The Role of Barriers beneath Stream Beds in Preventing Unplanned Discharges from Northern Appalachian Coal Mine Pools

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Abstract A high profile unplanned discharge at the Margaret #7 Mine in 1979 provided information on the performance of the strata barrier between the mine pool and the lowest point on the surface. Additional information collected from the Urling #1, #2, #3, and the Parkwood Mines provide examples of successful strata barrier designs. Three important factors were identified:

1. *The thickness of thestrata barrier*,
2. *The magnitude of the positive hydraulic head differential*, *and*
3. *The absence of high extraction ratio mining beneath stream channels*.

This study also found that strata barrier fracture permeability may be locally impacted by the overlying orientation and conditions of the stream channel. Conditions impacting fracture permeability include:

1. *The natural fracture systems*,
2. *Valley stress-relief*, *and*
3. *Excessive horizontal stress conditions*.

All of these factors and conditions should be considered when designing strata barriers to control unplanned discharge from Pennsylvania mine pools

Problem

Unplanned discharges from northern Appalachian coal mine pools, while infrequent, have the potential to negatively impact surface water quality. This is because the typical northern Appalachian coal mine pool often has a high metal content and does not meet United States (U. S.) clean water standards as mandated by the Surface Mining Control and Reclamation Act (SMCRA, 1977). Initially after the passage of this Act, engineers concentrated on the performance of down-dip coal barriers to resist discharges to surface waters (Figure 1). Barrier design, a difficult issue, not fully recognized until the 1979 high profile discharges occurred at the Margaret # 7 Mine in Indiana County, Pennsylvania. After these events, engineers focused on the performance of strata barriers between the mine pool and the overlying surface streams.

Background

Up until the passage of the SMCRA underground operations, with the potential to discharge waters not compliant with existing clean water standards, were allowed to mine up-dip, preventing mine pool development. Planned discharges of waters high in metals to surface streams were allowed not only during development but also after abandonment. SMCRA changed this practice by requiring operations to enter the coal reserve at its highest elevation and mine down-dip. This method causes water to pool within the mine after abandonment. A requirement for compliance is that the barriers surrounding the abandoned mine must contain the pool. These barriers must also prevent poor quality water from discharging to the surface.

What makes this problem particularly difficult to regulate is the diverse geologic character of both coal and strata (bedrock) barriers. The hydraulic characteristics of coal barriers are better understood (Iannacchione, el al., 2013b). The performance of strata barriers, the bedrock between the coal mine pool and the overlying stream channels, are not as well understood. For example, in the northern Appalachian Coal Fields, certain stream bedrock channels are recognized for a greater intensity of highly permeable fractures. High concentrations of near vertically oriented fractures within the bedrock below stream channel (this report will suggest an overburden less than 80-m) can cause:

- High water inflow from the stream into developing mine entries, especially at lower overburdens
- Unstable ground conditions
- Increased flow through highly fractured strata from

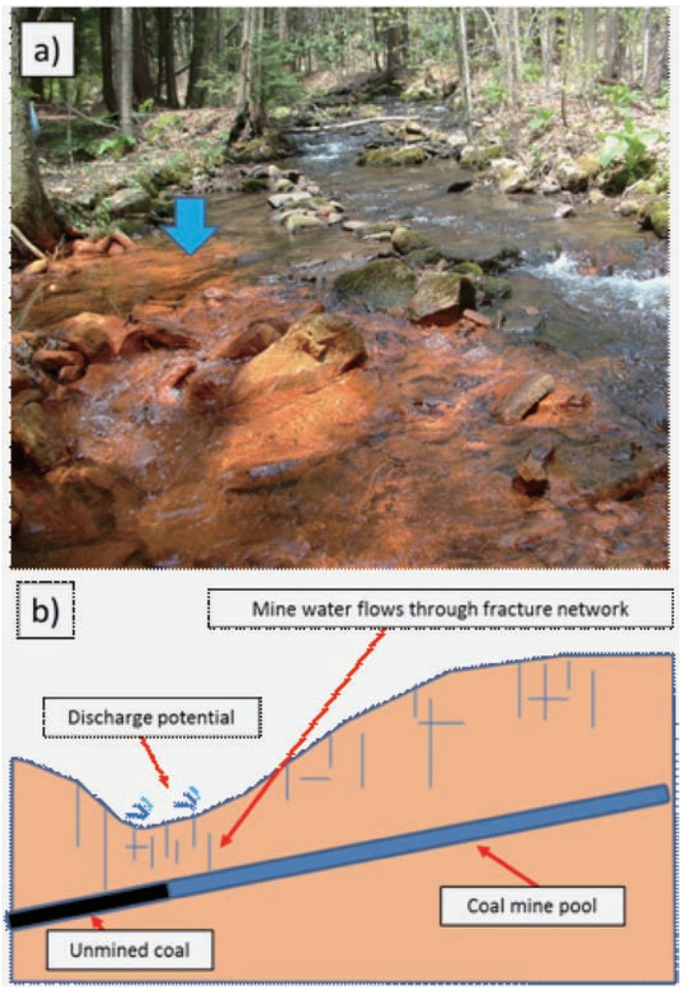

Fig. 1 a) Unplanned discharge at the Grove #1 Mine (Photo by B. Means in Iannacchione, et al., 2013a) and b) Generalized cross-section showing the potential from waters contained within an underground coal mine pool to discharge vertically through fractured bedrock to an overlying stream channel. In this case, the pool elevation must be above that of the overlying stream channel.

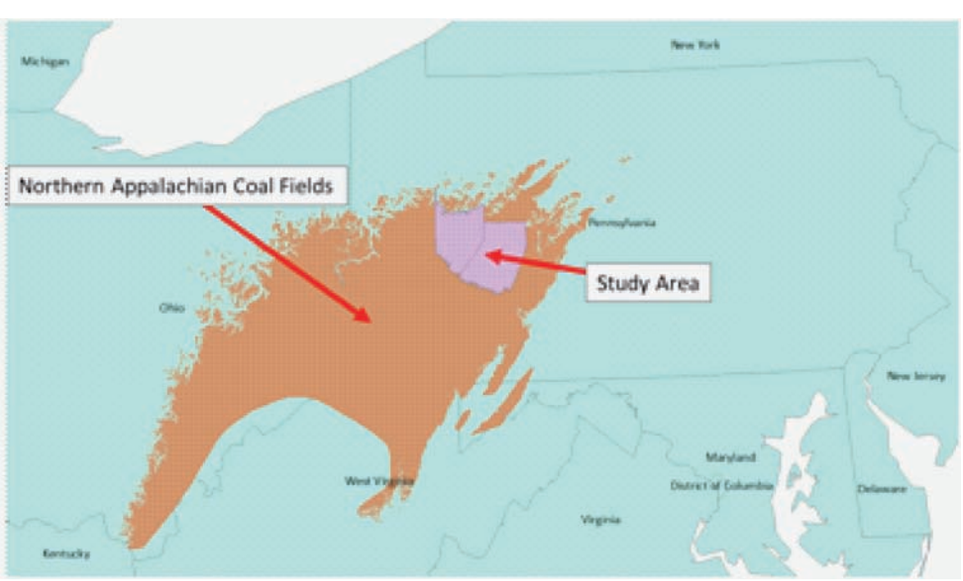

Fig. 2 Location of the study area within the northern Appalachian Coal Fields, U. S.

the mine to the surface when under a positive hydraulic head differential.

Study Area

The northern Appalachian Coal Field extends over four U. S. states: Maryland, Ohio, Pennsylvania, and West Virginia (Figure 2). The study area is located within two Pennsylvania Counties: Armstrong and Indiana. In this area, underground bituminous coal mining has occurred for more than 125 years. The Arab Oil Embargo of 1973 spurred a significant expansion in Pennsylvania coal production, resulting in the development of several large underground room-and-pillar mines. Most of the mines discussed in this study were either developed or expanded during or after this era.

In this study, seven underground bituminous coal mines were analyzed (Figure 3). Reasons for their inclusion are:

- Margaret # 7-An unplanned discharge occurred in 1979 shortly after the minehad been abandoned and reached its maximum pool elevation
- Yatesboro #2 & #3-This mine was abandoned prior to the development of Margaret # 7 and accepted discharge waters through a connection between the mines. It also established the maximum potential height for the Margaret # 7 mine pool.
- Urling #1-It is noteworthy because no unplanned discharge occurred while undermining Crooked Creek.
- Urling # 2-Significant water inflow and ground control problems were encountered when mining near or under Curry Run.
- Urling #3-Is connected to both Urling #1 via a set of horizontal entries and to Urling #2 via a vertical shaft, creating a large mine pool with significant elevation differences, hence large water head.
- Urling Complex-The three Urling mines (#1, #2, and #3) are connected, creating one large mine pool.
- Parkwood-Is developed adjacent to theUrling Complex mine pool, receiving some of its water within the box-cut side walls during maximum pool elevation.
- Tanoma-Provided solid evidence of the effects of valley stress-relief effects and horizontal stress conditions both of which can impact water inflow quantities and ground control conditions.

Lastly, it should be noted that the maximum mine pool elevation includes the waters contained in overlying connected fracture systems. This can often result in maximum pool elevations above the highest point in the mine.

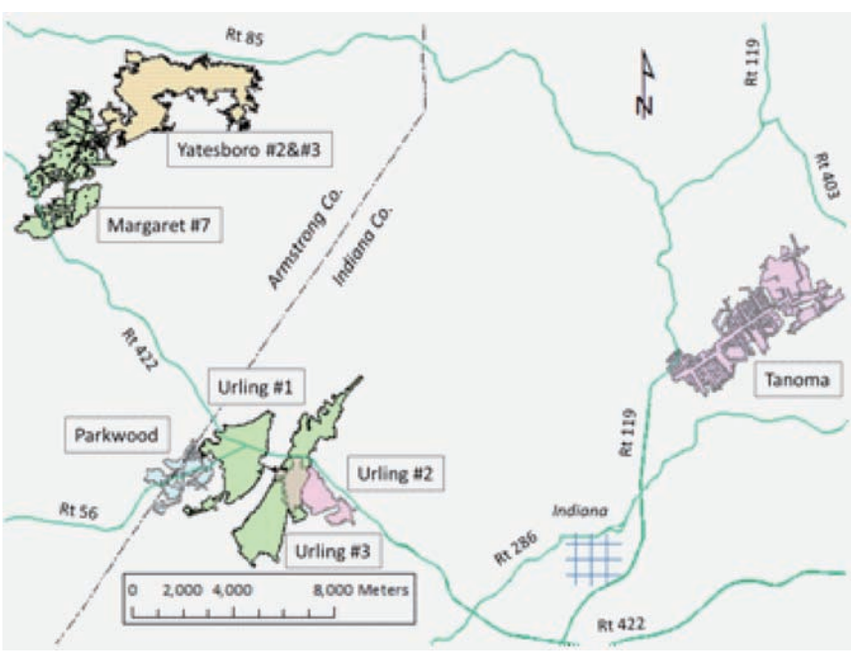

Fig. 3 Location of the seven mines within the study area. Also shown are the major state highway routes and county boundaries.

The 1979 Margaret #7 Mine Unplanned Discharge

A pollution problem was first noticed along a well-known trout fishing stream, Tributary 46340 (now referred to as the Tributary to Cherry Run, Figure 4), in January of 1979 (Ferrick, 1979). The pollution was soon identified as water discharge from the Margaret # 7 Mine. This unplanned discharge occurred through six 'holes' (probably open fractures) in the creek bottom. It took 1-year to draw

down the mine water and stop the discharge (Anon, 1979).

The Margaret #7Mine was first opened in the 1920's, closed in the 1950's, and resumed production in the 1960's until final abandonment in 1977. At this time, pumping ceased and the underground openings began to fill with water. The initial developments started near the outcrop of the Upper Freeport Coalbed in the north end of the reserve and mined down-dip, dropping approximately 80-m in elevation (Figure 4). The maximum overburden is 110-m under the hilltops in the southern portion of the mine. The elevation at the discharge point is 339.9-m, the lowest surface elevation over the mine. The strata barrier thickness, between the discharge point on the Tributary to Cheery Run and the underlying mine pool, is approximately 35-m.

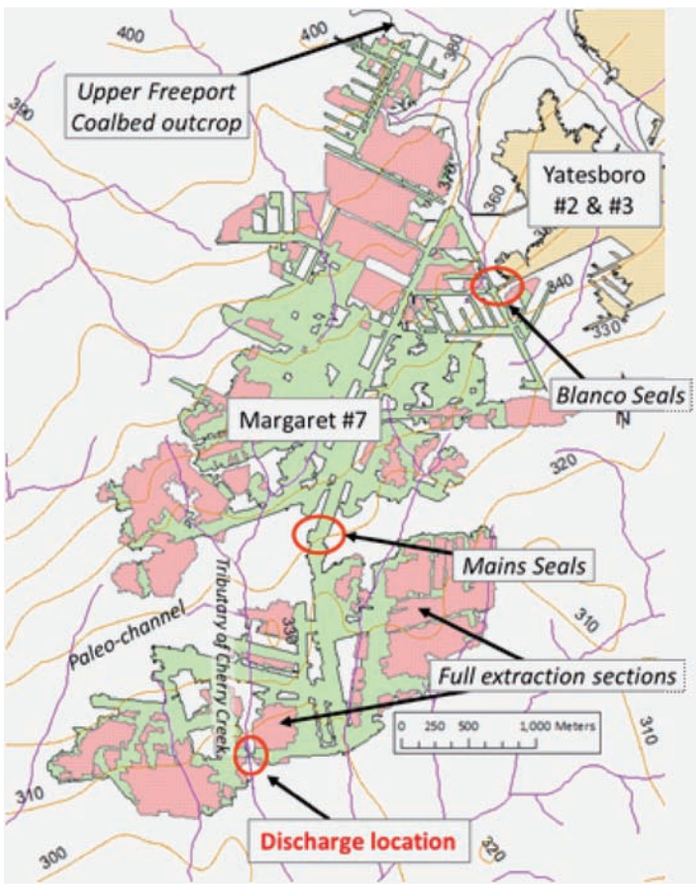

Fig. 4 Margaret #7 Mine outline showing the Upper Freeport Coalbed outcrop and structure elevation contours, location of mine seals, connection with the Yatesboro #2 and #3 Mines, stream channels above the mine, and location of the 1979 unplanned discharge. Note the close location of full extraction sections to discharge location.

At the time of this discharge, the mine was designed to have two independent pools (upper and lower) separated by four hydraulic seals (elevation of 329.2-m) along a north-south oriented mains (Figure 4). These mains drove through an area where the coalbed thickness was negatively affected by a large paleo-channel system (Figure 4). The upper mine pool occupied the area north of the paleo-channel and the associated seals. In addition, two hydraulic seals (Blanco Seals) were constructed along a set of connecting entries from Margaret #7, east to the Yatesboro #2 and #3 Mines. Prior to the passage of the SMRCA (1977) legislation, mines were not restricted from joining to form interconnected mine pools. A portion of the water from the lower pool could drain through a shaft at the southern end of the Margaret #7 Mine into the underlying Jane Mine. An important factor is that full extraction mining occurred within 46-m (27-m horizontal and 37-m vertical) of the discharge point on the surface.

When the 1979 discharge occurred, the mine pool would logically need to be, at a minimum, above the surface elevation of the stream bottom (339.2-m). This is unlikely since the fractures within the strata barrier could have produced resistance to the movement of the water. In this minimum mine pool scenario, the main entry seals must allow water to move from the upper to lower pool (Figure 5a, mine pool elevation = 339.2-m). Data collected after the discharge confirmed that the Blanco seals allowed Margaret #7 mine pool water to discharge into the Yatesboro #2 and #3 Mines (Legarsky, 2015). Therefore, the maximum elevation of the Margaret #7 mine pool during the 1979 discharge would

have been 351.3-m, the elevation of the Blanco Seals (Figure 5b). In the likely event that the mine pool were at this maximum elevation, a positive hydraulic head differential of 11.4-m would have been available to push water through the fracture network in the strata barrier between the Tributary to Cherry Creek and the underlying Margaret #7 mine pool. The orientation of this stream channel over the unsuccessful strata barrier is N 7° W.

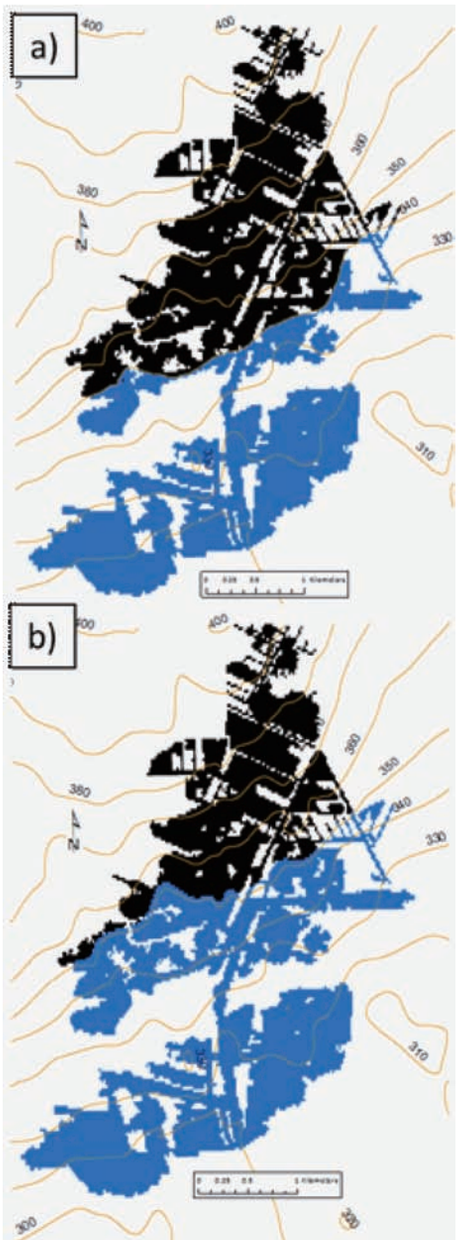

Fig. 5 Minimum and maximum possible Margaret #7 mine pool (blue color) elevations during the 1979 unplanned discharge along the Tributary to Cherry Creek. a) Minimum pool elevation (339.2-m) is equivalent to the surface elevation at the discharge point; b) Maximum pool elevation (351.3-m) is controlled by the leaking Blanco Seals allowing Margaret #7 water to enter the Yatesboro #2 and #3 Mines.

Other Study Area Bedrock Barriers that Prevented Discharges

Within the study area, another large mine pool, the Urling #1, #2, and #3 Mines (herein referred to as the Urling Complex), contained multiple strata barriers that successfully prevented unplanned discharges (Figure 6). These three mines were developed by the Keystone Coal Mining Corporation from 1973 to 1975. Urling #1 and #3 are both in the Lower Freeport Coalbed and the Urling #2 is in the Upper Freeport. In this area, the two coalbeds are separated by approximately 25-m, primarily comprised of bedded shales and sandstones. The Urling #1 and #3 mines are connected by a two-entry development that transects and paleo-channel. The Urling #2 and #3 Mines are connected via a common slope. All three mines were abandoned from 1989 to 1999. At one point, the Urling Complex mine pool reached a maximum elevation of approximately 300-m (Foster, 2015).

The most critical strata barriers in the Urling Complex mine pool occurred under Crooked Creek and above the Urling #1 Mine (red circle, Figure 7). At this location, the surface elevation is 296.6-m (lowest above all three mines) and the coal elevation is approximately 240-m. Therefore, the minimum strata barrier in this area is approximately 56-m thick. A maximum mine pool elevation of approximately 300-m would produce a positive hydraulic head differential of approximately 3.4-m. No discharges were observed along Crooked Creek in this area. The orientations of the major segments of Crooked Creek that comprised the successful strata barriers is, on average, N 62.5° W (Figure 7).

It should be noted that the adjacent Parkwood Mine in the Upper Freeport Coalbed (Figure 8a) reported relatively small amounts of water from the Urling Complex mine pool entered their box-cut side wall (Koricich, 2015). The Pennsylvania Department of Environmental Protection investigated this complaint and required that the Urling Complex mine pool be lowered below the elevation of the Parkwood box-cut. No further discharges were observed in the box-cut as a result of this action. Figure 8b shows the potential flow path from the Urling #1 Mine to the nearby Parkwood box-cut side wall. The water moves from the lower elevation Urling #1 Mine (252-m) to the higher elevation Parkwood Mine (283-m) under a positive hydraulic head differential. The flow path has a minimum distance of 330.5-m along a network of vertical joints and horizontal bedding planes (Figure 8b).

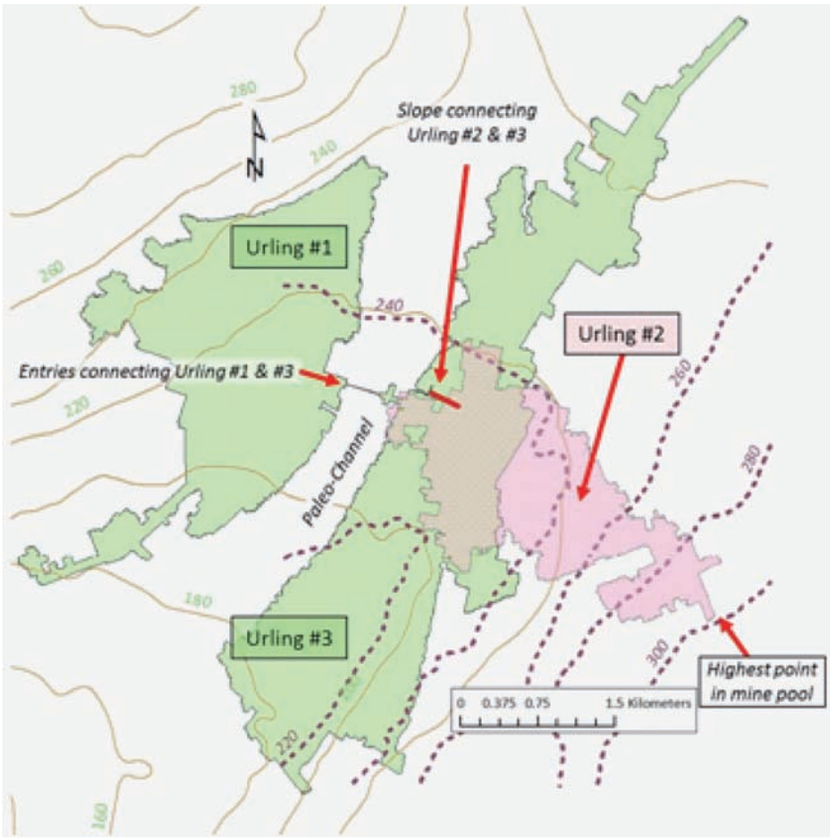

Fig. 6 Urling #1, #2, and #3 mine outlines and connecting features, i. e. slope between the Urling #2 and #3 and the entries connecting Urling #1 and #3. The Urling #1 and #3 are in the Lower Freeport Coalbed (structure elevation contours in green) while the Urling #2 is in the Upper Freeport Coalbed (structure elevation contours in pink).

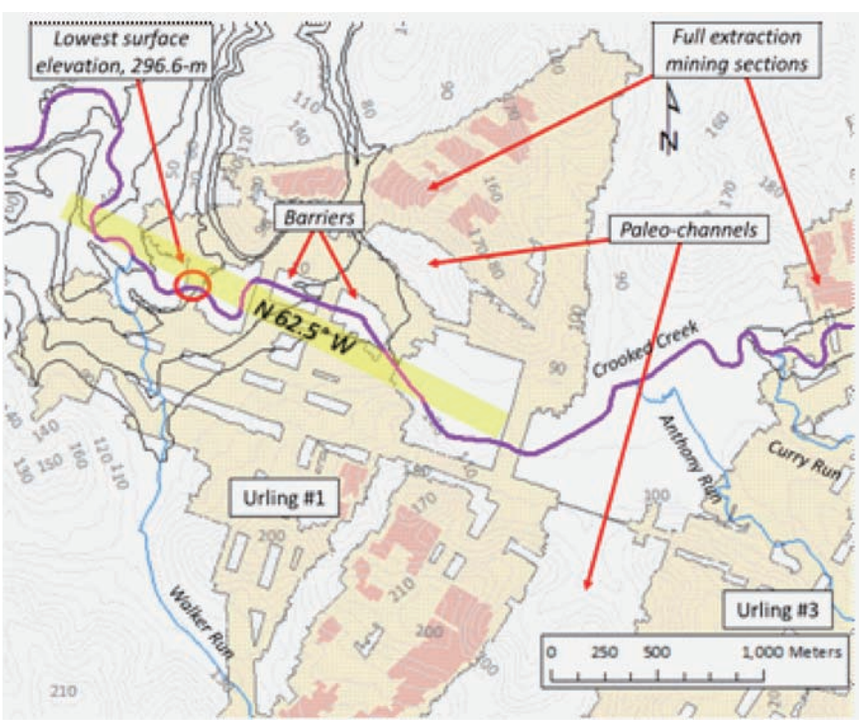

Fig. 7 Portions of the Urling #1 and #3 Mines underlying Crooked Creek, Curry Run, and Walker Run. Also shown is the lowest surface elevation (296.6-m) above the mine (along Crooked Creek). The overburden contours for the Urling #1 and #3 Mines are shown as black line (less than 80-m) or gray lines (greater than 80-m). The general orientation of the successful strata barrier stream channel is N 62.5° W.

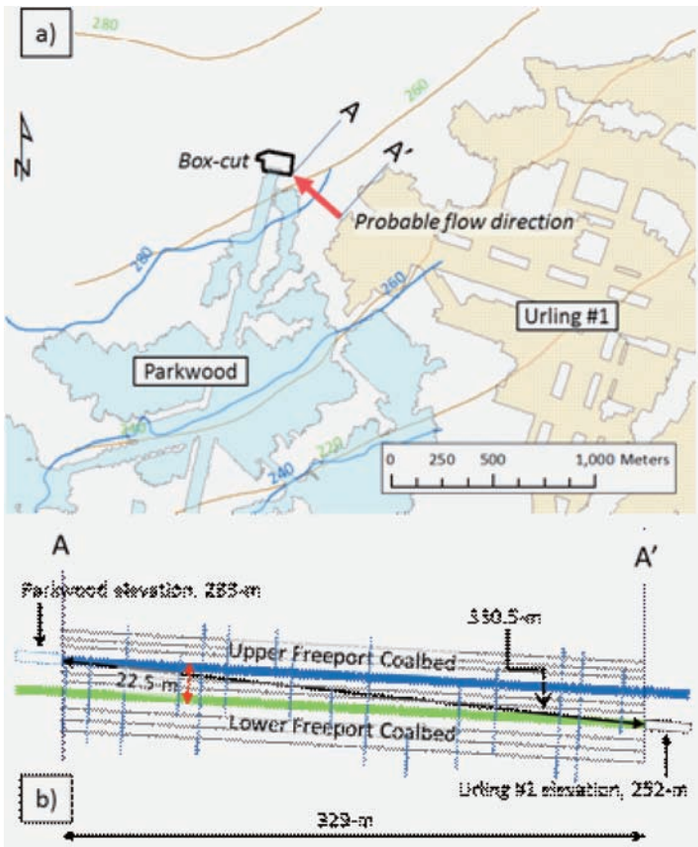

Fig. 8 Location of the Parkwood box-cut in relationship to the nearby Urling #1 Mine. a) shows the structure elevation contours for both the Upper (blue) and Lower (tan) Freeport Coalbeds. b) shows a generalized cross-section between the proposed flow path from the Urling #1 to the Parkwood Mine.

Discussion

Comparison of the Margaret #7 unplanned discharge and the successful containment of the extensive mine pool at the Urling complex (#1, #2, and #3 mines) provides valuable information for future design efforts. Table 1 lists the primary conditions of the two case studies. The successful Urling complex barriers has thicker bedrock barriers (21-m difference); less positive hydraulic head differential (8-m difference), and no full extraction mining. This study was not able to determine the relative importance of these three factors.

A potential additional factor has to do with how strata barrier fracture permeability is influenced by: 1) the natural fracture systems, 2) valley stress-relief, and 3) excessive horizontal stress conditions. Table 2 indicates that the study area barriers have different stream channel orientations. The unsuccessful discharge case (Margaret #7) has an orientation of N 7° W, while the successful cases (Urling Complex) range from N 74° W to N 35° W. These orientations are examined further in the following sections. Data presented in this paper suggest each of the above factors can prove locally important.

Tab. 1 Factors affecting unplanned discharges at the two case study mines.

	Margaret # 7	Urling Complex
Minimum surface elevation above mine, m	339.9	296.6
Maximum pool elevation, m	351.3	300
Bedrock barrier thickness, m	35	56
Coalbed elevation at bedrock barrier, m	308	240
Positive hydraulic head differential, m	11.4	3.4
Proximity to full extraction mining, m	46-m	None
Orientation of the stream channel	N 7° W	N 62.5° W

Role ofthe Natural Fracture Systems

The orientation and intensity (openness and frequency) of natural fracture systems is known to control strata permeability (Wyrick and Borchers, 1981). The orientation of these fractures was studied by Nickelson and Hough (1967) for Pennsylvania's portion of the Appalachian Plateau. They

found these fractures comprised systematic and nonsystematic sets intersecting at approximately 90 degrees. They also postulated that the systematic joints formed long-ago during the Appalachian orogeny. The systematic fracture trends are generally perpendicular to structural trends and represent extension fractures; nonsystematic joint trends are generally parallel to regional structural trends.

Puglio and Iannacchione (1979) measured fractures from outcrop and strip mine exposure over a nine quadrangle area, three of these quads covered portions of this study area (Figure 9, Elderton, Ernest, and Clymer). They found six major directional trends that correspond to three fundamental fracture systems (Table 2) discussed by Nickelson and Hough (1967). Figure 9 also shows the location of major streams and creeks in the study area. An inspection of these stream channel orientations suggest no dominate trend. Lastly, systematic fracture orientations measured in the Puglio and Iannacchione (1979) study don't correlate with the orientation of the tributary to Cherry Run involved in the unplanned discharge at the Margaret #7 Mine. While natural fracture systems play a role in strata bedrock permeability, their influence in the Margaret #7 discharge is not well understood.

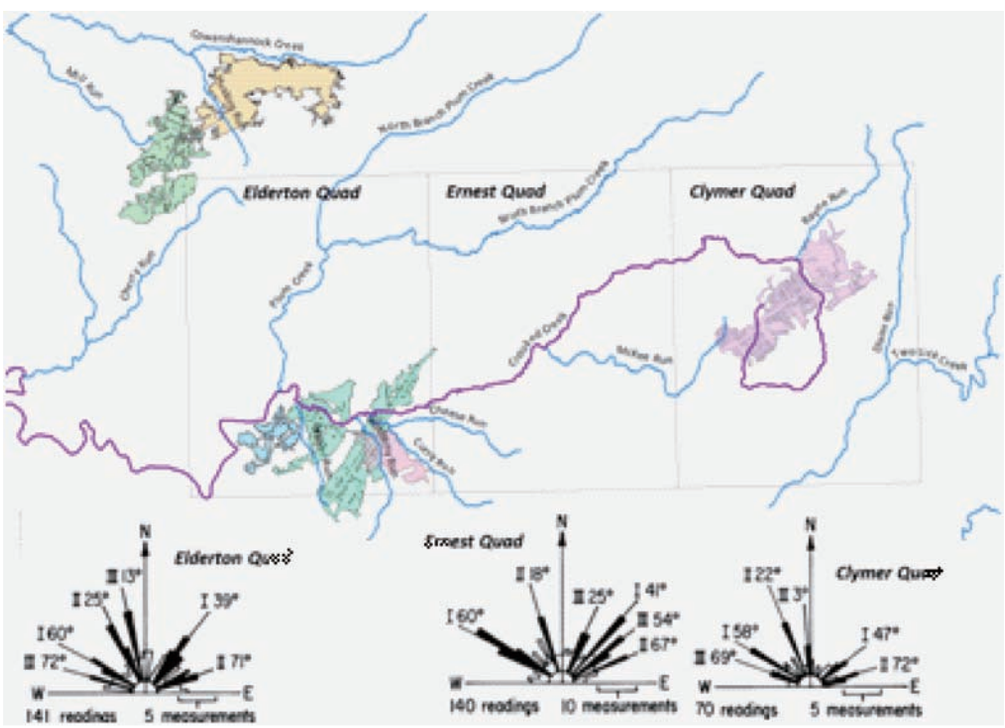

Fig. 9 Systematic and nonsystematic fracture trends measured at outcrops and strip mines by Puglio and Iannacchione (1979) within the Elderton, Ernest, and Clymer Quadrangles.

Tab. 2 Fundamental fracture systems for the Elderton, Ernest, and Clymer Quadrangles (Puglio and Iannacchione, 1979).

7' 30" quadrangles		Average trends of fundamental fracture system		Separation angle
		Systematic	Nonsystematic	
Elderton	I	N 60° W	N 39° E	99°
	II	N 25° W	N 71° E	96°
	III	N 72° W	N 13° E	59°
Ernest	I	N 60° W	N 41° E	101°
	II	N 18° W	N 67° E	85°
	III	N 25° E	N 54° E	29°
Clymer	I	N 58° W	N 47° E	105°
	II	N 22° W	N 72° E	94°
	III	N 69° W	N 3° W	66°

The Role of Valley Stress-Relief

In 1967, Ferguson published the now famous report discussing strata failures within a stress-relief vally, i. e. fractures oriented parallel to valley walls and heaving within the underlying valley bottom. These features are postulated to be caused by localized stress-relief, a phenomena referred to as the "valley stress-relief effect". The heaving in the stream bottoms is most likely caused by excessive horizontal stresses. Several examples are presented within the study area documenting difficult ground conditions while mining under stream valleys. Molinda, et al. (1992), discussed significant difficulty at the Tanoma Mine while mining under Crooked Creek (Figure 10). The Tanoma mine is in the Lower Kittanning Coalbed. At this location, the overburden

averaged 60-m across a wide, flat bottomed stream channel approximately 365-m wide. The mine operator reported difficult mining conditions whenever attempts were made to cross this valley bottom (the mining direction was east to west). These conditions consisted of significant water inflow, small displacement faults resembling parallel sets of thrusts, and highly fractured strata. The entries crossing Crooked Creek (Figure 10) required extraordinary supplemental support including steel sets, additional intrinsic rock reinforcement and, in some areas, tunnel liners (Molinda, et. al, 1996).

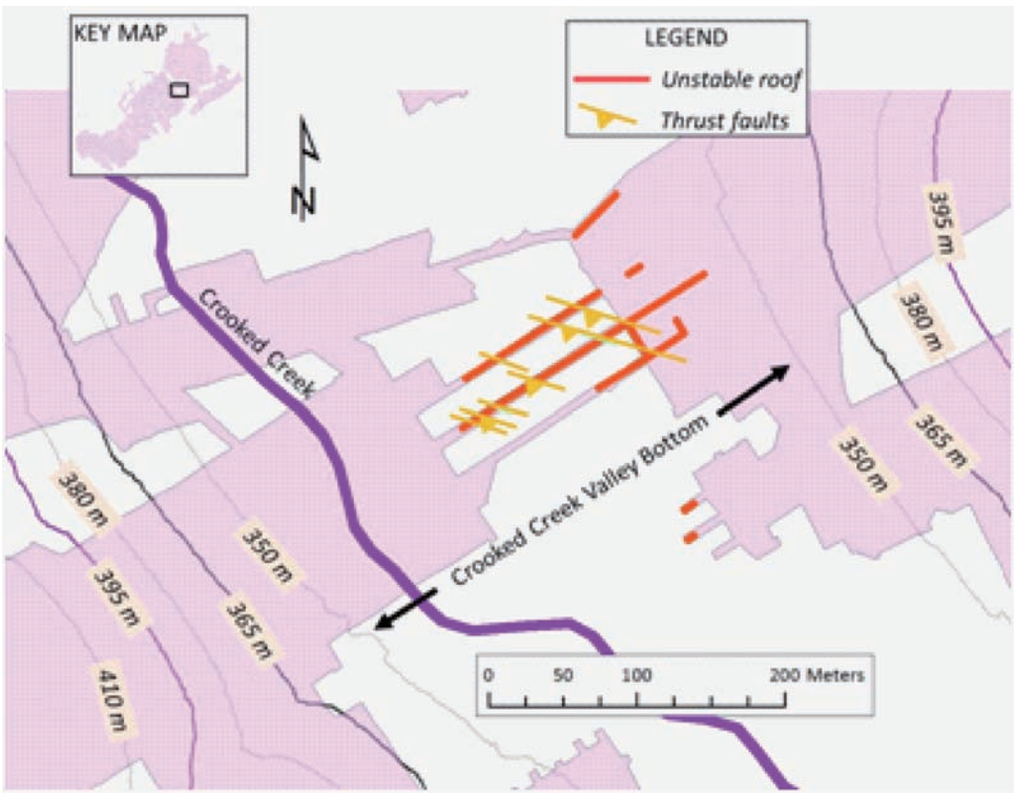

Fig. 10 Outline of the Tanoma Mine underlying Crooked Creek valley (N 38° W) showing the location of unstable roof conditions and small thrust faults within the mine's roof, ribs and floor.

Another mine in the study area, Urling # 2 (Lower Freeport Coalbed), also experienced significant challenges when mining under Curry Run, a Tributary to Crooked Creek (Figure 11). Whenever the mine entered beneath the stream channel, unstable ground and higher than normal water inflows were encountered (Legarsky, 2015). The overburden in the Curry Run area ranged from less than 30-m to as much as 80-m.

This study found a general stream channel orientation of the N 38° W where the mine crossed under Crooked Creek (Figure 10). In addition, the general orientation of N 44° W was measured along Curry Run adjacent to the Urling # 2 (Figure 11). Neither of these orientations match with the systematic fracture trends listed in Table 2. It should also be noted that mine developments were successfully completed under Anthony Run where overburdens were greater than 80-m.

The Role of Horizontal Stress

The northern Appalachian Coal Fields are known to have significant horizontal stress conditions even at low overburdens (Mark and Gadde, 2008). Within the study area, the Tanoma Mine contains examples of horizontal stress field conditions as well as documented information of its roof stability impacts. Dolinar, et al., 2000, conducted in-situ stress measurements with the hydraulic fracturing technique in an overlying sandstone member 8-m above the mine. The maximum horizontal stress was measured to be 44.2-MPa and oriented N 87° E. The minimum horizontal stress was 26.7-MPa oriented N 3° W. In this stress field, shear failures caused by roof beam and stream bed buckling are expected to be aligned with the minimum stress direction (N 3° W). The general location of this measurement is shown in Figure 12.

The orientations of roof falls, originally reported as N 30° W by Dolinar, et al. (2000), were located in this study from archived mining maps available from the PASDA (www. pasda. psu. edu) and incorporated into a GIS platform (Figure 12). Here again a dominant roof fall orientation aligned with entries driven N 30° W. The overburdens in these areas approach 200-m. In other areas to the north-

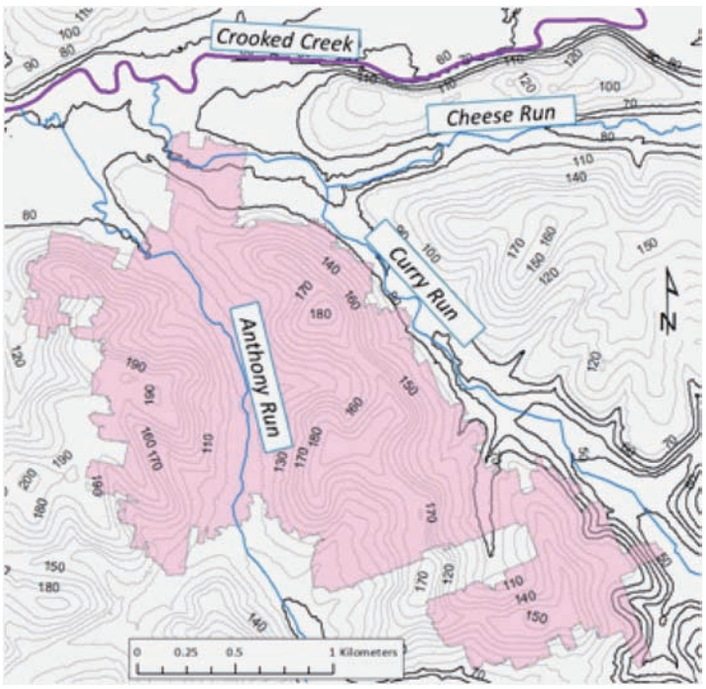

Fig. 11 The overburden above the Urling #2 Mine outline with the overlying major streams, i. e. Crooked Creek, Anthony Run, Curry Run, and Cheese Run. The overburden contours equal to or less than 80-m are shown in black. The gray contours are greater than 80-m.

east different roof fall orientations are observed. These areas are shallower and have different entry orientations. It is interesting that the roof-fall orientations in the southeastern portion of the Tanoma Mine don't mirror the N 3° W (maximum horizontal stress damage direction). Perhaps as Dolinar, et al. (2000) suggest, the unique 'advance and relief' mining method used in this area slightly altered the minimum horizontal stress direction (N 3° W). Regardless, the Tanoma Mine roof fall data confirms that significant horizontal stresses are present in the area and stream oriented from N 30° W to N 25° E may become aligned to the N 3° E minimum horizontal stress direction, potentially causing stream beds to buckle especially at low overburdens (< 80-m).

Summary and Conclusions

Seven underground coal mines are analyzed to determine what factors and conditions may influence the performance of strata barriers in preventing unplanned discharges to surface streams. Nominally, a discharge through a strata barrier can be prevented by keeping the mine pool elevation below that of the lowest point on the surface above the mine (this is typically a stream bottom). All Pennsylvania coal-bearing strata contain a complex arrangement of vertical fractures and horizontal bedding-planes that control groundwater flow. Both the fractures and the bedding-planes tend to be more permeable as the surface is approached. But it is also known that the fracture permeability of the strata can be greatest under

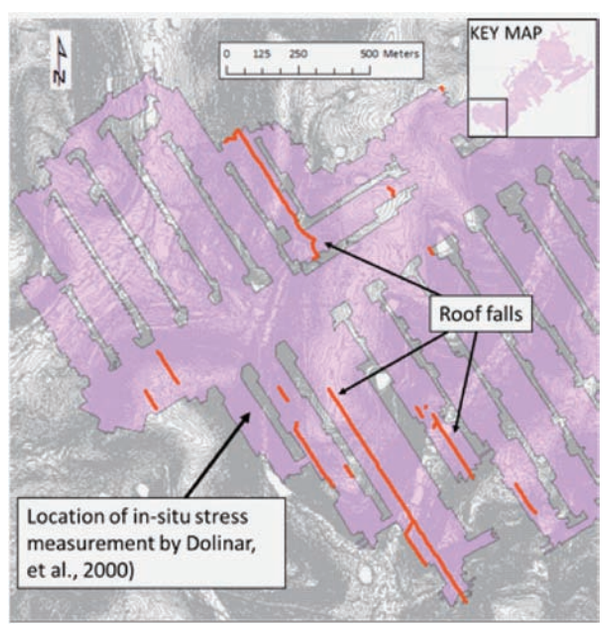

Fig. 12 Outline of the southeastern portion of the Tanoma Mine with location of 'running' roof falls and Dolinar, et al. 2000 stress measurement. These roof falls trend overwhelmingly in N 30° W orientation.

the stream channels. Designing strata barriers that can prevent measurable quantities of vertical water movement under a positive hydraulic head differential condition, requires detailed information of the barrier's geologic characteristics and mining history. This study analyzed two cases, one where

an unplanned discharge occurred under a positive hydraulic head differential of 11.4-m and another where no discharge was observed under a 3.4-m head.

Three primary (well known) factors in controlling unplanned discharges to surface streams are:

1. *The thickness of thestrata barrier*-The Commonwealth of Pennsylvania currently requires strata barriers to maintain a minimum thickness of 76-m.

2. *The magnitude of the positive hydraulic head differential*-If the highest elevation of the mine pool is below the lowest point on the surface above the mine, a discharge cannot occur. As soon as a positive hydraulic head is applied across the strata barrier, the condition and character of the fractured bedrock in the barrier becomes a prime design consideration.

3. *The absence of high extraction ratio mining beneath stream channels*-High extraction mining methods allow roof members to sag and possibly collapse. If this is done in the proximity of a stream channel, the creation of new fractures or the opening of existing fractures can negatively impact the barriers resistance to water flow.

This study also found that strata barrier fracture permeability may be locally impacted by the overlying orientation and conditions of the stream channel. This study suggested that three conditions should be analyzed when investigating strata barrier fracture permeability:

1. The natural fracture systems - While natural fracture systems play a role in strata bedrock permeability, in this study they might not have been a significant factor.

2. Valley stress-relief - This study found the N 38° W Crooked Creek (at the Tanoma Mine) and the N 44° W Curry Run (at the Urling #2 Mine) stream channels may have been affected by valley stress-relief effects.

3. Excessive horizontal stress conditions - The Tanoma Mine roof fall data confirms that significant horizontal stresses are present in the area and stream oriented with the N 3° E minimum horizontal stress direction, can cause stream beds to buckle, especially at low overburdens (<80-m). This orientation is very close to the orientation of the Triburary to Cherry Run above the Margaret #7 unplanned discharge (N 7° W). Perhaps the strata barrier at this site was further damaged by the significant horizontal stress.

These data suggest that the three primary factors and the three stream orientation conditions should be considered when designing strata barriers to control unplanned discharged from Pennsylvania mine pools.

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