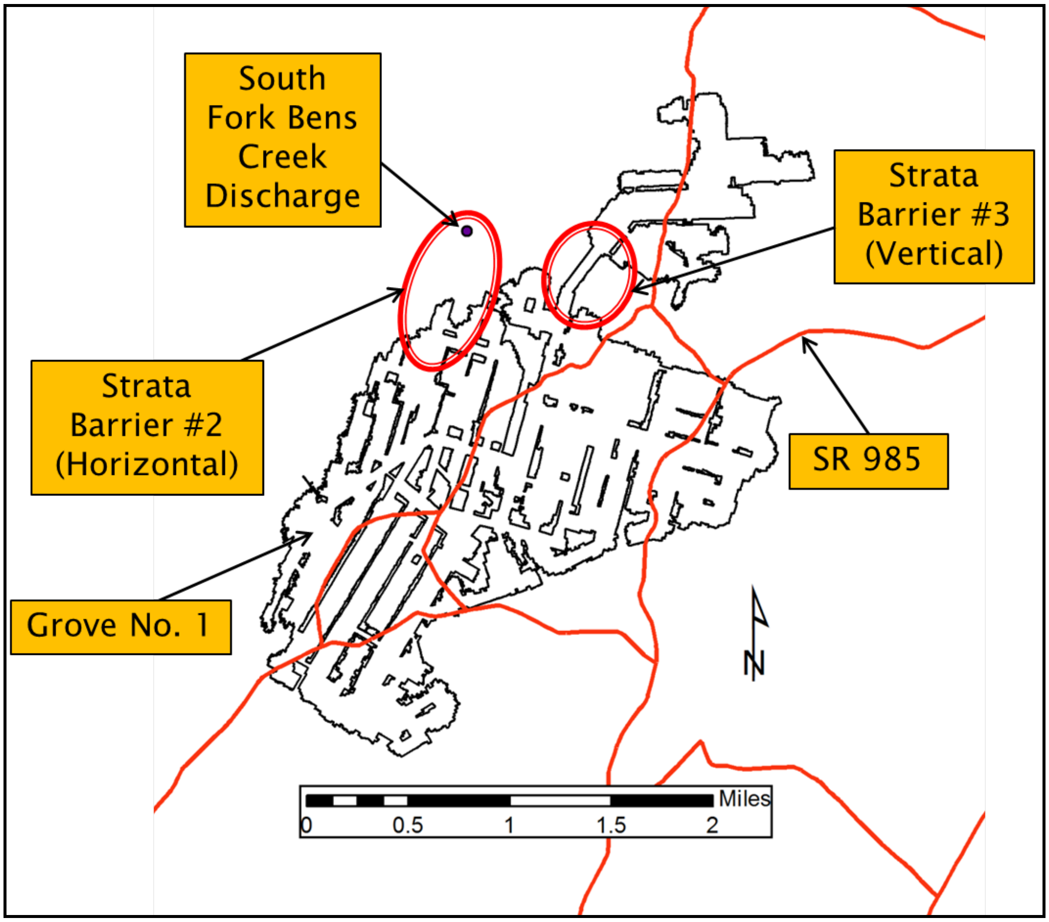


Figure 4.4: Grove No. 1 Mine Outline with location of Strata Barrier #2 and discharge to South Fork Bens Creek.

4.2.1 Mining Methods

A number of mining methods were utilized at the Grove No. 1 mine. Based on geologic conditions, (e.g., local dip of the Upper Kittanning), room-and-pillar mining occurred along with some partial and full extraction mining. In a previous study conducted by Iannacchione et al. (2013b), three primary areas of mining techniques were identified (Figure 4.5). The western region (Area #1) contained some pillar recovery with a majority consisting of room-and-pillar mining. Then mains progressed toward the Johnstown Syncline, encountering difficult mining conditions due to steep grades. This area was of particular concern due to the sharp dips and resulting ground control problems including unstable roof conditions. Area #2 (eastern portions of the mine) also contained dips, some up to 5°, due to the Johnstown Syncline. A number of pillar recovery sections were utilized throughout this region, most notably, some panels under South Fork Bens Creek. Lastly Area #3 is the region developed in the northern-most part of the mine. This involved crossing South Fork Bens Creek (strata barrier #3) to access additional reserves. The overlying water source dictated mostly room-and-pillar techniques throughout Area #3.

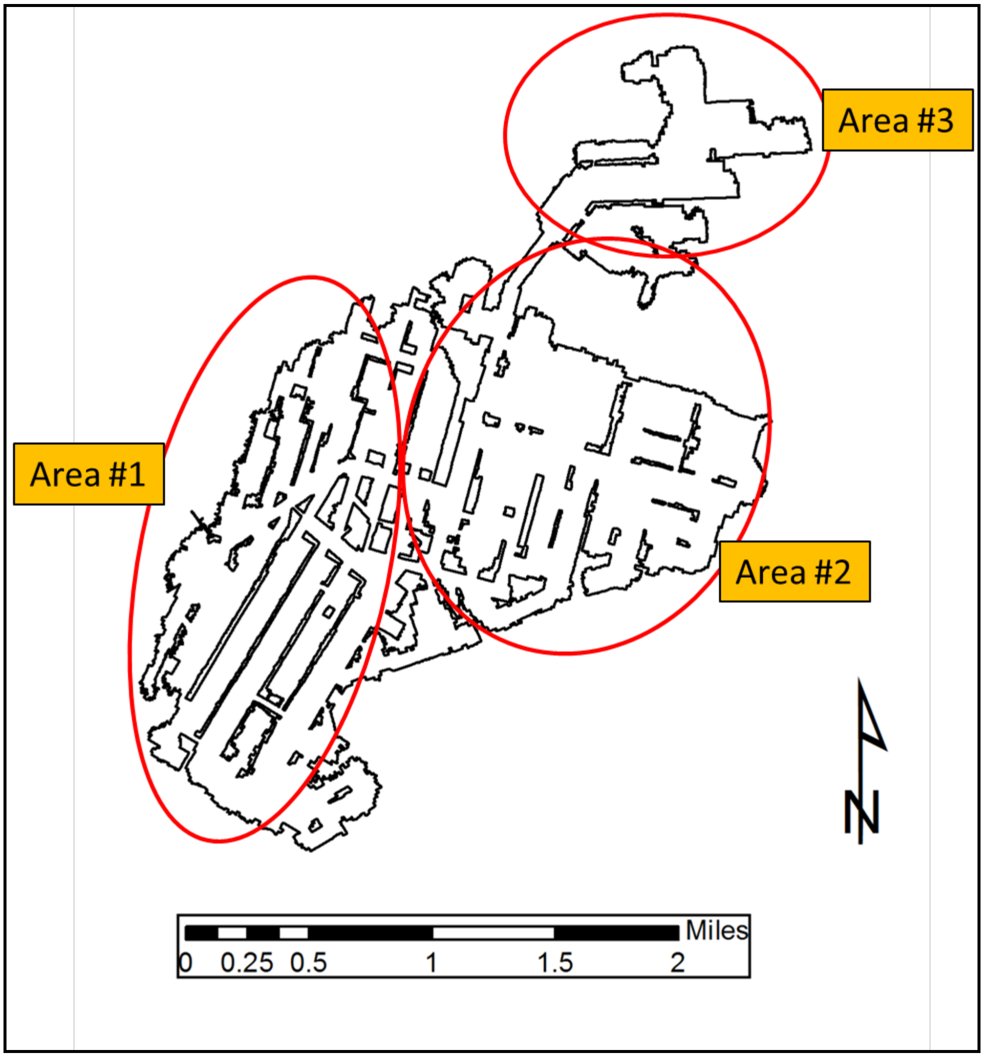


Figure 4.5: Grove No. 1 mining regions (Iannacchione et al., 2013b).

Within the production life of the Grove No. 1 operation, a number of seismic events were reported. No previous seismicity has been recorded in the region. Scharnberger (2003) reports of the first seismic activity which was a 2.6 magnitude event on February 3, 1982 centered near Jennerstown, PA. Located only a few miles from the Grove 1 mine, this event was labelled "mining induced." While several other events occurred between 1988 and 1995, perhaps the most notable findings come from a report by Wu et al. (1988). In 1988, they reported a series of vibrations that impacted the region surrounding Grove 1 that year. From their study, it appeared that these tremors were linked to pillar recovery sections within the mine. It was also noted that while smaller events are common during high extraction procedures, it is very uncommon that these events produce values similar to that of an earthquake (greater than 2.0 on the Richter Scale) during pillar recovery. As a result, it is apparent that mining methods, high extraction techniques in particular, were the cause of seismicity within the Grove No.1 region.

4.2.2 Geology

The geology within the region of the Grove No. 1 mine is unique. The large dips and wide range of overburden depths covering the mine operations create difficult mining conditions and post-mining discharge. By analyzing the region's geology and the effects mining methods have on geology, it is apparent that this operation has a discharge potential as a result of geologic factors.

Several major structural geologic features cut across the permitted region and the surrounding counties. According to Flint (1965), the Laurel Hill Anticline which runs through West Virginia and into southern Pennsylvania, dips at approximately 4°; however, due to faulting in the region, dips have been reported as high as 60° (Puglio and Iannacchione, 1979). Primary faults within the region, such as clay veins, are associated with slips along bedding planes due to lateral movement demonstrated in Figure 4.6. The many stratigraphic layers provide areas of discontinuity at their boundaries. Vertical stress due to increased overburden acting on the strata causes these slips.

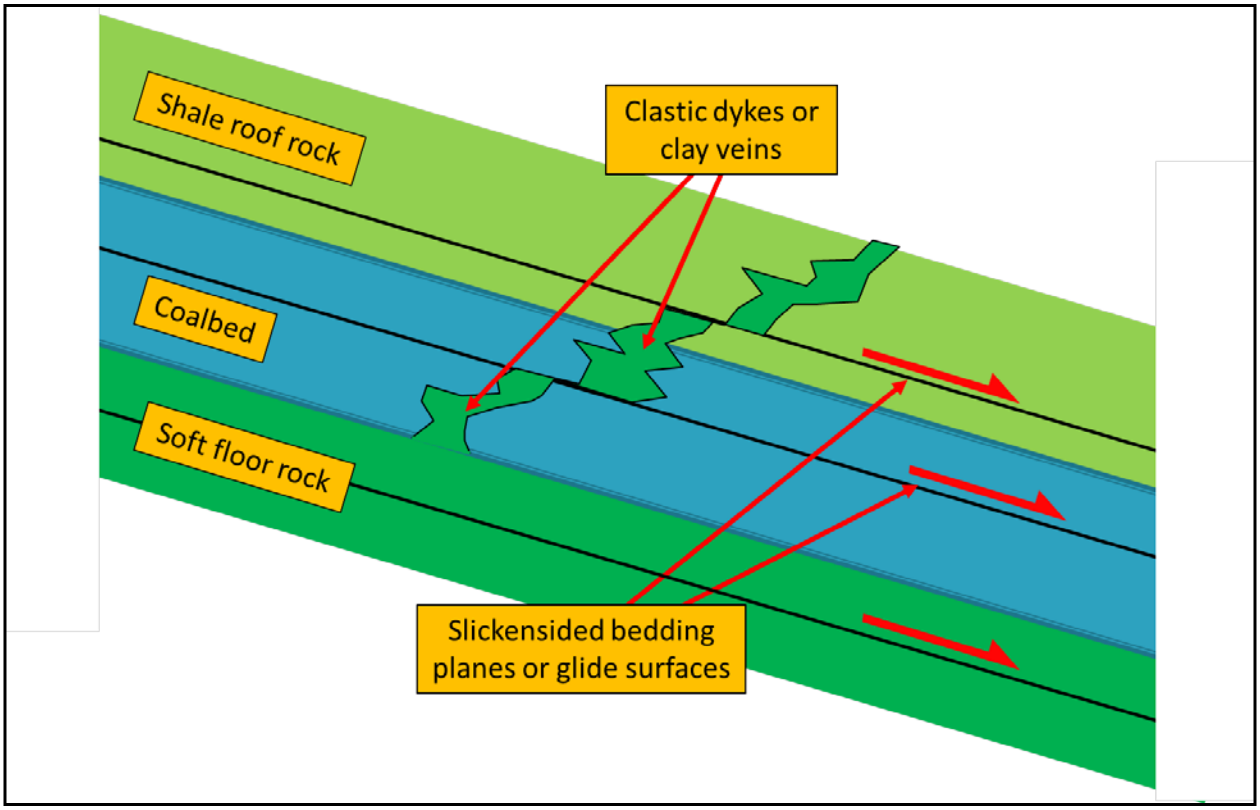


Figure 4.6: Pre-mining strata movement along bedding planes demonstrated by offsets in clay veins (Iannacchione et al., 2013b).

Overburden is a critical component in this case because of the deep cover and resulting stress on the underlying mine workings. Cover over Area #1 ranges from approximately 100 to 900 feet. Area #2 cover ranged from 600 to over 1000 feet. Similarly over Area #3, the depth of cover is approximately 500 feet above South Fork Bens Creek but as high as 800 feet under the hilltops. Generally the state is concerned when undermining occurs within 250 feet of the surface under streams due to the potential to discharge vertically (Means, 2009). In this case, cover is approximately twice as deep.

Fracture networks are important when considering the hydrogeological footprint that will be experienced due to mining. Because of the fault features and the seismicity within the mine, it can be assumed that fracture presence is relatively high throughout the region. Iannacchione et al. (2013b) infer that flow will be dominated through these naturally and mining induced fracture networks. Using a cubic law, discharge rates were input and fracture dimensions approximated. According to Romm (1966), the cubic law is results in using the following equation:

$$Q = \frac{\rho_w g b^2}{12\mu} * bw \frac{\delta h}{\delta L} \qquad (Eqn.\ 3)$$

Where:

Q = discharge (ft^3/s),

ρ_w = density of water (1.94 slugs/ft^3),

g = acceleration due to gravity (32.17 ft/s^2),

μ = viscosity (2.034×10^{-5} lbs/ft^2),

b = aperture opening (ft),

w = fracture width perpendicular to the flow direction (ft),

$\frac{\delta h}{\delta L}$ = hydraulic gradient (0.0143 and 9.38×10^{-3}).

The density and viscosity were based upon assumptions that the temperature was 20°C and the hydraulic gradient was determined using the height of the mine pool and two discharge locations. The recorded mine discharge of 60 gpm can be used to infer fracture widths and apertures using this theory. Table 3 displays the fracture widths and apertures based on this 60 gpm discharge. Because fracture flow provides a much larger conduit than flow through less fractured layers of strata due to narrower flow paths, the discharge at Grove 1 can be mostly attributed to flow through fracture networks and bedding planes.

Table 4.2: Projected Fracture Widths and Apertures using Romm Equation (Iannacchione, et al., 2013b).

Fracture Width, in. (mm)	Fracture Aperture, in. (mm)
0.012 (0.3048)	3.98 (101.0)
0.12 (3.048)	1.85 (47.0)
1.2 (30.48)	0.858 (21.8)
3.0 (76.2)	0.632 (16.1)
6.0 (152.4)	0.502 (12.8)
12.0 (304.8)	0.398 (10.1)
24.0 (609.6)	0.316 (8.03)
36.0 (914.4)	0.276 (7.02)
48.0 (1219.2)	0.251 (6.38)
120.0 (3048.0)	0.185 (4.7)
1200.0 (30,480.0)	0.0858 (2.18)

4.2.3 Hydrology

The permitted area above the Grove No. 1 operation has many water sources. Some of the primary waterways within the region are South Fork Bens Creek, North Branch South Fork Bens Creek, Flat Run, Gum Run, Roaring Run, and several tributaries off of each (Figure 4.7). As a result a flow analysis using Darcy's Law was performed to estimate hydraulic conductivities for the area. Iannacchione et al. (2013b) demonstrated the hydraulic conductivity using Darcy's Law and the water balance method which determines inflow rates into the mine based on pumping rates and mine pool height. In that study, the mine infiltration rate was determined to be 0.327 ft/day/ft^2 of mine area. This value was assumed constant throughout mining and while the discharge occurred. As a result, the hydraulic conductivity was calculated to range from 6.7

to 18.5 ft/day based on the 30 foot head difference and the barrier which ranged from 2100 ft to 3200 ft. Obviously these values are much higher than the reported values of hydraulic conductivity for coal and other related strata; however, in the case of intensely fractured rock, these values are reasonable.

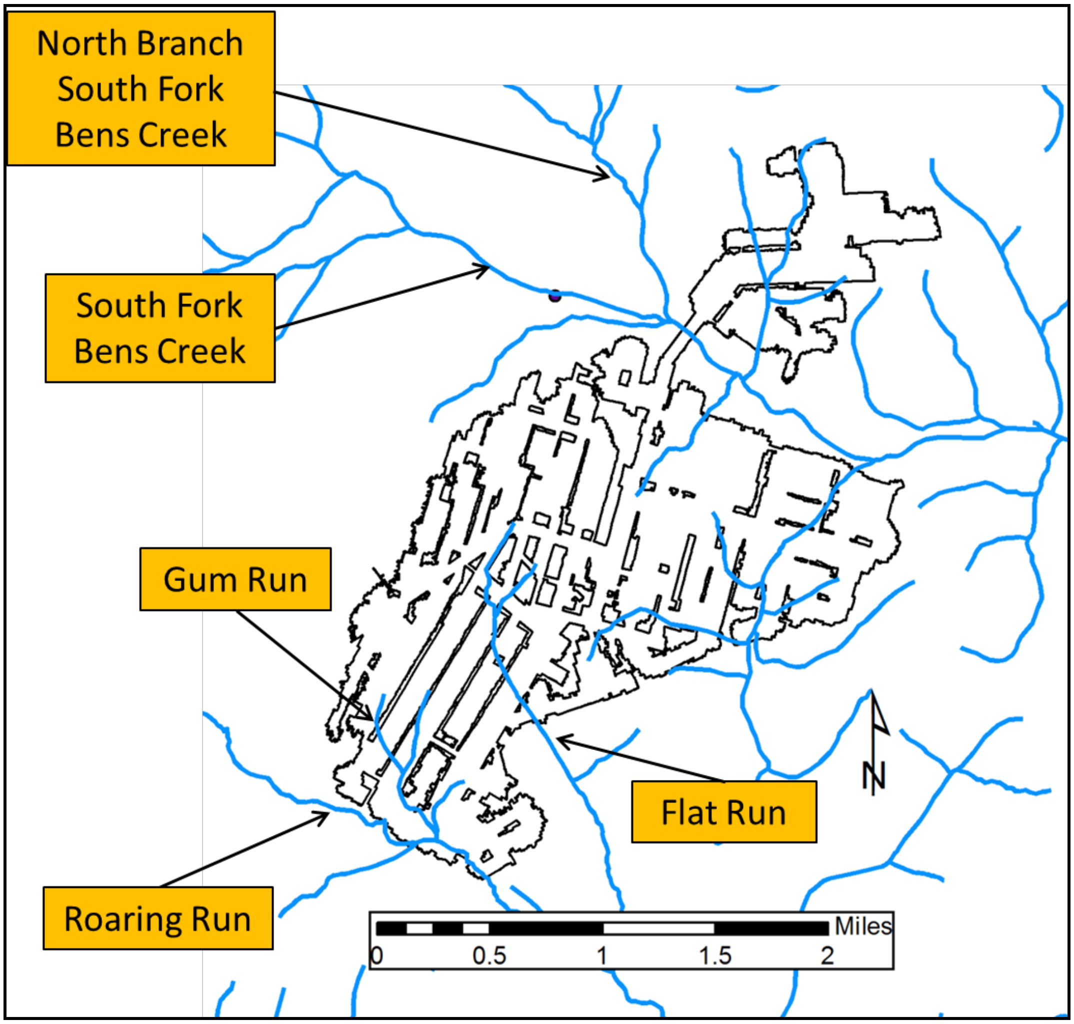


Figure 4.7: Grove No. 1 mining operations and overlying streams within the permitted area.

4.2.4 Analysis

The Grove No. 1 mine discharged iron rich waters to South Fork Bens Creek post-mining. This is a unique scenario as the failed strata barrier contained highly fractured zones and enabled mine pool water to travel greater than expected distances. The hydraulic head acting on the overlying strata was produced a discharge between 2100 and 3200 feet away. The practice of high extraction mining techniques produced increased fracturing and led to seismic events within the region. The seismicity expanded existing fractures, increasing potential fluid flow. Fracture analysis using Romm theory inferred the fracture widths and apertures using flow. Hydraulic conductivities for the region were also estimated using Darcy’s Law and were noticeably higher than literature values. This discrepancy likely arises from increased fracture conductivity created by high extraction mining and subsequent seismicity throughout the area.

A vertical strata barrier was also present at this operation. The barrier is located above the mains that cross under South Fork Bens Creek. The lowest overburden is 400 feet and the hydraulic head acting on the barrier is 146 feet above the elevation at the surface. The effective prevention of discharges is attributed to the thickness of the overburden as well as the reduced mining in the region which prevented intense fracturing of the overburden.

4.3 KEYSTONE EAST

The Keystone East coal mine (MSHA ID 3609193) is located in the Upper Freeport coal seam on the eastern border of Armstrong County, Pennsylvania. Mining operations began in 2004 and ended in 2008 under the ownership of Rosebud Mining Company. The permitted area of 768 acres contains many water sources including Keystone Reservoir to the west of the mine, South Branch Plum Creek to the south, and several other tributaries. The vertical strata barrier is located over production panels on the western side of Keystone East due to shallow overburden there (Figure 4.8).

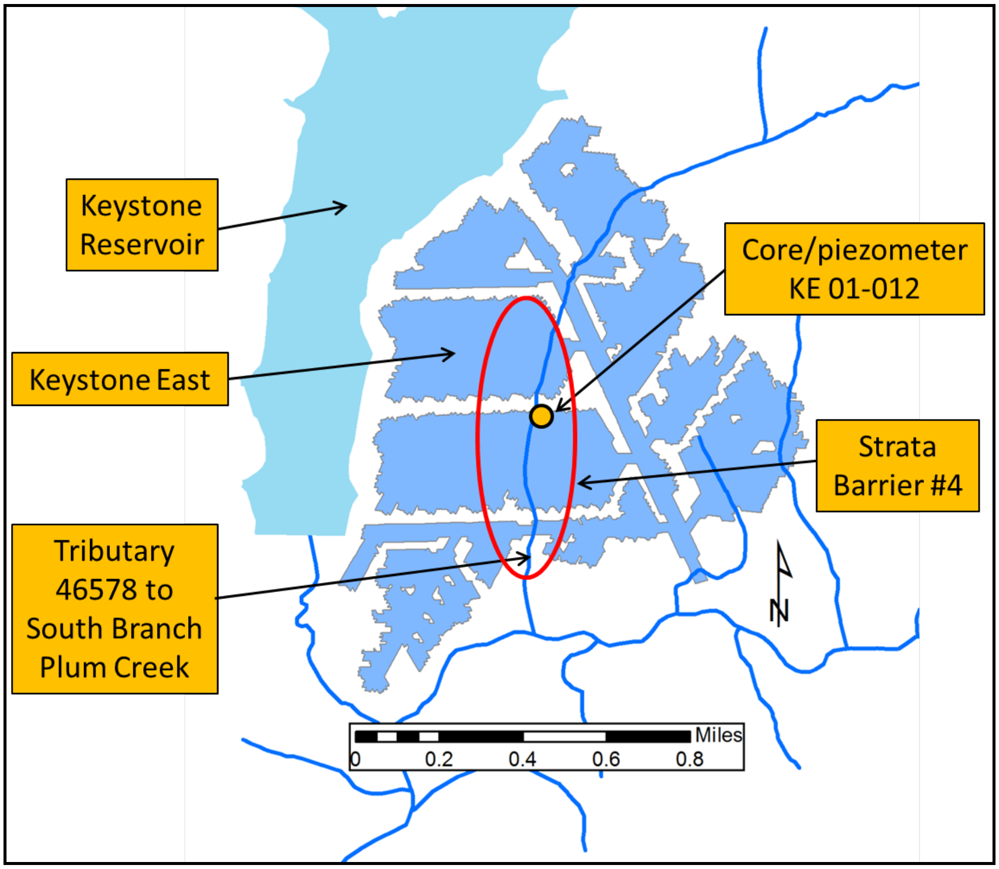


Figure 4.8: Keystone East surrounding water sources, core sample/piezometer KE 01-012, and Strata Barrier #4 location.

4.3.1 Mining Methods

Keystone East was created through development room-and-pillar techniques. Only one surface activity site was developed, consisting of an excavated box-cut with three drift entries allowing underground access to the coal seam. There were very few limitations made before mining. A 200-ft barrier was set in place around Keystone Lake to the west and no mining would be performed in areas where the overburden was less than 90 feet. Production began in the third quarter of 2004 and throughout the life of the mine it produced over 1.6 tons of coal with its most productive year in 2006.

As mentioned in the DEP's pre-mining report, mining was not restricted by surface structures during permitting (Keystone East Application: Module 10). The impact potential of underground mining operations on surrounding public parks, historic places, and fish and wildlife habitat was assessed. No features were identified and proper design techniques, implementation of operations, and management of facilities, resulted in no adverse environmental effects.

Coal extraction ratios were calculated in a variety of locations throughout the mine. The first region was toward the northern most production panel within the strata barrier. This area was chosen because it is located near piezometer and core sample KE 01-012 and the overburden is 116 feet. The highest extraction was calculated at this location, 62.21%. Three rows of pillars were then examined in the southern part of the strata barrier near the lowest surface elevation of approximately 1004 feet. These pillars averaged a 58.17% extraction ratio while supporting nearly 100 feet of overburden. These two locations were below the stream valley of Tributary 46578 to South Branch of Plum Creek. Lastly, the main entries were selected for analysis to determine the stability of the pillars. As expected, the lowest values were calculated in this location, 54.66%, while the overburden was approximately 140 feet.

4.3.2 Geology

The local geologic structure of Armstrong County has its own distinctive arrangement. The regional geology is dominated by the Glenshaw Formation and the Allegheny Group. The Glenshaw formation is predominantly composed of sandstones and mudstones along with thin limestone and coal layers (Martino, 2004). The mining area of Keystone East is located on the western side of the Punxsutawney-Caledonia Syncline which trends to the northeast and forms a basin in the permitted region. The coal of the Upper Freeport seam is known to dip only slightly, generally 1° in the mined area.

Fracture analyses and relevant geologic data were compiled by the DEP prior to mining. There are few prevalent joint features detected in the core. Most discontinuities are secondary features likely caused by stress relief following erosion of overburden (Keystone East Application, Module 7).

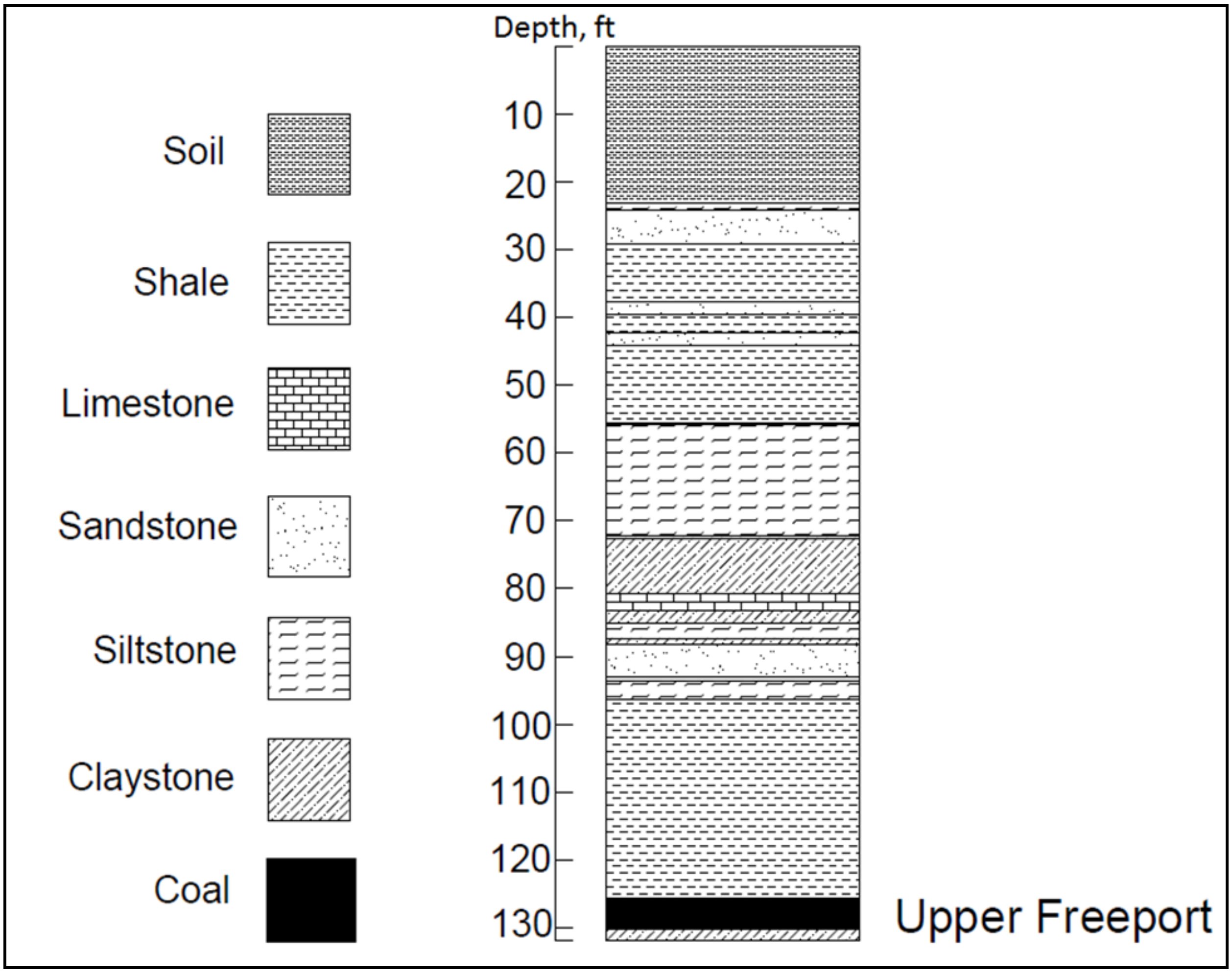


Figure 4.9: Keystone East core sample KE 01-012 located within Strata Barrier #3 (Iannacchione et al. 2013a).

There were no major fractures or fault zones identified during exploration of the property. There are a few near vertical joints related to stress relief and some separation of bedding planes in the valleys but these fractures are relatively minimal for the area. Several cores were drilled to examine the stratigraphy (e.g., Figure 4.9, drilled in the strata barrier). Many different rock layers form the column, a majority softer rock. Approximately 70% of the column is composed of shales, siltstone, claystone, and coal while limestone and sandstone layers compose 12%. RQD was available in surrounding samples. These cores that were sampled contained similar stratigraphic properties as the overburden contained within the strata barrier. The average RQD value for core KE 01-010 was determined to be 97% with the lowest value located within a shale layer at 88% (Figure 4.10). KE 01-011 had an average RQD of 96% with the lowest values of 93% located within shale layers. A majority of these samples were considered “excellent,” (i.e., RQD =90% - 100%), with only a few as low as “good,” (i.e., RDQ = 75% - 89%). As a result, the strata within the region are very competent.

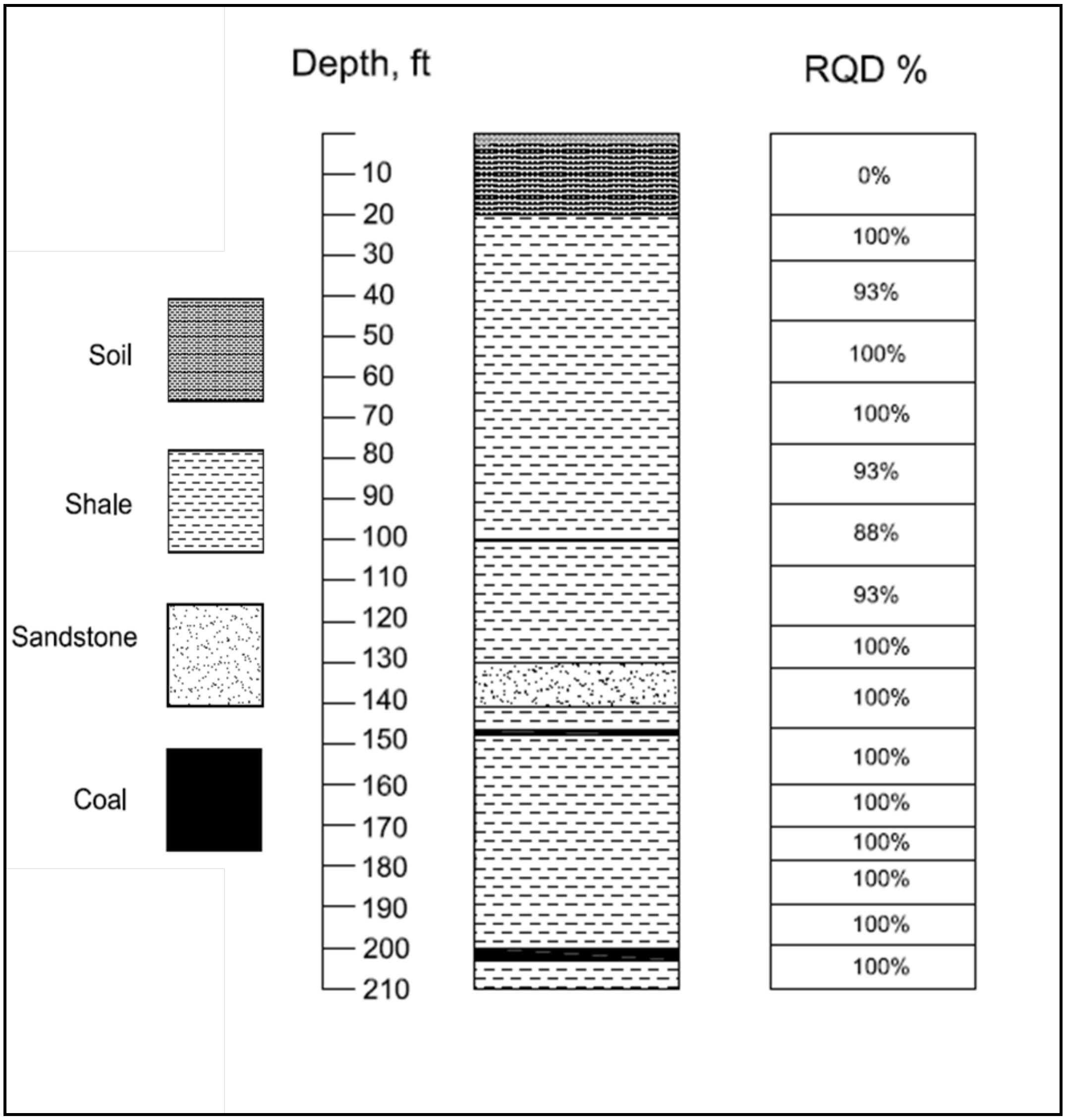


Figure 4.10: Keystone East core sample KE 01-010 and associated RQD values demonstrate the rock quality within the region.

4.3.3 Hydrology

As mentioned previously, a number of waterways are present on the surface above the permitted area of Keystone East. The neighboring reservoir, stream to the south, and its tributaries provide a surface water supply that was monitored throughout the mining process. The mining region is approximately 9600 feet from Elderton, where the Eastern Armstrong County Municipal Authority water supply wells are located. No waterways experienced adverse effects from existing surface mining operations. As a result, no negative hydraulic impacts were predicted prior to mining and there have been none recorded since the operation's closure.

The PA DEP characterized groundwater as the result of detailed water supply surveys in the region and piezometer data from within in the permitted area. Groundwater is found in both shallow and deep aquifers throughout the region. The shallow aquifers are unconfined and are composed of unconsolidated materials and weathered bedrock. In contrast the deeper aquifers include unconfined, semi-confined, and confined conditions. Since regional stratigraphy is primarily composed of shales, siltstone, limestone, sandstone, and coal, there is relatively low permeability between the layers. As a result, it is typical for most of the transmission of water below the surface to take place along bedding planes. It is also common for wells that intercept fractures to have significantly higher yields than those that do not come into contact with as many fracture networks (Keystone East, Module 8).

Groundwater movement throughout the permitted region was tracked in the pre-mining period at Keystone East. Because the flow of groundwater is dictated by the hydraulic gradient, water will move from areas of higher hydraulic head to regions where the hydraulic head is lower (Williams and McElroy, 1997). Within the permitted area, the flow gradients are approximated by the surface topography. The general trend is that groundwater moves from the hilltops down into the valleys below. The primary topographic features consist of a north-south oriented tributary to South Branch Plum Creek which divides the operating area down the middle and a series of hilltops on the eastern and western sides above the mine.

Groundwater was monitored through a series of piezometers located close to the mine workings. Core hole KE 01-012 contained a deep piezometer to monitor the Upper Freeport coal seam as well as a shallow piezometer, KE 01-010. The fluctuation in groundwater flow is seen in Figure 4.11. The Upper Freeport was pumped throughout mining which demonstrates the noticeable loss of elevation during mining but has nearly returned to pre-mining elevations and the shallow groundwater is less unaffected due to mining. Pre-mining elevations average 1011 feet compared to the 1005 feet post-mining average elevation.

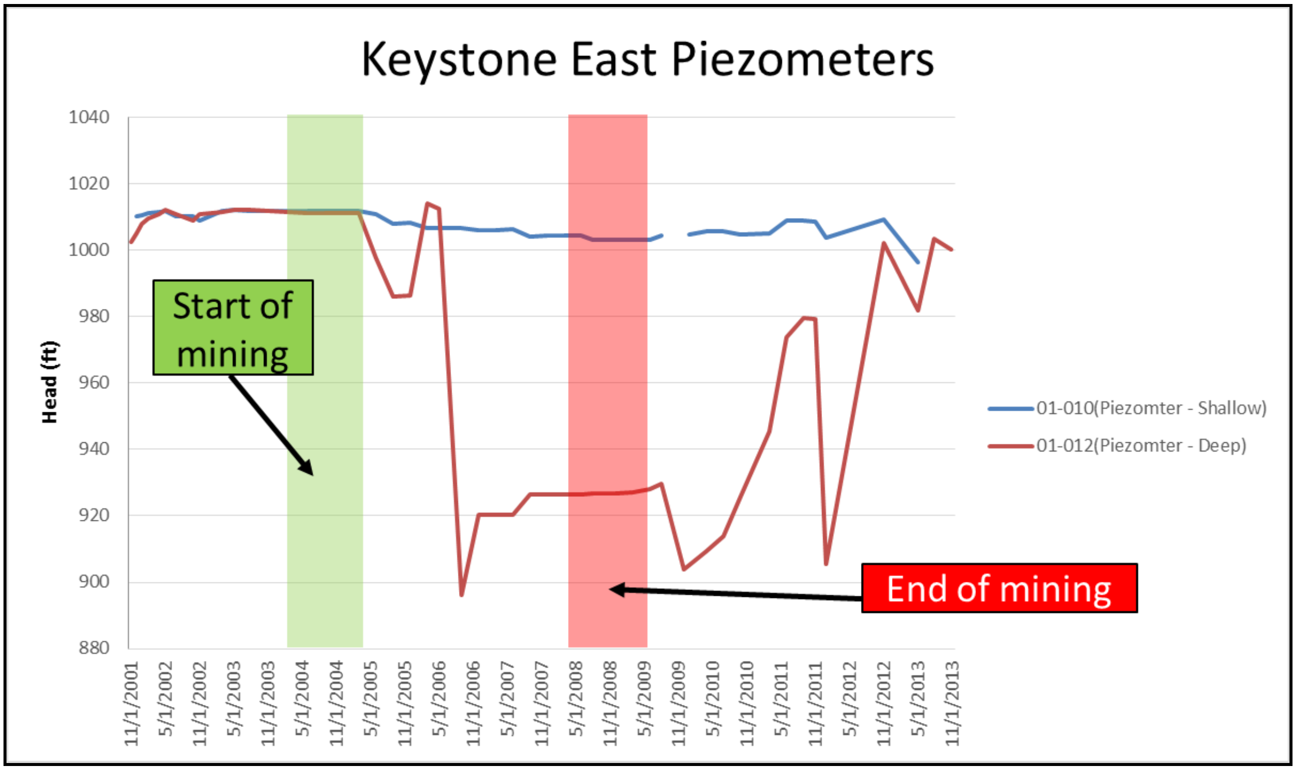


Figure 4.11: Keystone East piezometers reflect the effect of mining on the shallow groundwater and deep piezometer which monitors the Upper Freeport.

Pre-mining analyses predicted the elevation of the mine pool. No discharges were predicted based on the elevation at the portals of approximately 1010 feet after the box-cut was filled. The highest coal elevation in the Upper Freeport within the permit boundary is approximately 954 feet. As a result, the mine pool was predicted to reach 954 feet, substantially lower than the surface elevation at the portal of 1010 feet. To monitor the development of the mine pool, MP-1, a monitoring point was established after mining was completed. The most recent elevation measured in November of 2013 shows that mine pool levels have reached approximately 1001 feet as seen in Table 4.3 (Figure 4.12).

Table 4.3: Keystone East: MP-1 monitoring point.

Date	Upper Freeport Mine Pool Elevation (ft)
4/20/2010	909.35
7/14/2010	914.5
10/13/2010	927.05
3/24/2011	946.1
6/17/2011	974.6
9/28/2011	980.65
11/2/2011	980.85
1/20/2012	980.35
11/20/2012	1000.35
7/23/2013	1001.65
11/12/2013	1000.5
11/27/2013	1001.25

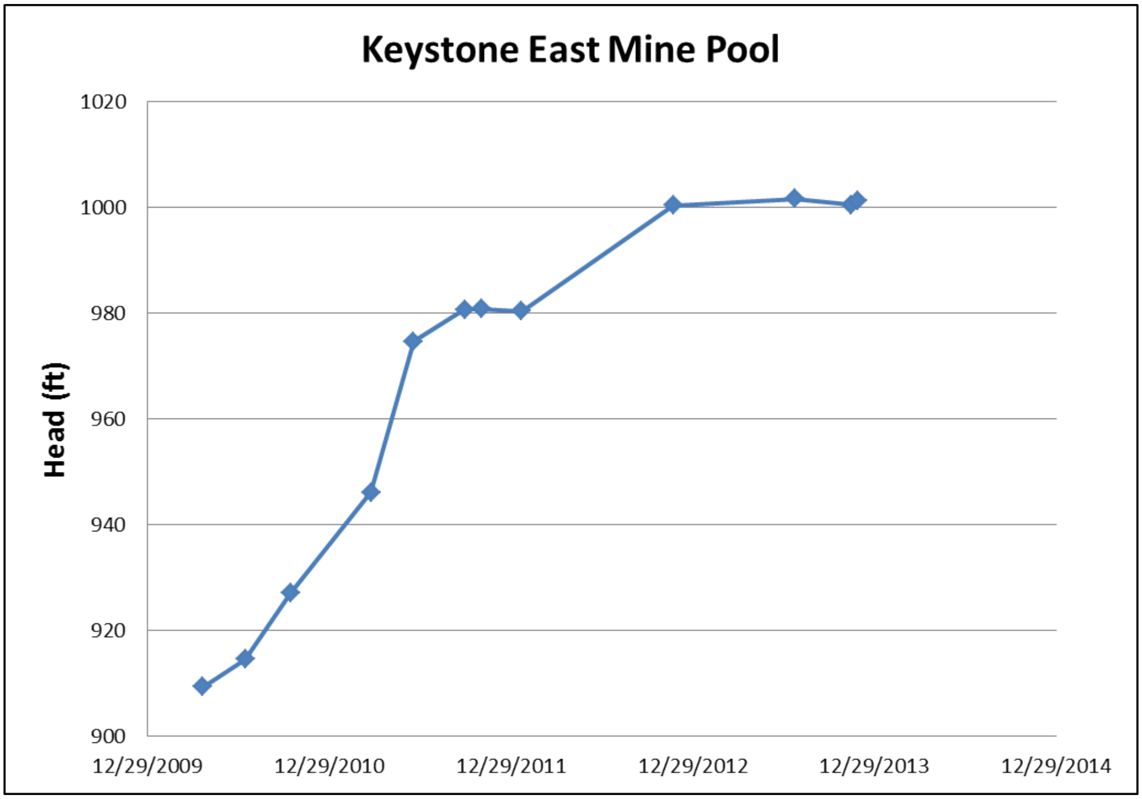


Figure 4.12: Keystone East mine pool data from monitoring point MP-1, created once the mine pool began to develop.

4.3.4 Analysis

The Keystone East mine is an example of a successful strata barrier that prevented discharges from the mine pool. Numerous waterways and streams are located within the permitted area where valleys are present. The overburden ranged from approximately 90 feet to almost 400 feet with a majority of the overburden contained in the strata barrier between 100 and 140 feet. This shallow depth of cover has contained the mine pool to date. The surface elevation gets as low as 1001 feet within 14 feet of the mine workings and in the summer of 2013, the Upper Freeport aquifer was measured near the mine at 1004 feet with the mine pool level just below at approximately 1001 feet. Pre-mining piezometer data indicates that the Upper Freeport water elevation was as high as 1011 feet in 2004. Hydraulic head acting on the strata barrier may return to this pre-mining elevation in the future.

4.4 URLING NO. 1, 2, AND 3

The Urling mines, No. 1 (MSHA ID 3604852), No. 2 (MSHA ID 3604853), and No. 3 (MSHA ID 3605658) are room-and-pillar mines located in western Indiana County (Figure 4.13). Urling No. 1 and No. 3 were developed in the Lower Freeport coal seam and No. 2 was developed in the Upper Freeport via a slope within No. 1. Urling No. 2 was confirmed to have discharged (pers comm Dave Yingling, 2014 and Joe Matyus, 2013); however, the state contained the discharge by lowering the mine pool. The overburden characteristics at the discharge location and geologic conditions, which dictated production, are examined in this case study.

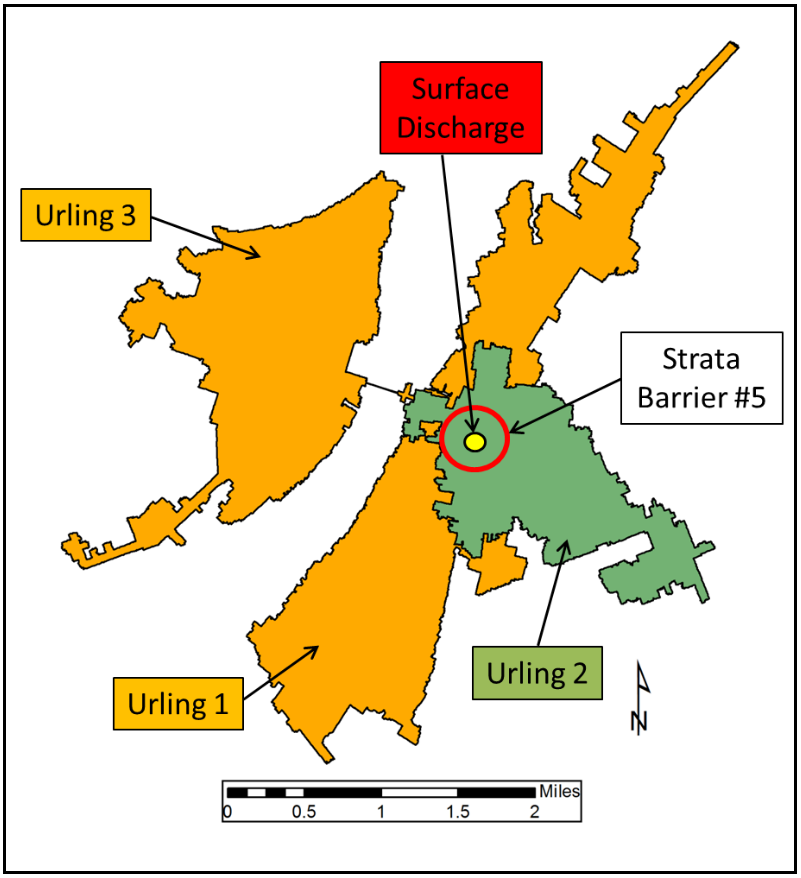


Figure 4.13: Urling No. 1, 2, and 3 of Indiana county, Pennsylvania and surface discharge location. No. 1 and 3 are located in the Lower Freeport and No. 2 is in the Upper Freeport coal seam.

4.4.1 Mining Methods

The Urling mines developed simultaneously throughout the 1980s and into the 1990s through the use of multiple seam mining techniques. Urling No. 1 and 3 utilized room-and-pillar mining as well as pillar recovery while the overlying Urling No. 2 used development and thin pillar room-and-pillar mining methods. The strata barrier above Urling No. 2 contained both development and thin pillar mining with extraction ratios ranging from 0.55 to 0.65. The overburden above Urling No. 2 at the barrier was 260 feet and was located at one of the lowest surface elevations, approximately 1012 feet.

Mining was dictated by several hydrogeological features. Only a single, narrow passage connects the mine workings of Urling No. 1 and No. 3 (Figure 4.14) due to a massive sandstone channel runs between the two mines and makes mining or tunneling in the region very cumbersome. Areas within this channel between the mines were therefore not mined. Stream valleys are at a high risk of being fractured due to their orientation and shape relative to horizontal stresses acting upon them and associated stress relief within valleys. As a result, the crossing of Curry Run was prevented due to water influxes from fracturing.

Throughout production, strata control also became problematic. Poor roof quality resulted in multiple roof falls throughout all three operations, particularly at Urling No. 2. Unstable roof, water inflows, and multiple seam interactions slowed production and dictated mining direction throughout the life of the operation.

4.4.2 Geology

The Urling mine developments provide an example of how mine structures are often times established because of the natural features of the region. In this case, geologic makeup and increased fracturing due to horizontal stress and stress relief dictate the progression of mining operations. Faults, such as the sandstone channel within the permitted region, were also observed at this site which impacted production. After discussing mining operations with several industry professionals and seeing the progression of No. 1 and No. 3 on mine maps, it was apparent that there were no problems crossing underneath Crooked Creek. Crooked Creek runs in the east-west direction above the mine workings of No. 1 and No. 3; however, Urling No. 2 was reported to have many problems when operations came into close proximity of Curry Run to the East. The original plan involved crossing Curry Run as Crooked Run was undermined previously with no hindrances. It was reported that great inflows of water were experienced, approximately 350 gpm, on site as mining was attempted under Curry Run. As a result, production was driven to the northwest and continued alongside the stream but it was never successfully undermined.

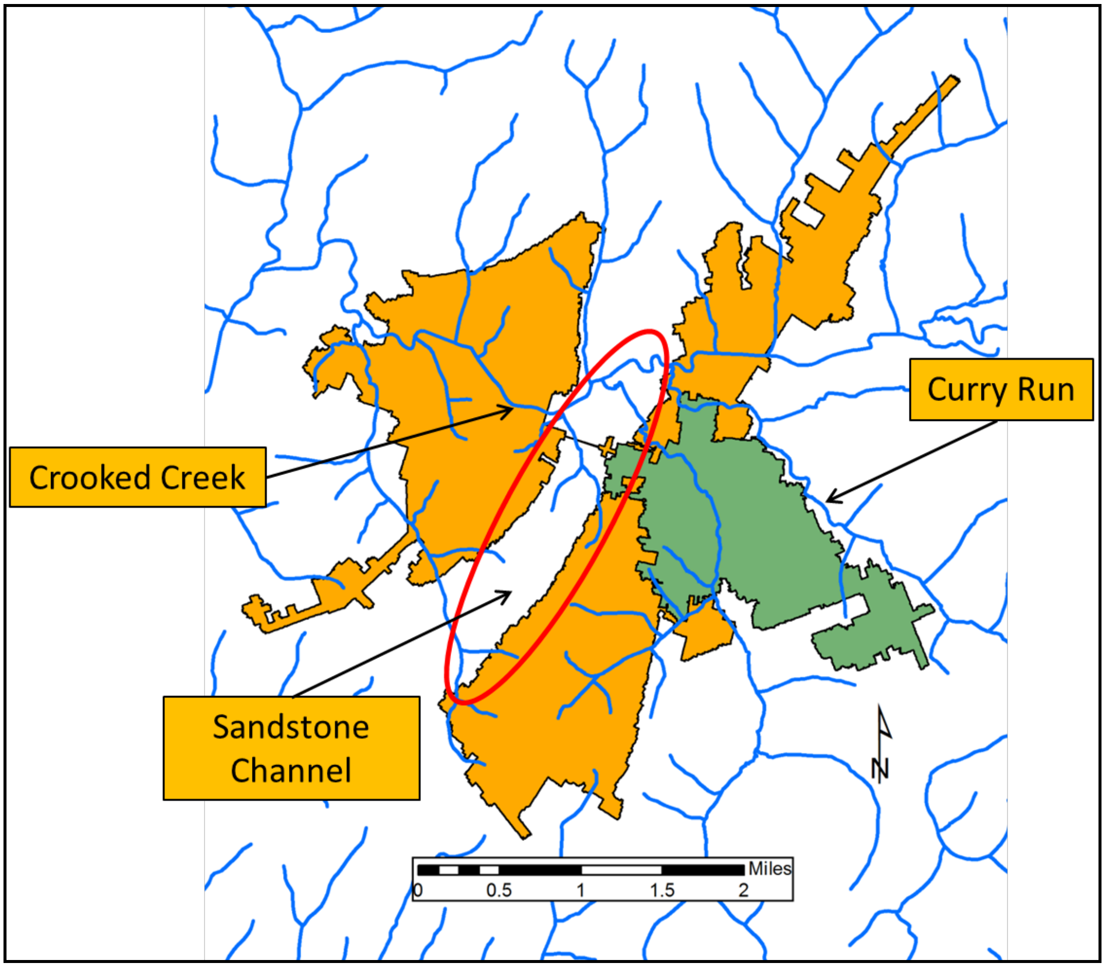


Figure 4.14: The primary streams taken into consideration throughout production were Crooked Creek and Curry Run as well as a sandstone channel that runs between No. 1 and No. 3.

4.4.3 Hydrology

Mine pool data was obtained from the PA DEP for Urling No. 1 and No. 3 but due to the development of No. 2 within No. 1, all three mines were hydraulically connected. The mine pool reached elevations (998.1 feet) above the highest coal elevation (981.1 feet) within the overlying Urling No. 2 mine according to the Urling Hydrologic Monitoring Report of Urling No. 1 (Urling Application, Module 8). Joe Matyus (2013) of the PA DEP, however, reported the mine pool reaching 1008 feet, just four feet below the lowest surface elevation of 1012 within the Anthony Run stream valley. Discharges were reported at the surface as a result of hydraulic head due to the mine pool. As a result, the state pumped the pool down and the discharge disappeared. Figure 4.15 represents the mine pool, recorded from Urling No. 1 and No. 3 and represents the overall mine pool of the Urling mines.

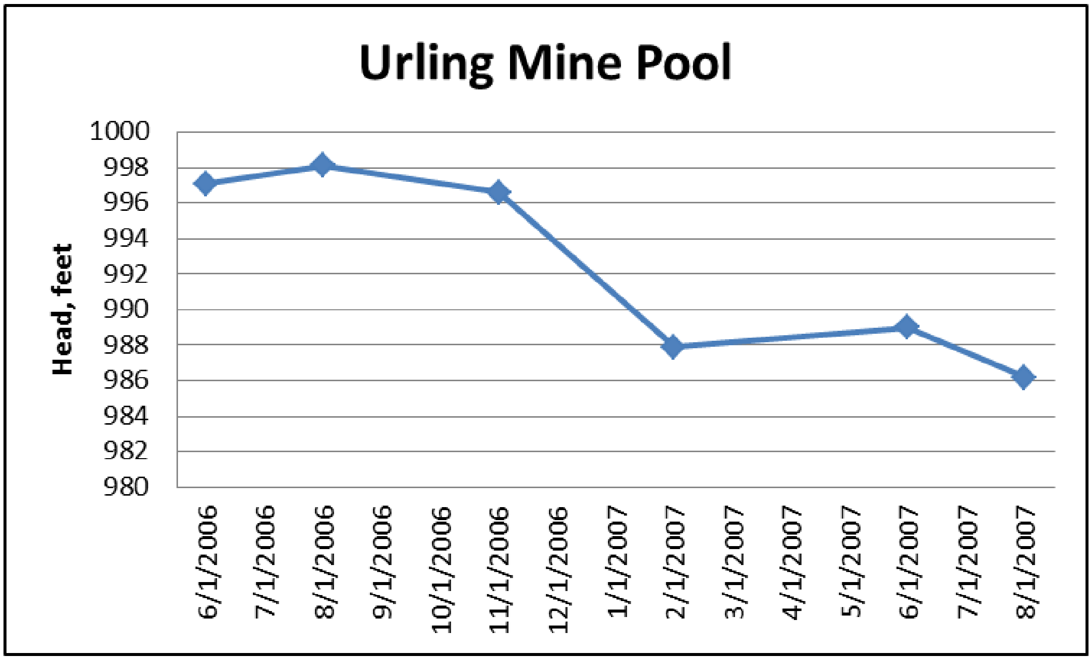


Figure 4.15: Urling mine pool over time.

4.4.4 Analysis

A surface discharge is thought to be the result of intensified fracturing and hydraulic head acting on the barrier at this site. The overlying Anthony Run has an orientation similar to that of Curry Run which was confirmed to have increased fracturing. Multiple seam mining also likely caused additional fracturing within the interburden between the mines and overburden above Urling No.

2. Mine pool levels reached 17 feet above the highest coal elevation and at one point even reached 27 feet higher according to Joe Matyus (2013).

Although core logs were not available, evidence of fractured rock was present at the site near the Curry Run stream valley. Inflows on this site likely occurred through intensified fracture networks due to horizontal stress and stress relief fracturing in the valley. In Figure 4.16, it is possible to see the orientation of the streams relative to the principal horizontal stress axis for the region. Crooked Creek is separated from the surface by more overburden and runs at a favorable angle to the axis while Curry Run is perpendicular to the axis and Urling 2 is closer to the surface. Curry Run also has a much more straight orientation which would be consistent with long term fracturing of the valley. This also explains the high fracture intensity in the stream valley as mentioned earlier according to Peng (2008) and Zoback and Zoback (1989).

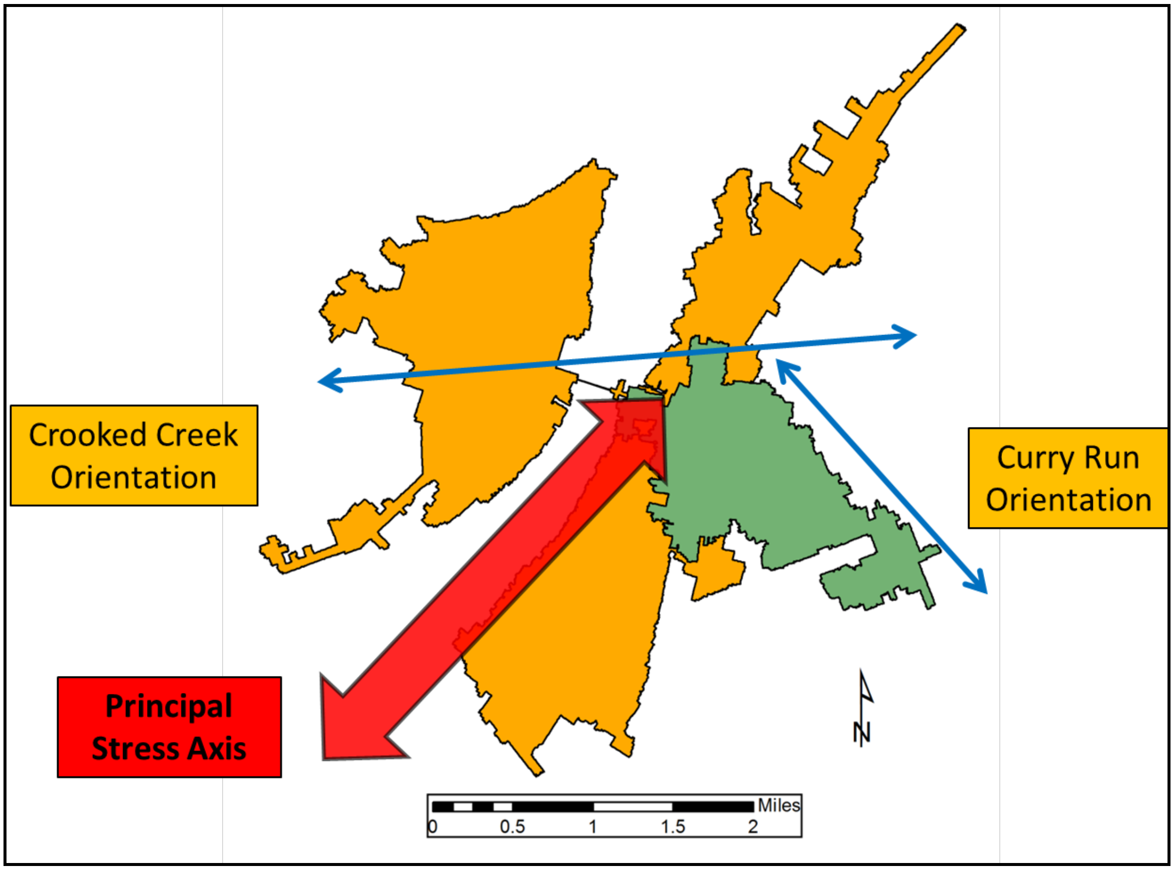


Figure 4.16: Stream orientation relative to the principal stress axis for the region. Curry Run is oriented perpendicular to the stress field which results in high stress concentrations and poor mining conditions.

4.5 BARBARA NO. 1 AND 2

The Barbara No. 1 (MSHA ID 3607045) and No. 2 (MSHA ID 3608508) coal mines are room-and-pillar mining operations in eastern Somerset County, Pennsylvania. Barbara No. 1 was developed first in the Upper Kittanning followed by No. 2 in the Lower Kittanning coal seam. Fracture flow often dictates water movement through the subsurface. In the case of the Barbara mines, flow was driven through a human-induced "fracture." The strata barrier was compromised due to insufficient grouting techniques. Upon the closing of Barbara No. 2 around 2001, discharges were reported near several core holes that were drilled just south of SR 31 (Figure 4.17). Net positive heads within both mines acting on surrounding strata caused mine pool water to pass through the drilled cores and discharge in Somerset County.

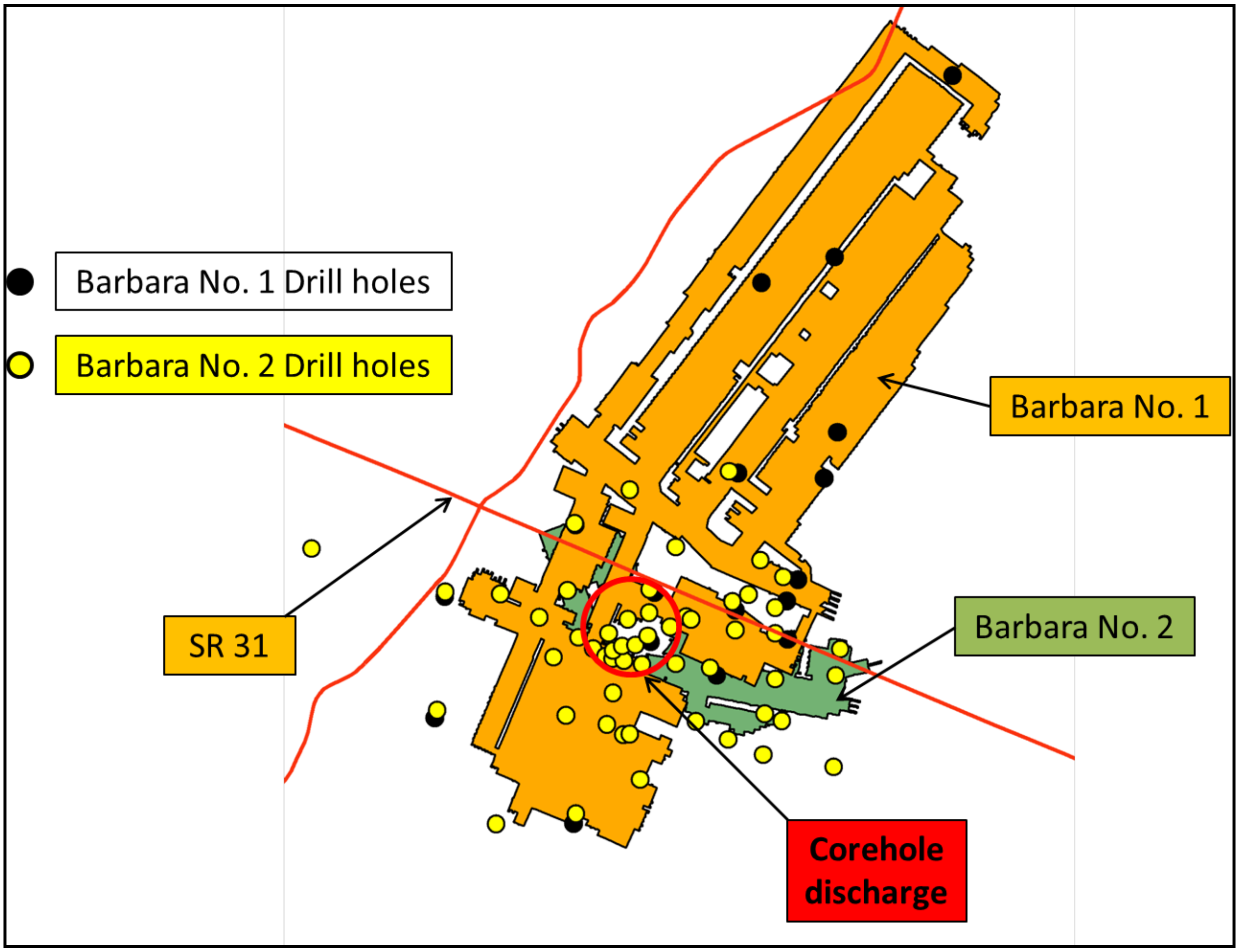


Figure 4.17: Barbara No. 1 and 2 mining operations and drill holes are represented as well as the discharge location.

4.5.1 Mining Methods

The Barbara No. 1 and No. 2 mines operated using room-and-pillar development and thin pillar mining methods. Pillar recovery was utilized in the overlying Barbara No. 1 mine but the extent of No. 2 did not reach the overlying full extraction methods. A vertical strata barrier was established with respect to the surface discharge that occurred at this site. Throughout the pre-mining and exploration process, a number of cores were drilled within the permitted region. Insufficient sealing techniques would eventually connect the two mines hydraulically which led to the discharge. The extraction ratio of the overlying Barbara No. 1 mine ranged from 0.53 to 0.57 at the barrier.

The overlying Barbara No. 2 developed down-dip with the portal elevation at approximately 90 feet below the surface. The highest overburden would reach 475 feet and all but small portions in the mains by the portals and to the east of the mine would be shallower than 200 feet of overburden. The shallowest pass of an overlying stream was Reitz Creek, where the overburden is approximately 173 feet but mining did not appear to be impacted and no discharges were reported at that location despite having extraction ratios between 0.60 and 0.70.

4.5.2 Geology

The geology of the region contains a variety of components. Several core logs were analyzed to determine the stratigraphic composition within the permitted region. The sandstone component within the region within the interburden between the two mines was evaluated since fracturing of the “hard” and rigid sandstone would provide a prevalent fracture network for fluid to move between the overlying Barbara No.1 and Barbara No. 2 below. The interval between the two mines ranges from ~70 feet to 100 feet. A weighted average was taken of the cores that intercepted both mines to determine the average percent sandstone between the Upper and Lower Kittanning coal seams within the permitted region. On average, 8.1% of the interburden within the cores were sandstone with ranges of 6 feet to 23 feet of sandstone present.

4.5.3 Hydrology

Piezometer data and mine pool measurements were limited at this site; however, mine pool data was obtained from the state for Barbara No. 1. The mine pool elevation reaches 2328 feet which is approximately 70 feet greater than the highest coal elevation within the mine. This hydraulic head is 34 feet higher than the elevation at the surface near the core logs identified by Joe Matyus (2013); the discharge was reported to have occurred within the proximity of these cores (Figure 4.18). The 34 feet of head acting on the barrier with induced “fracturing” created by the channel of the core was sufficient to produce a surface discharge near the lowest elevation at the surface.

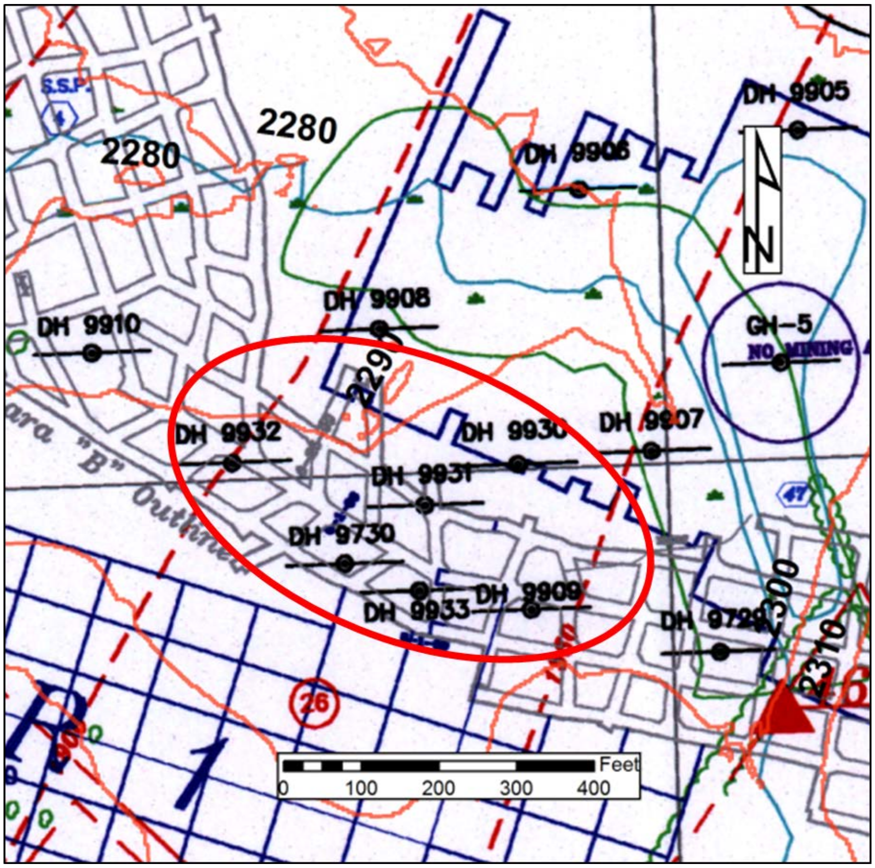


Figure 4.18: Approximate location of Barbara discharge and associated cores.

4.5.4 Analysis

Barbara No. 1 and 2 demonstrate the necessity to obtain fracture knowledge within a particular region. The core provided a conduit from the mining operations to the surface which enabled the water to pass through this human made fracture and a discharge was observed at the surface. The effects of insufficient mining procedures such as grouting techniques are also observed at this location. As a result, the strata barrier was compromised despite a majority of the mine containing overburden between 200 and 400 feet of overburden.

Multiple seam mining and pillar recovery methods were used at this site. Throughout previous studies, these techniques have been confirmed to produce increased fracturing and deformation to the overburden and interburden. It is likely that the strata within the stratigraphic column contained within the mined region is highly fractured which could also contribute to subsurface groundwater flow.

4.6 LITTLE TOBY

The Little Toby coal mine (MSHA ID 3608847) is located in in Elk County, Pennsylvania (Figure 4.19). The operation was developed in the Lower Kittanning coal seam from 2003 to 2011 by Rosebud Mining Company. One below drainage barrier exists adjacent to mining operations, an engineered barrier of coal and the surrounding strata, where the coal seam passes under the Mead Run to the west of the mine. No discharges have occurred to date despite mine pool levels exceeding the elevation of the hydraulic seals within the mine.

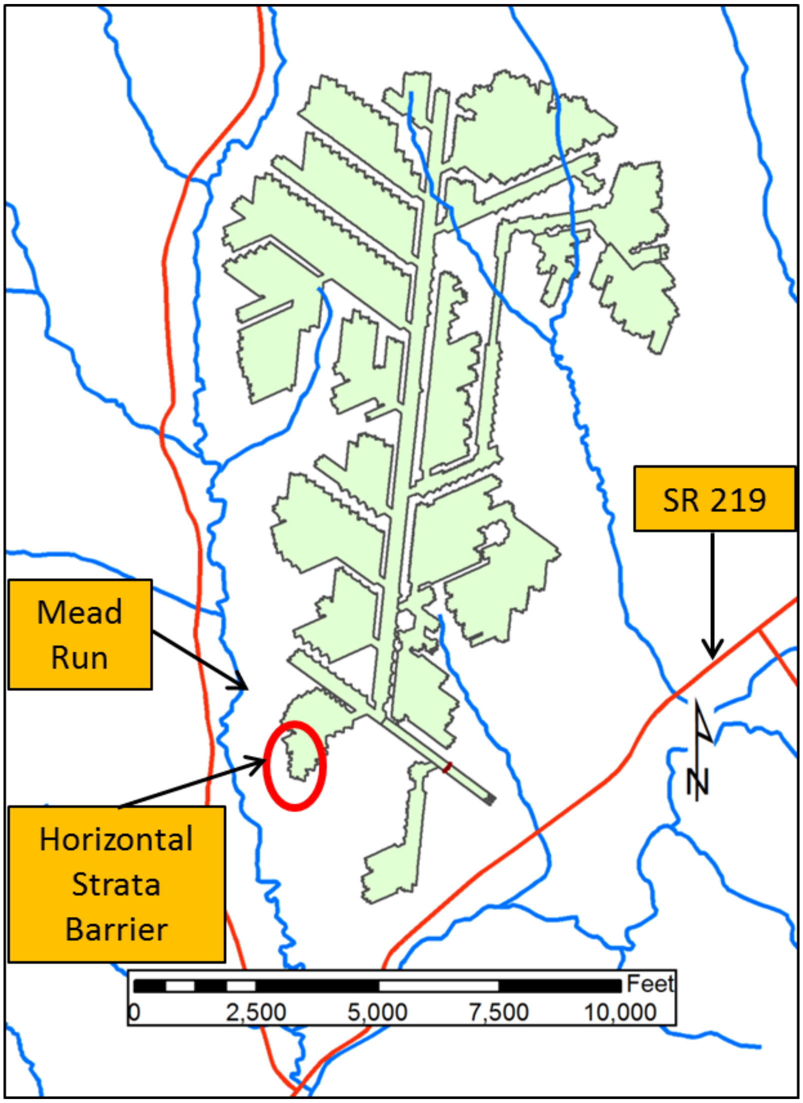


Figure 4.19: Little Toby mining operations and horizontal barrier adjacent to Mead Run.

4.6.1 Mining Methods

Little Toby was developed using room-and-pillar mining techniques. The three portal entries were created within a box-cut to access the mine. The coal extraction reached greater than 70% in some parts of the mine as thin pillar methods were utilized. The below drainage strata barrier is located adjacent to thin pillar techniques that registered an extraction ratio as high as 0.72.

The barrier was chosen based on net hydraulic head acting on the coal surrounding the mine to the west and the neighboring Mead Run which runs parallel to Little Toby on the west. Hydraulic seals were placed within the main entries near the end of mining operations to prevent the mine pool from reaching the box-cut.

4.6.2 Geology

The geology of Elk County is dominated by several “soft” rock components, particularly shales. The overburden above the mine ranges from 65 feet at the portals to 356 feet in the northern most region of the mine. The overlying strata above the mining operations have prevented a discharge to the surface to date.

Throughout the pre-mining stages, core logs were drilled within the permitted region. RQD analysis was performed in several samples to determine the competency of the strata. Two cores were examined and the region contained “poor quality” strata within the stream valley, particularly near the surface; however, much of the overburden was also very competent containing “good to excellent” quality. One core log taken upstream within the Mead Run stream valley contained fractured rock near the surface but more competent strata from the Lower Kittanning coal seam to approximately 50 feet below the surface (Figure 4.20). The overall core weighted average was determined to be 78% which is within the “good” overall range.

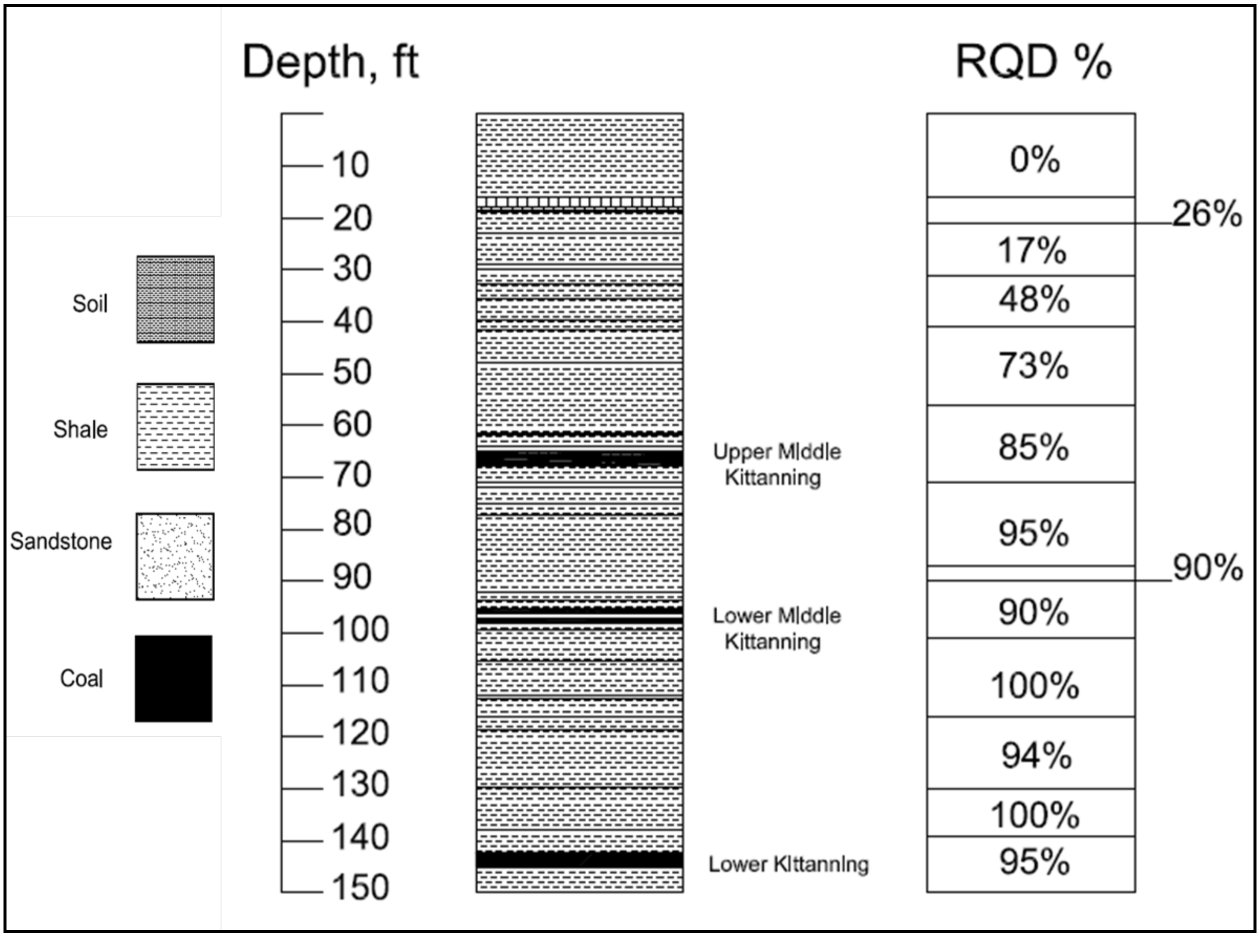


Figure 4.20: Little Toby core log Brock 96-8, located upstream within the Mead Run Stream valley with a weighted average RQD of 78%.

4.6.3 Hydrology

Streams cover the surface within the permitted region but Oyster Run and its tributaries are minimally undermined in the northern section of the mine and no vertical discharges have occurred through the strata. According several state representatives including Jay Hawkins (2013), Mead Run to the west continues to be carefully monitored for changes to water quality and quantity because of its exceptional pre-mining condition.

Groundwater throughout the region was monitored through several nests of piezometers. The common trend revealed that the intermediate and deep piezometers were all affected due to mining but have nearly recovered to pre-mining levels. Shallow groundwater appears to be relatively unaffected due to the mining operations. This trend is demonstrated by Piezometer A, located in the Mead Run stream valley upstream from the horizontal barrier.

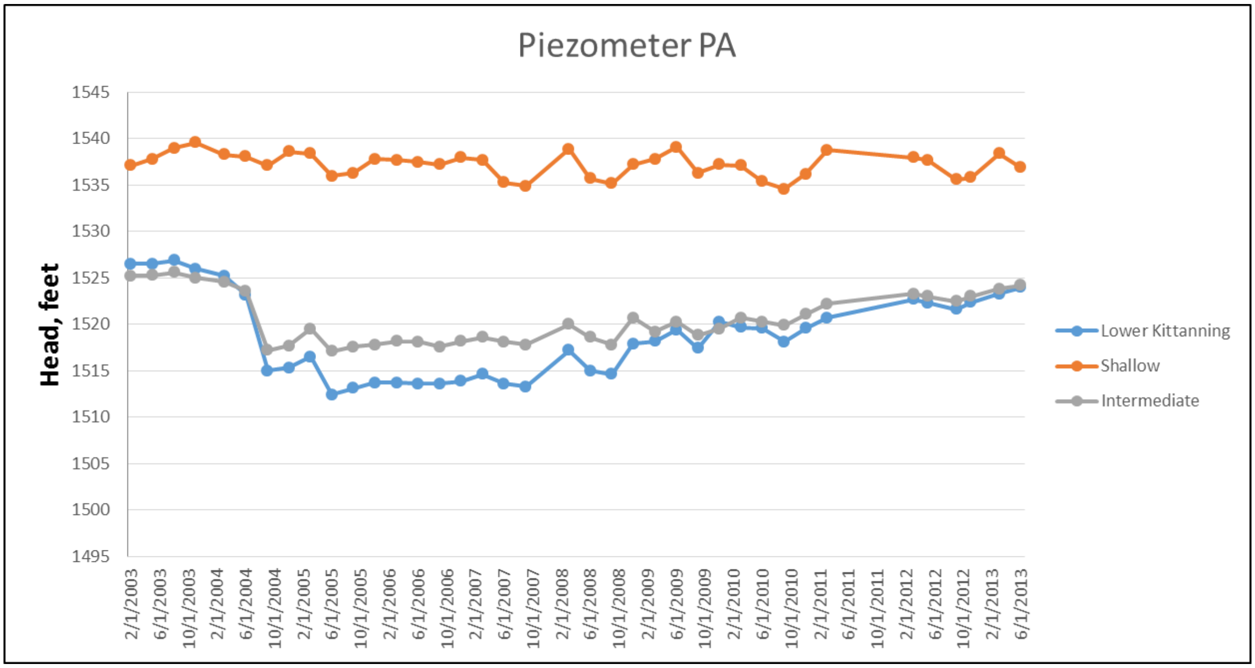


Figure 4.21: Little Toby Piezometer A (PA) monitoring shallow, intermediate, and deep aquifers.

The mine pool was monitored post-mining through two observation wells within the mine, MW-1 and MW-2. The mine pool is currently at 1529 feet which exceeds the elevation of the hydraulic seals which were installed in the main entries at an elevation of 1520 feet.

4.6.4 Analysis

The Little Toby mine is an example of a successful horizontal barrier with net hydraulic head acting on it. The coal and surrounding strata have contained the mine pool despite the head and shallow depth of cover within the stream valley. RQD measurements taken within the permitted region give insight to the competency of the strata surrounding the mining operations. Although there are some low RQD, the samples taken within the stream valley have a competent structure overall; however, due to the low RQD associated near the surface, particularly when the overburden is less than 50 feet, the strata below Mead Run is expected to be highly fractured as well. As a result, the coal appears to be successfully containing the mine pool since no discharges have occurred through the strata below Mead Run.

5.0 DISCUSSION

Several strata barrier case study mines were examined throughout this study. The potential to discharge was analyzed based on barrier characteristics, mining methods, and hydrologic properties. Although each case had site specific conditions, several common trends were determined and factors surrounding successful and unsuccessful barriers delineated.

Overburden characteristics affect the success rate of barrier containment of mine pool water. In three of the four successful barriers, Genesis 17, Keystone East and Little Toby, shallow overburdens were observed, 192 feet, 90 feet, and <50 feet respectively. These characteristics are generally of concern to the state based on the potential of water to move vertically across these "short" distances (<250 feet). In both of the vertical cases, the strata have been able to resist the flow of water to the surface. In the horizontal case at Little Toby, the barrier of coal beneath the stream valley has prevented flow from the mine pool to move through the fractured stream valley to the surface. This can most likely be attributed to the quality of the strata within these two sites, where fracturing was minimized by utilizing solely room-and-pillar mining methods. The vertical barrier below South Fork Bens Creek represented the final successful barrier. The shallowest depth of cover in the valley was 400 feet which was sufficient to contain the head which reached 146 feet above the lowest elevation on the surface.

The overburden was evaluated using RQD where it was available. Several RQD core logs were available on three of the four successful barrier locations. These samples were taken in valleys, generally areas of known increased fracturing; however, RQD values averaged approximately 94% for Genesis 17, 97% for Keystone East, and 78% for Little Toby. RQD considers primarily horizontal fractures and faults based on the interception of horizontal discontinuities by vertical drilling. Despite the limitation and inability to capture a majority of the vertical fracturing, this technique is still used by the state to examine rock competency. Bieniawski (1989) states that this technique is useful because it is simple and inexpensive, even though it does not consider joint orientation and tightness. According to Deere and Deere (1988), this method provides “a measurement of the percentage of ‘good’ rock interval of a borehole.” As a result, it is apparent that the state relates the horizontal fracturing of a region to the vertical fracturing and that high RQD values are associated with minimal fracturing in both the horizontal and vertical directions because of the “good” rock contained within the core. Conversely, on the Grove 1 site, there was evidence of highly fractured strata due to natural and mining induced conditions near the horizontal strata barrier. The presence of faults, which were magnified by full extraction mining, led to seismicity. The seismic events represent an amplification of the fracture intensity at this site.

Hydrogeological properties influenced discharge potential. In all seven barriers examined in this study hydraulic head is acting on surrounding barriers and in five of the six mines, mine pool elevations reached higher than the highest coal or hydraulic seal elevation (Figure 5.1). Genesis 17 has exceeded pre-mining piezometer heads but the mine pool has been contained by the overlying strata. Keystone East has a mine pool that is near the height of the lowest elevation and pre-mining piezometer data indicates that the mine pool has the potential to rise; however, no discharges have been reported as the strata has successfully contained the mine pool. Little Toby has also been successful at preventing discharges despite mine pool levels exceeding the hydraulic seal elevations within the mine. Grove 1 contained a mine pool which provided head on surrounding fractured strata at the horizontal barrier location near full extraction mining. The mine pool was able to move along this highly fractured rock and discharged into the nearby South Fork Bens Creek. The vertical strata barrier under South Fork Bens Creek was able to prevent a discharge to the surface at that location due to the thickness of the barrier, 400 feet at the most shallow depth. The Urling and Barbara mine pools have exceeded the highest coal elevations within the overlying mines at each location. They both discharged as a result of hydraulic head from the mine pool acting on fractures.

The effects of the natural and mining induced environments were observed through the case studies. Geologic discontinuities were demonstrated by faults and movement along joints at the Grove 1 mine and discharges were observed. The sandstone channel within the Urling property limited the mining between Urling No. 1 and No. 3. Increased fracture networks within stream valleys caused by horizontal stress and valley stress relief were demonstrated at Urling No. 2 where mining was hindered greatly due to great influxes of water reaching 350 gpm. Lastly, fracture flow was observed in the Grove 1 mine as a result of seismicity linked with high extraction mining and through insufficient grouting of core holes drilled at the Barbara mine site.

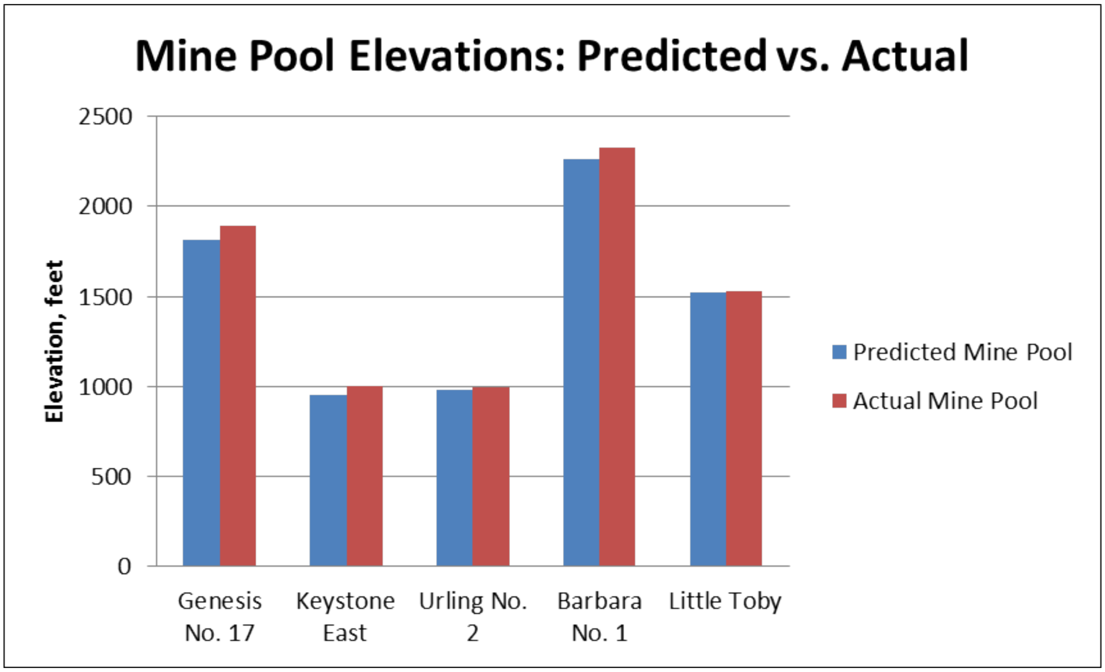
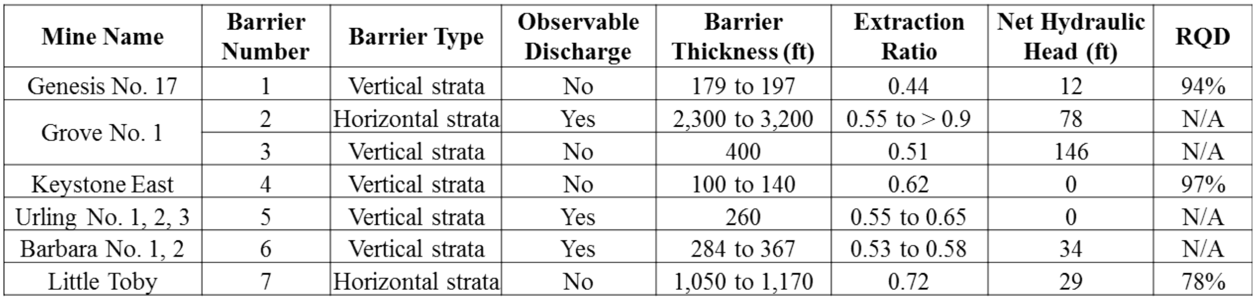


Figure 5.1: Case study predicted and actual mine pool elevations.

6.0 SUMMARY

This study examined a variety of abandoned mines in western Pennsylvania. Several below drainage barriers were examined to identify characteristics associated with each operation and the factors that affect discharges to the surface. Of the seven below drainage barriers examined, four have been successful at preventing a post-mining discharge (vertical strata barriers at Genesis No. 17, Grove No. 1, and Keystone East, and horizontal barrier at Little Toby). Two vertical barriers (Urling and Barbara) and one horizontal barrier (Grove No. 1) experienced a discharge through the barrier. The characteristics associated with each barrier are displayed in Table 6.1.

Table 6.1: Barrier characteristics summary table.



Mine Name	Barrier Number	Barrier Type	Observable Discharge	Barrier Thickness (ft)	Extraction Ratio	Net Hydraulic Head (ft)	RQD
Genesis No. 17	1	Vertical strata	No	179 to 197	0.44	12	94%
Grove No. 1	2	Horizontal strata	Yes	2,300 to 3,200	0.55 to > 0.9	78	N/A
	3	Vertical strata	No	400	0.51	146	N/A
Keystone East	4	Vertical strata	No	100 to 140	0.62	0	97%
Urling No. 1, 2, 3	5	Vertical strata	Yes	260	0.55 to 0.65	0	N/A
Barbara No. 1, 2	6	Vertical strata	Yes	284 to 367	0.53 to 0.58	34	N/A
Little Toby	7	Horizontal strata	No	1,050 to 1,170	0.72	29	78%

The geology contained within the successful vertical strata barriers proved to be sufficient in quality and thickness (100-400 feet). The horizontal barrier at Little Toby has also been successful at containing the mine pool. The Grove 1 mine horizontal strata barrier, however, discharged as mine pool water passed along seismic induced fractures and bedding planes due to pillar recovery techniques. Two vertical strata barriers were also insufficient at preventing a discharge to the surface. The human-induced fracture at the Barbara mine site caused the compromise of the strata which led to its eventual discharge after the mine pools developed in both mines. Multiple seam mining at Urling led to a vertical discharge through strata to the lowest surface elevation as well. Several characteristics were determined to be of influence when examining the potential to discharge:

- Mining methods – At the four successful barrier locations (vertical barriers at Genesis No. 17, Grove No. 1, and Keystone East, and horizontal barrier at Little Toby), room-and-pillar methods were utilized while in the failed horizontal strata barrier (Grove No. 1), high extraction methods were employed. At the Barbara and Urling mines, multiple seam mining took place and discharges occurred at both locations.
- Overburden properties – Highly fractured overburden provided a more direct method of fluid flow and led to the discharges at Grove 1, Barbara and Urling; however, the strata with exceptional quality at Genesis 17, Keystone East, and Little Toby was able to contain the mine pool despite having a shallow thickness. Fracture presence greatly increases the hydraulic conductivity of a system and provides a method for discharge to the surface like in the cases of Urling and Barbara. The Grove 1 vertical barrier had an overburden that was at least 400 feet thick (not generally considered at risk by the state since >250 feet).
- Hydraulic head – Since discharge potential is related to the net hydraulic head acting on the barrier, mine pool predictions are crucial and dictate the amount of

head that the barrier will experience. Contrary to previous thoughts, the mine pool is not limited by the highest coal elevation within the mine or the seal elevation. In five of six cases, the mine pool exceeded the highest heights of the mine and in the case of Genesis 17, it exceeded pre-mining piezometer data as well. Although the cause of this rise is uncertain, it could be attributed to the box-cut by possibly providing a conduit for fluid flow. It is also possible that coal extraction changes the properties of the coal seam which causes piezometer elevations to adjust; i.e. the piezometers in the higher elevation coal seam will be lower, whereas the piezometers in lower coal will rise after mining.

7.0 CONCLUSIONS

This study examined the naturally occurring and mining induced factors of strata barriers between mine pools and the surface within abandoned room-and-pillar operations in western Pennsylvania. The characteristics of the strata composed in the overburden are critical when determining the possibility of a discharge to the surface. Several factors were identified as risk adverse conditions and provide increased threat to compromise the barrier and produce a discharge to the surface:

1. Overburden thickness – The thickness of the overburden must withstand the hydraulic head acting on it. As a result, the ideal overburden (barrier) thickness would be a depth which puts the lowest surface elevation higher than the maximum potential mine pool. At shallow overburdens of ~100 feet seen at Keystone East, some effects were seen to shallow groundwater aquifers whereas at ~200 feet of overburden at Genesis No. 17, the barrier functioned effectively and greater depth of cover such as the 400 feet at Grove No. 1 was also successful.
2. Net hydraulic head – Discharge potential is related to the net hydraulic head acting on the barrier; if the height of the mine pool is higher than the lowest surface elevation, there is net positive head acting on the barrier which means there is a potential for discharge. Net hydraulic head was applied to each of the barriers within this study.

3. Mine pool development – The mine pool is not limited by the height of the coal or hydraulic seals so pre-mining piezometer data are useful in determining the trends and post-mining pool elevation prediction. In five of the six case studies (all but Grove No. 1), mine pools exceeded the highest coal elevations within the mine or the hydraulic seals. Contrary to previous practices for pre-mining pool prediction, the highest elevation of the coal or elevation of the hydraulic seals does not always limit the height of the mine pool. This increase in head above the predicted values can possibly be attributed to two things: 1) the box-cut may provide a method of fluid flow from the surface which adds to the head potential created by the mine pool; or 2) the coal extraction prevents the hydraulic gradient from remaining uniform throughout the coalbed which causes a constant height throughout the extracted zone.
4. High extraction mining – High extraction such as pillar recovery mining causes caving events which generate increased fracturing and deformation to the overburden. Highly fractured overburden within or adjacent to a barrier will raise the hydraulic conductivity of the strata which may prevent it from containing mine pool water.
5. Multiple seam mining – Multiple seam mining interactions increase fracturing and deformation to the column of strata between the mines (interburden) and elevates the potential for fracturing within the strata contained in the overburden. The increased fracturing may lead to higher hydraulic conductivity and consequently, increase the potential for groundwater movement to the surface. The Urling mines reached mine pool levels above the highest coal elevation in the overlying No. 2 mine and the head acting on the barrier caused a discharge to the overlying stream valley. In Barbara, the grouting was insufficient which caused an unplanned connection of the No. 1 and No. 2 mines.

Both the Urling and Barbara mine sites discharged, likely as a result of multiple seam mining interactions.

6. Mining below stream valleys – Mining under stream valleys has been identified by the state as being a potential risk due to increased fracturing and has been observed through previous studies. Horizontal stress fracturing has the potential to increase hydraulic conductivity below streams. In this study, the effects of stream valley fracturing were found in one such case, Urling No. 2, where great inflows into the mine resulted from Curry Run and a surface discharge resulted into the stream valley of Anthony Run. Just as fracture flow allowed water to pass from the surface to the mine near Curry Run, mine pool water passed from the mine void to the surface near Anthony Run.
7. Fracture flow – Since flow is dominated through openings in the subsurface, fractures play an important role in barrier competency. RQD observed at multiple sites demonstrated competent or “good” rock quality and no discharges were found at Genesis No. 17, Keystone East, and Little Toby. Where fractures were prevalent, fracture flow was observed. The discharges at the horizontal barrier at Grove No. 1 were a result of increased fracturing due to mining operations. At the surface above the Barbara mines, insufficient grouting techniques resulted in a compromised vertical strata barrier. As a result, natural and mining induced fracturing result in increased risk to discharge potential.

8.0 RECOMMENDATIONS

To conclude this study, a set of risk factors has been established which mirrors those discoveries found in earlier research (Iannacchione et al. 2013a). Based on the case studies observed, several factors are highlighted that are associated with the prevention of post-mining discharges and future work will assist with minimizing them:

1. Mining methods – High extraction ratios have been directly linked to the cause of post-mining discharges due to excessive fracturing to the overburden and surrounding strata and higher associated hydraulic conductivity. These methods should be used with caution adjacent to barriers and near stream valleys.
2. Fracture intensity – In regions of highly fractured strata, water is more likely to pass through these regions. RQD analysis allows identification of highly fractured zones and horizontal faults. Angled drilling is a possible way to observe vertical fracturing.
3. Hydraulic conductivity – Knowledge of hydraulic conductivity is beneficial because flow rates are able to be approximated from them which can assist with discharge prediction. The wide range of hydraulic conductivity values published in literature are site specific. Investigations on the value of hydraulic conductivity for a particular region will help greatly with predicting the necessary barrier size

to prevent a discharge. The presence of fracturing results in dramatically higher hydraulic conductivity values and higher likelihood of discharge to the surface.

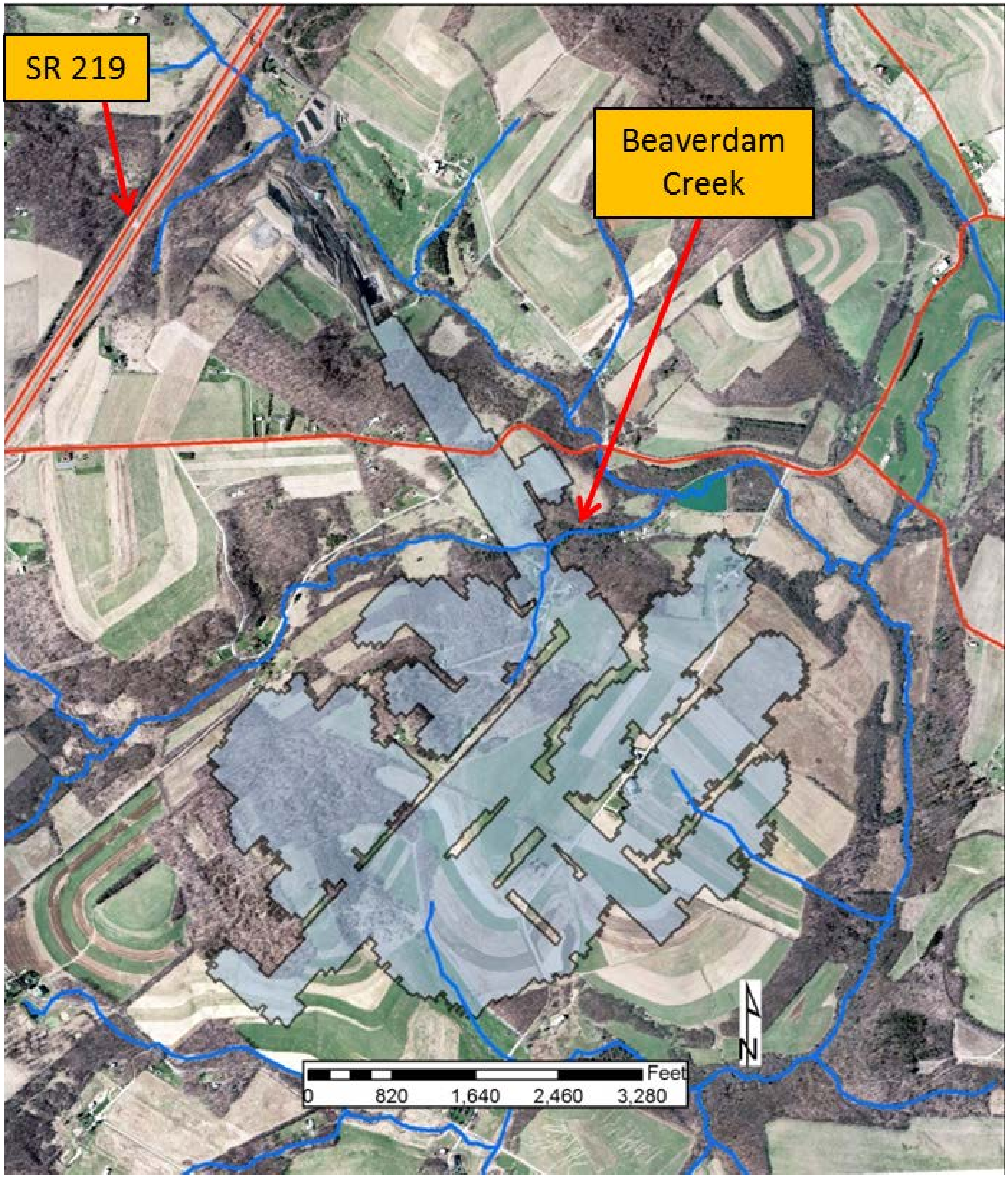
4. Overburden thickness – The overburden should be designed to contain the head of the mine pool; i.e. the thickness should be at least great enough so that the mine pool elevation is lower than the surface. Overburden that is shallower than 250 feet should be monitored to observe fluctuation of groundwater and discharge possibilities.
5. Box-cuts – Since box-cuts have the potential to allow fluid into the backfilled area, their effect on hydraulic head is still relatively unknown. It has the potential to rise due to increased fracturing within the backfilled material so additional analyses should be done to consider the design and dimensions of the box-cut and the possible effect it has on post-mining pool elevation.
6. Piezometer data – Pre- and post-mining piezometer data is crucial to determining the mine pool elevation and the effect of the hydraulic gradient due to mining. Since the coal extraction causes changes to post-mining piezometer data, studies to continually monitor them after mining would be beneficial to understand the effect of mining on groundwater movement and mine pool development. Often times the groundwater monitored by the piezometers is still rising even after the bond has been released so longer monitoring of these sites would be beneficial for future design knowledge.

APPENDIX A

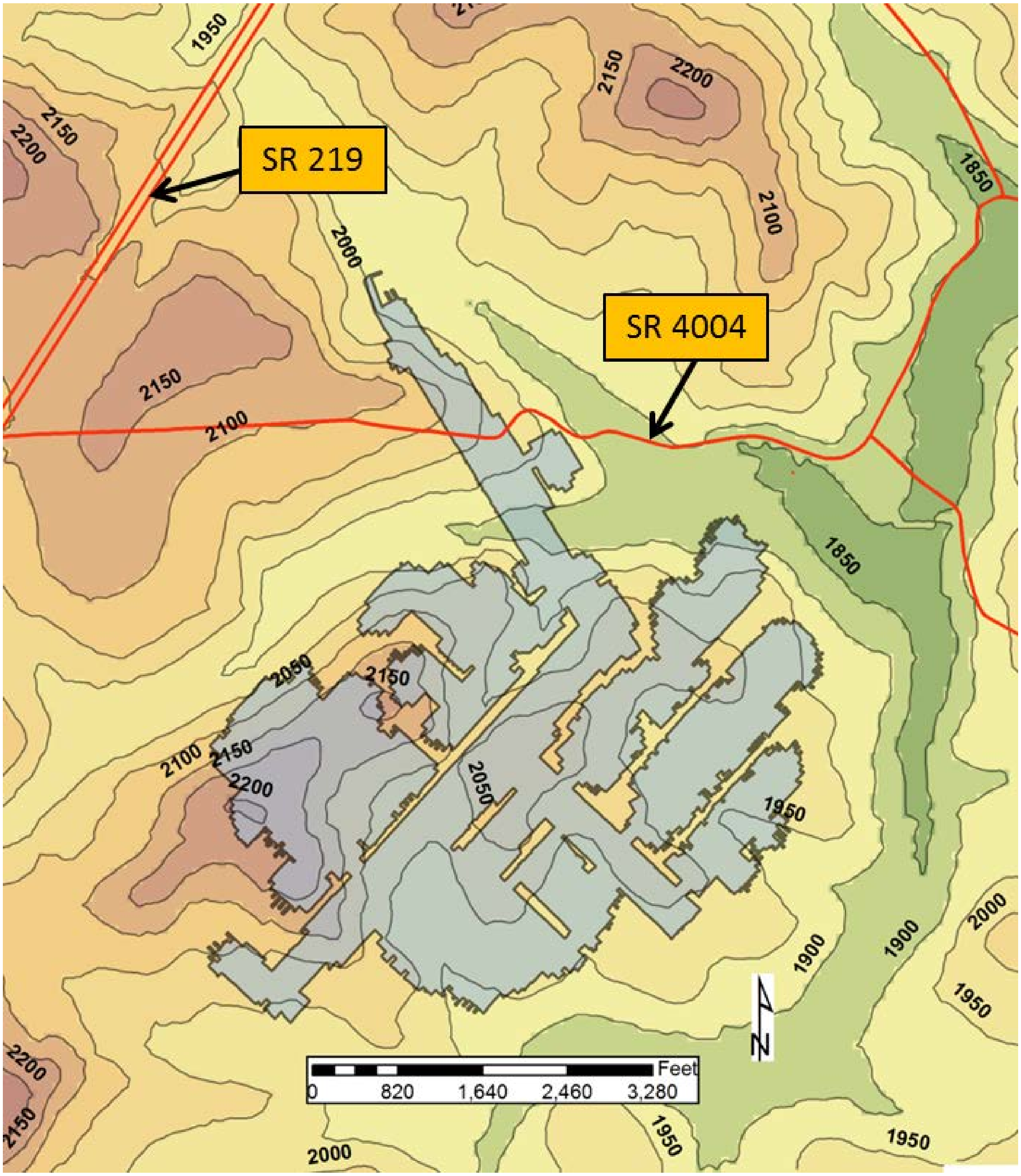
GENESIS NO.17

The contents of Appendix A are the supplemental data and maps generated for Genesis No.17. These figures were generated through the use of Geographic Information Software, ArcMap 10.1. The mine outlines, contour maps, and plotted points were created from 6-month mining maps composed by individual companies and obtained by the state and also topographic maps found through online resources (PASDA).

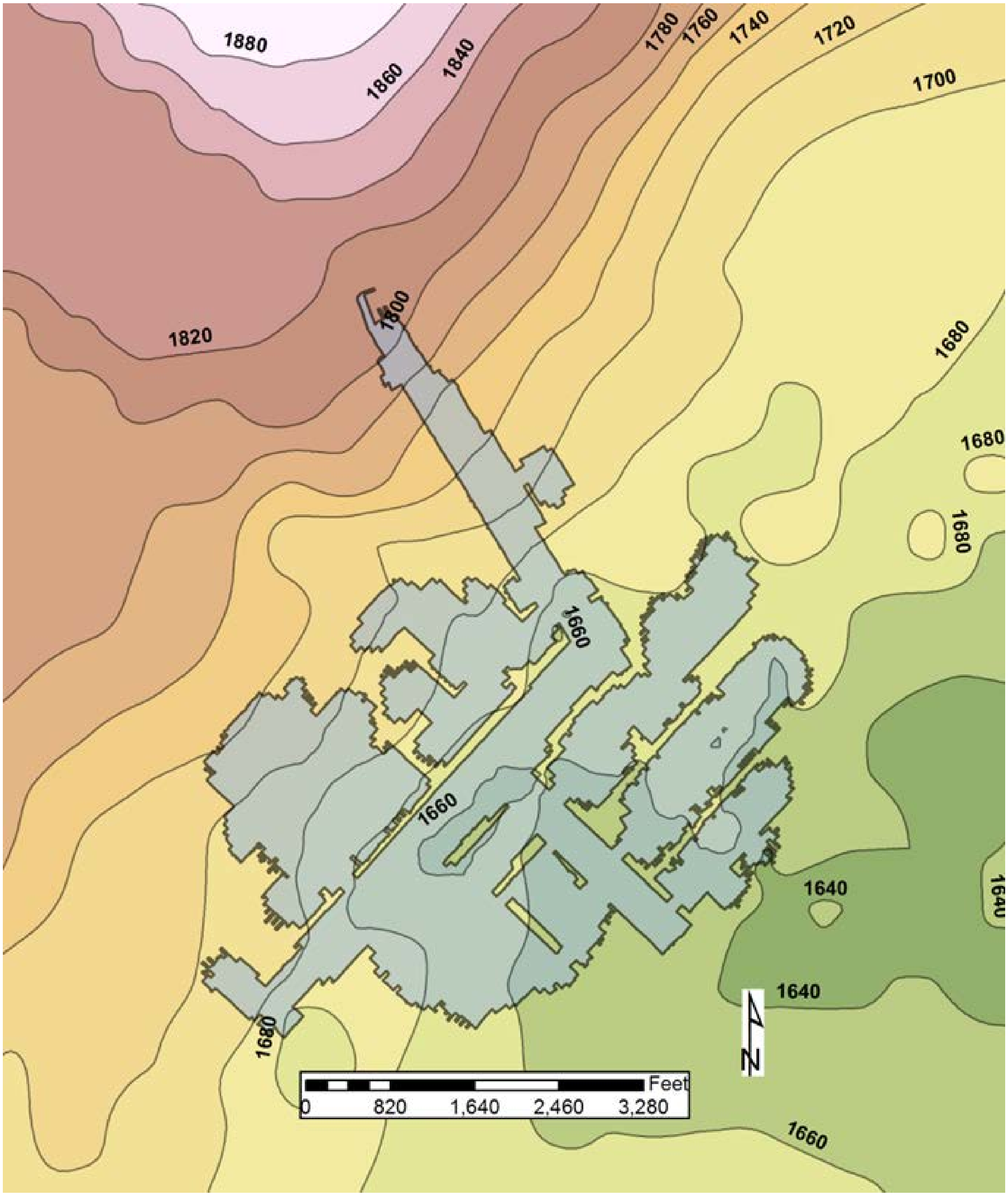
A.1 Genesis No. 17 Satellite Image Map with State Roads and Streams



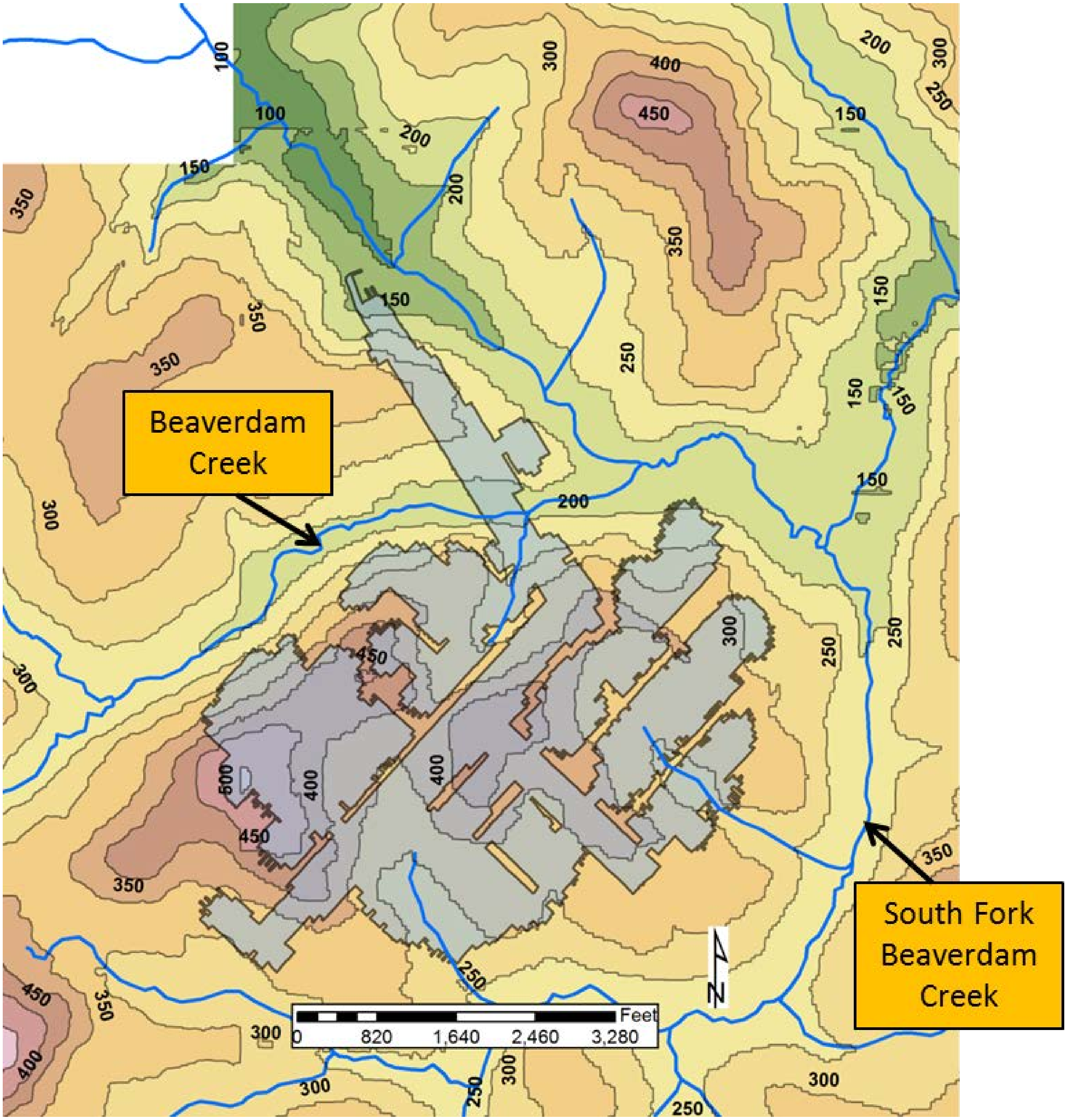
A.2 Genesis No. 17 Surface Contour Map with State Roads



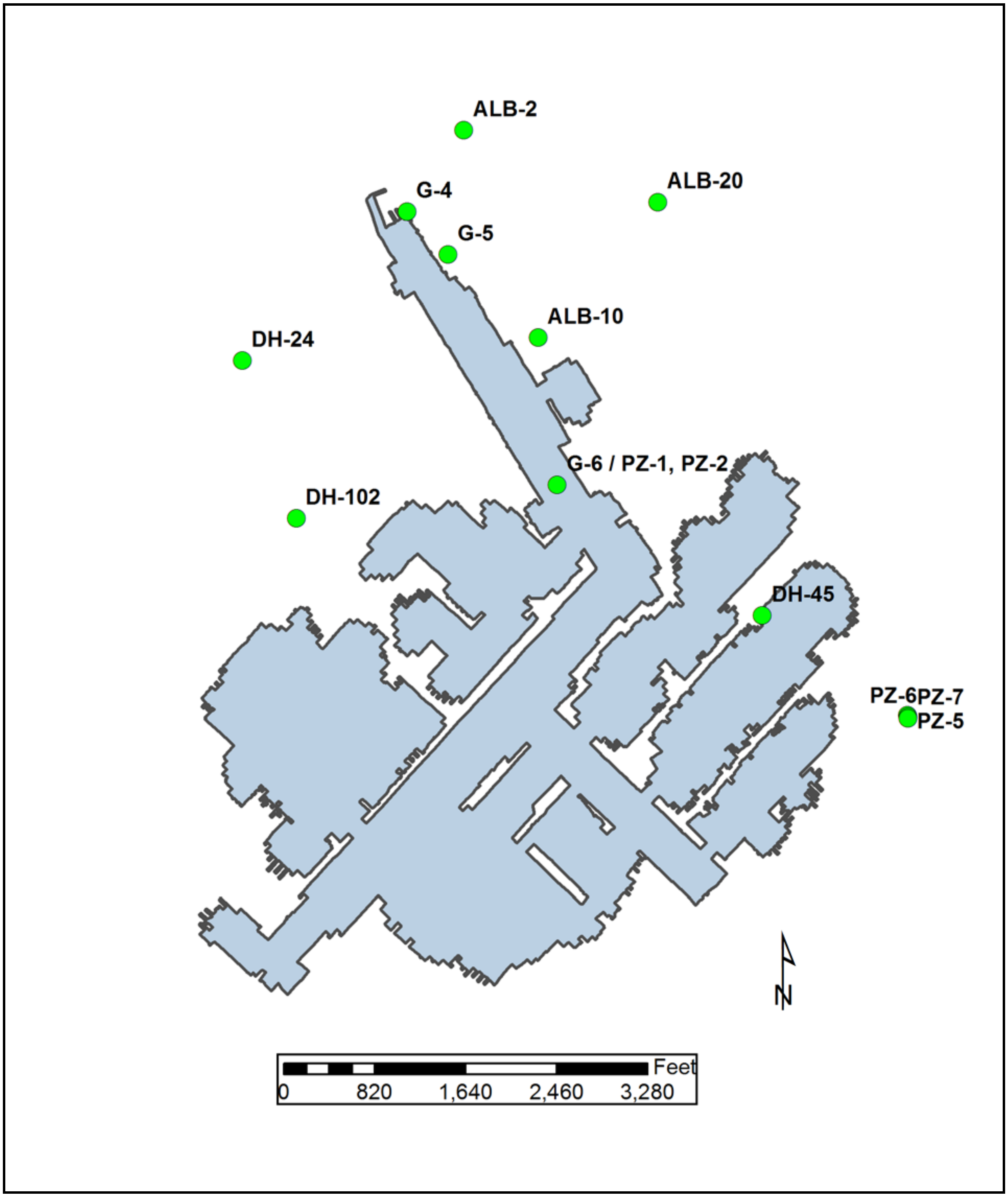
A.3 Genesis No. 17 Coal Structure Contour Map



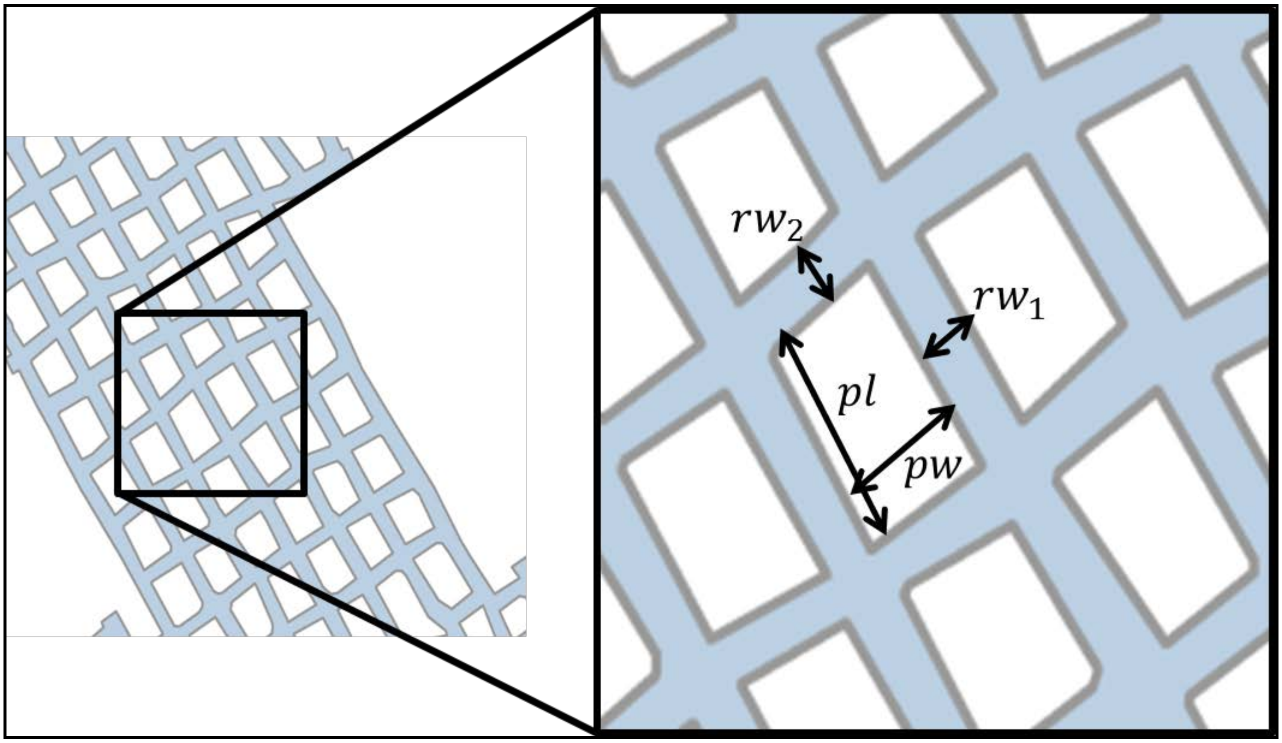
A.4 Genesis No. 17 Overburden Contour Map with Streams



A.5 Genesis No. 17 Core Logs (ALB-, G-, DH-) and Piezometer (PZ-) Locations



A.6 Genesis No. 17 Extraction Ratio Calculation within Barrier #1



$$Re = \frac{(pw + rw_1)(pl + rw_2) - (pl * pw)}{(pl + rw_2)(pw + rw_1)}$$

Where:

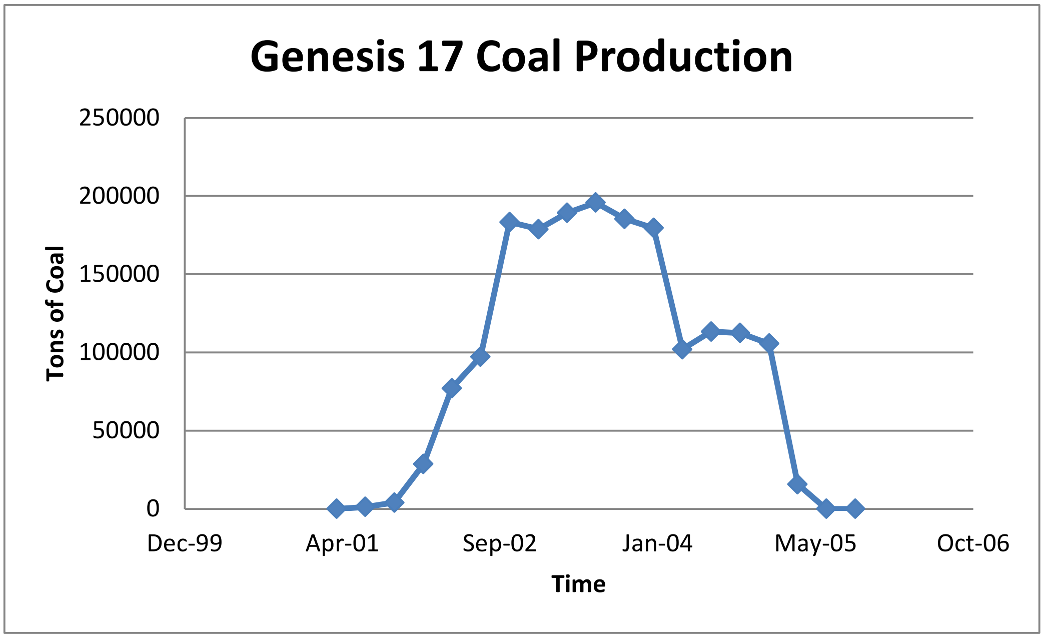
$pw = pillar\ width,$

$rw = row\ width,$

$pl = pillar\ length$

$$Re = \frac{(59.467\ ft)(73.244\ ft) - (61.947\ ft)(39.480\ ft)}{(73.244\ ft)(59.467\ ft)} = \frac{1909.9\ ft^2}{4355.6\ \ ft^2} = 0.43850 = 43.85\%$$

A.7 Genesis No. 17 Coal Production Timeline (MSHA, 2014)

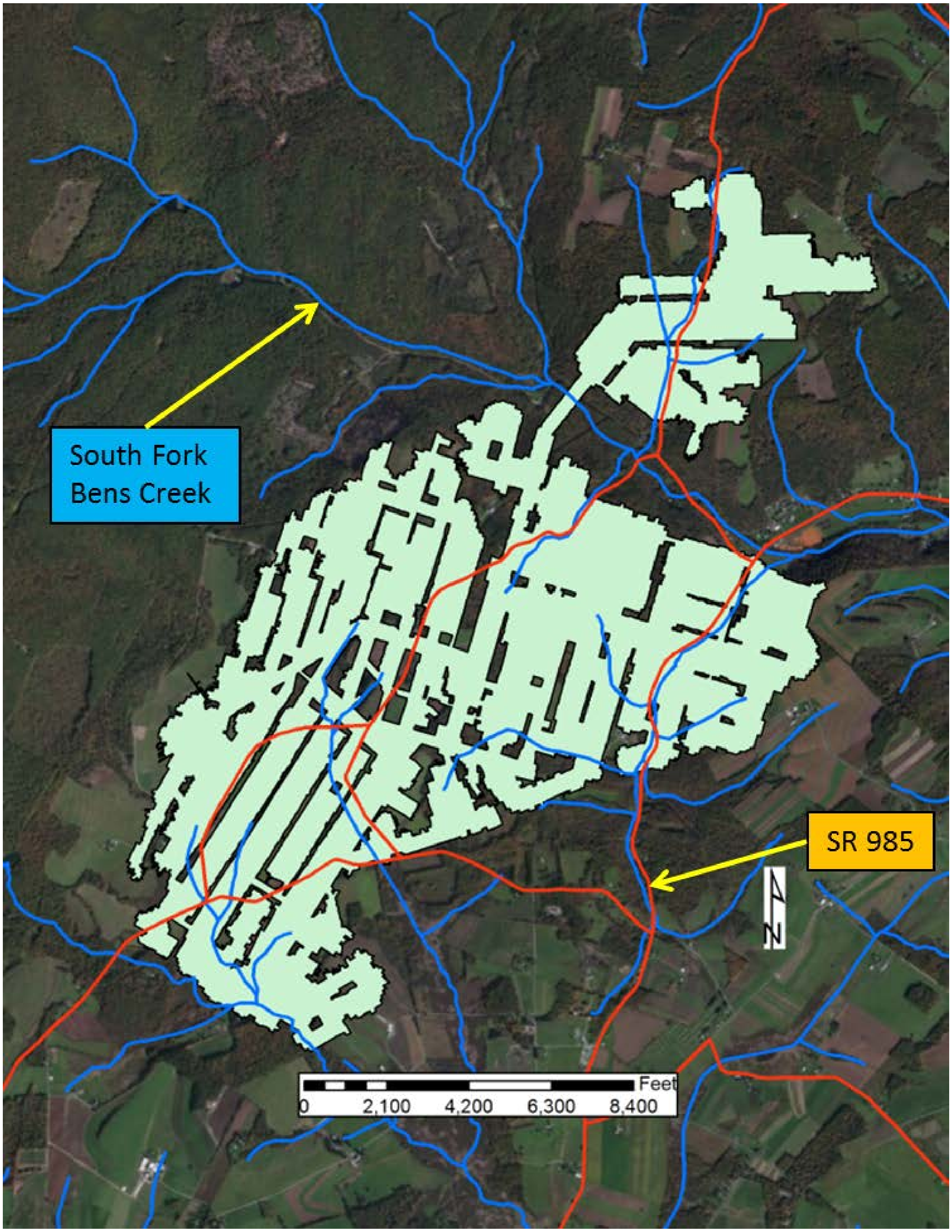


APPENDIX B

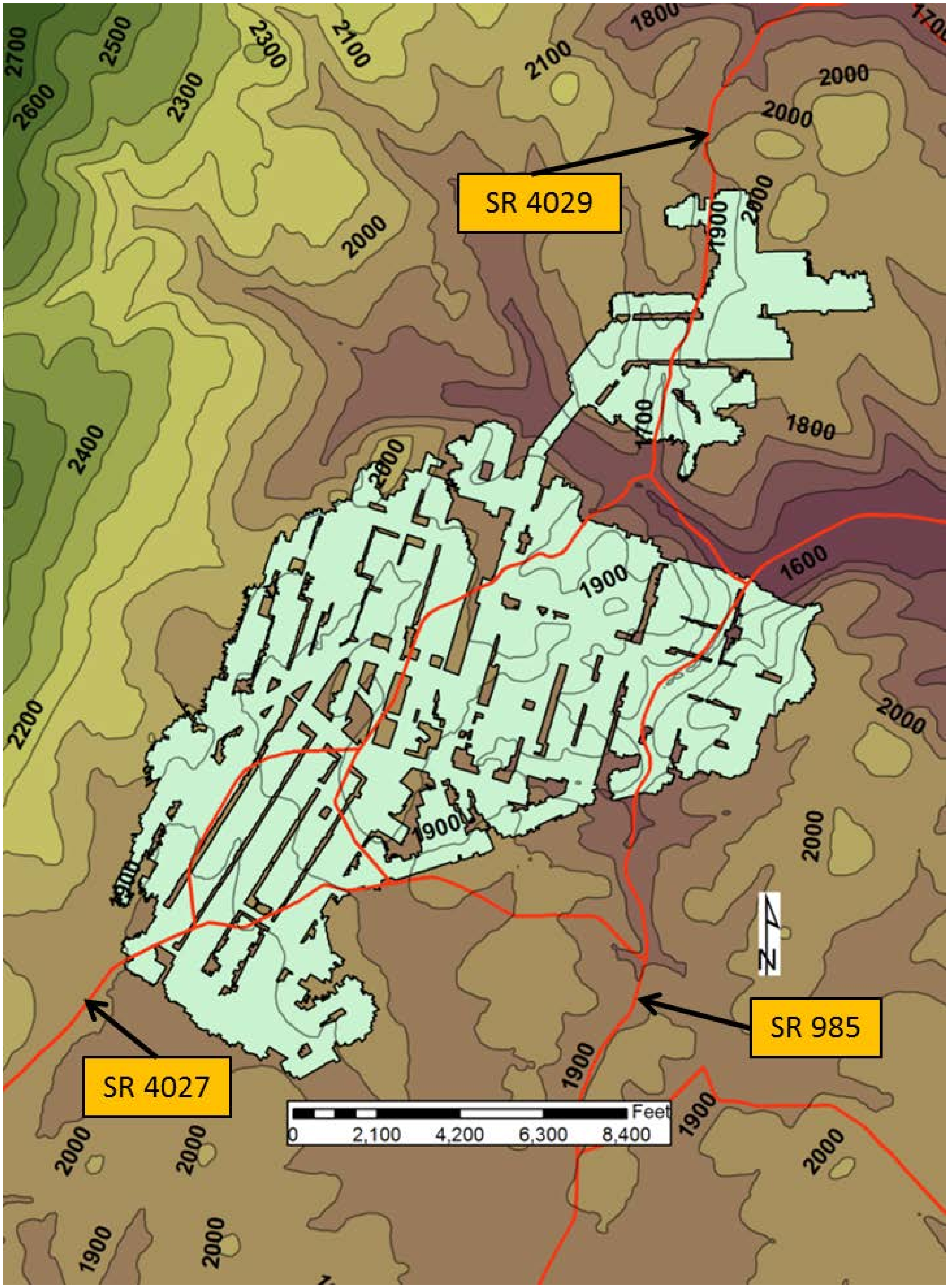
GROVE NO. 1

The contents of Appendix B are the supplemental data and maps generated for Grove No.1. These figures were generated through the use of Geographic Information Software, ArcMap 10.1. The mine outlines, contour maps, and plotted points were created from 6-month mining maps composed by individual companies and obtained by the state and also topographic maps found through online resources (PASDA).

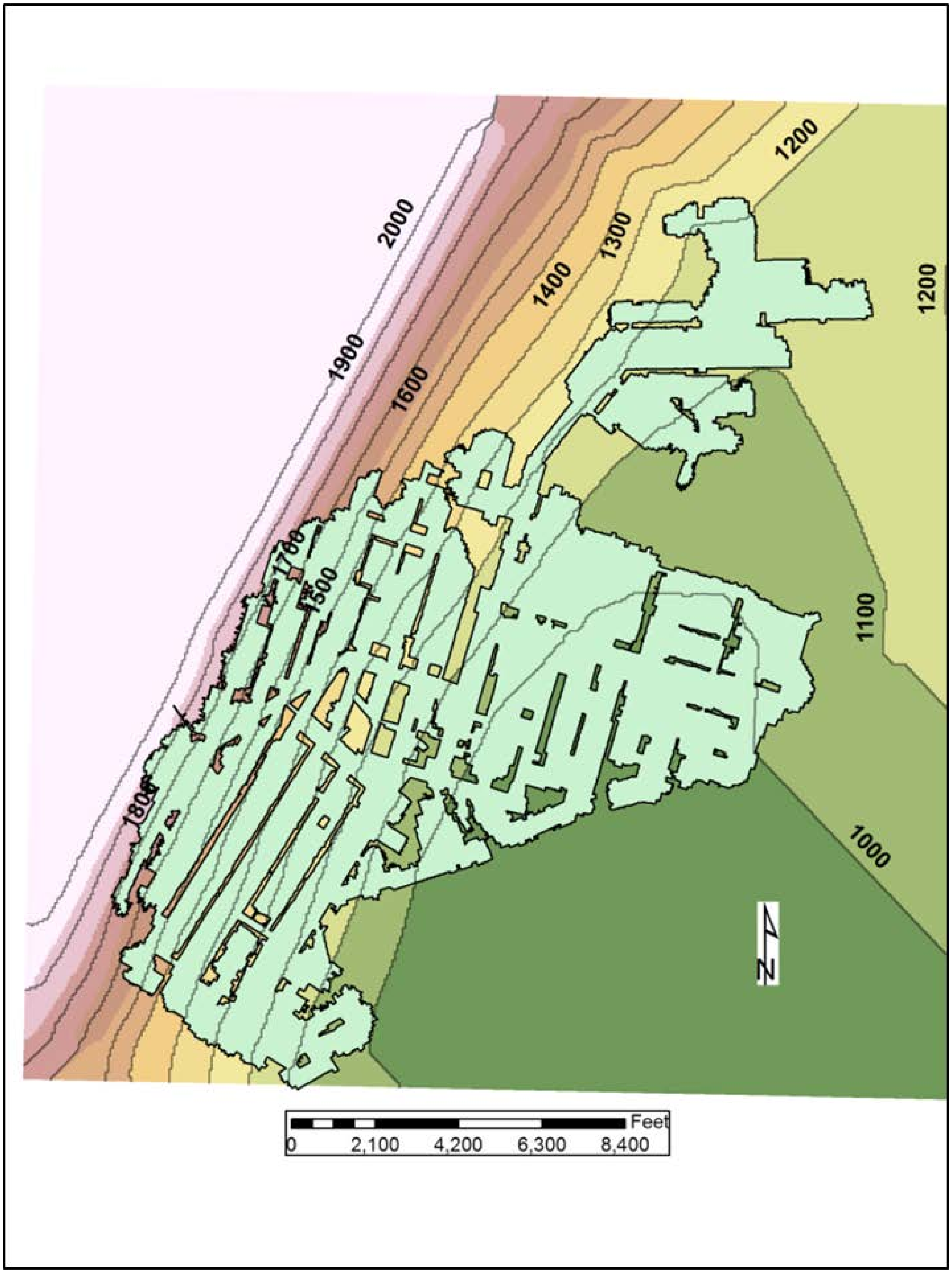
B.1 Grove No. 1 Satellite Image Map with State Roads and Streams



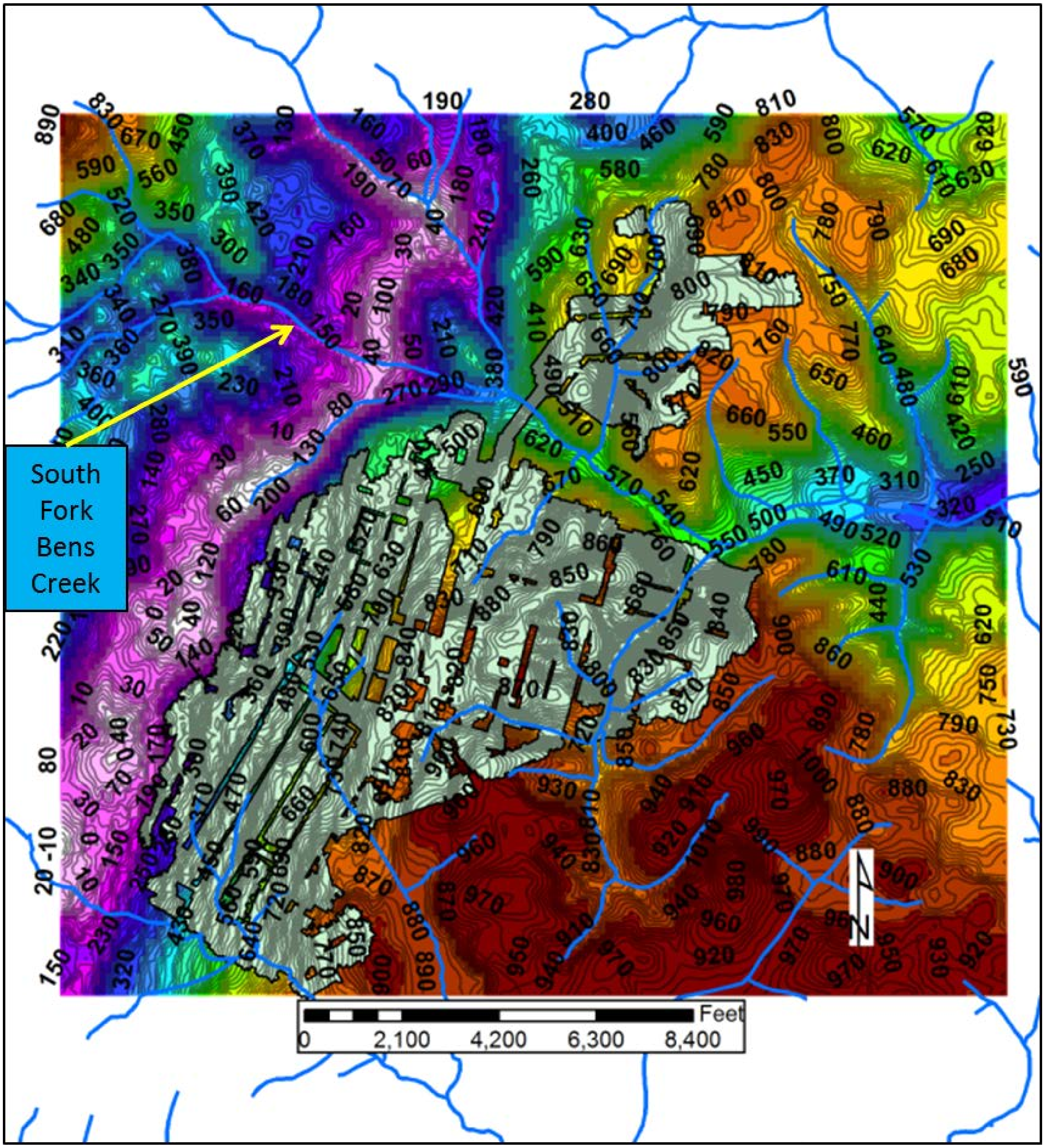
B.2 Grove No. 1 Surface Contour Map with State Roads



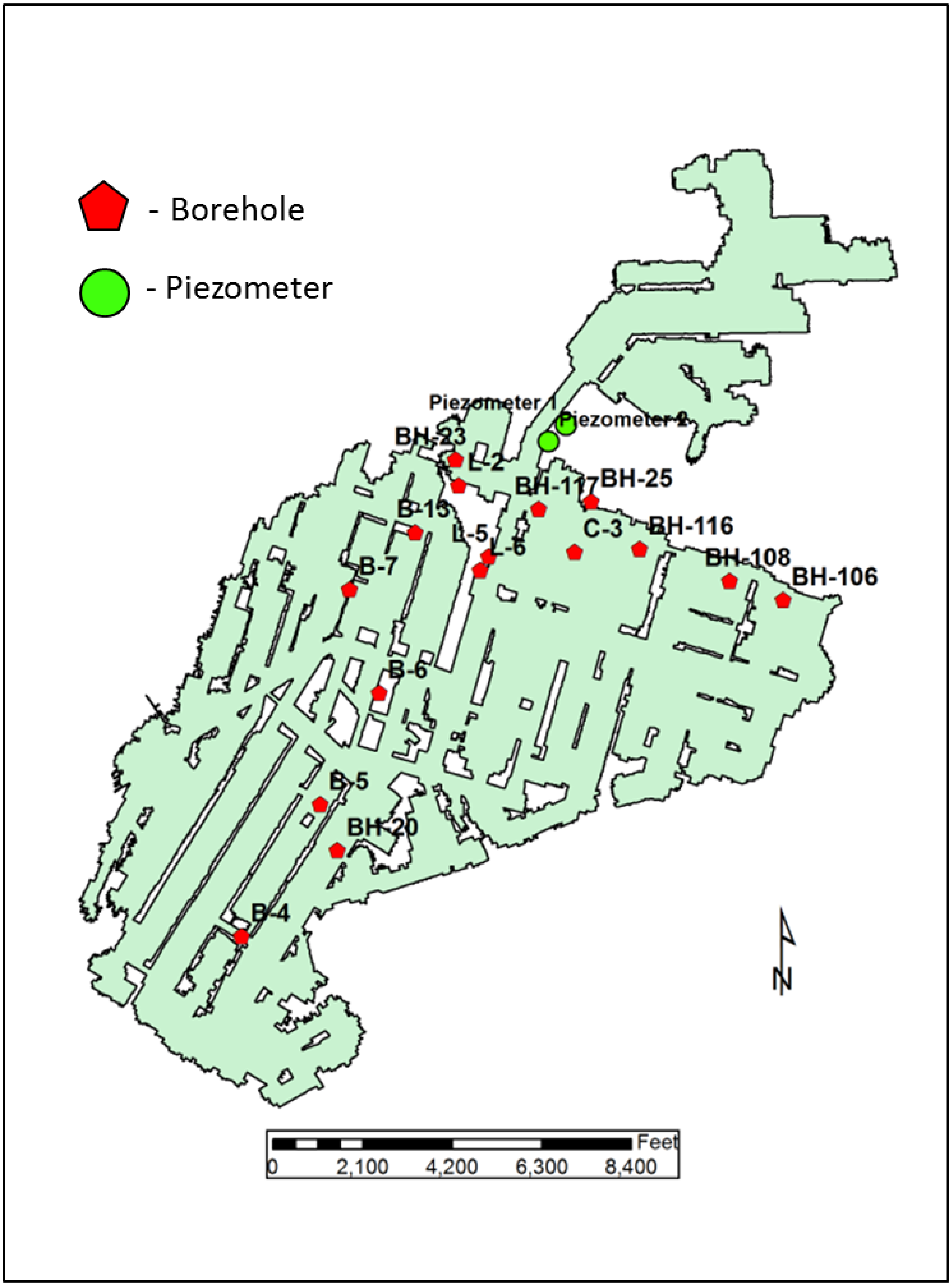
B.3 Grove No. 1 Coal Structure Contour Map



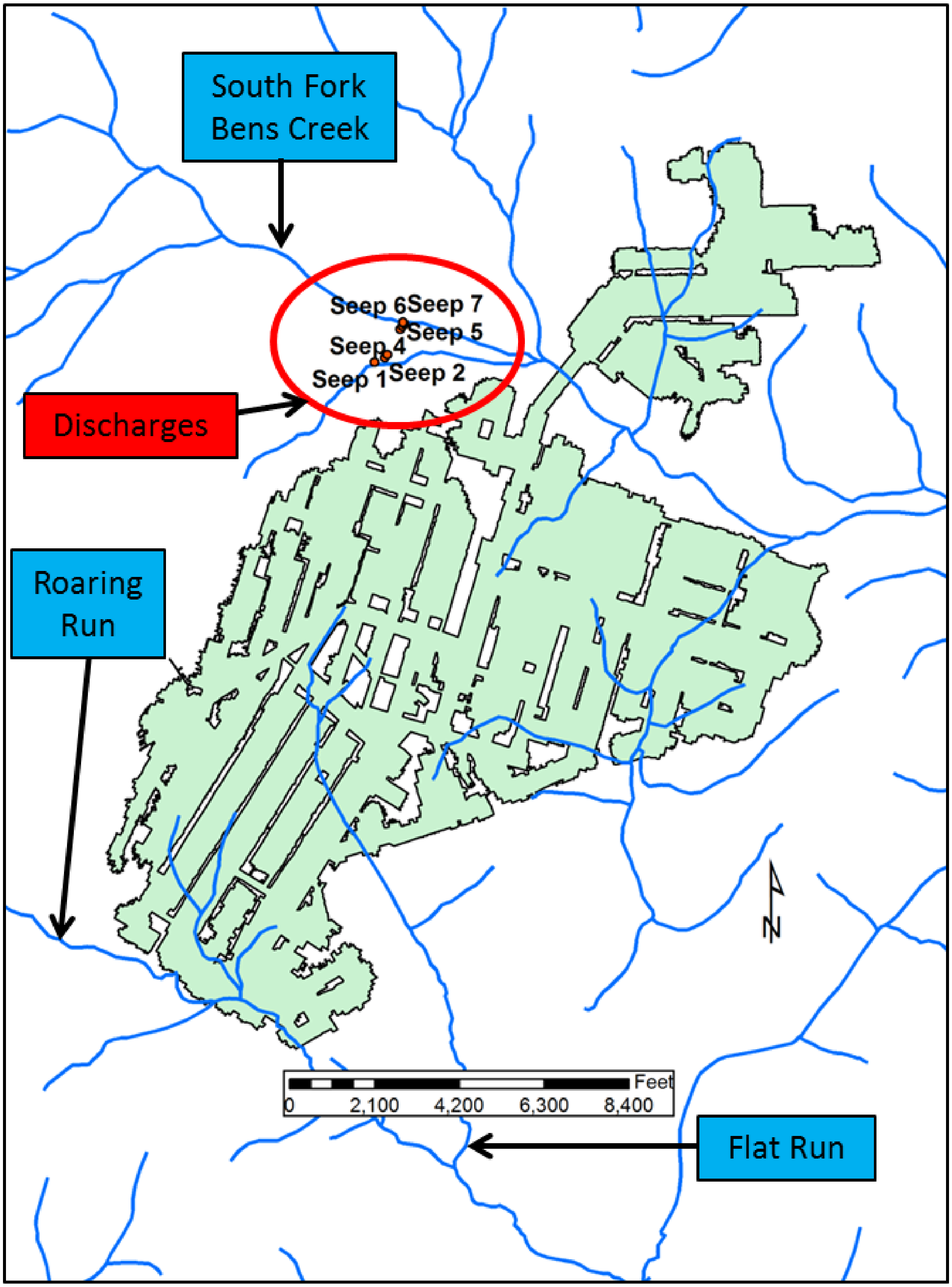
B.4 Grove No. 1 Overburden Contour Map with Streams



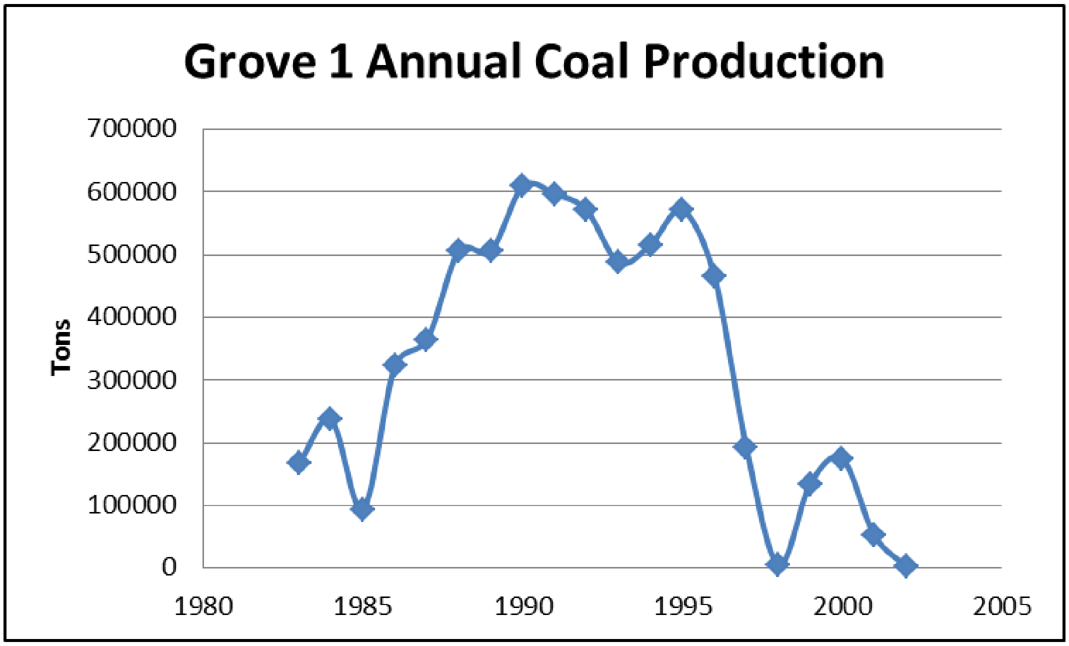
B.5 Grove No. 1 Core and Piezometer Locations



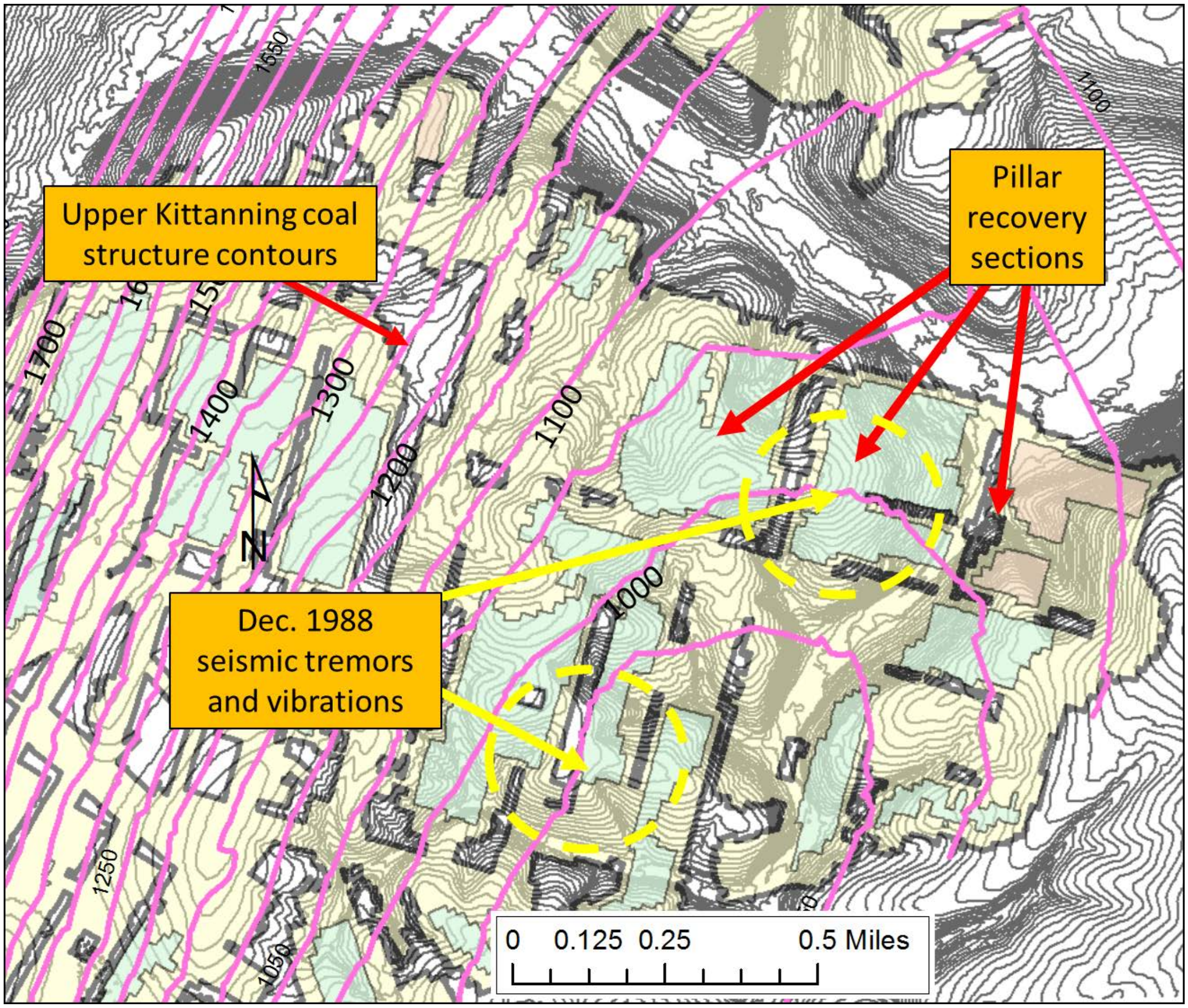
B. 6 Grove No. 1 Surface Discharge Locations



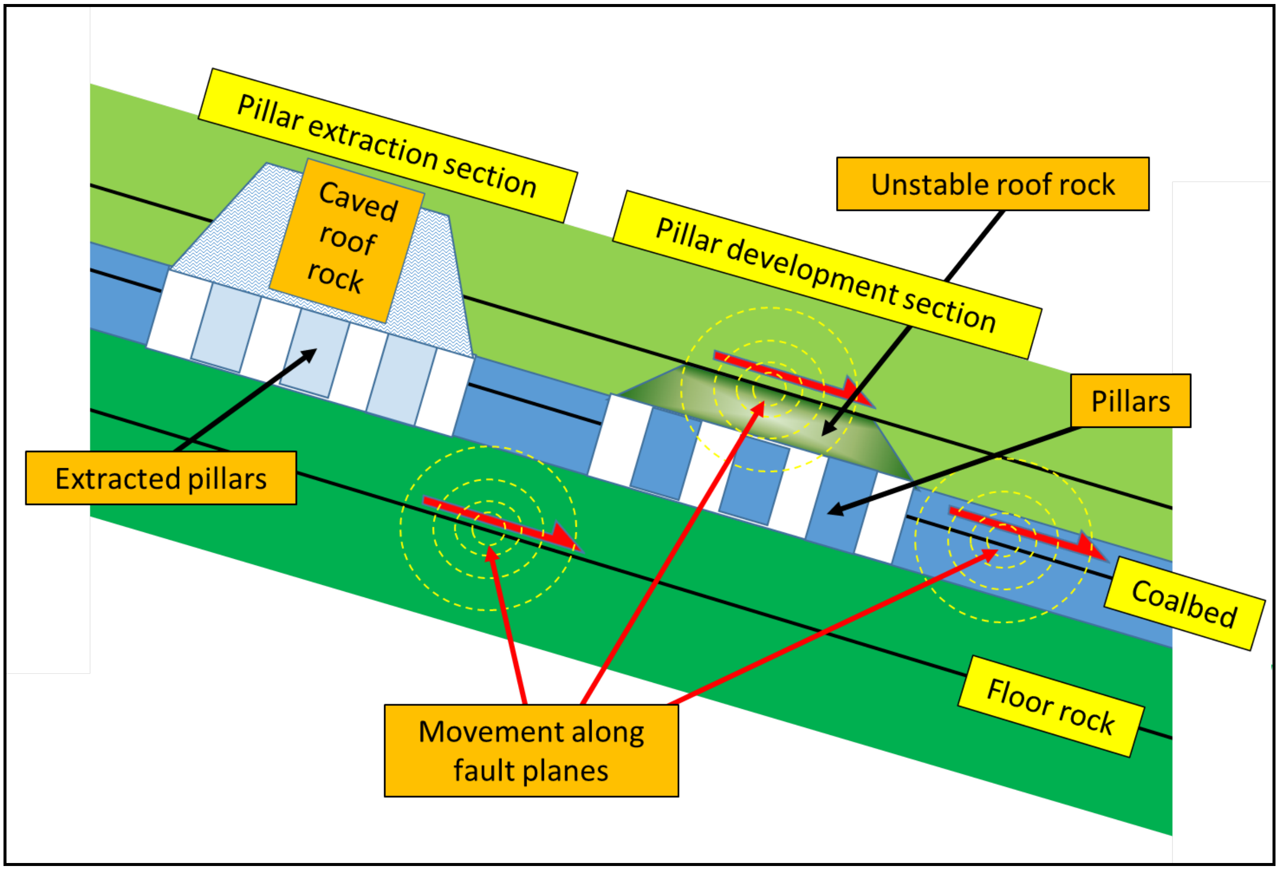
B. 6 Grove No. 1 Coal Production Timeline (MSHA, 2014)



B.7 Grove No. 1 Seismicity Locations (Iannacchione et al., 2013b)

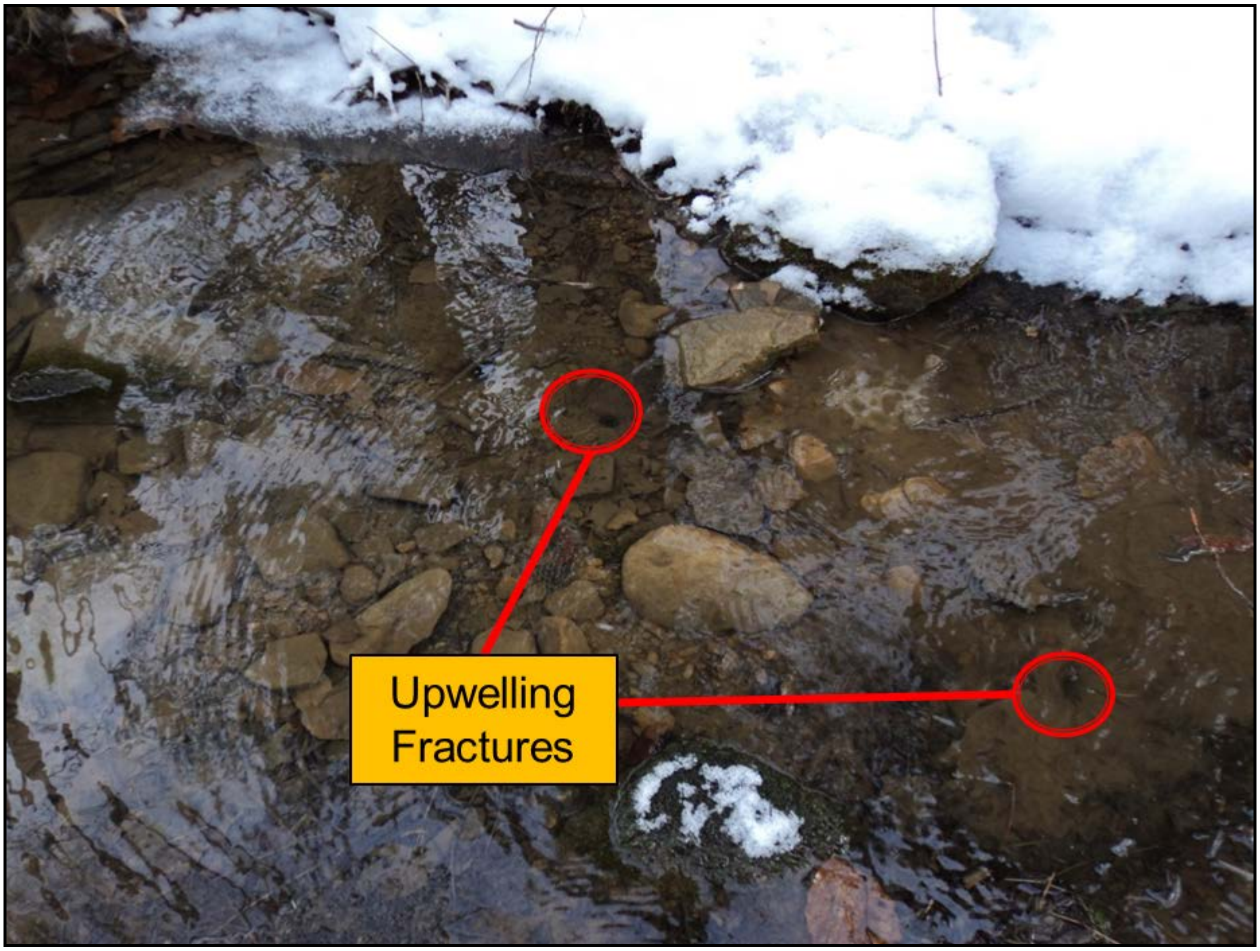


B.8 Grove No. 1 Mining Method and Seismicity Conceptual Model (Iannacchione et al., 2013b)



B.9 July 2001 Discharge in South Fork Bens Creek (Photo by Brent Means, Office of Surface Mining)

B.10 Upwelling Fractures, South Fork Bens Creek (Photo by Anthony Iannacchione, Feb. 2013)

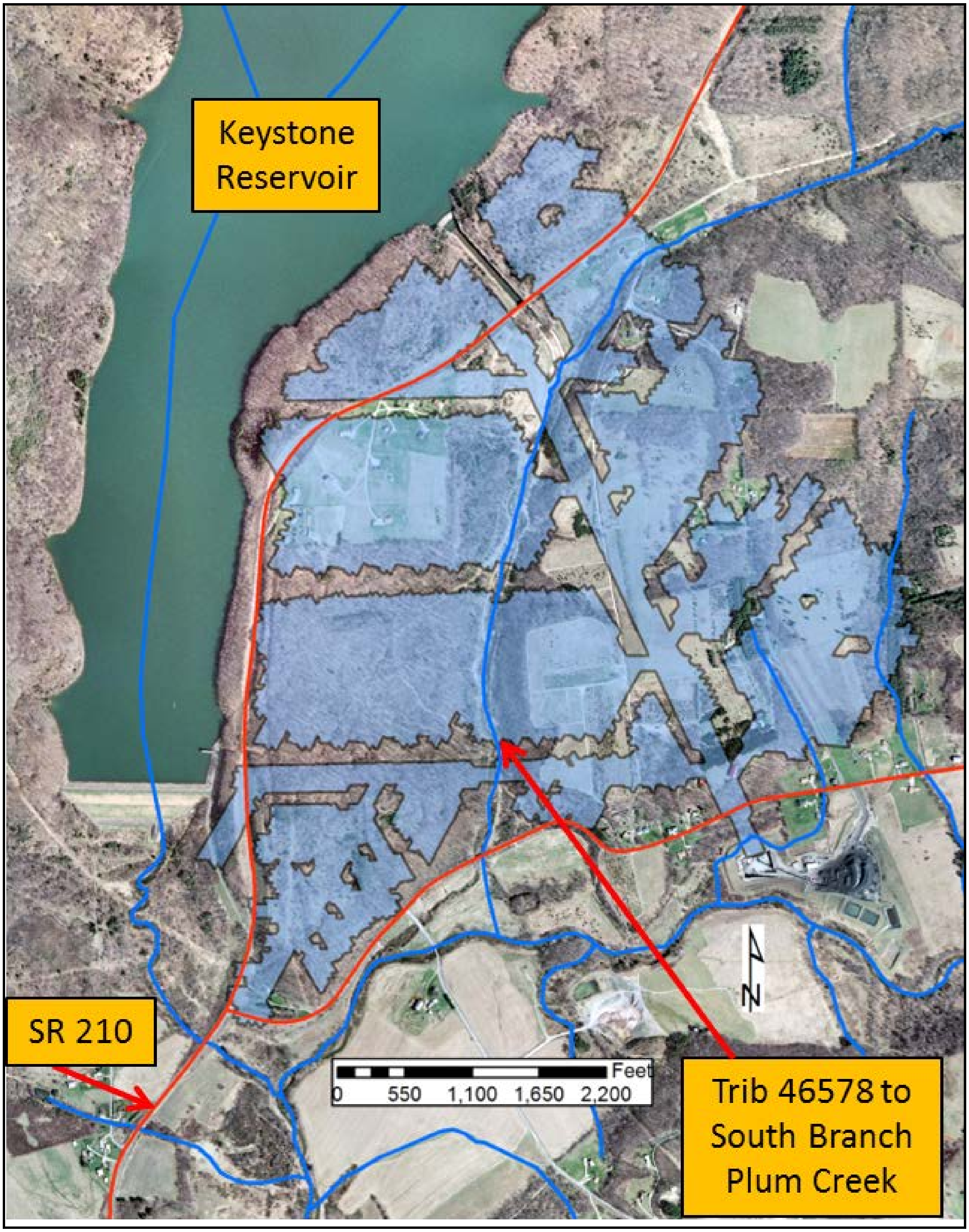


APPENDIX C

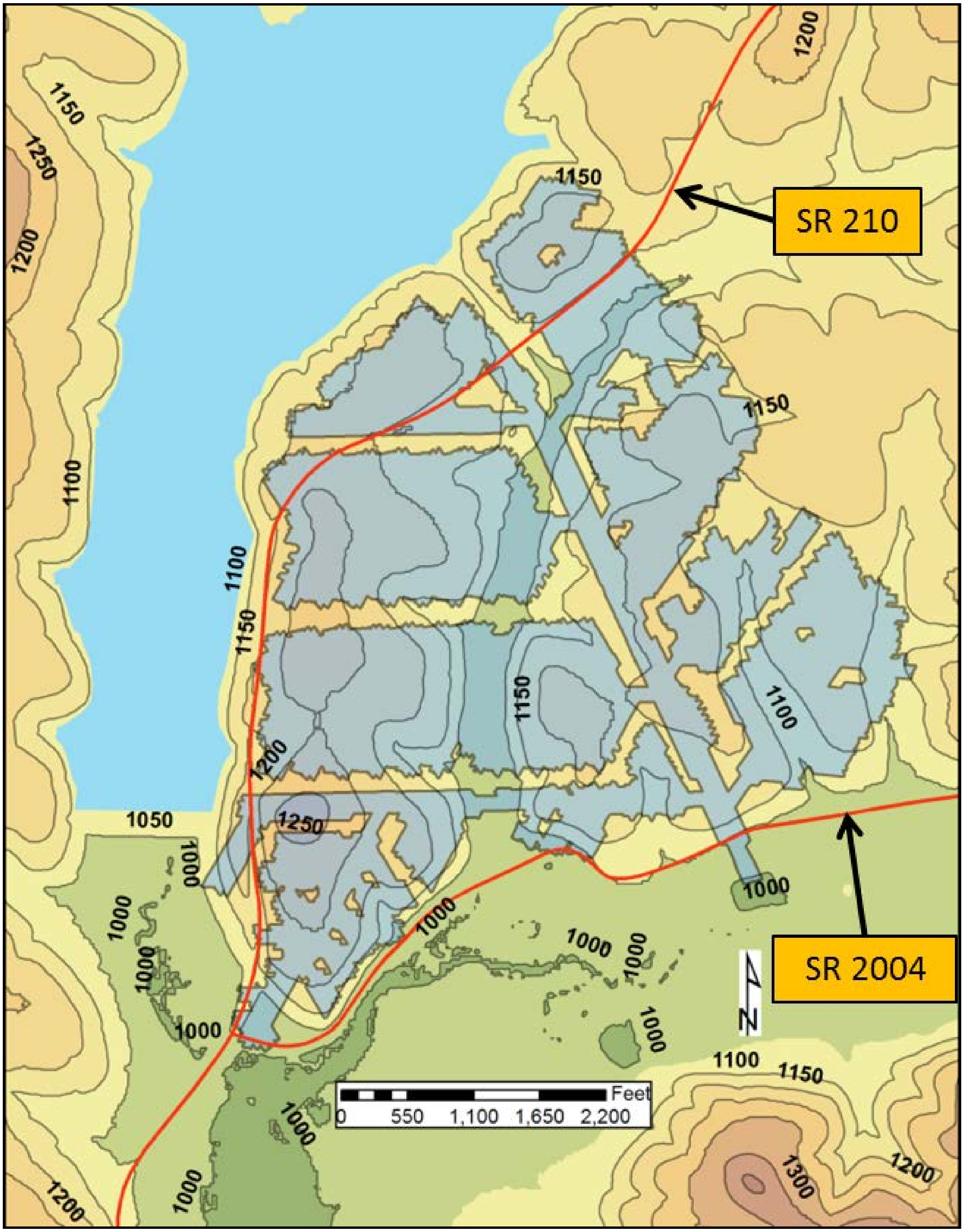
KEYSTONE EAST

The contents of Appendix C are the supplemental data and maps generated for Keystone East. These figures were generated through the use of Geographic Information Software, ArcMap 10.1. The mine outlines, contour maps, and plotted points were created from 6-month mining maps composed by individual companies and obtained by the state and also topographic maps found through online resources (PASDA).

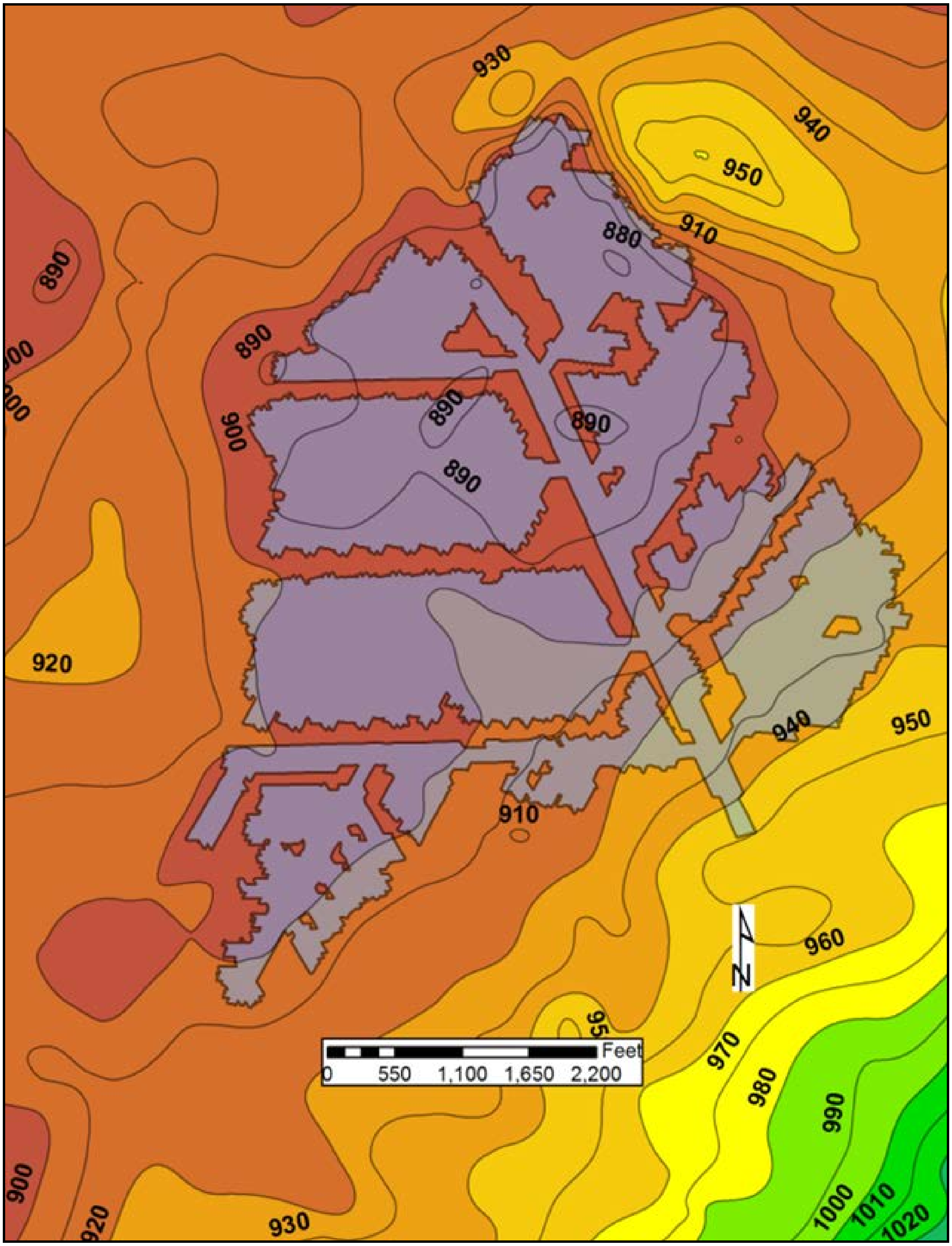
C.1 Keystone East Satellite Image Map with State Roads and Streams



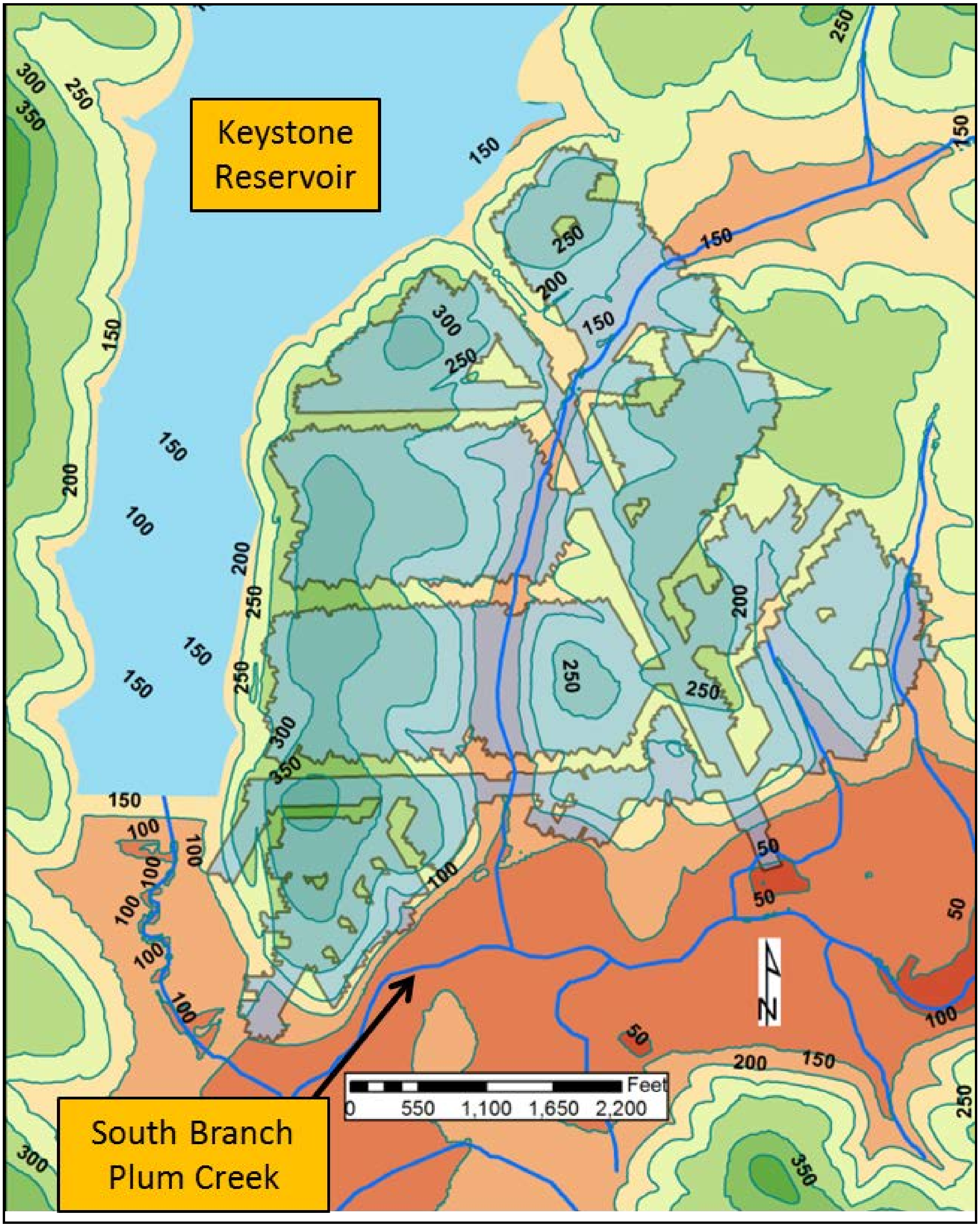
C.2 Keystone East Surface Contour Map with State Roads



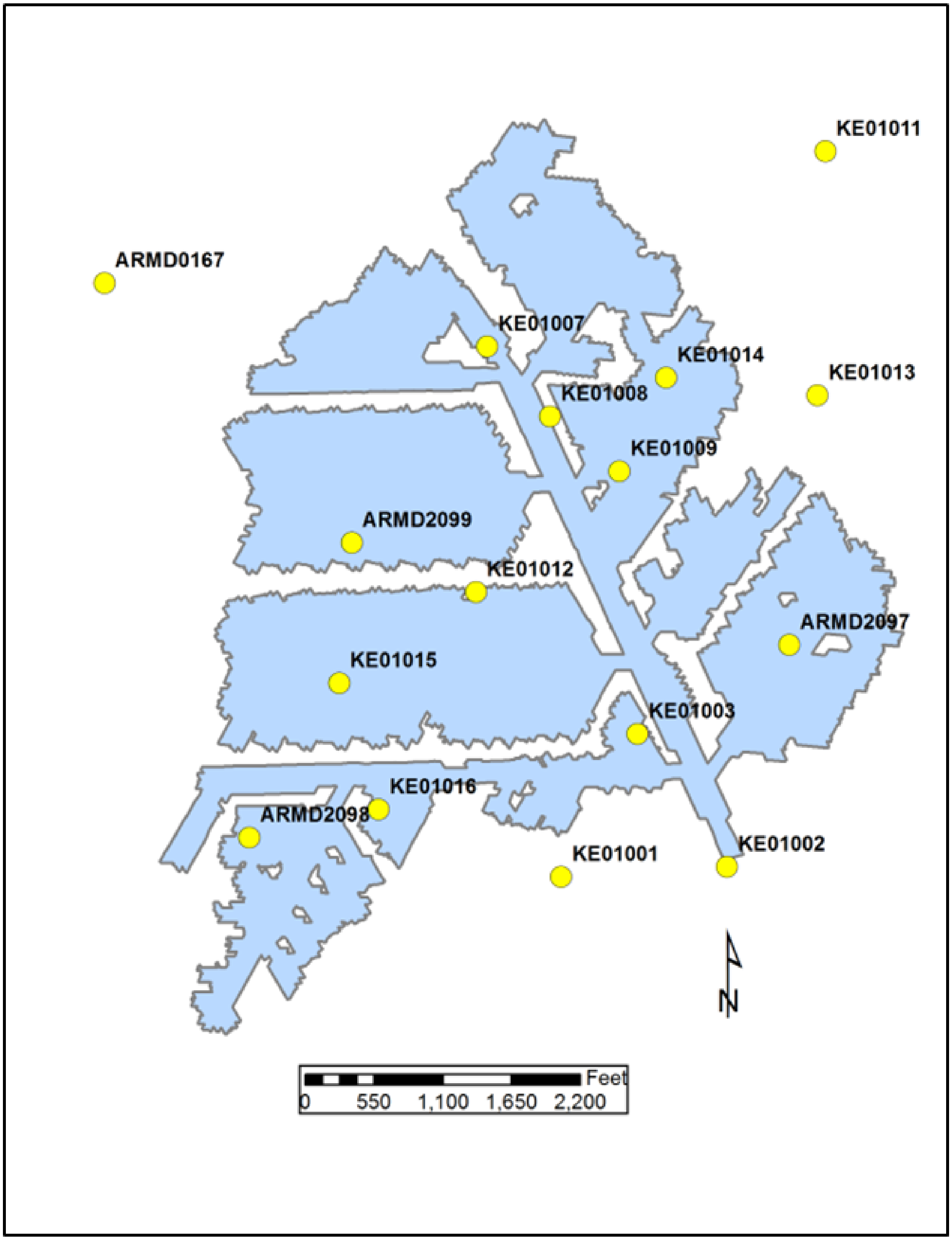
C.3 Keystone East Coal Structure Contour Map



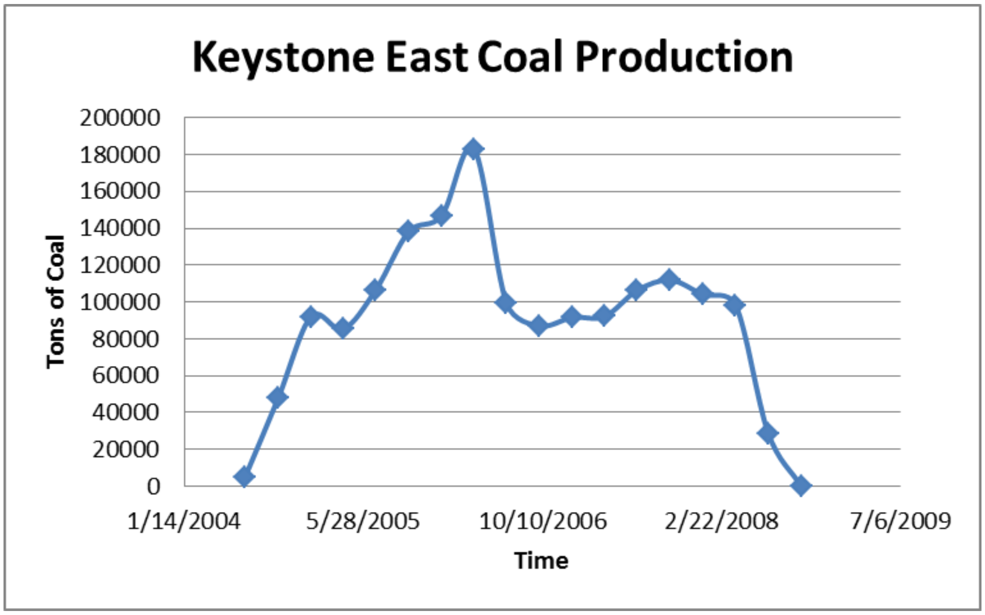
C.4 Keystone East Overburden Contour Map with Streams



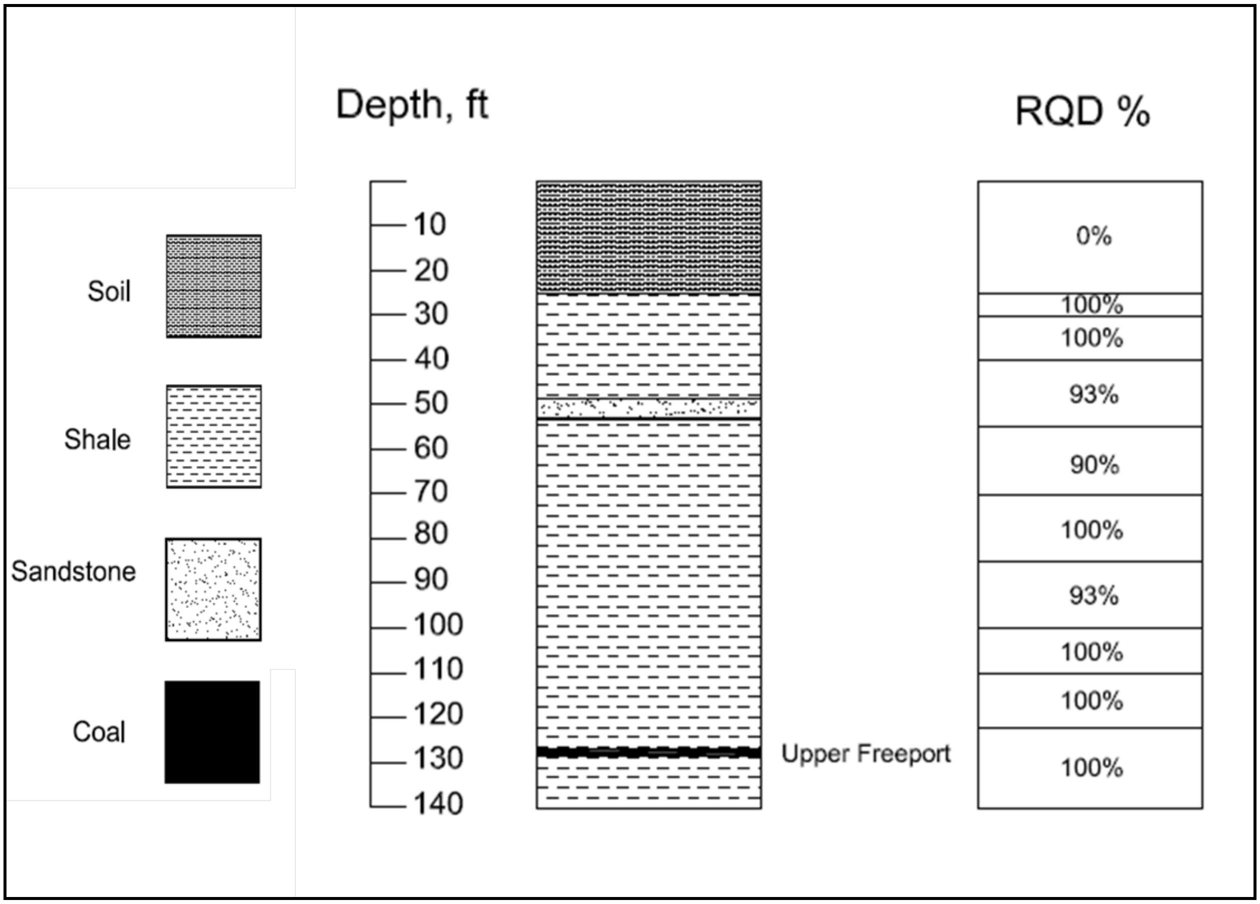
C.5 Keystone East Core Logs and Piezometer (KE 01-012) Locations



C.6 Keystone East Coal Production Timeline (MSHA, 2014)



C.7 Keystone East Core Log KE 01-011 and RQD

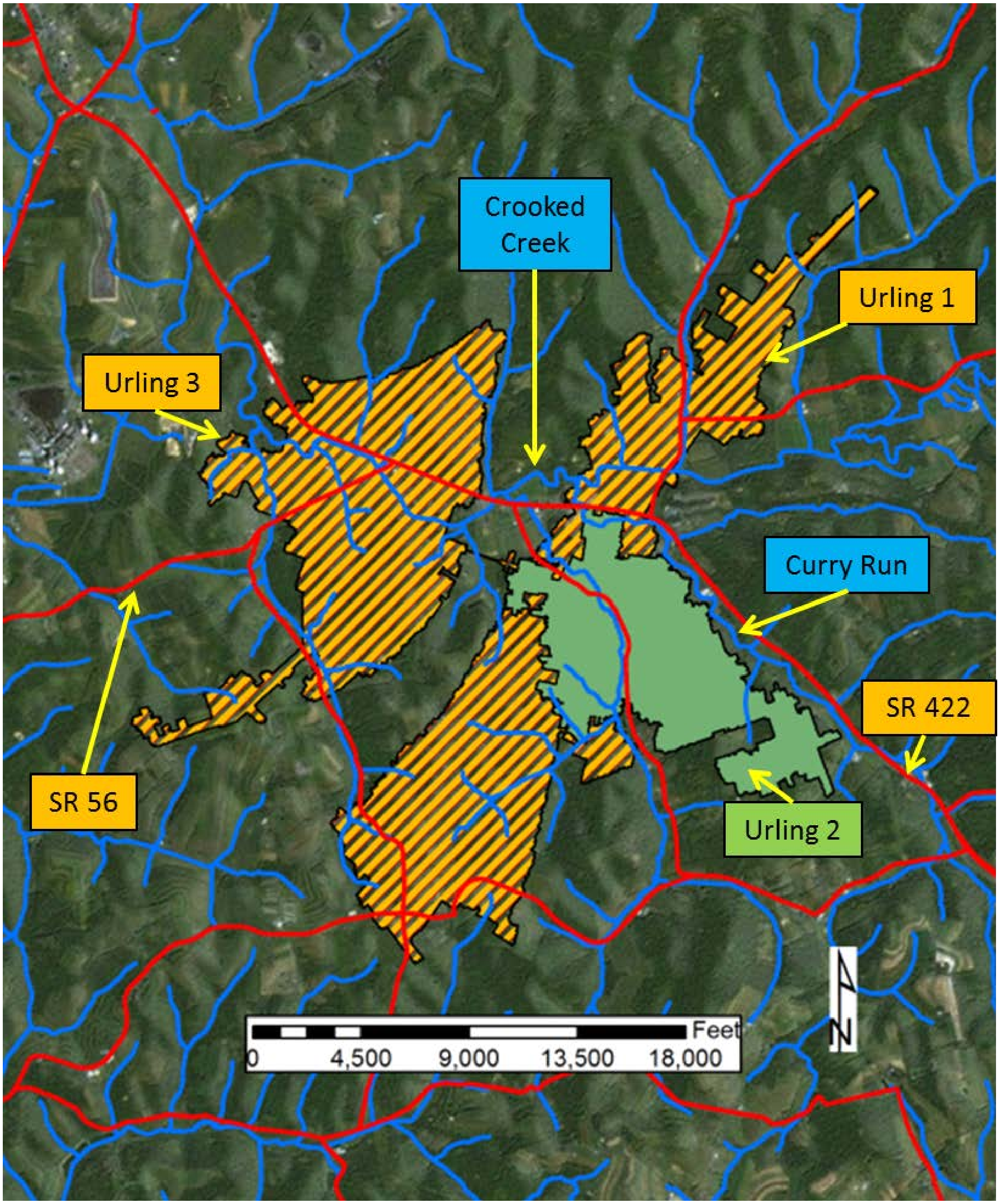


APPENDIX D

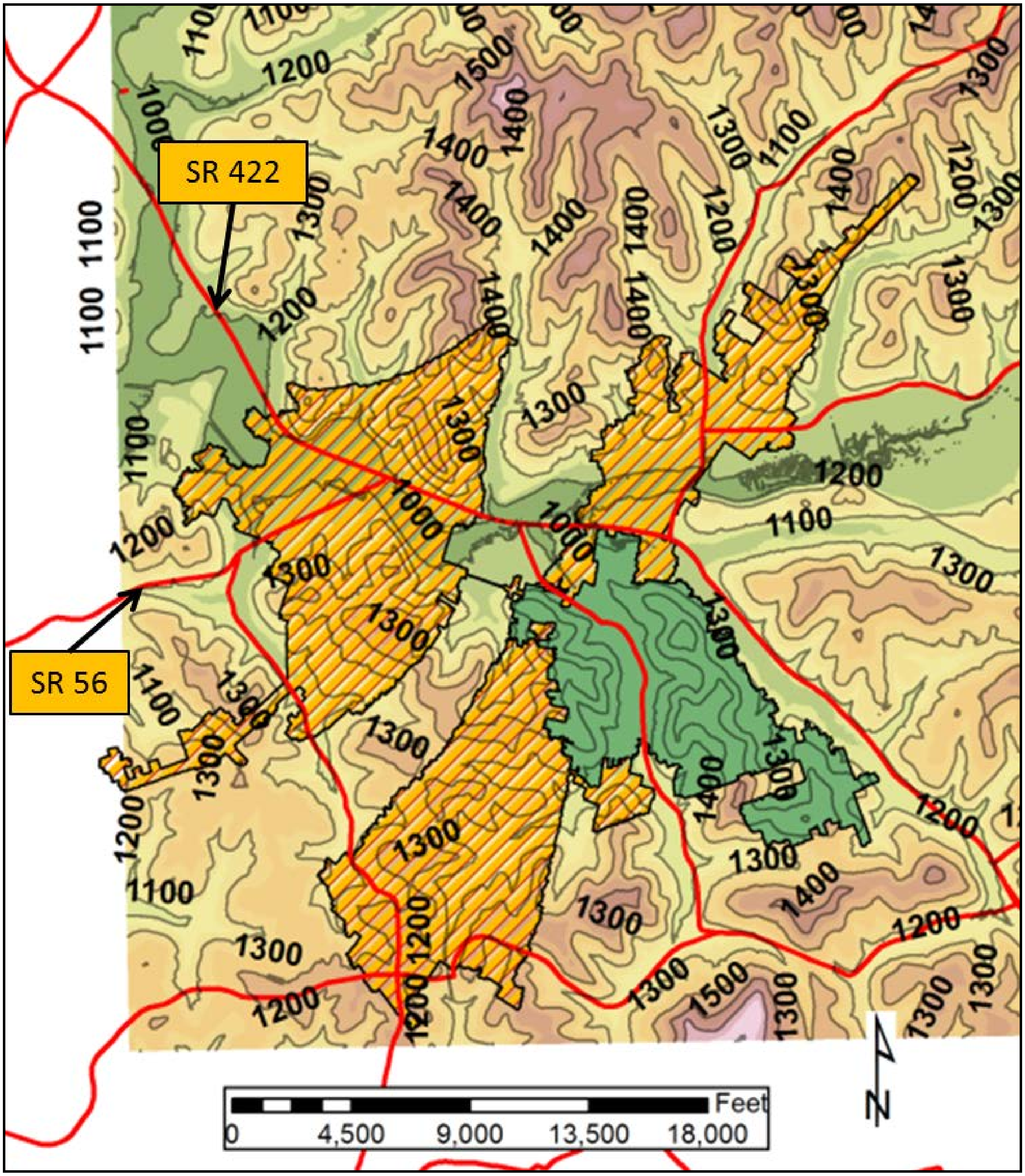
URLING NO. 1, 2, & 3

The contents of Appendix D are the supplemental data and maps generated for Urling No. 1, 2, and 3. These figures were generated through the use of Geographic Information Software, ArcMap 10.1. The mine outlines, contour maps, and plotted points were created from 6-month mining maps composed by individual companies and obtained by the state and also topographic maps found through online resources (PASDA).

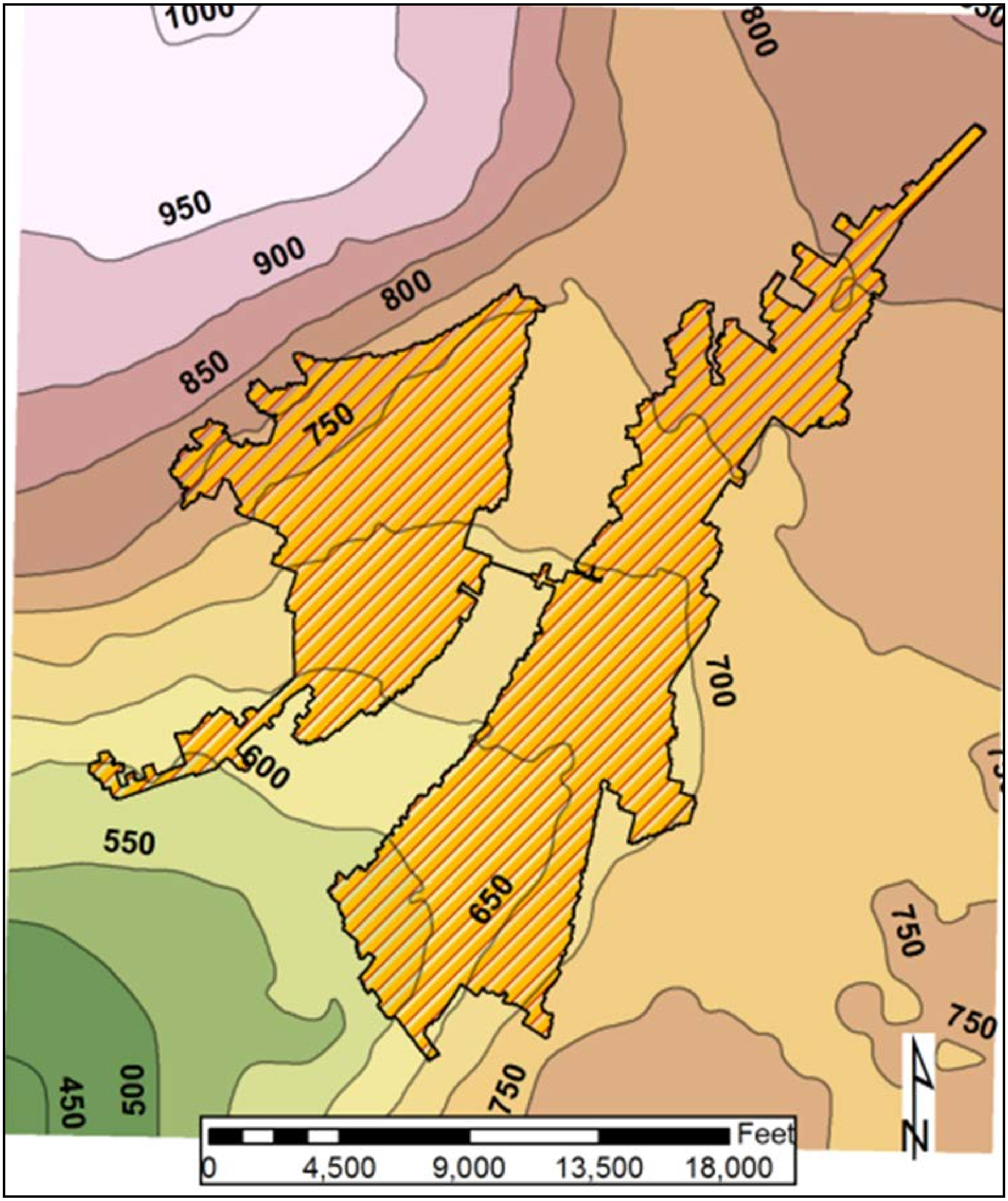
D.1 Urling Satellite Image Map with State Roads and Streams



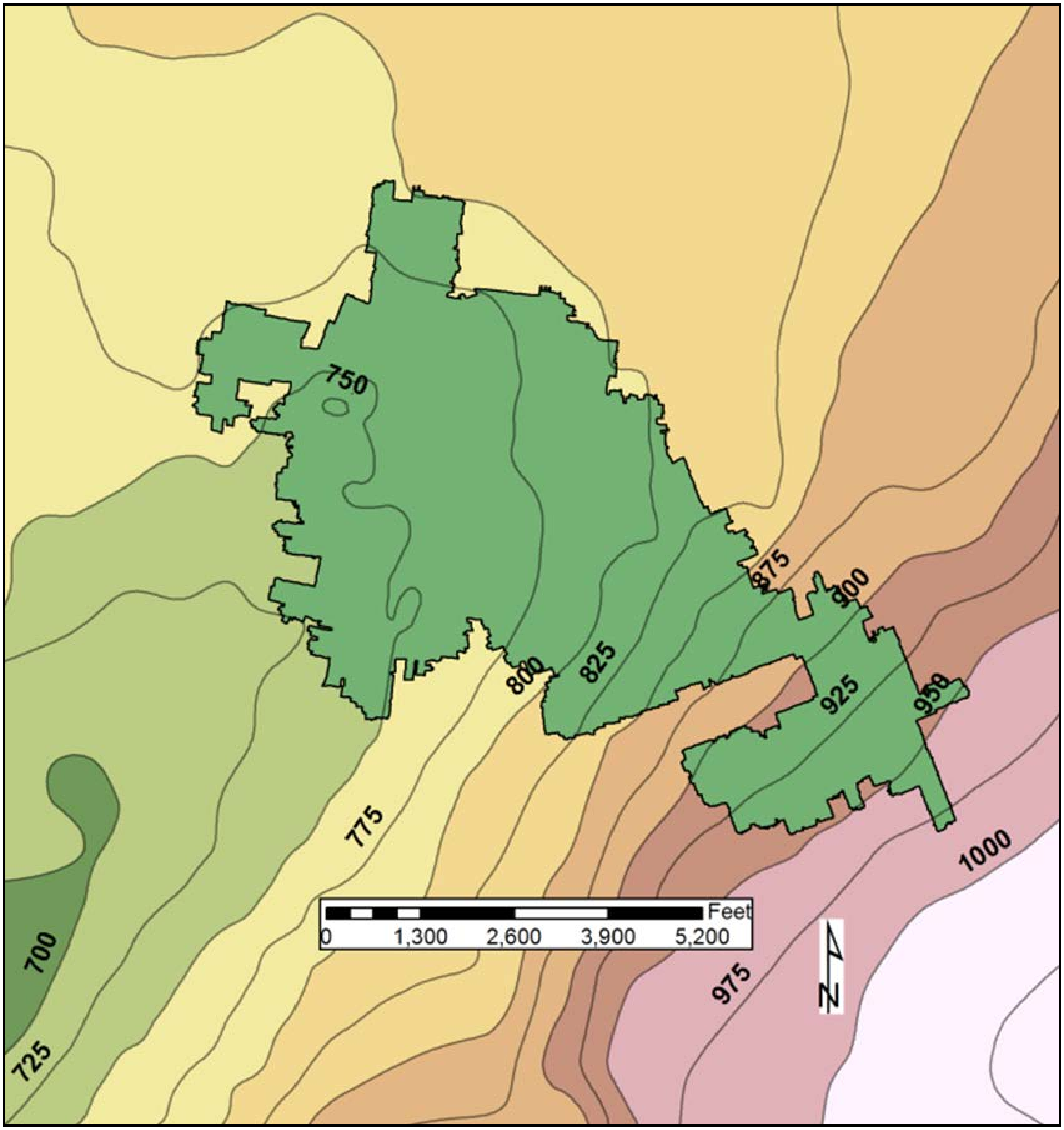
D.2 Urling Surface Contour Map with State Roads



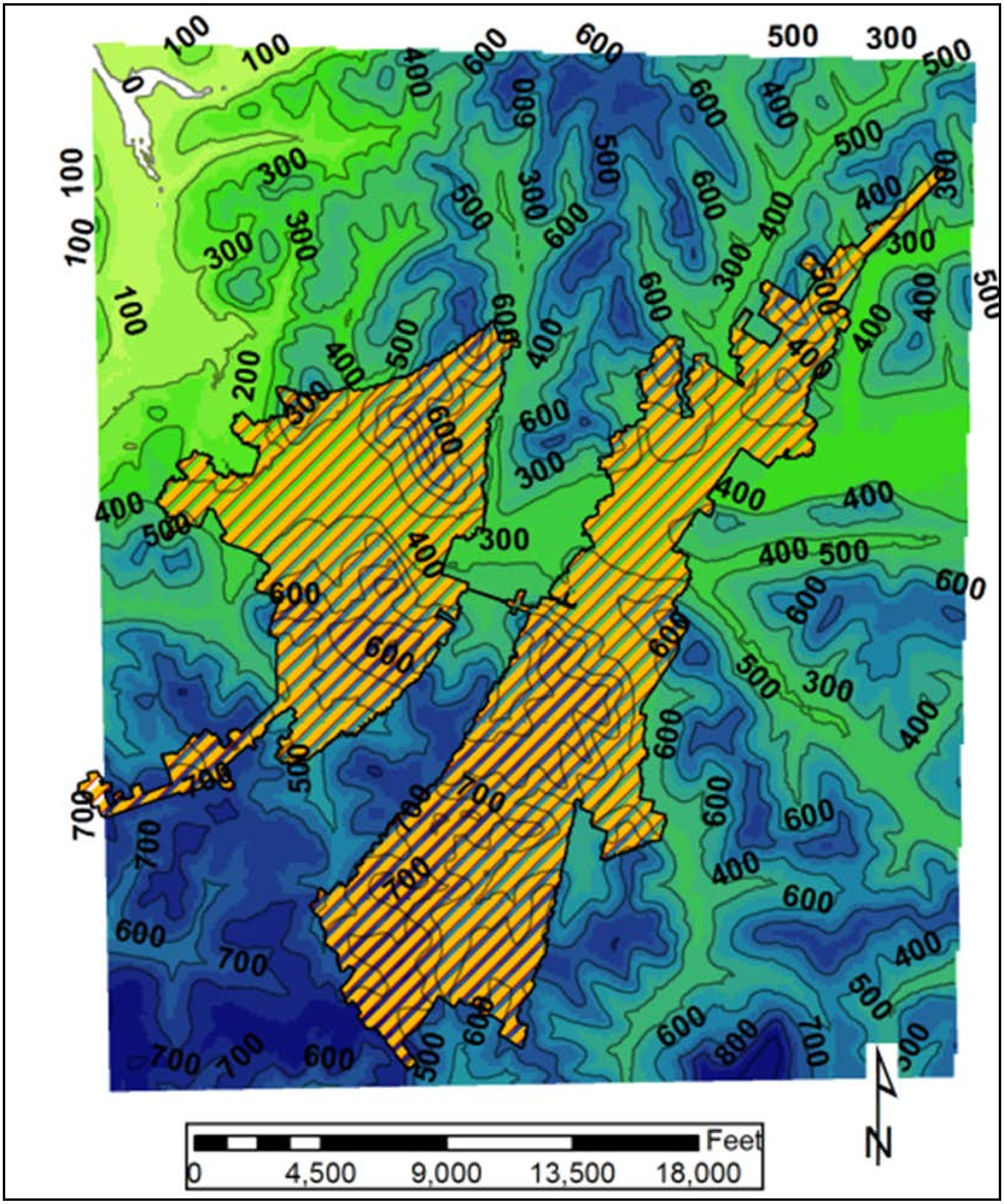
D.3 Urling No. 1 and No. 3 Coal Structure Contour Map



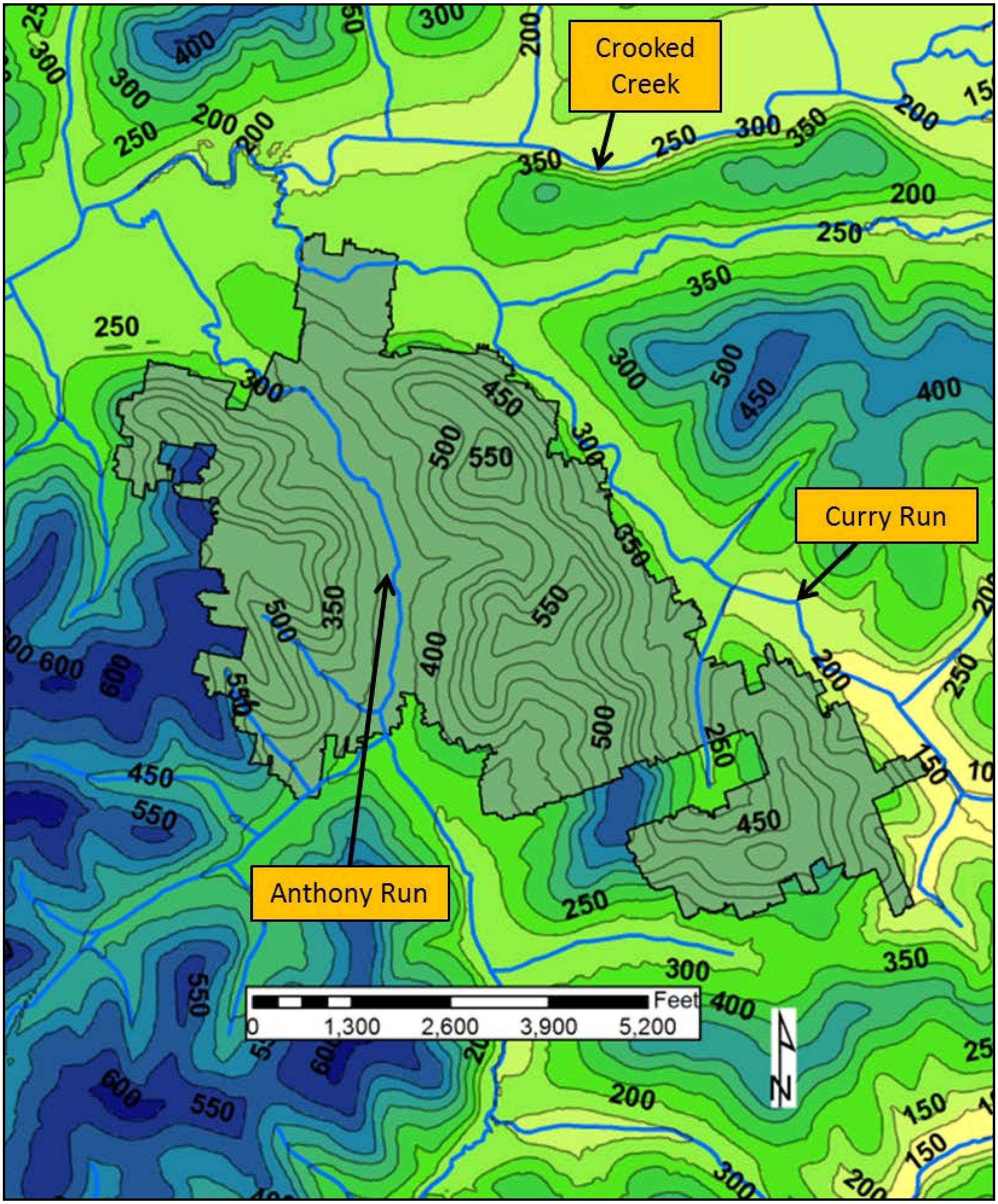
D.4 Urling No. 2 Coal Structure Contour Map



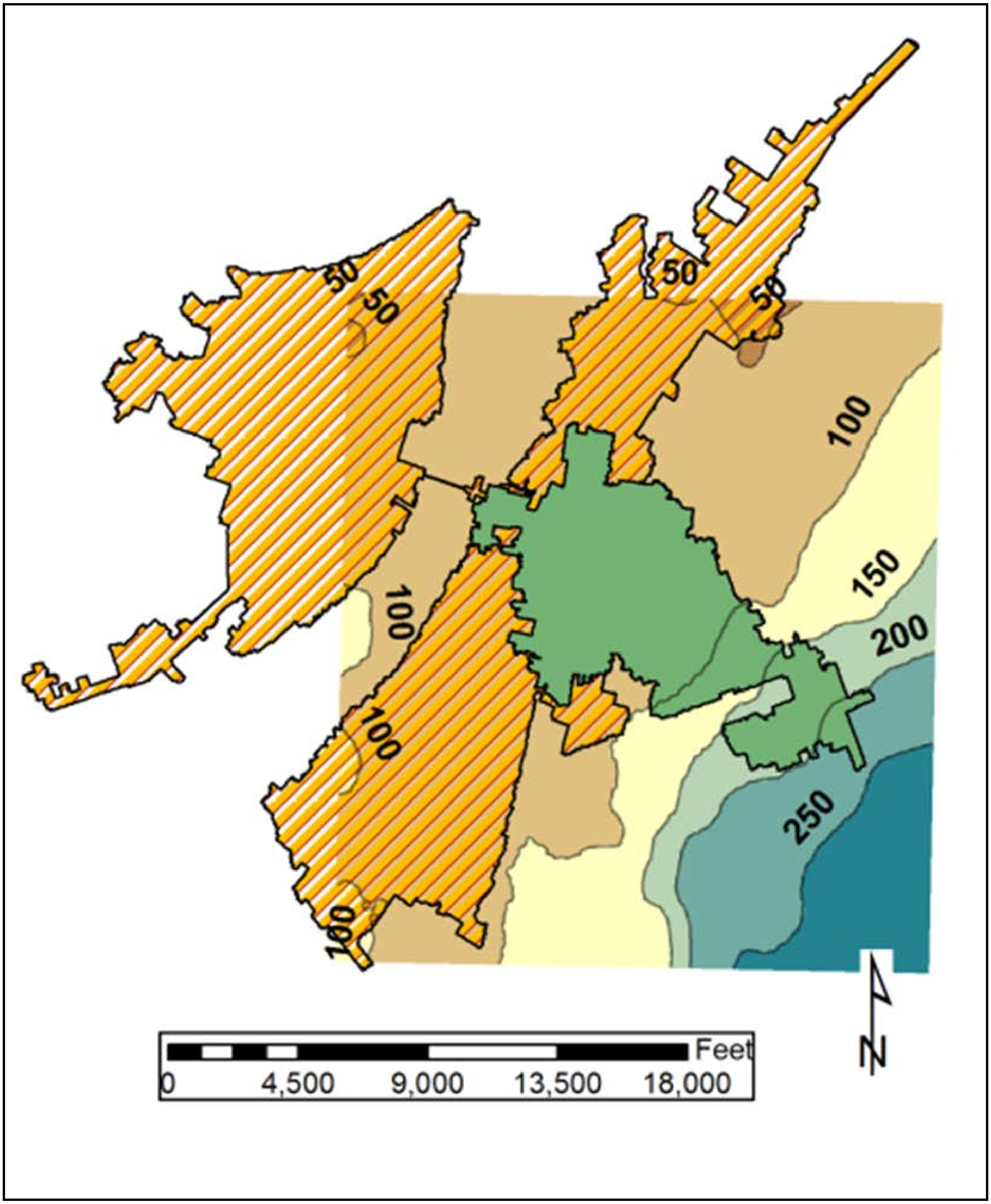
D.5 Urling No. 1 and No. 3 Overburden Contour Map



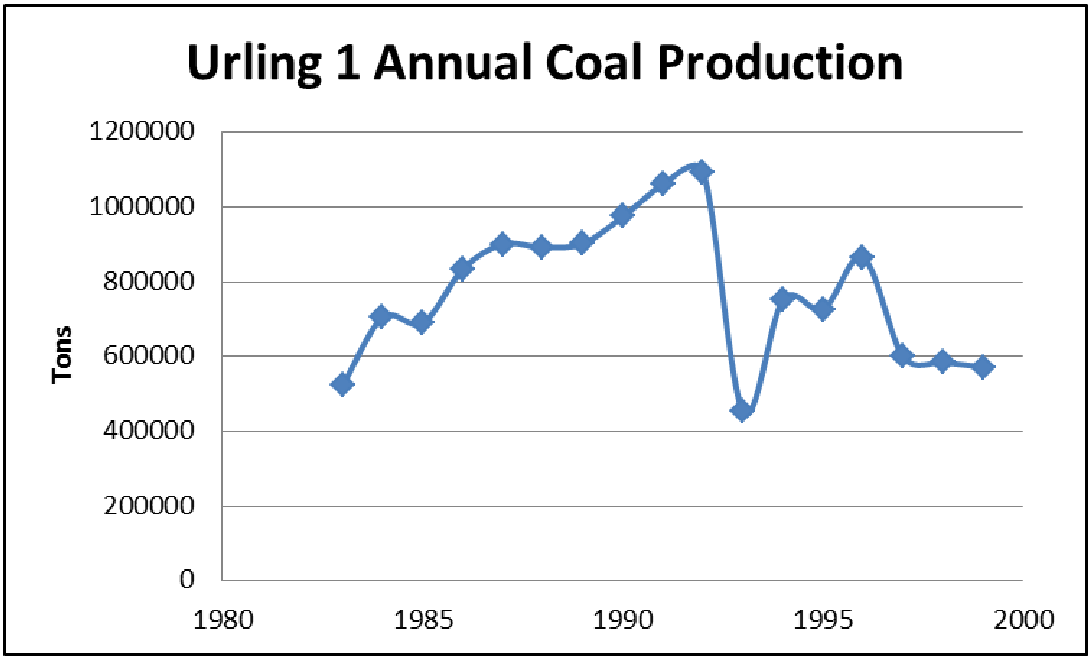
D.6 Urling No. 2 Overburden Contour Map with Streams



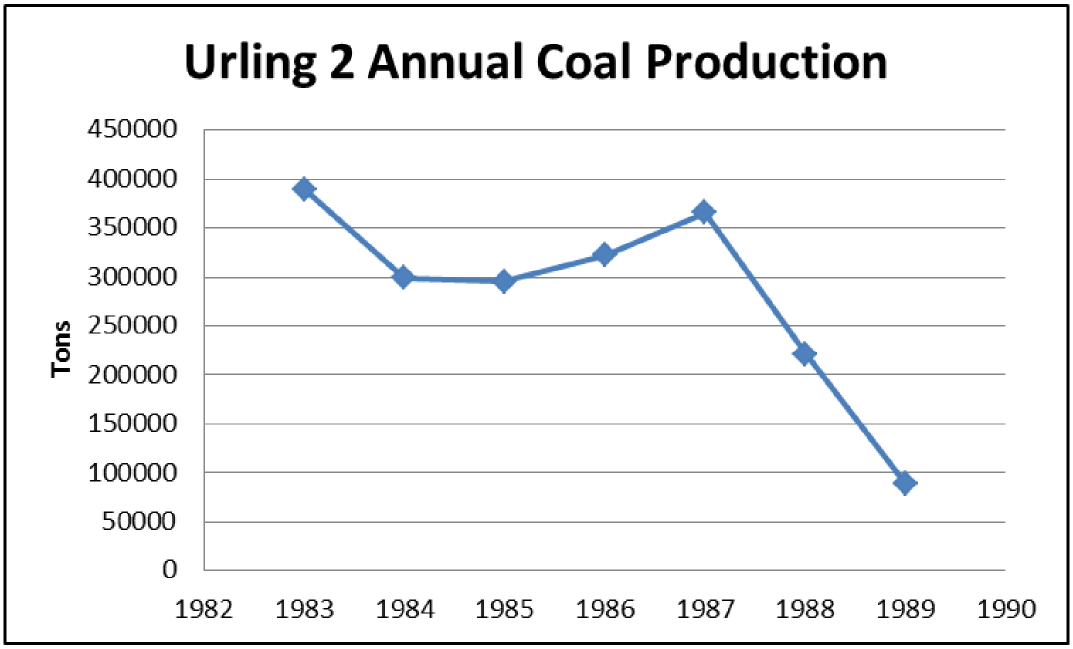
D.7 Urling Interburden Contour Map



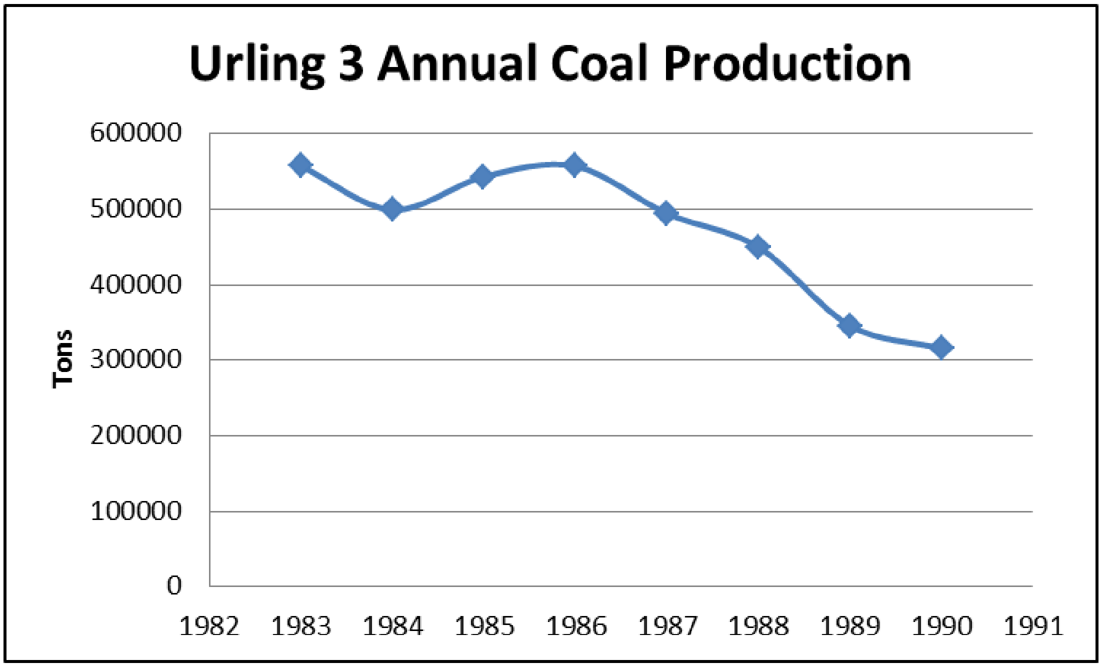
D.8 Urling No. 1 Coal Production Timeline (MSHA, 2014)



D.9 Urling No. 2 Coal Production Timeline (MSHA, 2014)



D.10 Urling No. 3 Coal Production Timeline (MSHA, 2014)

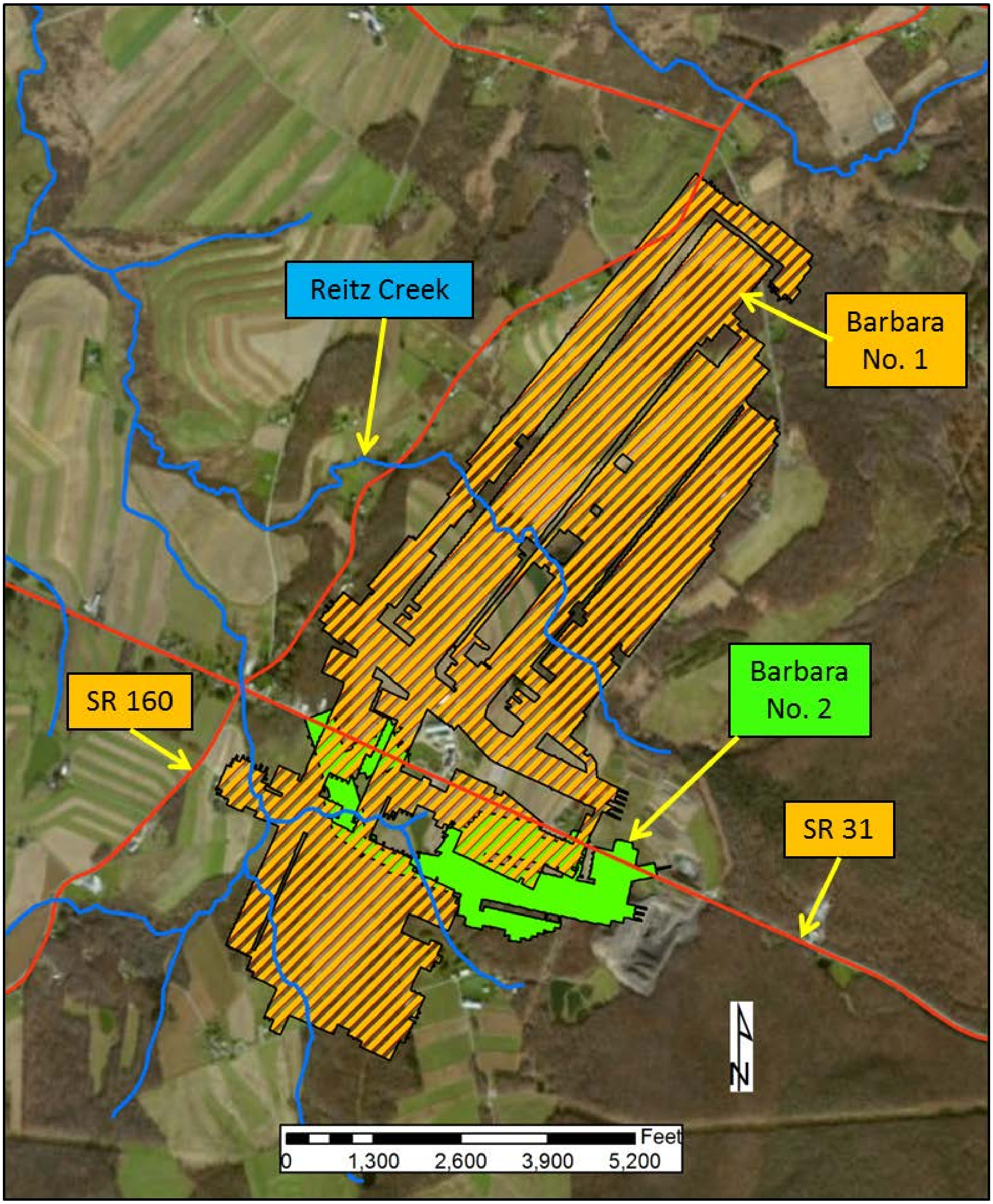


APPENDIX E

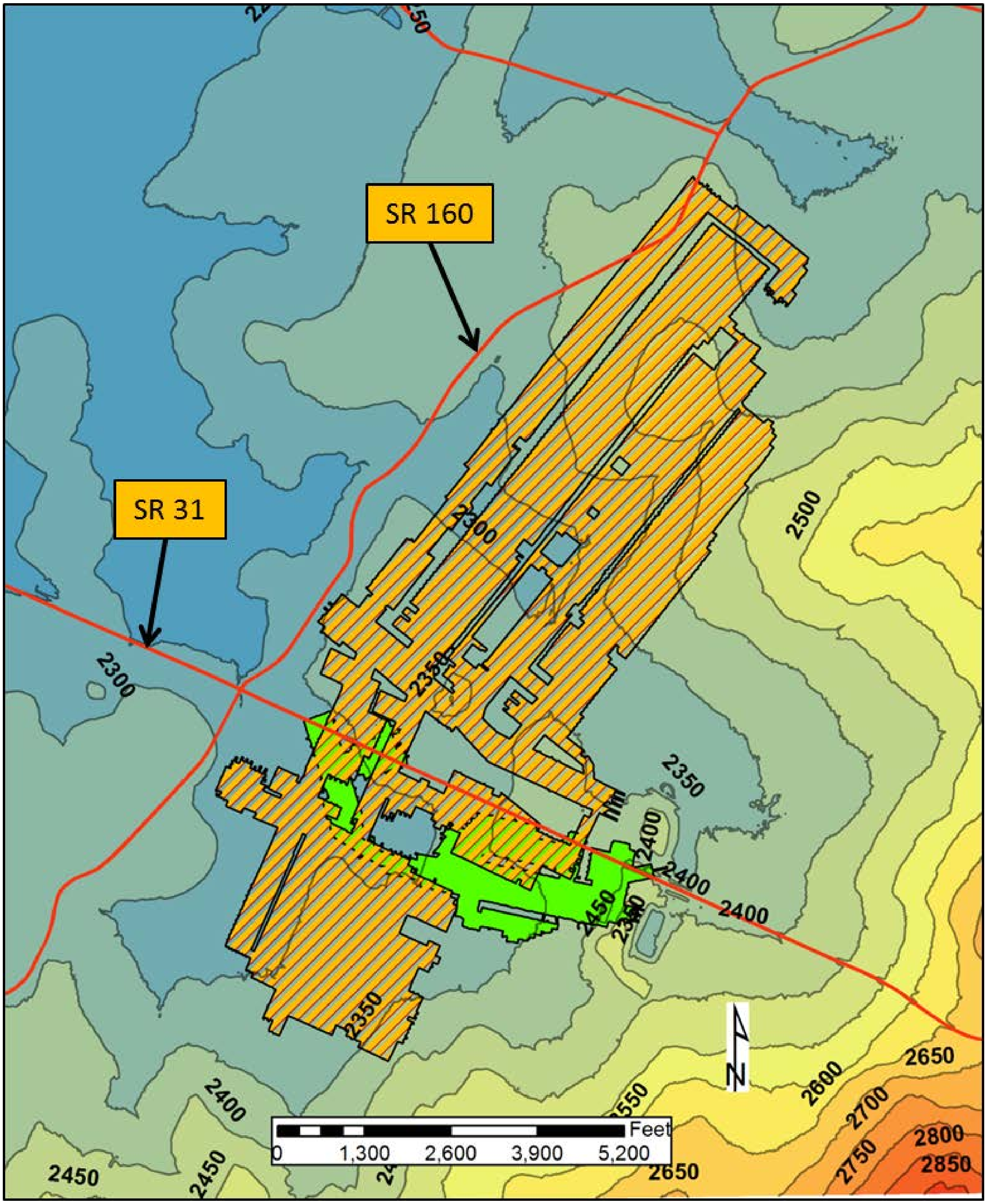
BARBARA NO. 1 & 2

The contents of Appendix E are the supplemental data and maps generated for Barbara No. 1 and 2. These figures were generated through the use of Geographic Information Software, ArcMap 10.1. The mine outlines, contour maps, and plotted points were created from 6-month mining maps composed by individual companies and obtained by the state and also topographic maps found through online resources (PASDA).

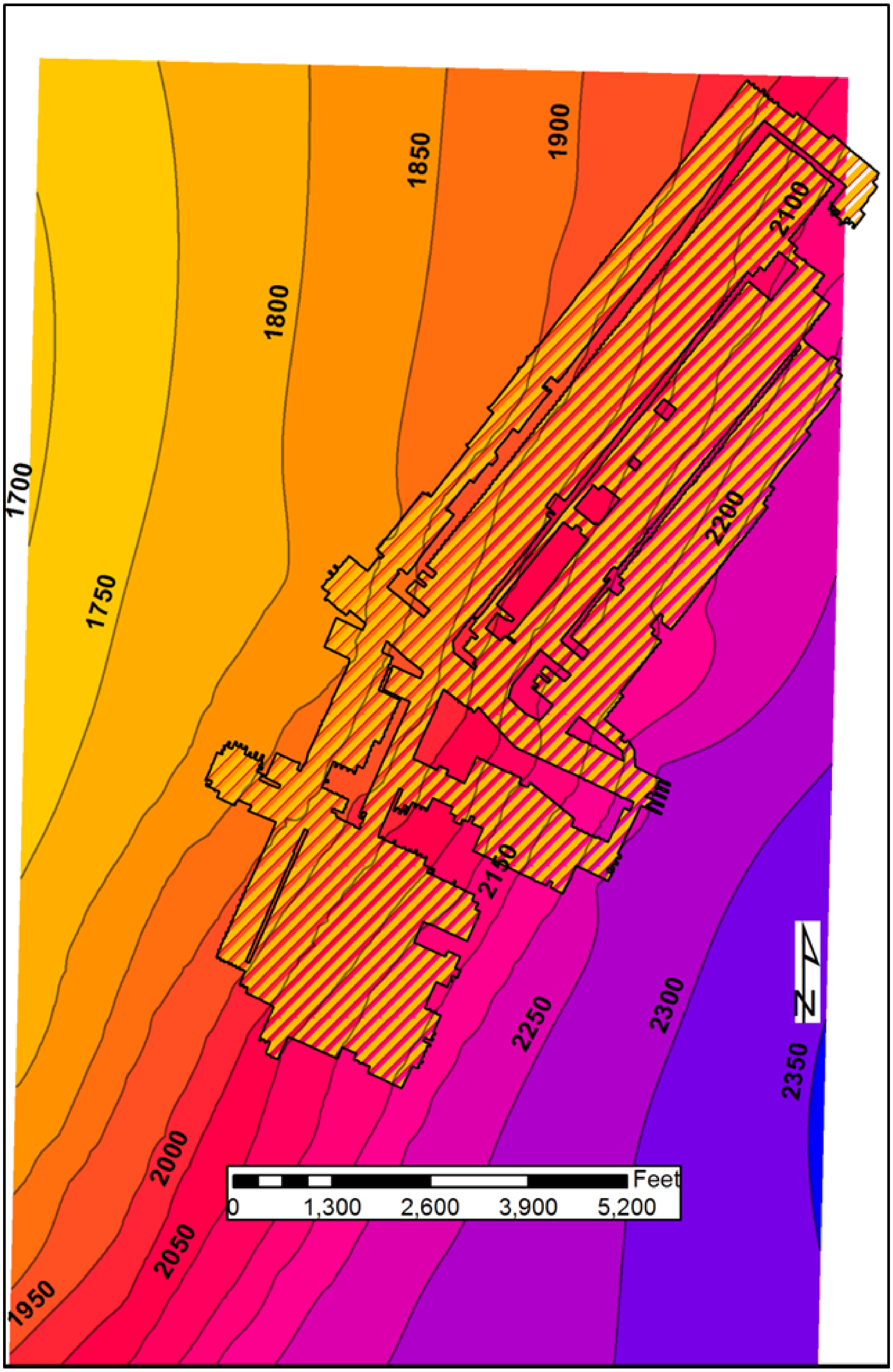
E.1 Barbara Satellite Image Map with State Roads and Streams



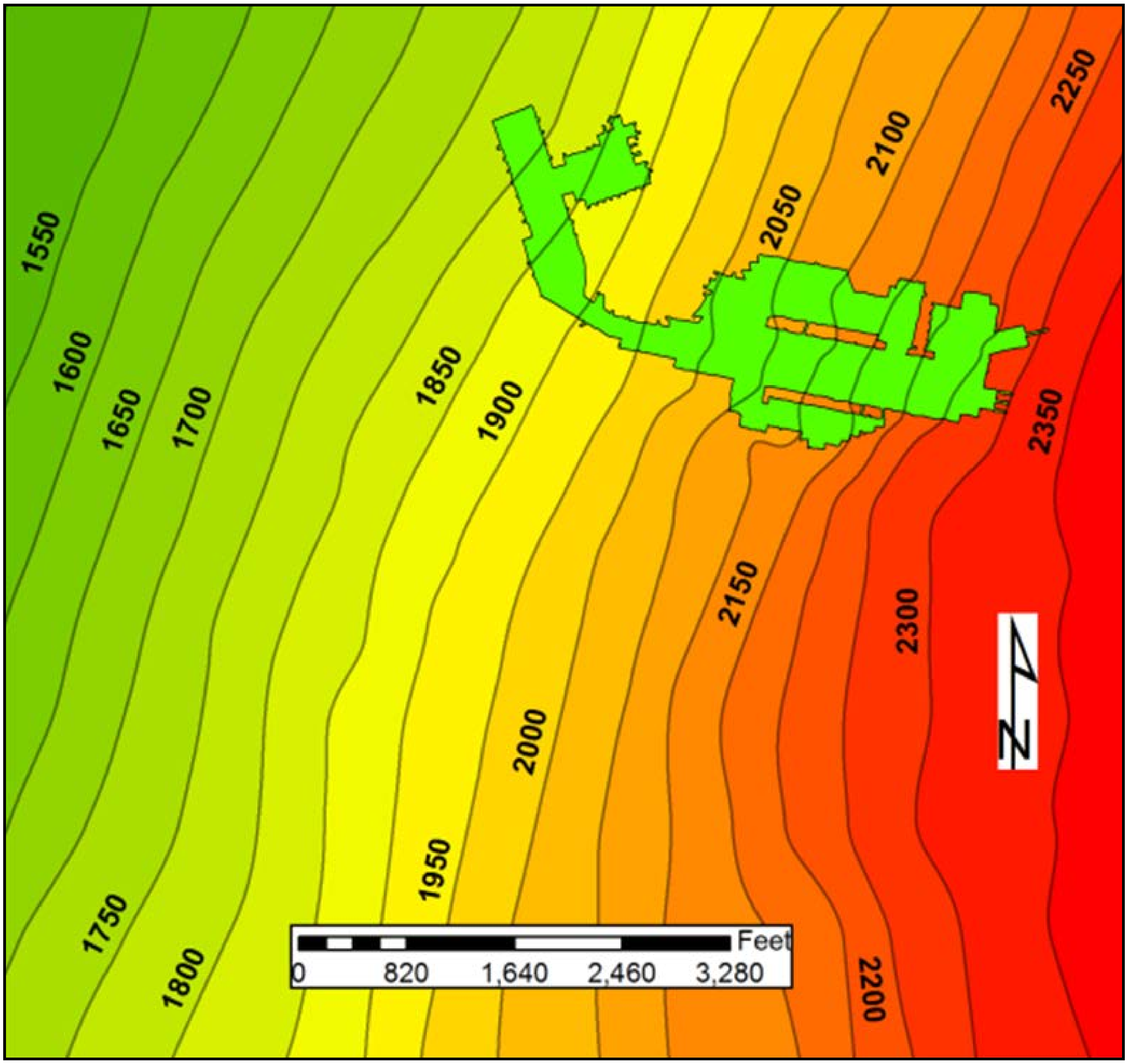
E.2 Barbara Surface Contour Map with State Roads



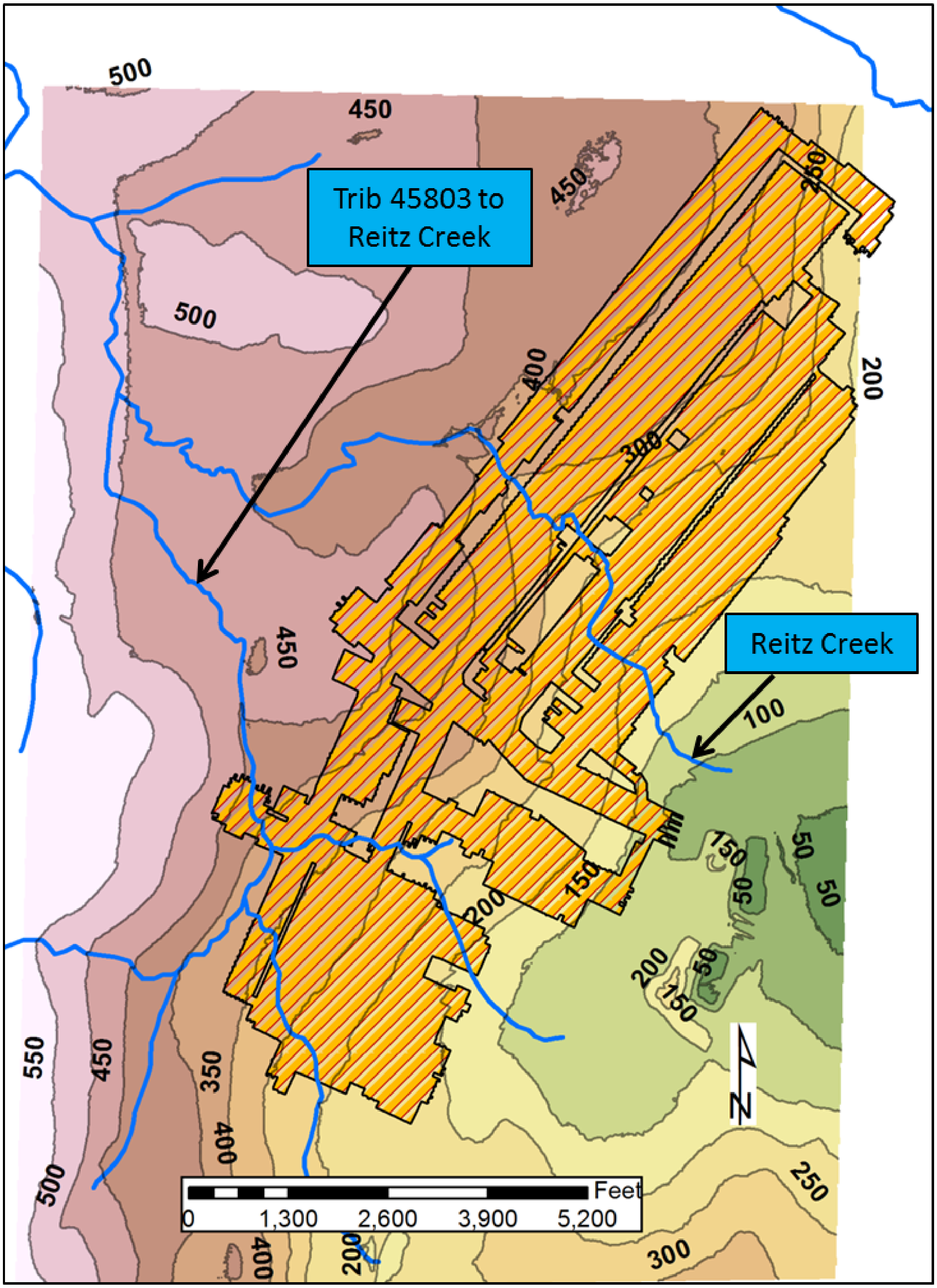
E.3 Barbara No. 1 Coal Structure Contour Map



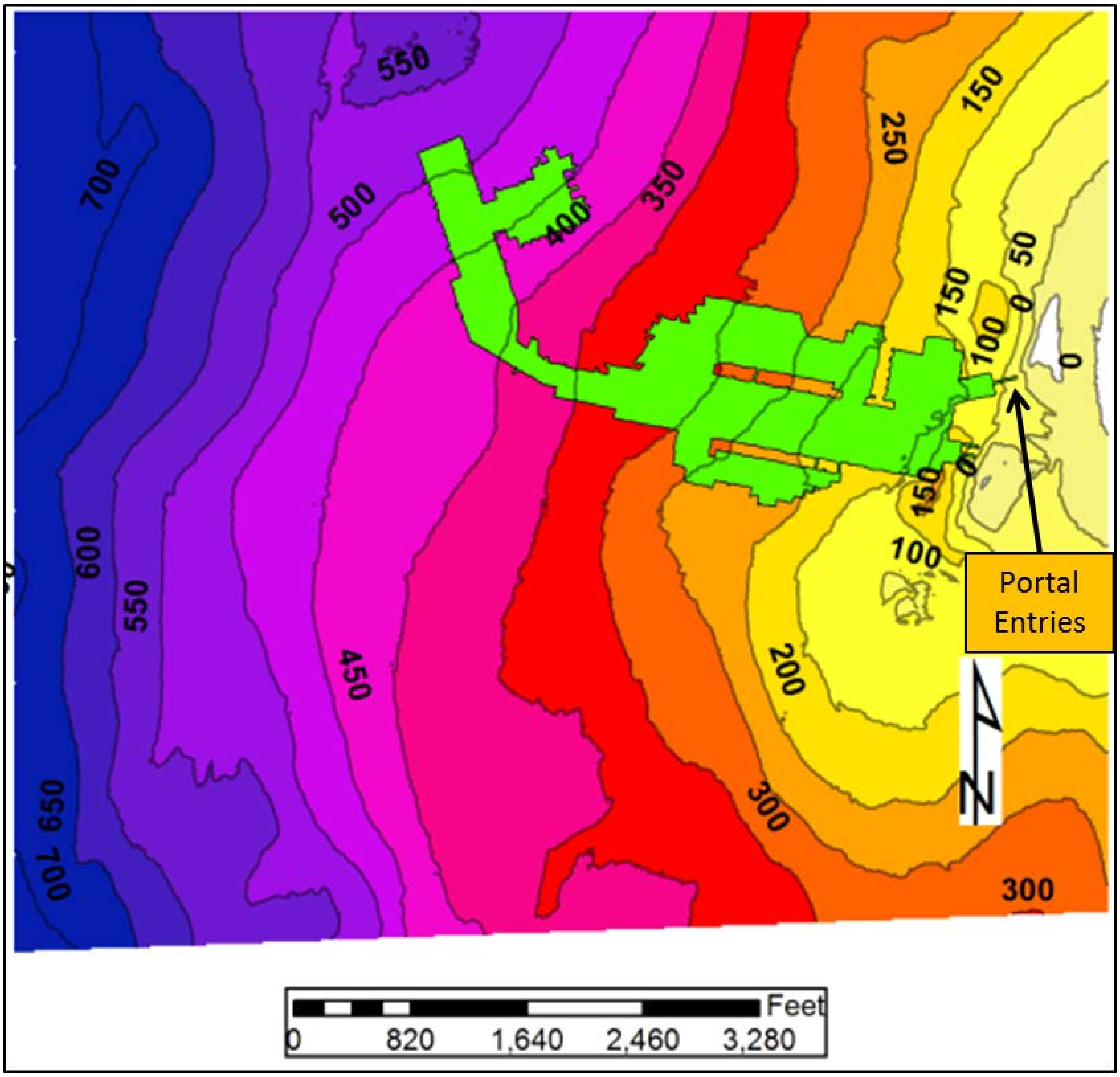
E.4 Barbara No. 2 Coal Structure Contour Map



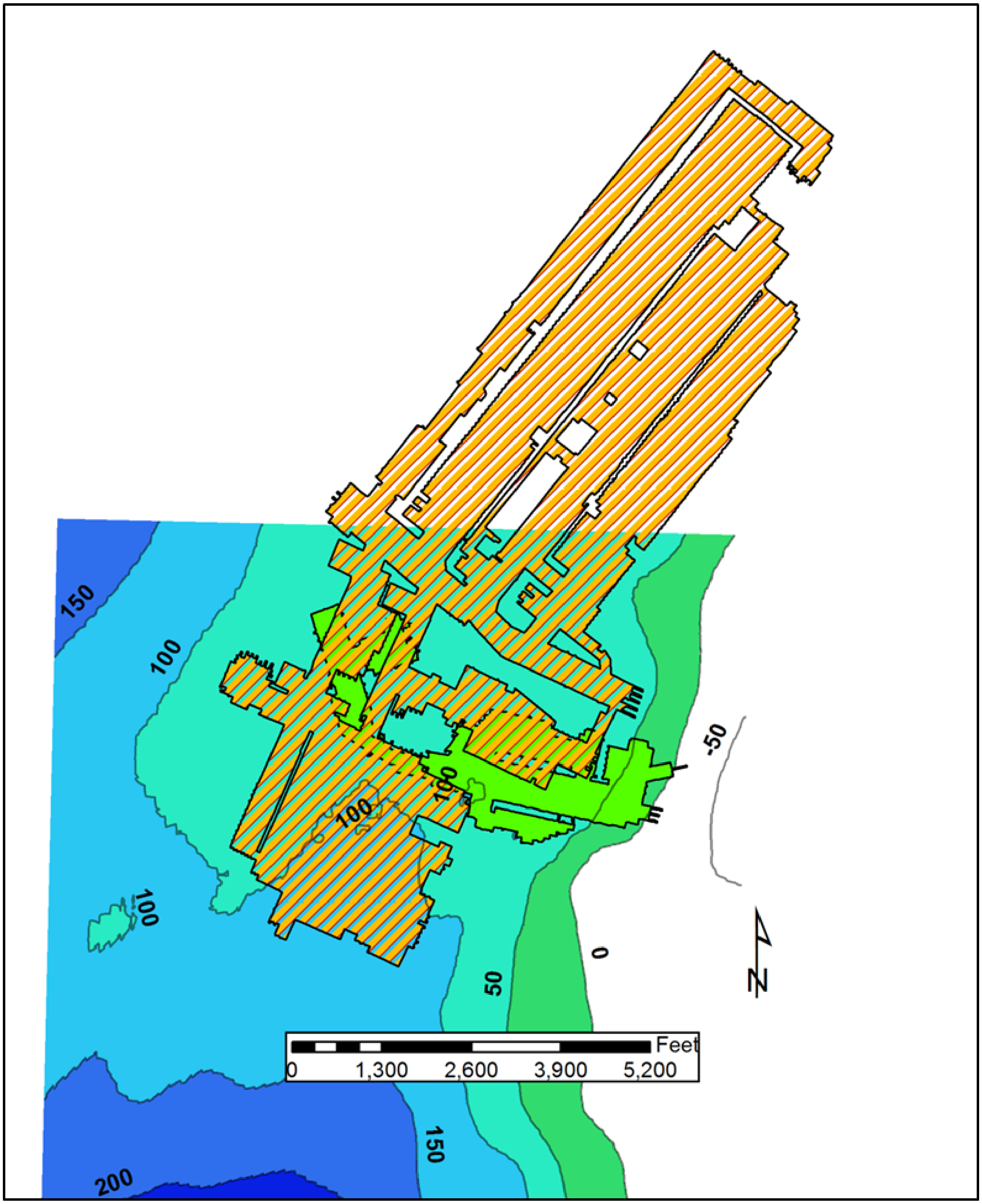
E.5 Barbara No. 1 Overburden Contour Map with Streams



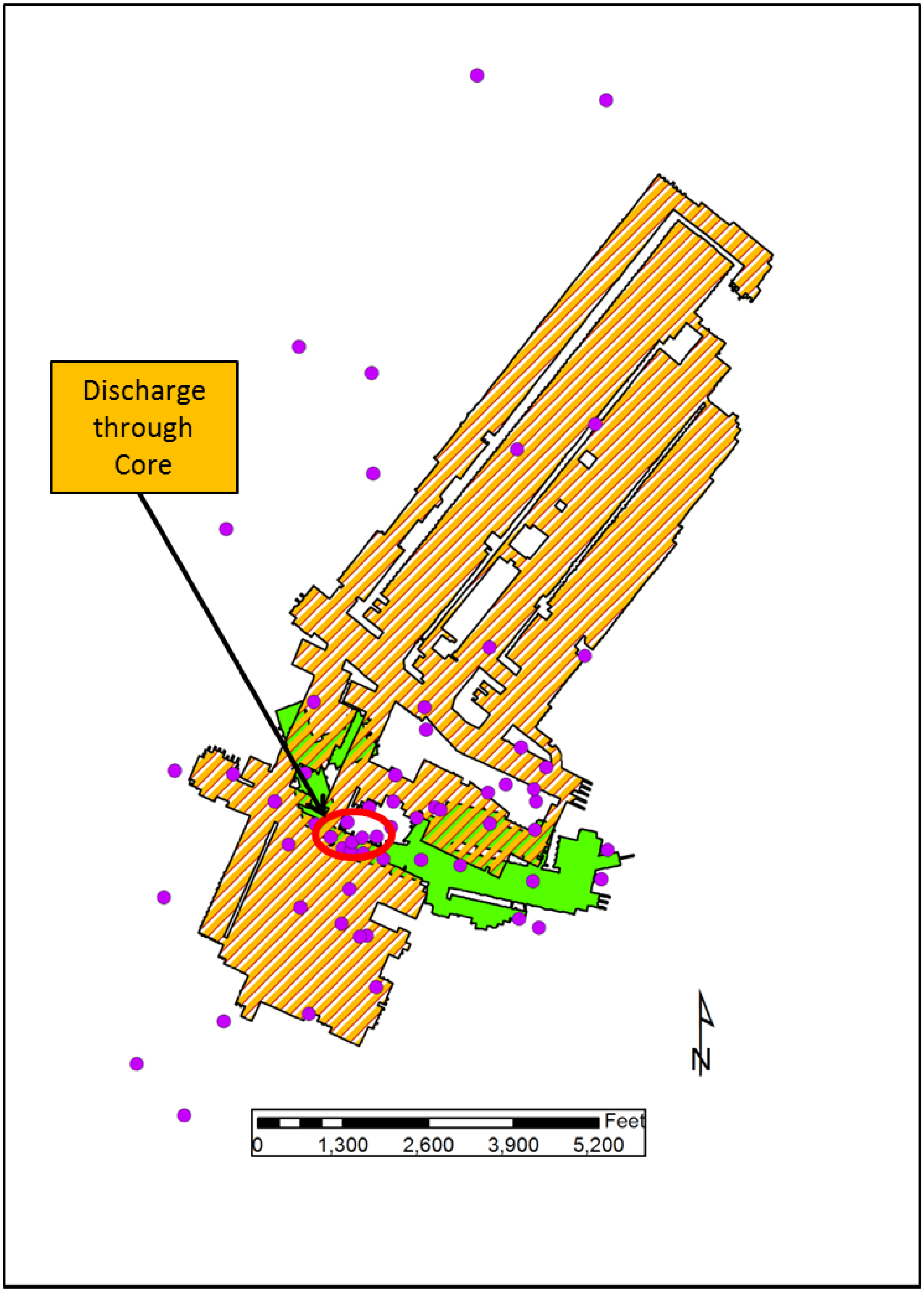
E.6 Barbara No. 2 Overburden Contour Map



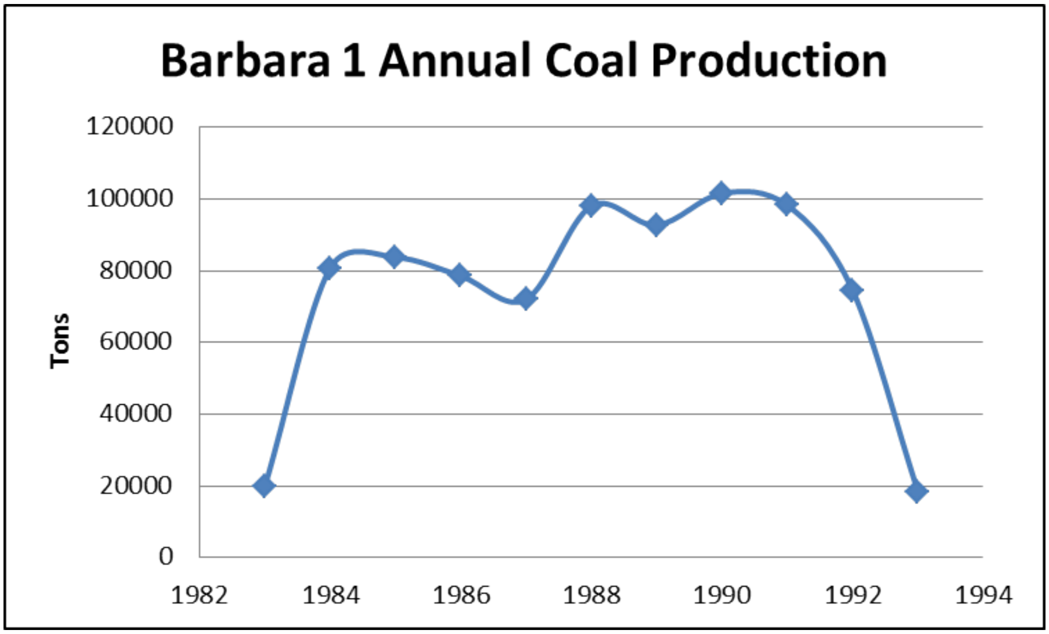
E.7 Barbara Interburden Contour Map



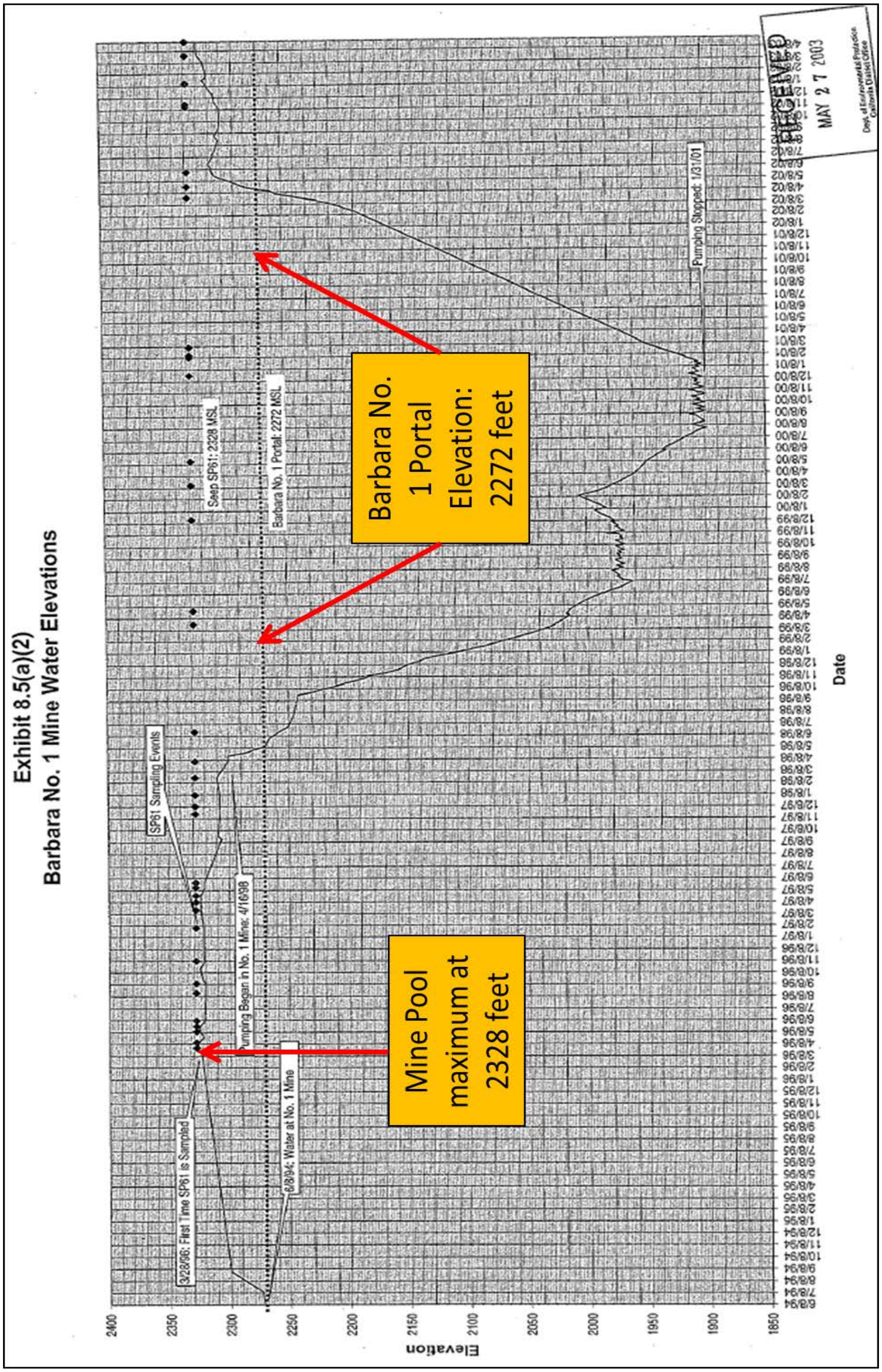
E.8 Barbara Core Logs Locations



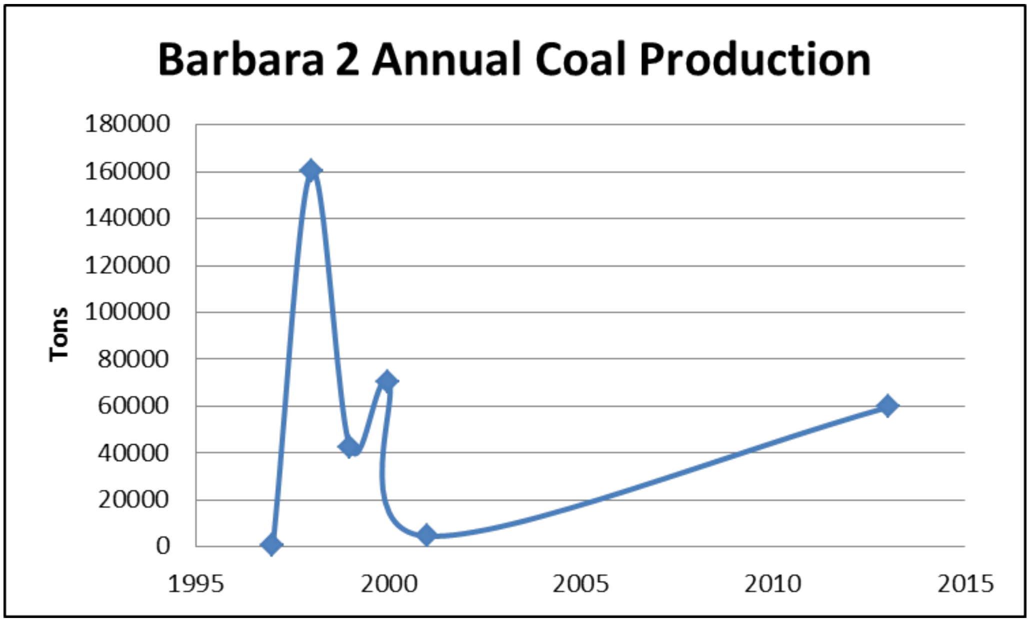
E.9 Barbara No. 1 Coal Production Timeline (MSHA, 2014)



E.10 Barbara No. 1 Mine Pool (Barbara Application: Module 8)



E.10 Barbara No. 2 Coal Production Timeline (MSHA, 2014)

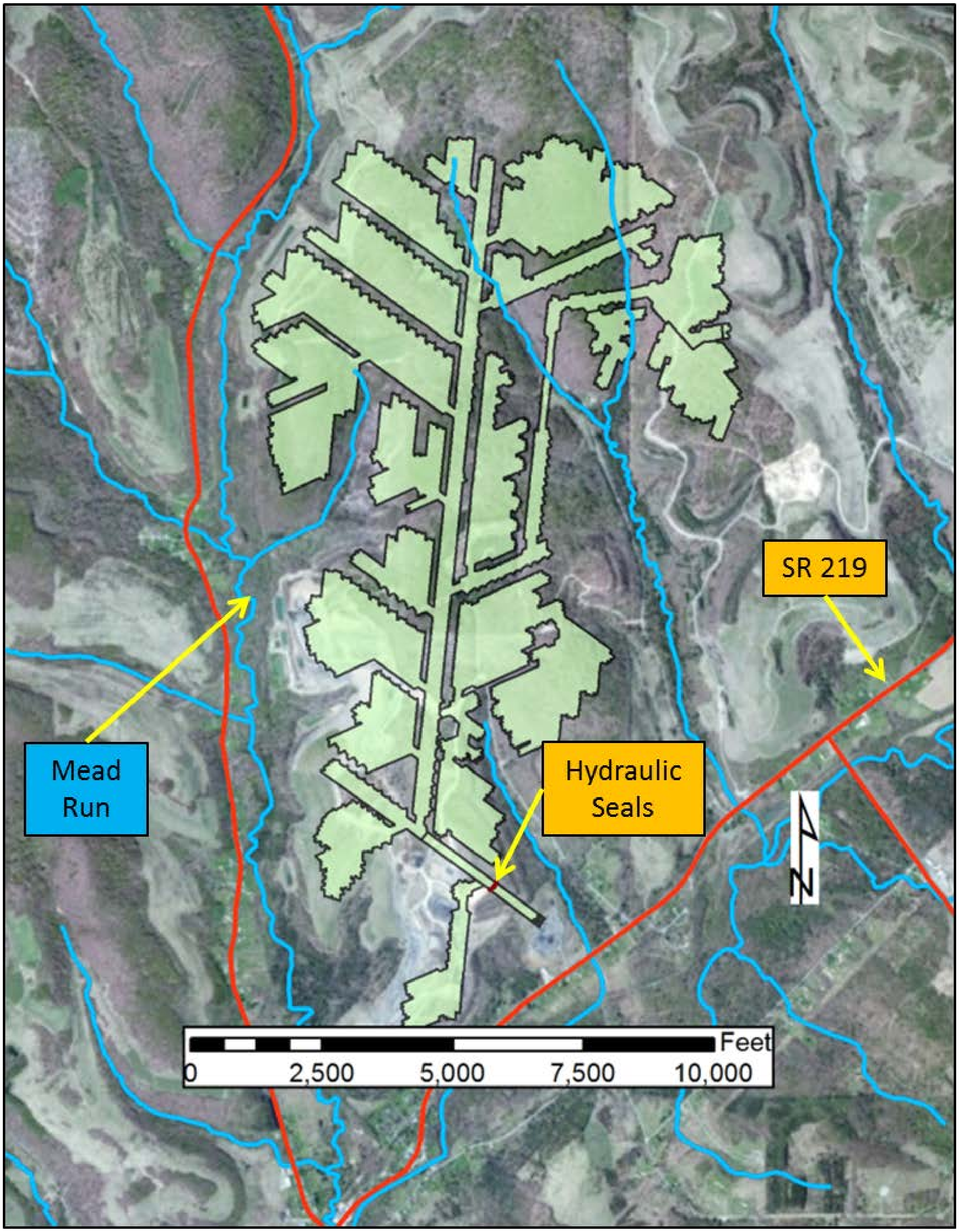


APPENDIX F

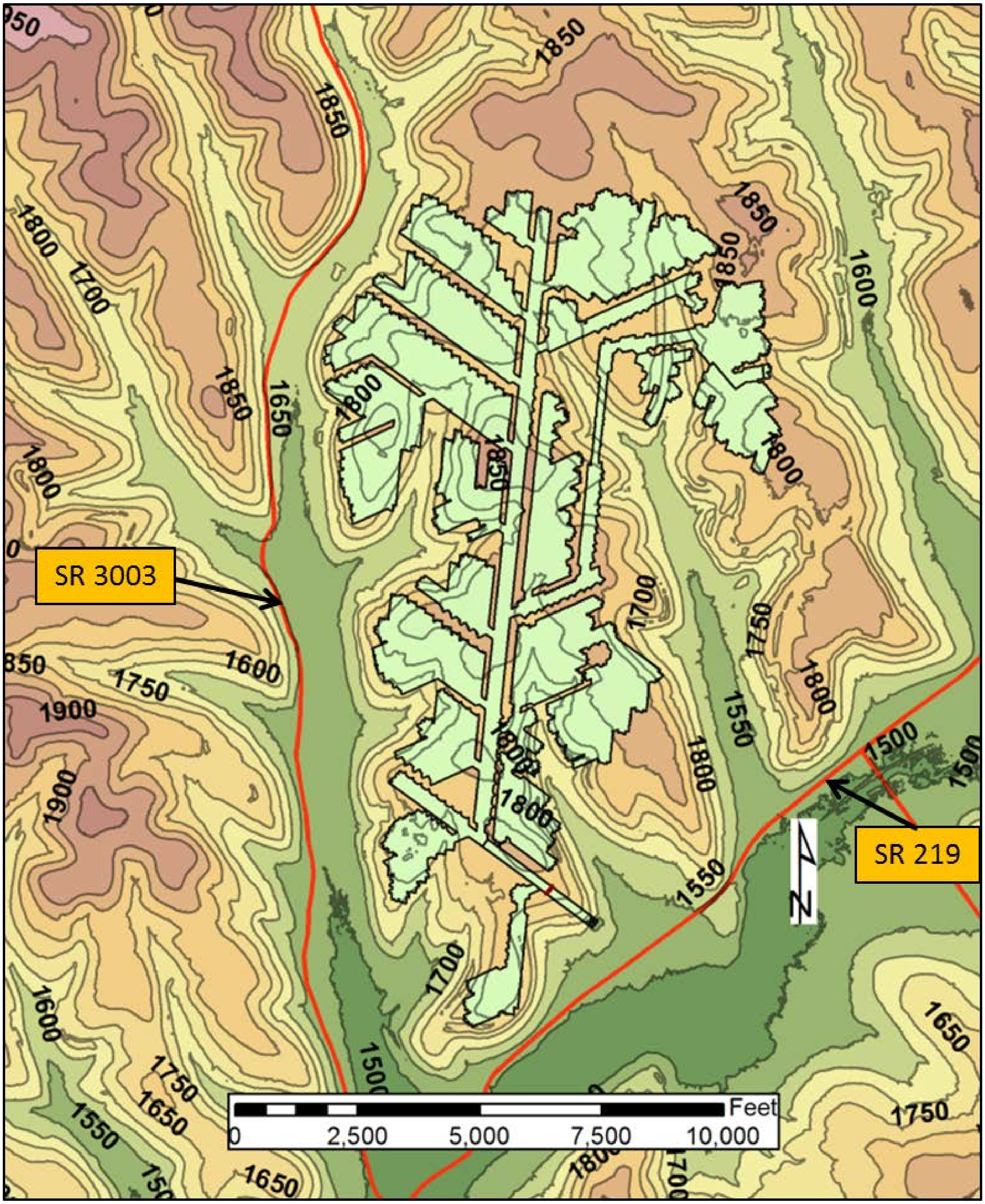
LITTLE TOBY

The contents of Appendix F are the supplemental data and maps generated for Little Toby. These figures were generated through the use of Geographic Information Software, ArcMap 10.1. The mine outlines, contour maps, and plotted points were created from 6-month mining maps composed by individual companies and obtained by the state and also topographic maps found through online resources (PASDA).

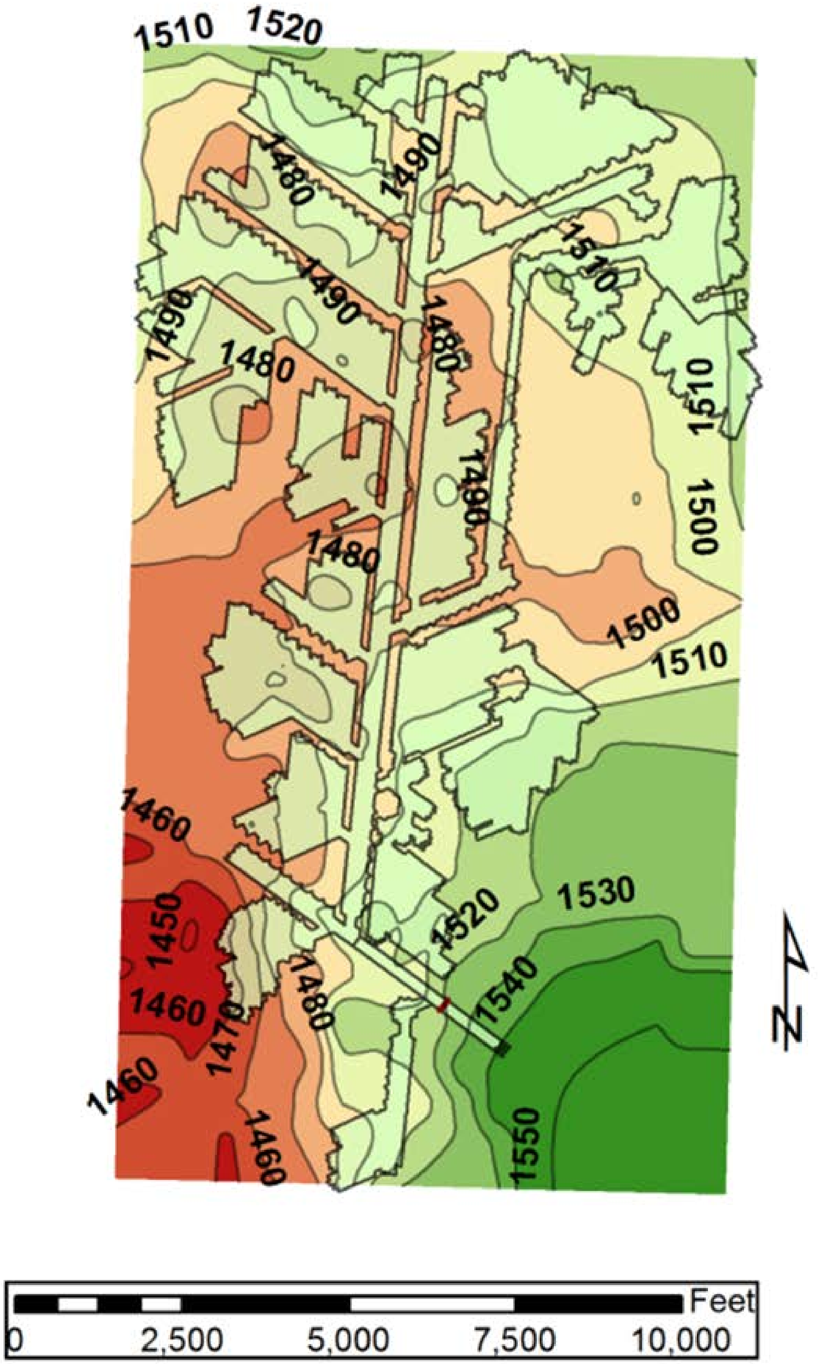
F.1 Little Toby Satellite Image Map with State Roads and Streams



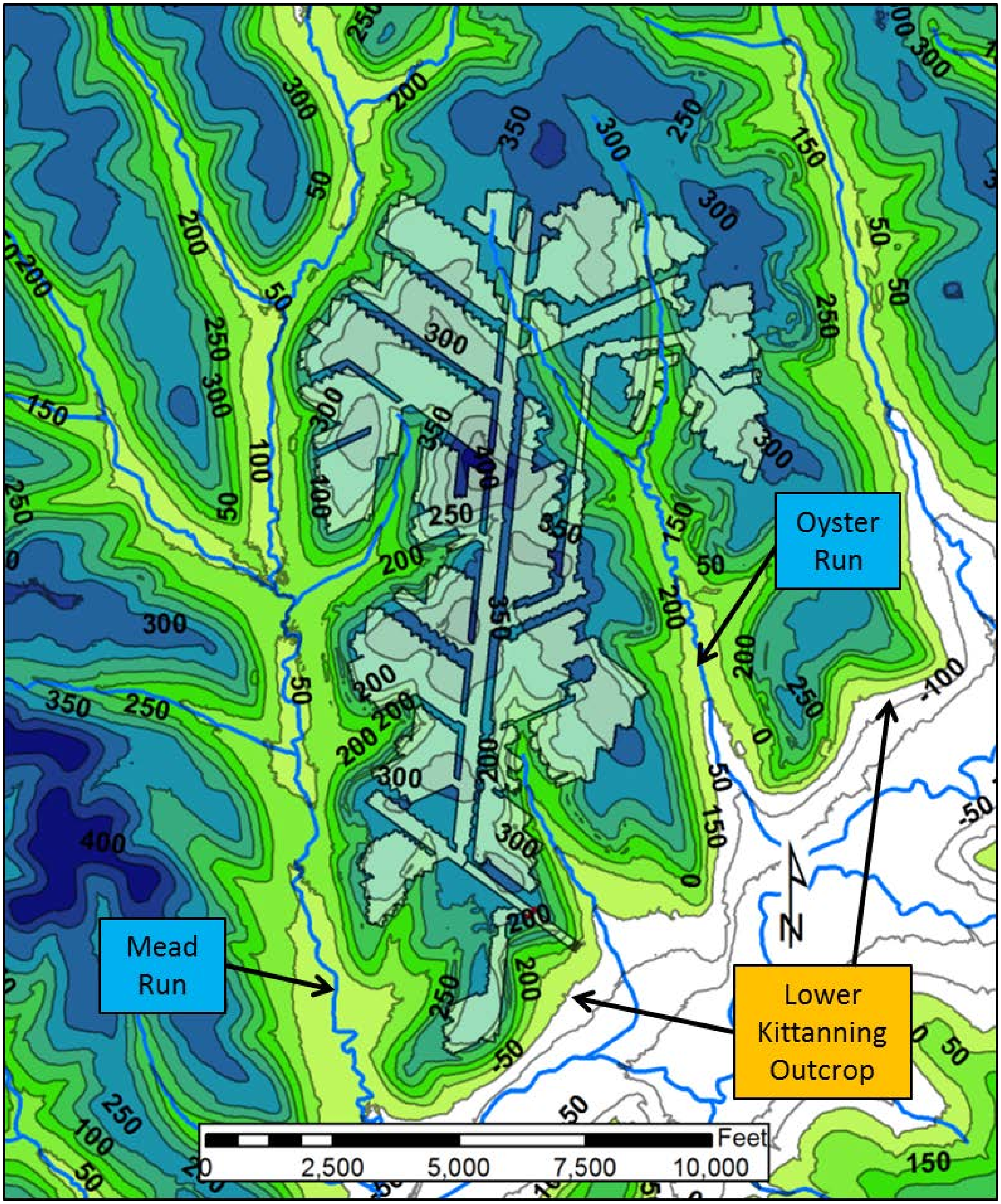
F.2 Little Toby Surface Contour Map with State Roads



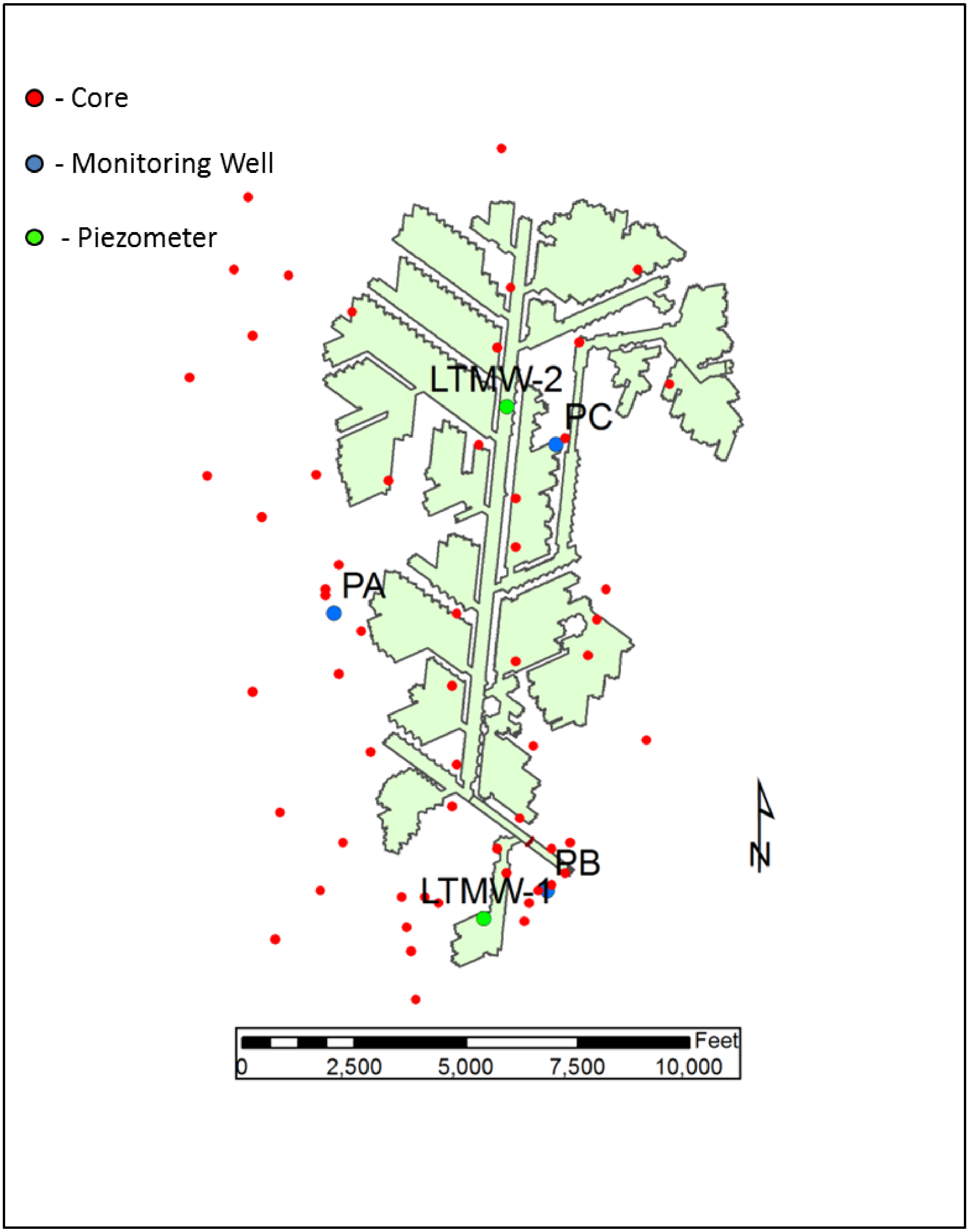
F.3 Little Toby Coal Structure Contour Map



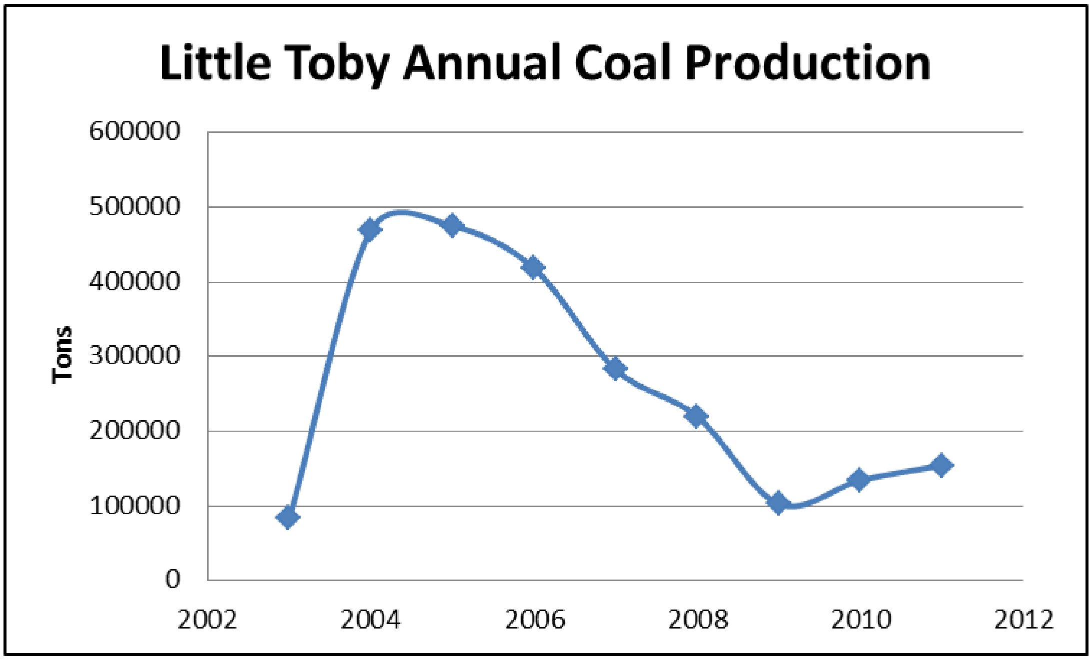
F.4 Little Toby Overburden Contour Map with Streams



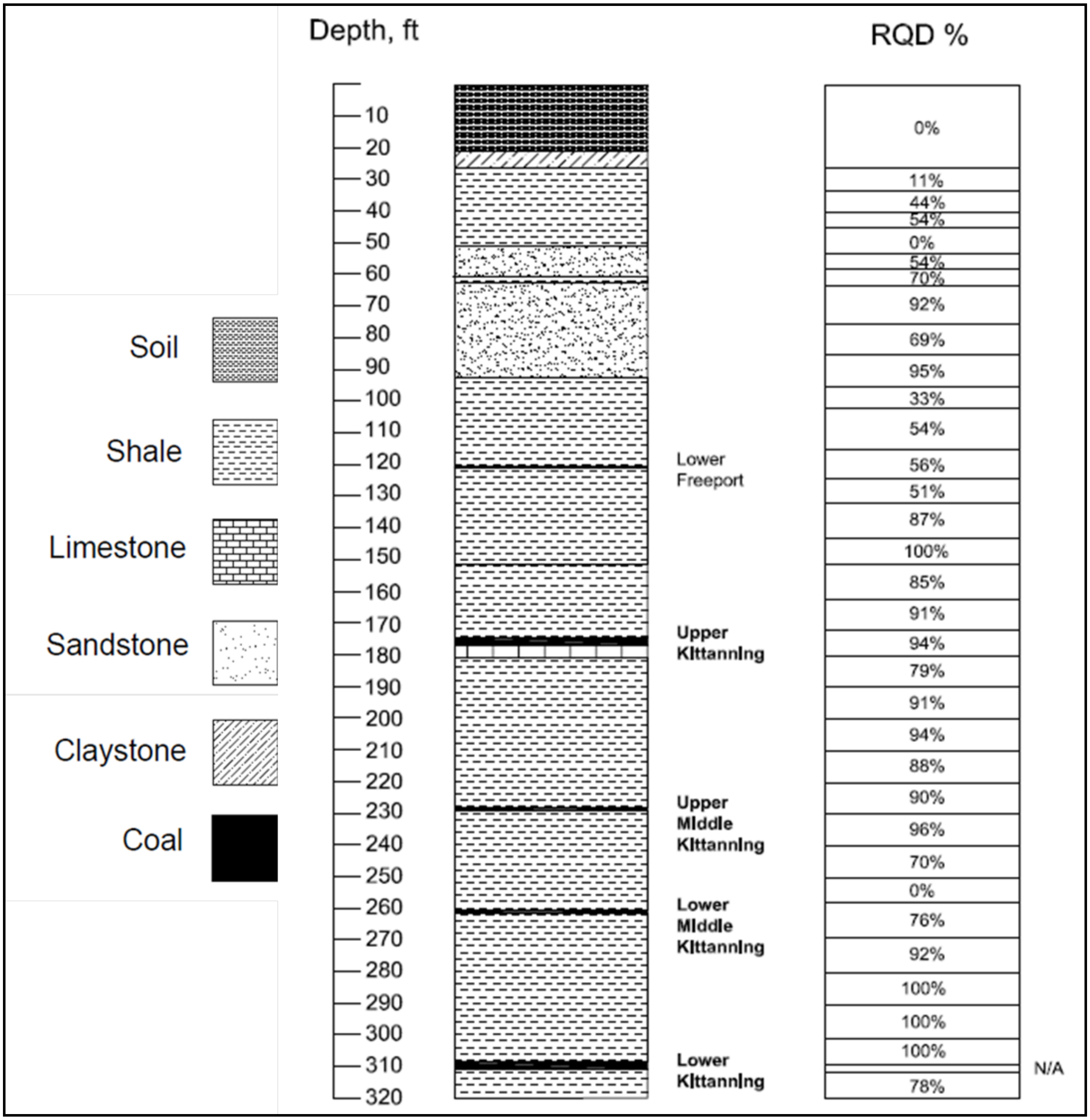
F.5 Little Toby Core Logs and Piezometer Locations



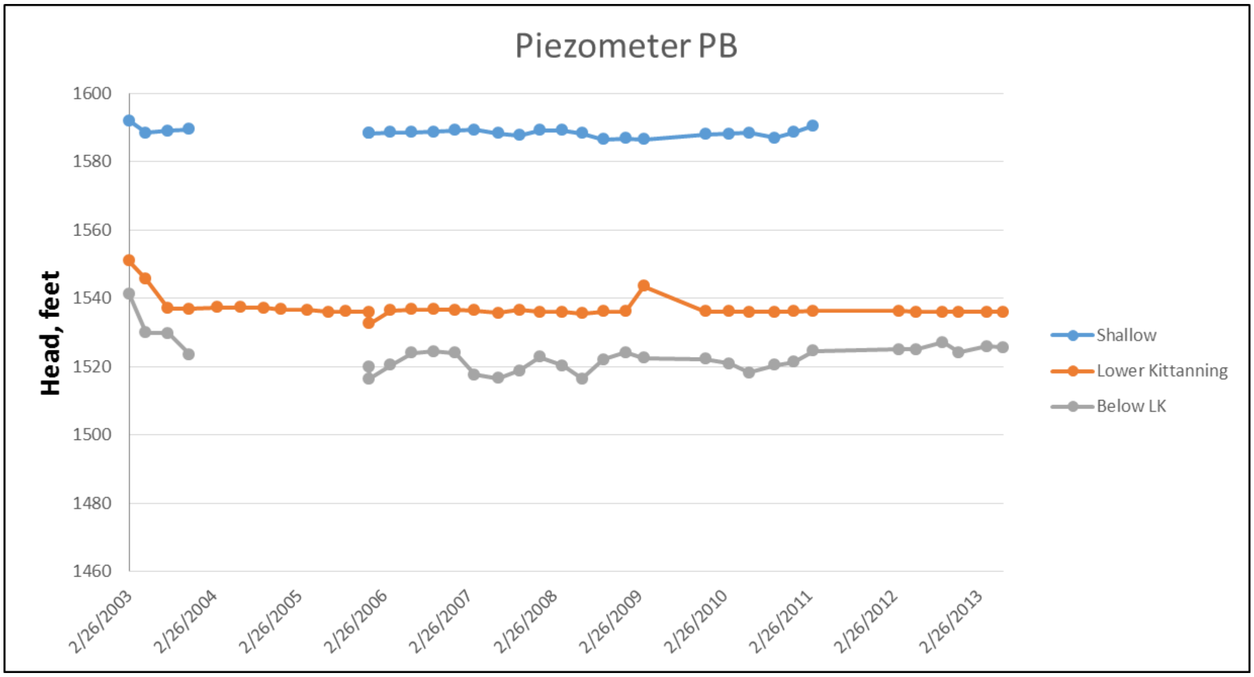
F.6 Little Toby Coal Production Timeline (MSHA, 2014)



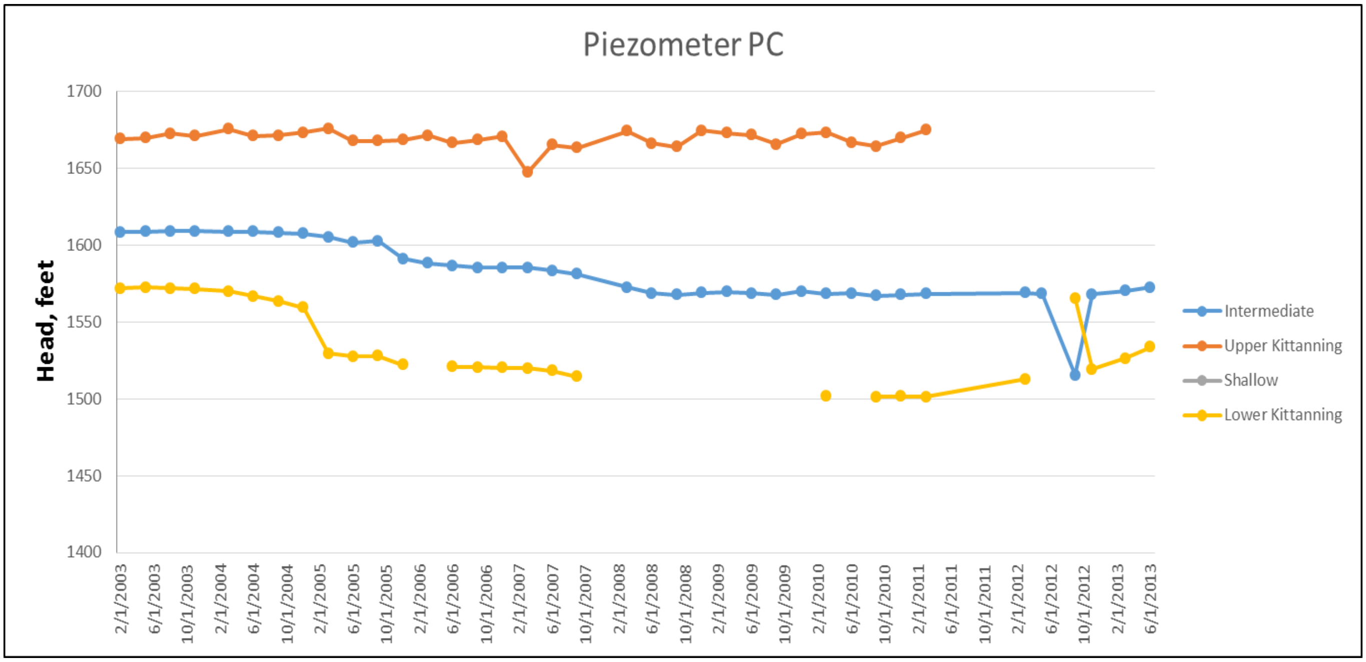
F.7 Little Toby Core Log Brock 96-1 and RQD Values



F.8 Little Toby Piezometer PB



F.9 Little Toby Piezometer PC



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