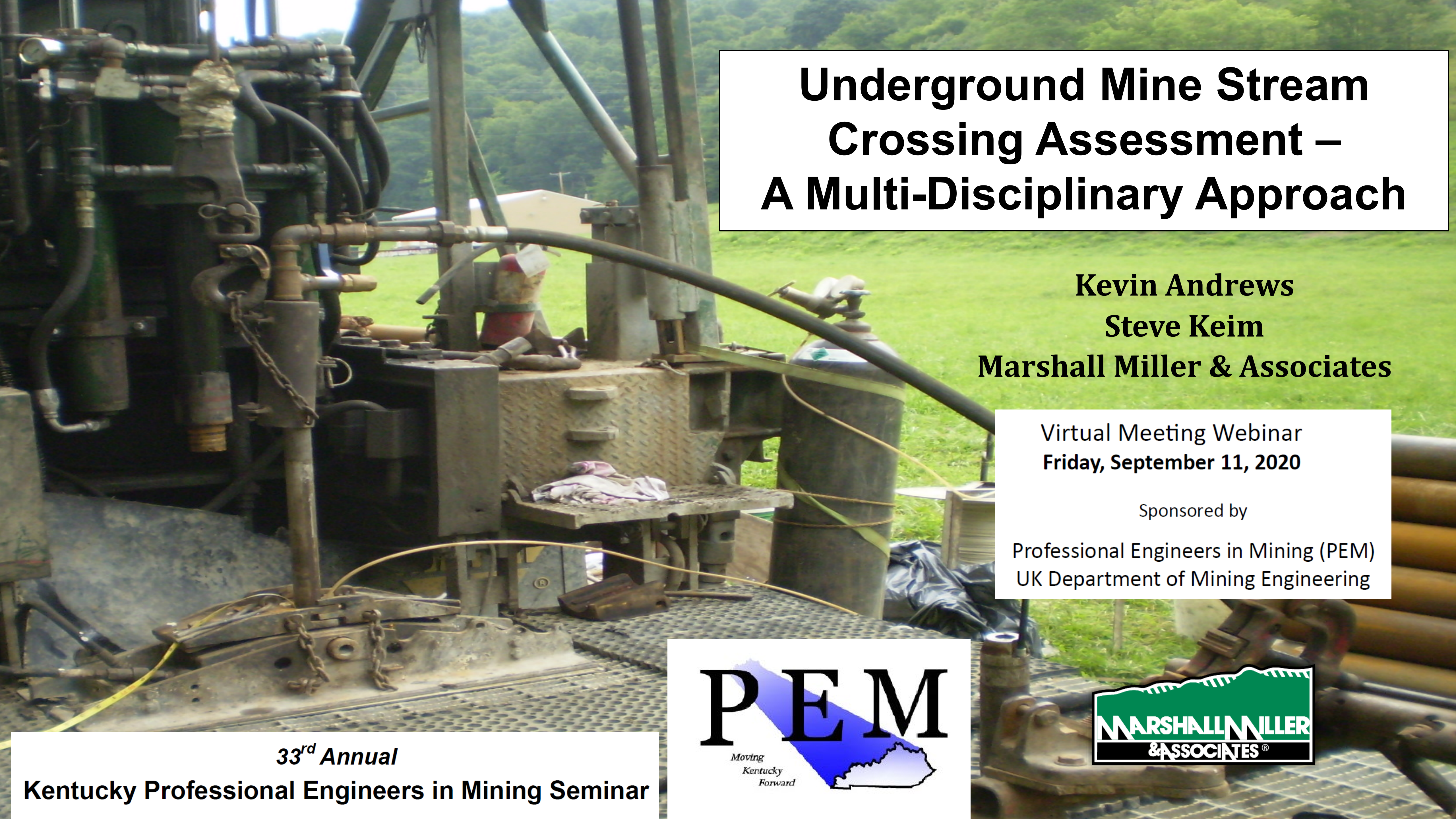

Underground Mine Stream Crossing Assessment – A Multi-Disciplinary Approach

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Marshall Miller & Associates

Virtual Meeting Webinar
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Introduction

- Underground mines typically try to avoid extraction beneath streams and rivers; *however, there are times when it is necessary.*
- Overburden rock thickness between the stream bed and the mine is thin.
- Potential issues with mining beneath streams include:
  - excessive groundwater inflow to the mine;
  - weak ground (roof, floor, and pillar) conditions;
  - horizontal stress effects;
  - as well as stream loss and other potential adverse environmental effects.
  - Often, stream crossings are completed without thorough assessment, potentially resulting in increased costs, decreased safety, and, in some cases, **failure to advance the mine**.
  - Stream crossing investigations require geological, hydrogeological, geotechnical, and geophysical expertise.

Introduction (continued)

> Phases of investigation include:
- desktop evaluation of maps and aerial photography,
- stream bed observations,
- Drilling and detailed rock core logging,
- downhole geophysical surveying,
- hydraulic conductivity testing (packer testing),
- geotechnical laboratory testing,
- assessment and reporting.

> **Deliverables include geological, geotechnical, and hydrogeological characterization of potential stream crossing locations; classification of favorable and unfavorable crossing locations; recommendations for entry design and pillar sizing; and recommendations for grouting activities.**

Introduction (continued)

- In practice it is not possible or practical to evaluate every crossing in all available ways.
- Spectrum of possible scenarios may range from assessing multiple crossing sites with multiple holes on each side of the stream to testing one crossing site with a single hole.
- **Extremely thorough assessment is often impractical** due to budget and time, **but a minimal approach increases the risk** that the collected data is not representative of actual conditions.
- Limitations:
  - budget, time, access, weather, and other factors,
  - ***in some cases, evaluations are not conducted simply because mine operators are unaware or unfamiliar with available capabilities and techniques for assessment, or unsure of the benefits of such studies.***
- **This paper is intended to provide general awareness of the process and benefits.**

Phases of Stream Crossing Investigations

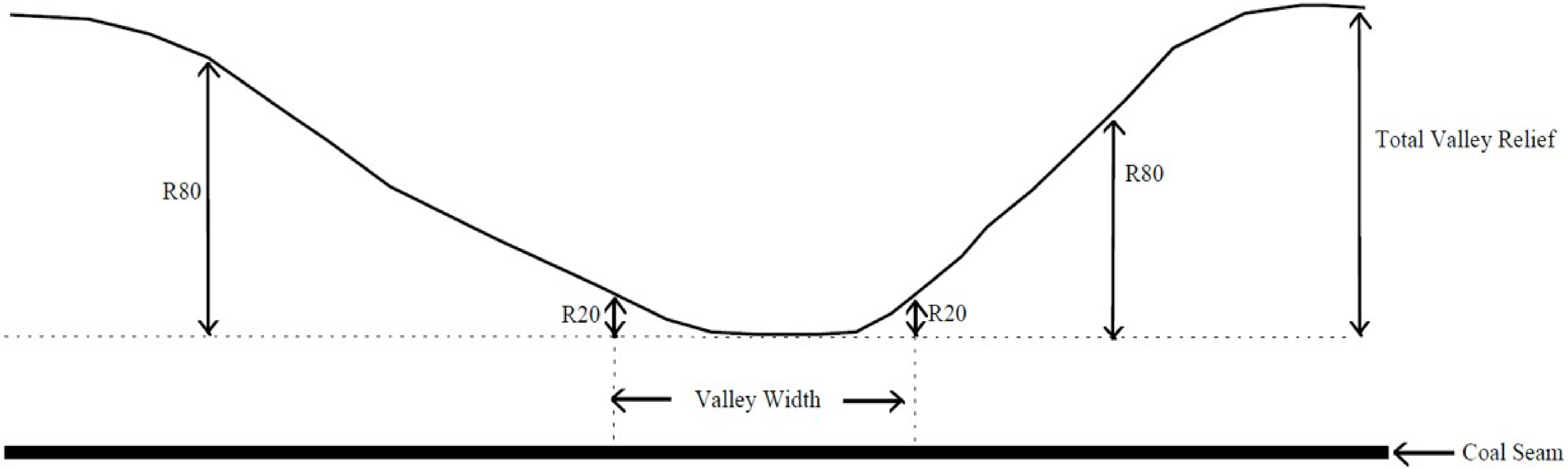
1. **Desktop Evaluation** to Identify Significant Factors (topography, lineaments, etc.) and Select Locations (as necessary)
2. **Core Drilling with Geological Logging, Geotechnical Logging, and Core Photography** to Define Depth to Bedrock, Geologic Framework, and Fracture Zones
3. **Geotechnical Laboratory Sample Collection and Testing**
4. **Downhole Geophysical Logging** to Define Fracture Zones and Enhance Core Logging Records
5. **Packer Testing** Guided by Geotechnical and Geophysical Logging to Define Hydraulic Conductivity of Rock Overburden Between Mine and Creek
6. **Geotechnical and Hydrogeological Assessment** to Characterize Unconsolidated and Bedrock Material in Overburden and to Define Expected Mining Conditions; recommendations for grouting

Desktop Evaluation

- Review mine maps, coal seam structure maps, topography mapping
- Review existing core hole data including geology/geotechnical logs and any laboratory data
- Evaluate **R20** and conduct **lineament study** specific to stream crossing site(s)
- Discuss typical mining conditions and groundwater inflow conditions with mine personnel; review pumping rates (as available)
- Assist with hole locations for investigation, if not already defined by client
    - Hole locations are generally located to enable complete characterization of entire stream crossing zone (if possible)
    - Budget, property issues, railroad tracks, roads, and other restrictions often dictate, to some extent, the number and locations for holes to be drilled

Valley Width Defined for the "R20 Method"

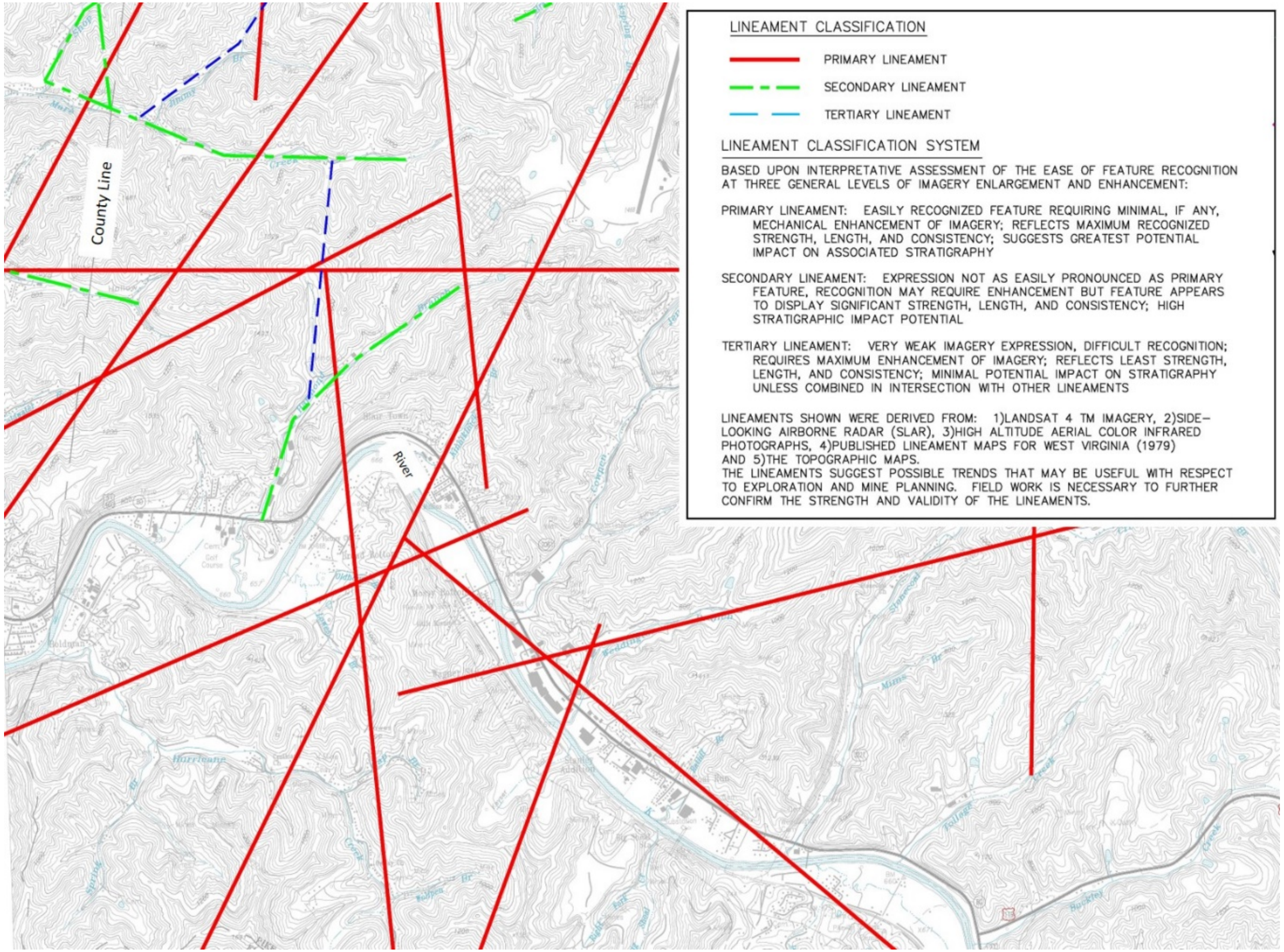
- Confinement ratios for the subject stream valley calculated to identify crossing locations along the stream that are expected to be less prone to mine roof falls.
- The methodology is based on a significant correlation between mine roof falls and valley geometry.
- Confinement Factor = ratio of total valley relief to valley floor width, with valley floor width defined as the width of the valley at a height above the valley floor equal to 20-percent of the total relief.
- Confinement Factors between 0.4 to 0.6 tend to be more susceptible to mine roof falls.



Molinda, G.M., Heasley, K.A., Oyler, D.C., and Jones, J.R. 1992. Effects of Horizontal Stress Related to Stream Valleys on the Stability of Coal Mine Openings. USBM RI 9413, 26 pages.

Lineament Mapping Results with Lineament Classification System

- **<u>lineament</u> = *naturally occurring, reasonably linear or slightly curved feature.***
- **Landsat Thematic Mapper data, Side-Looking Airborne Radar data, color-infrared photographs, topographic maps, and other sources**
- **Topographic alignments that may be indicative of subsurface structural features that could adversely affect mining conditions**
- **Fault scarps, fault traces, truncated geologic structures, unusually straight stream reaches, linear vegetation anomalies, aligned stream segments or depressions, soil anomalies, or other features.**
- **Exclude cultural and man-made features.**
- **Do not always correlate to the presence of underground mining issues, but the technique has been successful in many cases and is a relatively quick initial step.**



LINEAMENT CLASSIFICATION

━━ PRIMARY LINEAMENT
━ ━ ━ SECONDARY LINEAMENT
— — TERTIARY LINEAMENT

LINEAMENT CLASSIFICATION SYSTEM

BASED UPON INTERPRETATIVE ASSESSMENT OF THE EASE OF FEATURE RECOGNITION AT THREE GENERAL LEVELS OF IMAGERY ENLARGEMENT AND ENHANCEMENT:

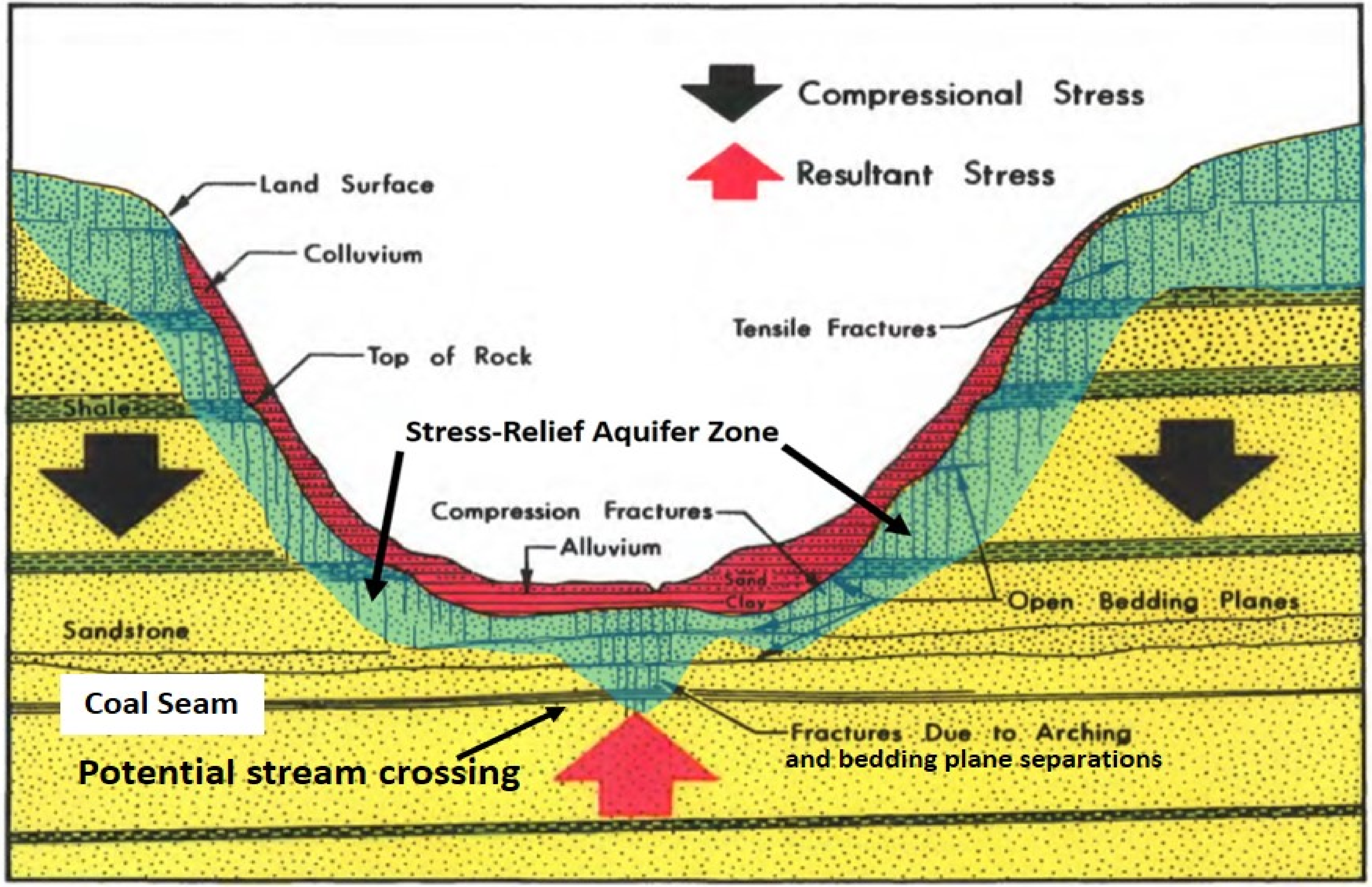
PRIMARY LINEAMENT: EASILY RECOGNIZED FEATURE REQUIRING MINIMAL, IF ANY, MECHANICAL ENHANCEMENT OF IMAGERY; REFLECTS MAXIMUM RECOGNIZED STRENGTH, LENGTH, AND CONSISTENCY; SUGGESTS GREATEST POTENTIAL IMPACT ON ASSOCIATED STRATIGRAPHY

SECONDARY LINEAMENT: EXPRESSION NOT AS EASILY PRONOUNCED AS PRIMARY FEATURE, RECOGNITION MAY REQUIRE ENHANCEMENT BUT FEATURE APPEARS TO DISPLAY SIGNIFICANT STRENGTH, LENGTH, AND CONSISTENCY; HIGH STRATIGRAPHIC IMPACT POTENTIAL

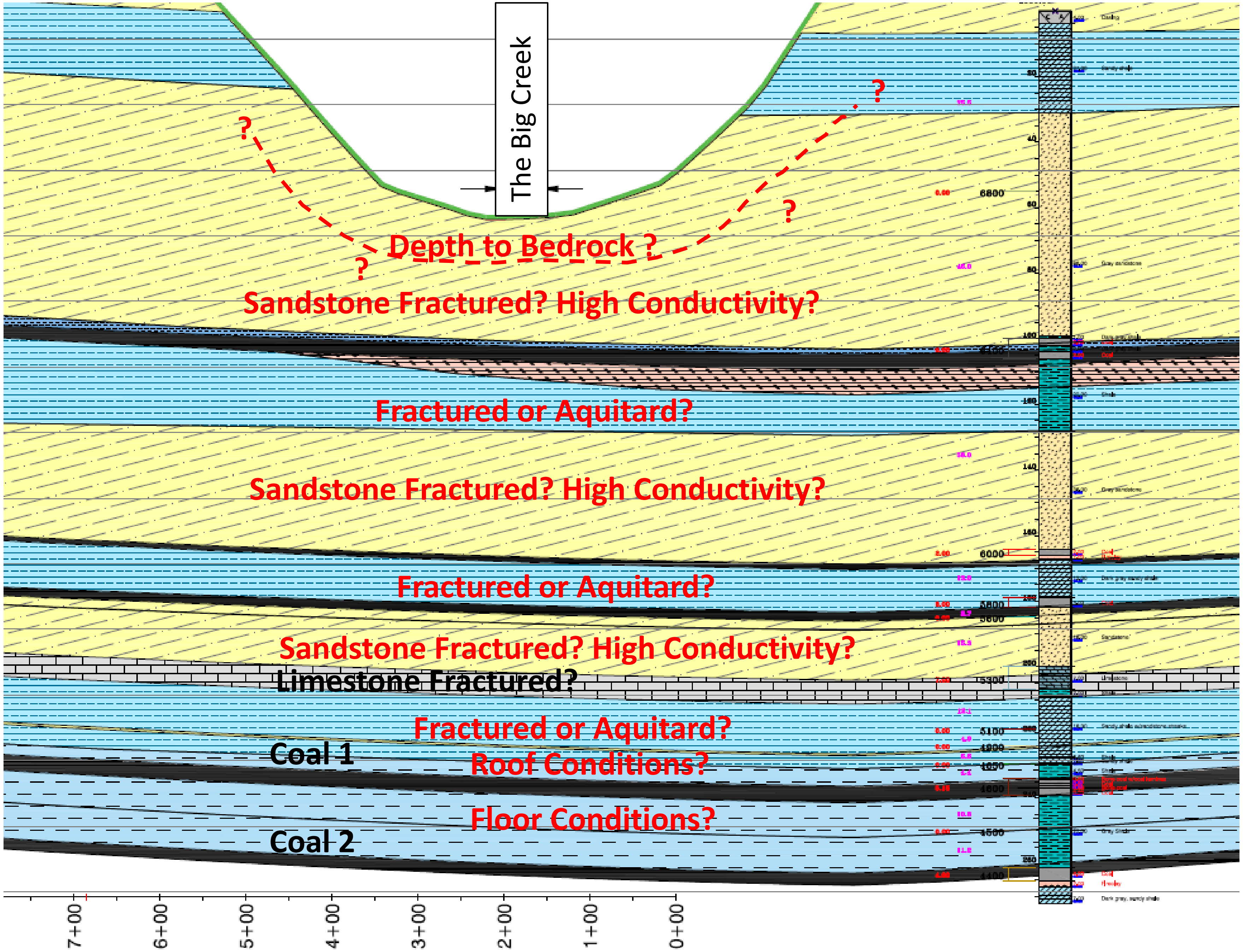
TERTIARY LINEAMENT: VERY WEAK IMAGERY EXPRESSION, DIFFICULT RECOGNITION; REQUIRES MAXIMUM ENHANCEMENT OF IMAGERY; REFLECTS LEAST STRENGTH, LENGTH, AND CONSISTENCY; MINIMAL POTENTIAL IMPACT ON STRATIGRAPHY UNLESS COMBINED IN INTERSECTION WITH OTHER LINEAMENTS

LINEAMENTS SHOWN WERE DERIVED FROM: 1)LANDSAT 4 TM IMAGERY, 2)SIDE-LOOKING AIRBORNE RADAR (SLAR), 3)HIGH ALTITUDE AERIAL COLOR INFRARED PHOTOGRAPHS, 4)PUBLISHED LINEAMENT MAPS FOR WEST VIRGINIA (1979) AND 5)THE TOPOGRAPHIC MAPS.
THE LINEAMENTS SUGGEST POSSIBLE TRENDS THAT MAY BE USEFUL WITH RESPECT TO EXPLORATION AND MINE PLANNING. FIELD WORK IS NECESSARY TO FURTHER CONFIRM THE STRENGTH AND VALIDITY OF THE LINEAMENTS.

Typical Stress-Relief Aquifer Zone and Potential Issues to be Encountered by Underground Mine Stream Crossing



Wyrick, G.G. and Borchers, J.W. 1981. Hydrologic Effects of Stress-Relief Fracturing in an Appalachian Valley. U.S. Geological Survey Water-Supply Paper 2177, 51 pages.

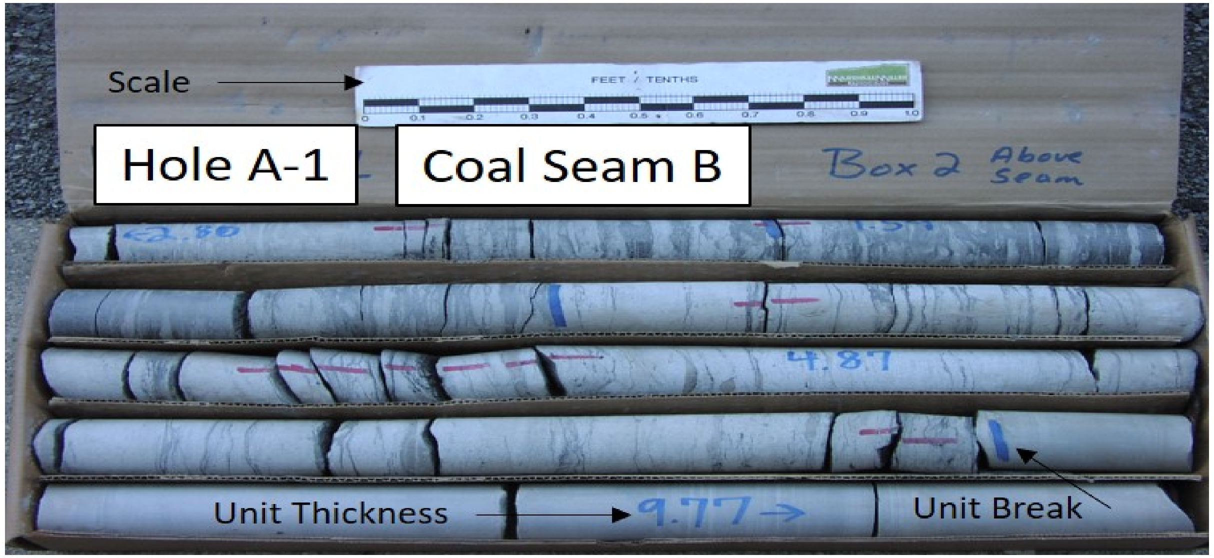


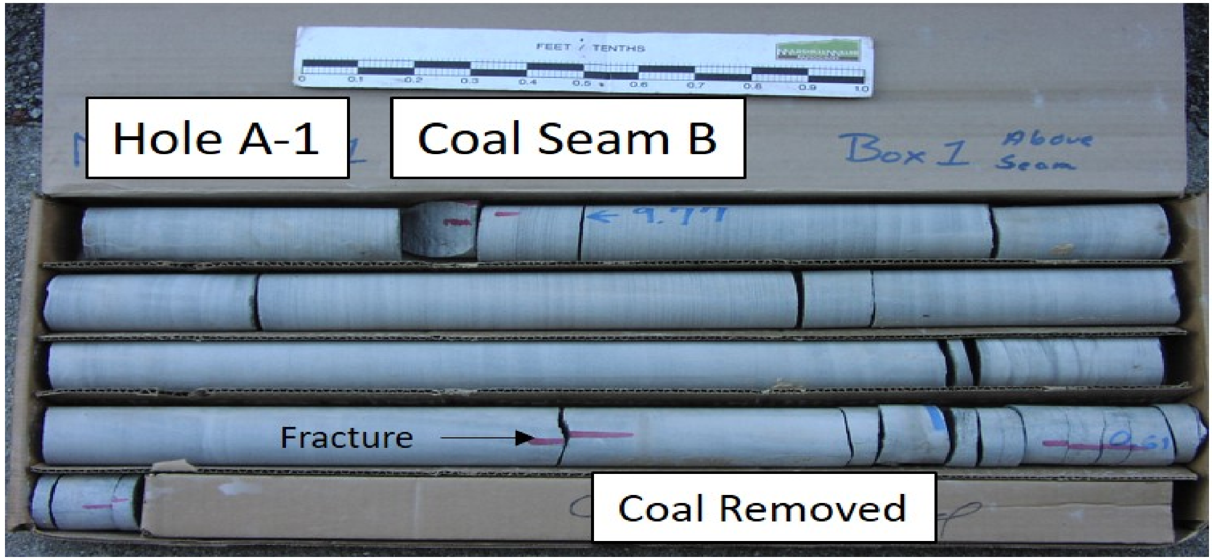
Conceptual Stream Crossing Section - Questions to be Investigated

Core Drilling with Geological Logging, Geotechnical Logging, and Core Photography

- Logging completed at drill site as core extracted to preserve as-drilled core condition and to accurately track core recovery for each run
- Includes Rock Quality Designation (RQD), fracture descriptions, weathering observations, moisture sensitivity classification, and overall qualitative rock quality characterization
- Core photography completed in a systematic manner
- Drill site location descriptions and photographs are also collected; in particular, zones of visible bedrock in creek and other stream features are noted

Example Core Photography for Immediate Roof Rock Section

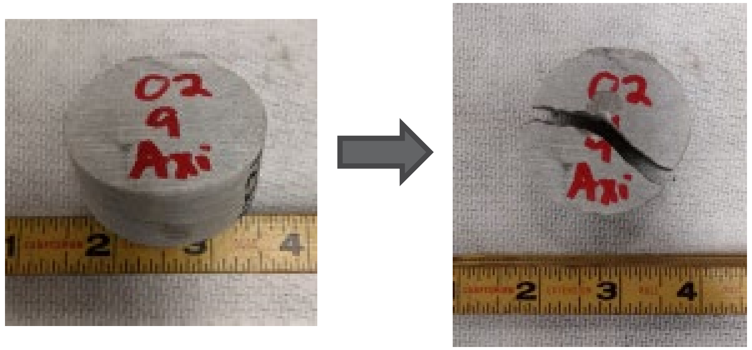


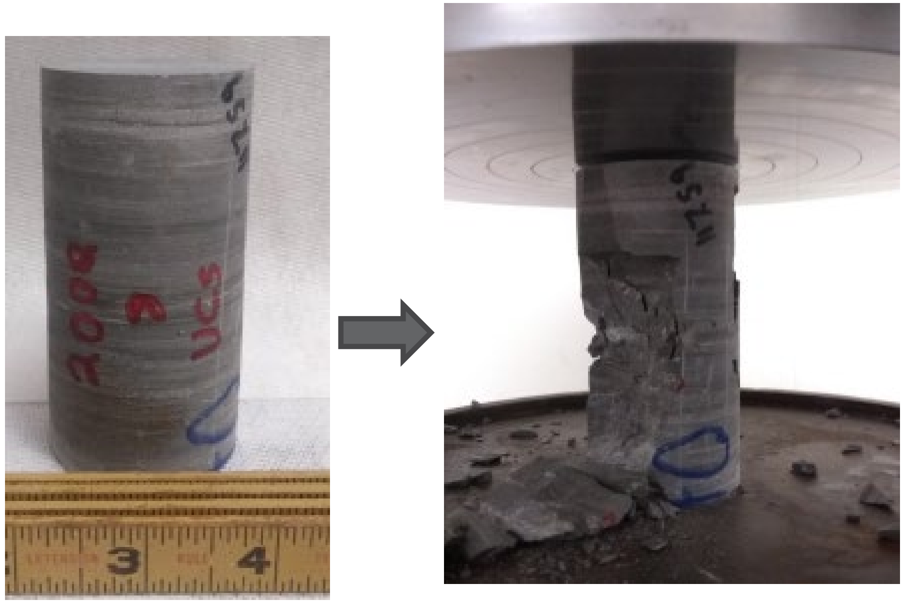


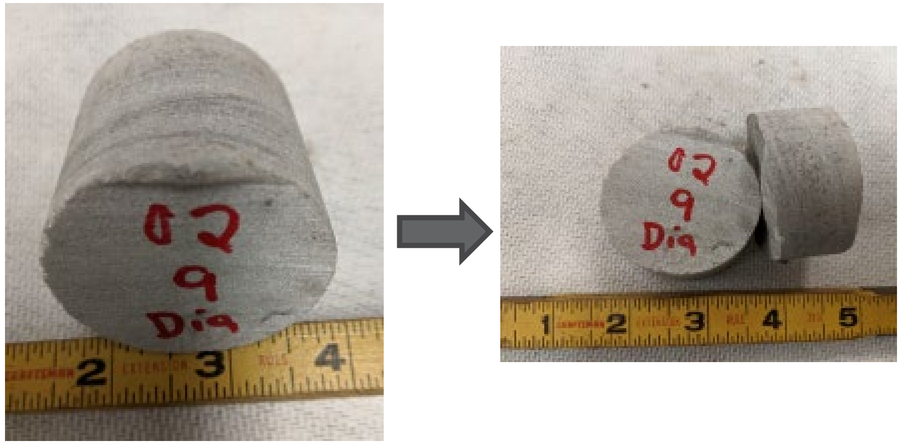
Geotechnical Laboratory Sample Collection and Testing

- **Geotechnical Rock Core Testing may include:**
  - Uniaxial Compressive Strength (UCS) with or without strain gauges
  - Point Load Testing (PLT)
  - Brazilian Tensile Strength
  - Density
  - Triaxial Compression
  - Moisture Sensitivity

- **Core samples collected in field and shipped to third-party laboratory**







Downhole Geophysical Logging

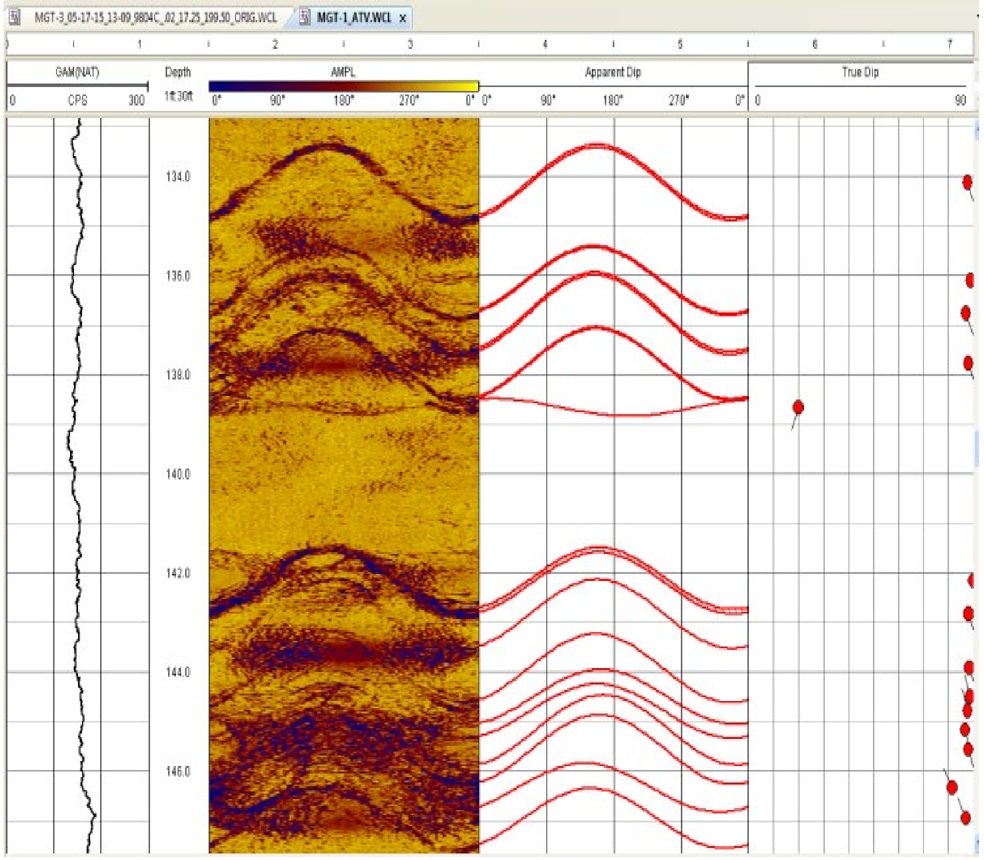
- Typical suite for stream crossing investigations includes:
  - Density and Gamma logs – standard logs for geologic interpretation
  - Temperature Log – detects changes in temperature indicative of flow zones in strata
  - Resistivity log – detects changes in resistivity indicative of flow zones in strata
  - Caliper log – identifies larger fracture zones
  - Acoustic Televiewer log - accurately identifies fractures and their depth and orientation; primary tool for planning packer testing intervals
  - Sonic Log – enhances fracture characterization; indicative of relative changes in rock strength; often used to identify potential soft floor zones

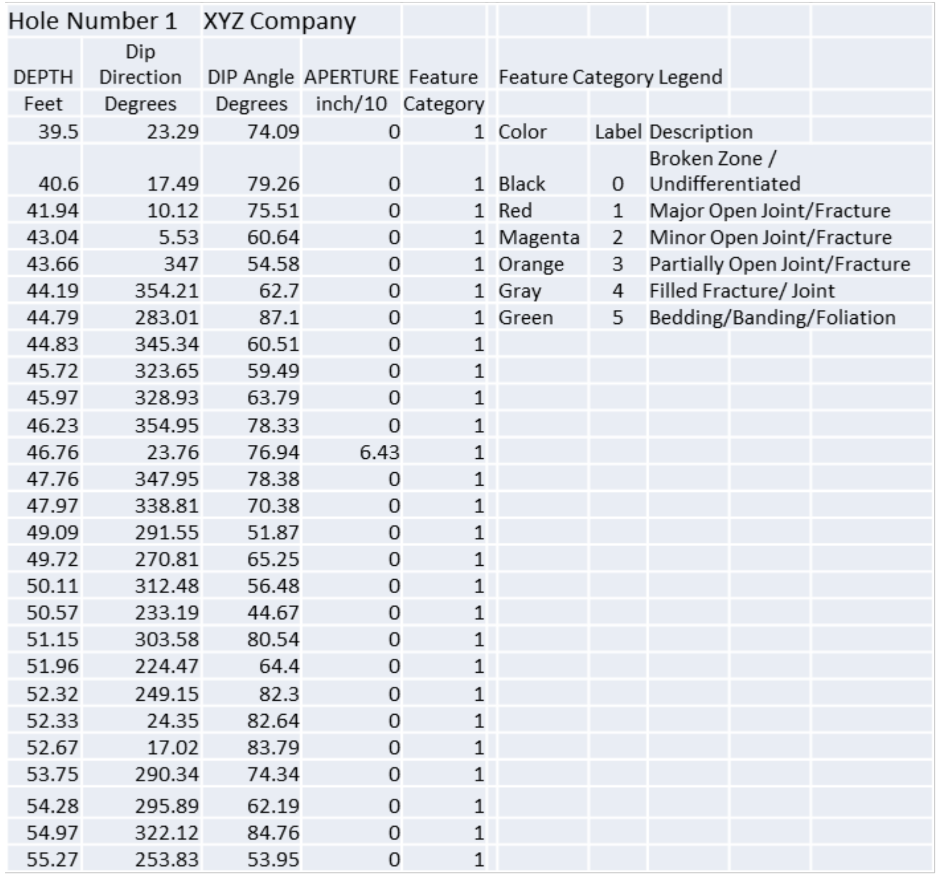
Example Acoustic Televiewer Log Data Summary

Acoustic Televiewer Log Image

Interpreted Fractures Projection

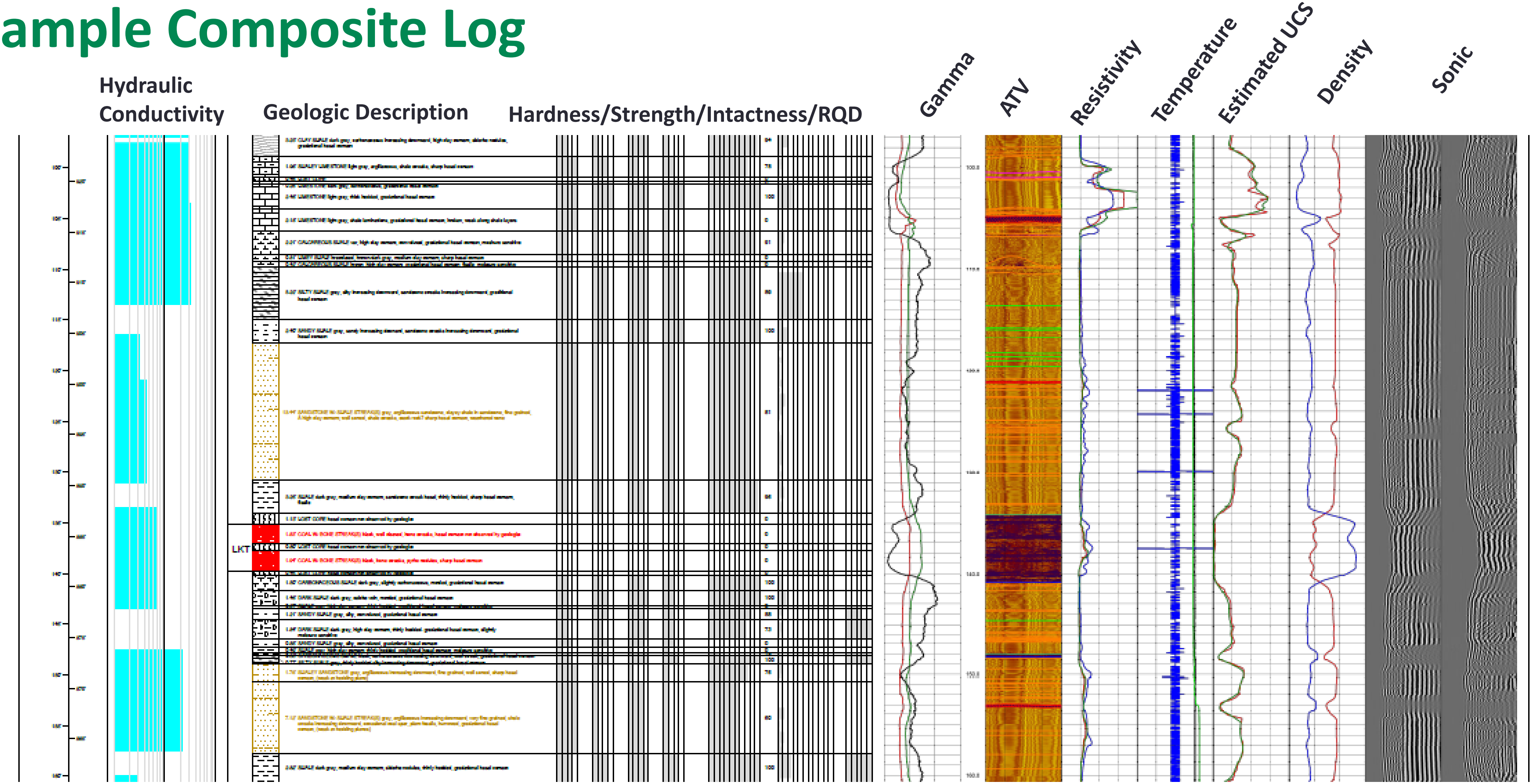
Tadpole Plot





Hole Number 1	XYZ Company						
DEPTH Feet	Dip Direction Degrees	DIP Angle Degrees	APERTURE inch/10	Feature Category	Feature Category Legend		
39.5	23.29	74.09	0	1	Color	Label	Description
40.6	17.49	79.26	0	1	Black	0	Broken Zone / Undifferentiated
41.94	10.12	75.51	0	1	Red	1	Major Open Joint/Fracture
43.04	5.53	60.64	0	1	Magenta	2	Minor Open Joint/Fracture
43.66	347	54.58	0	1	Orange	3	Partially Open Joint/Fracture
44.19	354.21	62.7	0	1	Gray	4	Filled Fracture/ Joint
44.79	283.01	87.1	0	1	Green	5	Bedding/Banding/Foliation
44.83	345.34	60.51	0	1			
45.72	323.65	59.49	0	1			
45.97	328.93	63.79	0	1			
46.23	354.95	78.33	0	1			
46.76	23.76	76.94	6.43	1			
47.76	347.95	78.38	0	1			
47.97	338.81	70.38	0	1			
49.09	291.55	51.87	0	1			
49.72	270.81	65.25	0	1			
50.11	312.48	56.48	0	1			
50.57	233.19	44.67	0	1			
51.15	303.58	80.54	0	1			
51.96	224.47	64.4	0	1			
52.32	249.15	82.3	0	1			
52.33	24.35	82.64	0	1			
52.67	17.02	83.79	0	1			
53.75	290.34	74.34	0	1			
54.28	295.89	62.19	0	1			
54.97	322.12	84.76	0	1			
55.27	253.83	53.95	0	1			

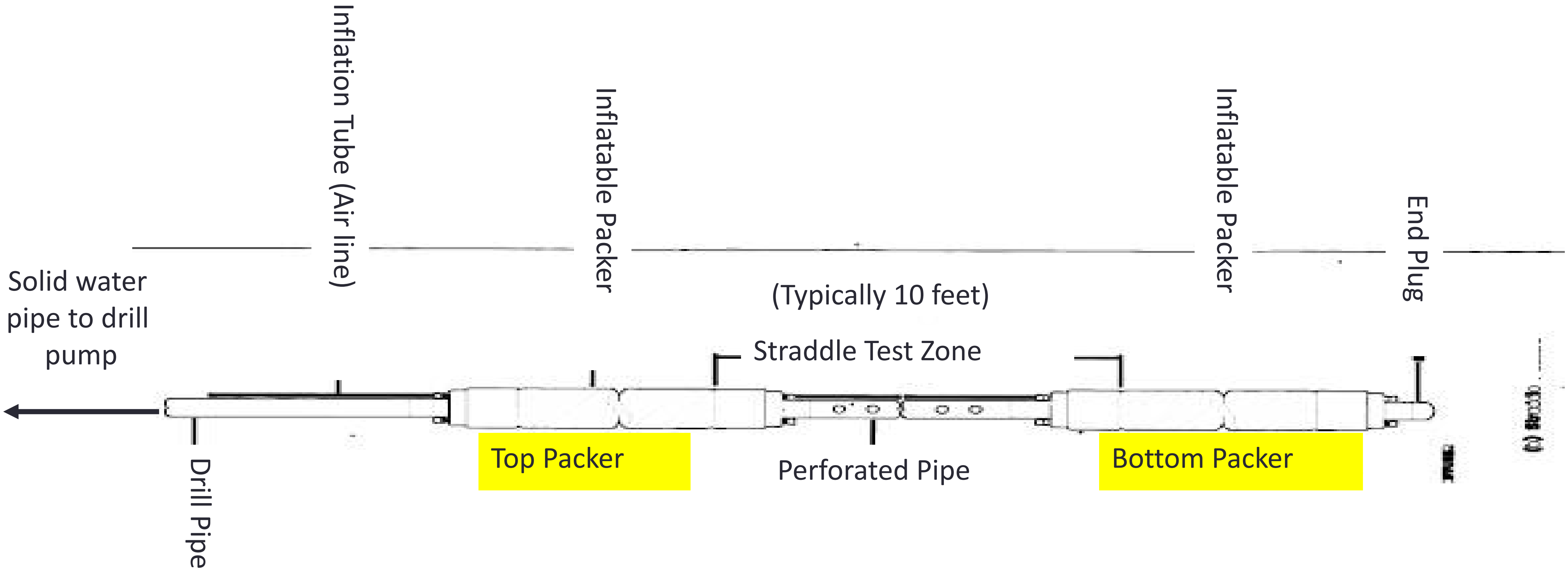
Example Composite Log



Packer Testing

- Isolate zones within the strata to determine hydraulic conductivity
- Assembly includes: perforated zone of water pipe with inflatable packers; assembly connected to a drill pump at the surface via a string of solid water pipe
- To test:
    - packer assembly is positioned over a 10-ft long interval at a selected depth
    - packers inflated to isolate the selected zone, and
    - water is pumped under pressure out of the perforated section of pipe and into the strata zone;
    - measurements of pressure, flow, and volume are recorded and used to calculate the hydraulic conductivity of each selected test zone.

Example Packer Assembly Diagram



Inflation Tube (Air line)

Inflatable Packer

Inflatable Packer

End Plug

(Typically 10 feet)

Solid water pipe to drill pump

Straddle Test Zone

Top Packer

Perforated Pipe

Bottom Packer

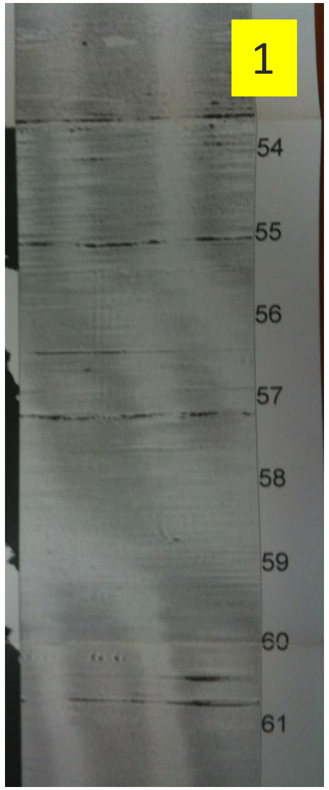
Drill Pipe

Example Comparison of Fractures and Coal Zones Shown in Acoustic Televiewer Log to Injection Flow Rate

Note: Multiple scattered fractures at zone 2 showed equal amount of flow as coal bands in zone 3.

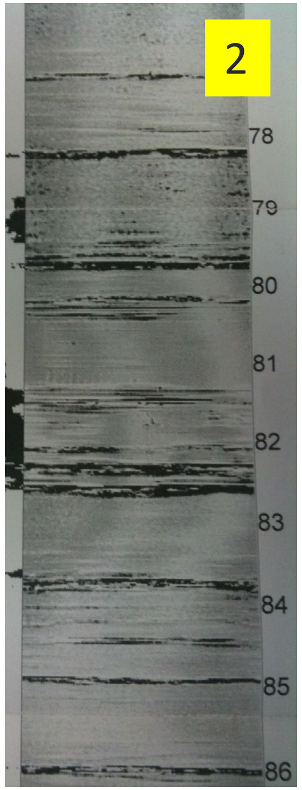
Few bedding plane fractures

Flow=
0.04 GPM



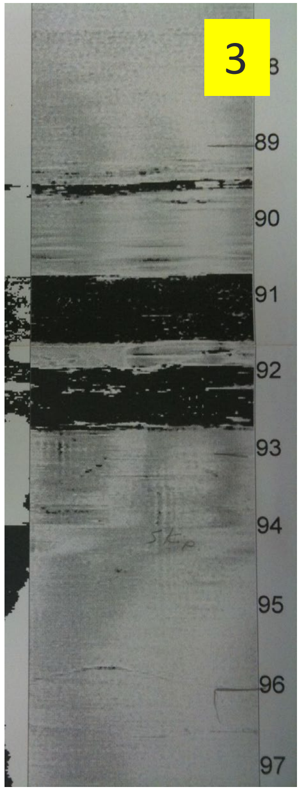
Highly fractured zone

Flow=
23 GPM



Coal seam

Flow=
23 GPM



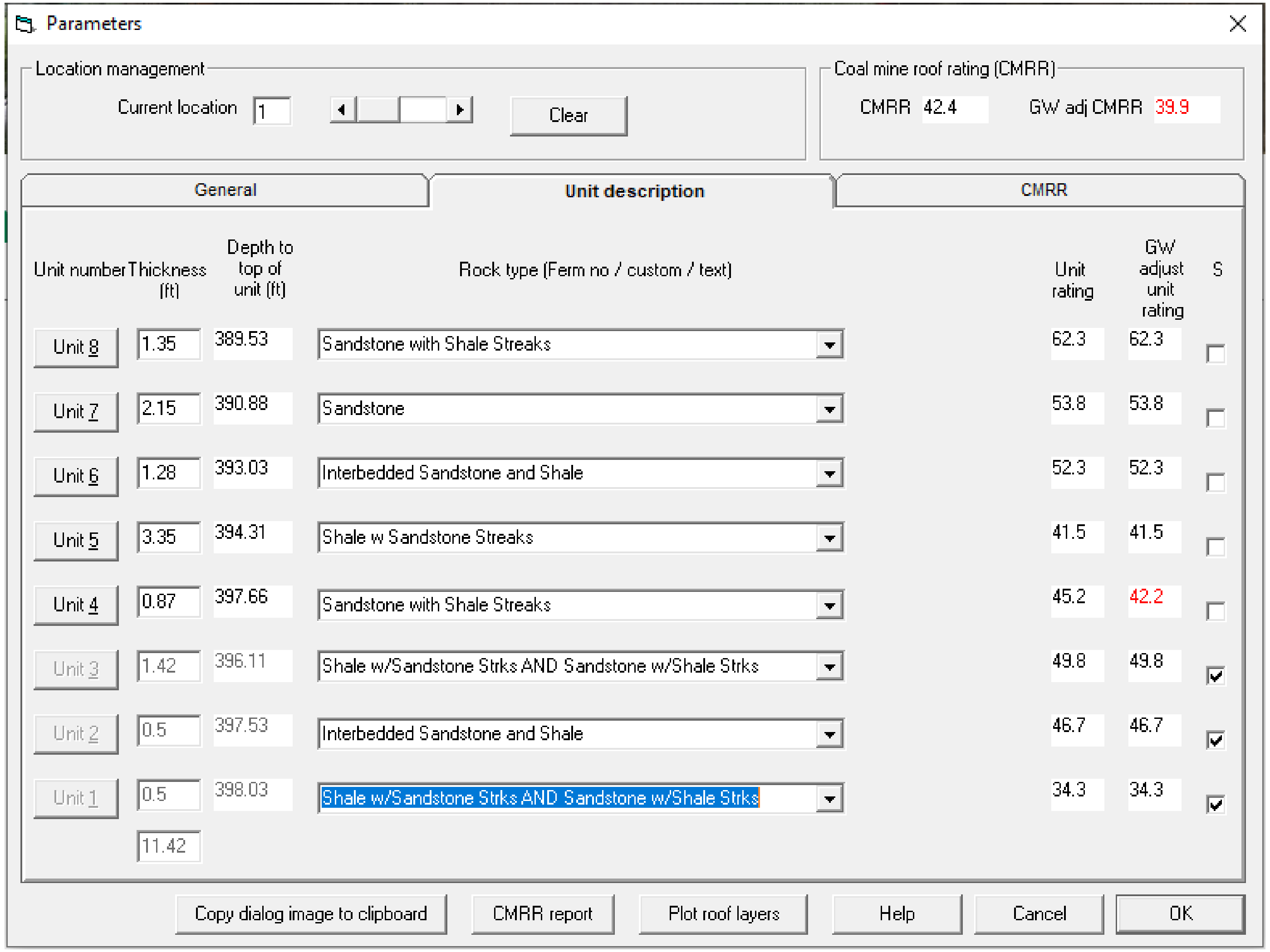
Notes on Field Work

- **All holes in stream crossing area MUST be backfilled properly!!!!**
- Drill sites should adequately define the stream crossing zone (as possible); mining often encounters the worst conditions directly beneath the streambed, so **placing some holes as near to the stream as possible is generally recommended**; angled drilling is sometimes used for larger water courses, but can complicate packer testing.
- **Logging of core at drill site recommended** for any detailed, site-specific geotechnical investigation where core loss, drilling damage to core, and core transport damage have the potential to cause significant misinterpretations of the conditions.
- Packer testing concepts are straight-forward, **but identifying/troubleshooting/mitigating testing problems in the field often requires experienced personnel** to avoid collection of erroneous data

Geotechnical and Hydrogeological Assessment

- Incorporates all geological, geotechnical, and hydrogeological data to characterize the subject stream crossing zone and identify the strong and weak/fractured zones, and potential aquifers/aquitards
  - **Rock Mass Rating (RMR)** or **Coal Mine Roof Rating (CMRR)** classifications for roof
  - Mine floor characterization using geologic and geotechnical data, coupled with geophysics and rock lab data
  - Packer test results are processed and matched to geology and geotechnical logs
- Identifies potential problems with entry stability (roof or floor conditions)
- Pillar design sometimes included.
- Potential water inflow zones are identified and general grouting recommendations provided
- Reporting summarizes characterization of the overburden and seam conditions at the site; highlights zones of expected instability and increased water inflow; provides recommendations for mitigation of recognized potential issues.

Example Coal Mine Roof Rating (CMRR) Assessment



Parameters

Location management

Current location: 1

Clear

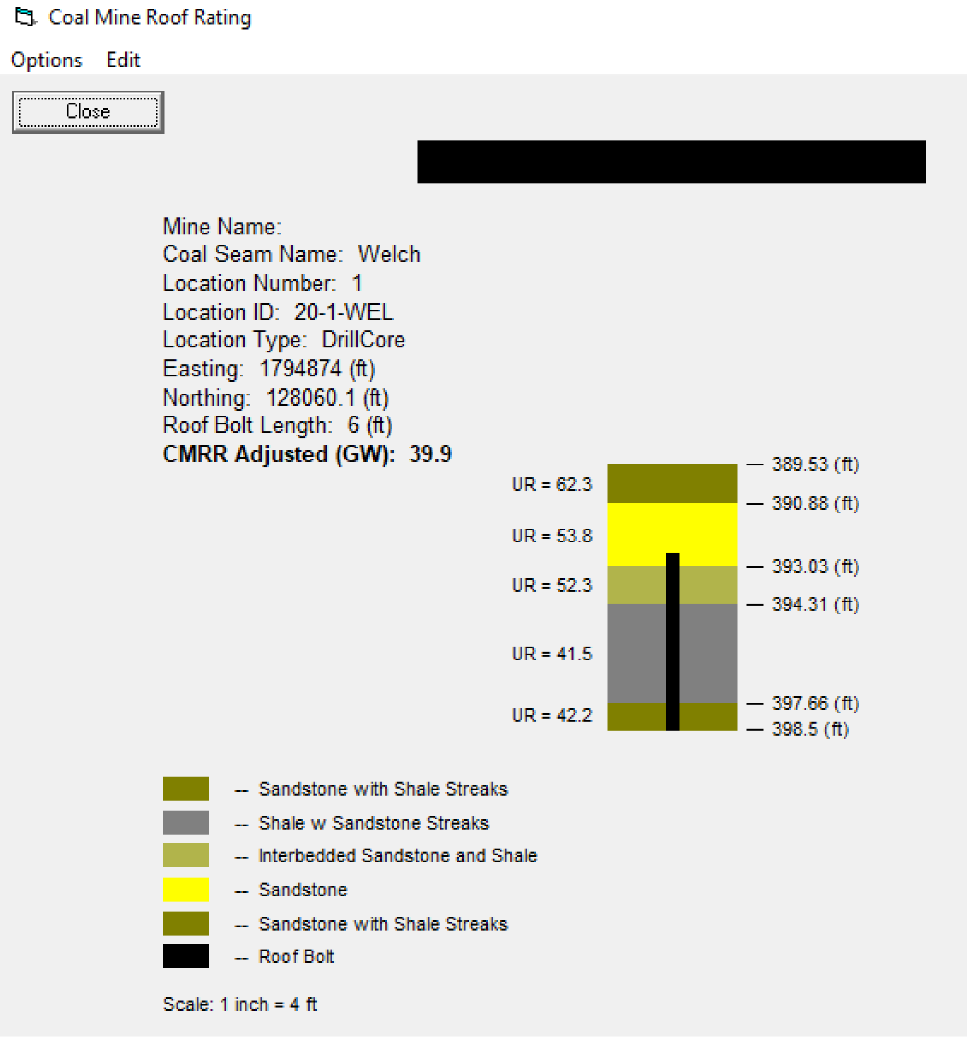
Coal mine roof rating (CMRR)

CMRR: 42.4

GW adj CMRR: 39.9

General | **Unit description** | CMRR

Unit number	Thickness (ft)	Depth to top of unit (ft)	Rock type (Ferm no / custom / text)	Unit rating	GW adjust unit rating	S
Unit 8	1.35	389.53	Sandstone with Shale Streaks	62.3	62.3	☐
Unit 7	2.15	390.88	Sandstone	53.8	53.8	☐
Unit 6	1.28	393.03	Interbedded Sandstone and Shale	52.3	52.3	☐
Unit 5	3.35	394.31	Shale w Sandstone Streaks	41.5	41.5	☐
Unit 4	0.87	397.66	Sandstone with Shale Streaks	45.2	42.2	☐
Unit 3	1.42	396.11	Shale w/Sandstone Strks AND Sandstone w/Shale Strks	49.8	49.8	☑
Unit 2	0.5	397.53	Interbedded Sandstone and Shale	46.7	46.7	☑
Unit 1	0.5	398.03	Shale w/Sandstone Strks AND Sandstone w/Shale Strks	34.3	34.3	☑
	11.42					



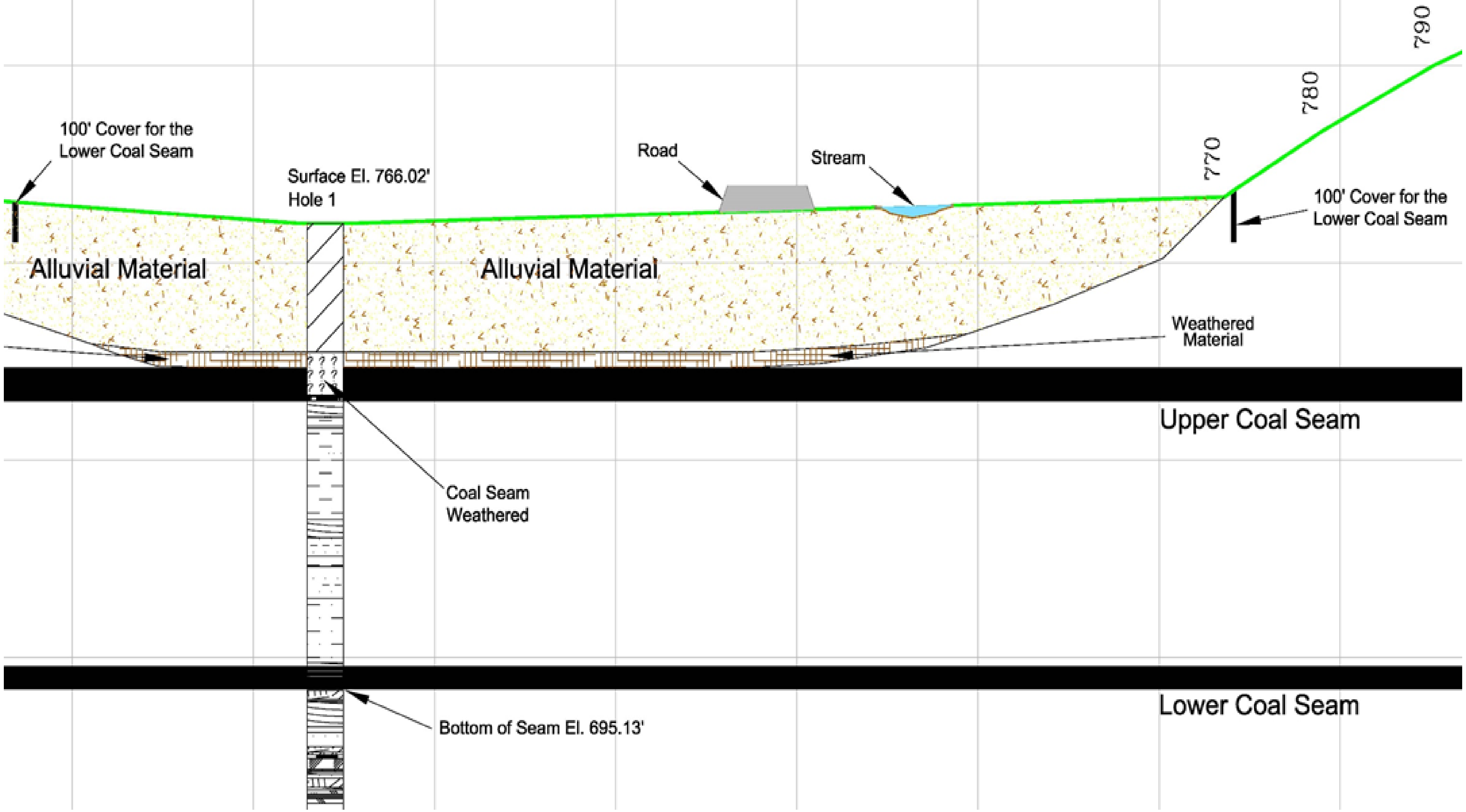
[redacted]

Mine Name:
Coal Seam Name: Welch
Location Number: 1
Location ID: 20-1-WEL
Location Type: DrillCore
Easting: 1794874 (ft)
Northing: 128060.1 (ft)
Roof Bolt Length: 6 (ft)
CMRR Adjusted (GW): 39.9

■ -- Sandstone with Shale Streaks
■ -- Shale w Sandstone Streaks
■ -- Interbedded Sandstone and Shale
■ -- Sandstone
■ -- Sandstone with Shale Streaks
■ -- Roof Bolt

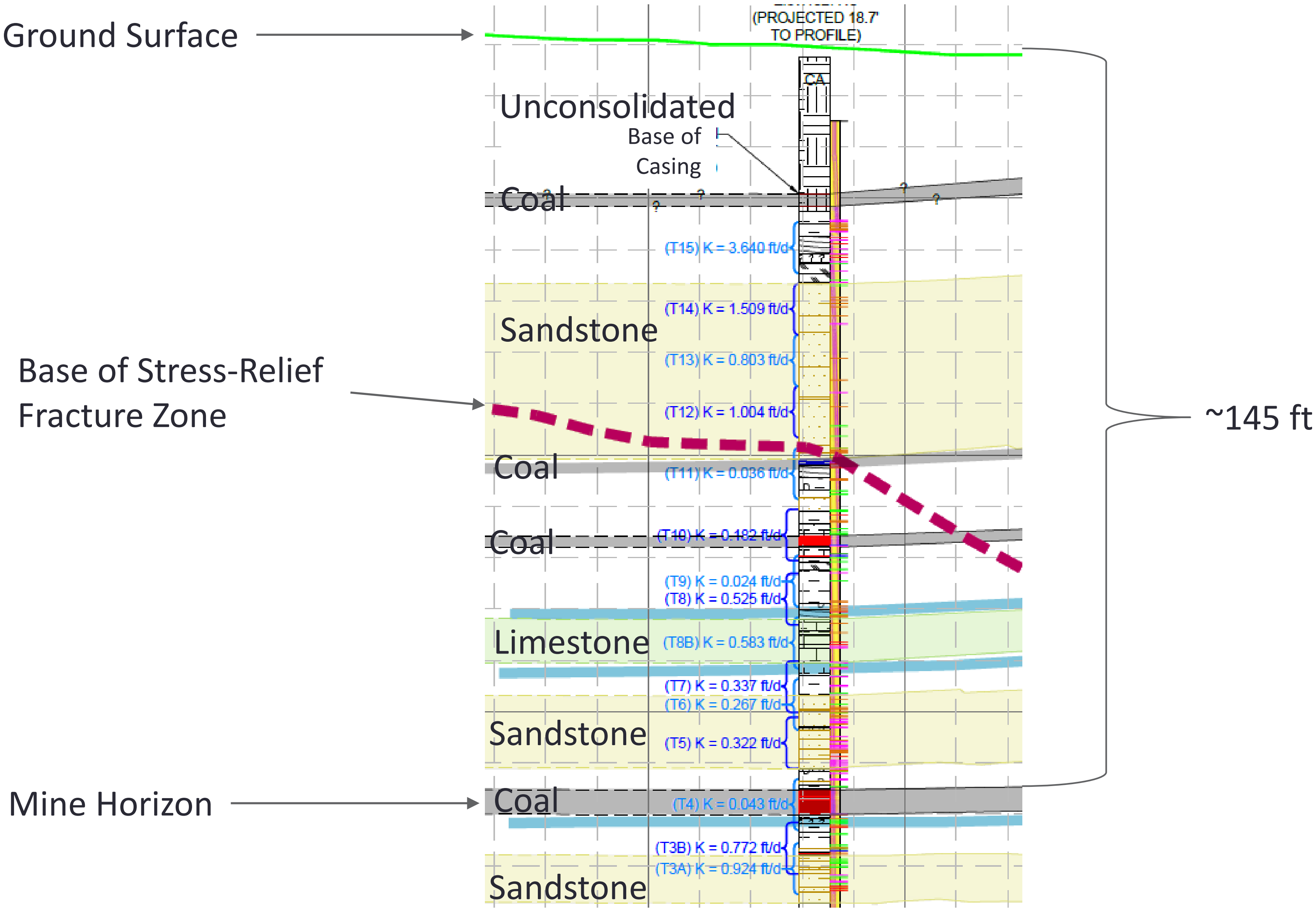
Scale: 1 inch = 4 ft

Cross-Section for Stream Crossing Assessment



No vertical exaggeration!!

Example Hydraulic Conductivity Characterization

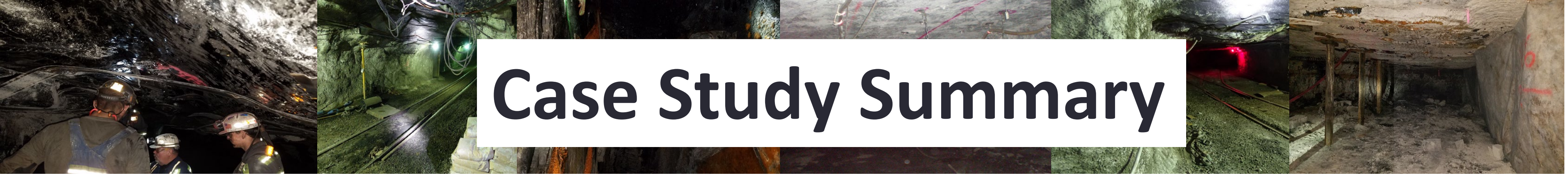


Ground Surface

Base of Stress-Relief Fracture Zone

Mine Horizon

~145 ft



Case Study Summary

Case Study	1	2	3	4	5
Holes Drilled	3 holes, all on one side of creek	1 core hole, 1 rotary boring	3 core holes	4 core holes, 2 on each side of creek	5 core holes, 3 on one side of creek and 2 on other
Depth to Bedrock (ft)	20-30	10	21 to 50	13-23	20-25
Depth to Top of Coal Seam (ft)	52	85-100 average with 60 minimum	145-160	55-60 in stream valley with minimum of 50 below stream bed	110
Alluvial Valley Width (ft)	130	300-450	500	200-250	300-500
R20 Valley Width (ft)	1000	600-900	900 to 1150	720	850
Total Valley Relief (ft)	510	580	700	633	360
Confinement Factor	**0.51 (more susceptible to roof falls)**	0.97 to 0.72 (narrow)	0.78 to 0.61 (marginal)	0.88 (narrow)	**0.42 (more susceptible to roof falls)**
Roof and Floor Notes	Rock quality predominantly poor or very poor	80% of overburden fair to good and 20% somewhat poor to poor; no high angle fractures; poor immediate floor	most roof rock is fair or good; floor is weak	most immediate roof rock is good to fair, with poor zone 12 feet above seam; floor rock varies from very good to very poor	immediate roof is fair to poor; floor is weak and clay-rich
Hydraulic Conductivity (K) Notes	Ranged from 0.001 ft/day to 15 ft/day	0.01 ft/day in roof; 1.2 ft/day in coal; low in floor	0.007 to 0.7 in coal; up to 9 ft/day in shallower overburden; low K in floor	0.1 to 0.85 ft/day in coal; 0.001 to 4.1 ft/day in roof with higher values due to bedding plane separations	0.1 to 0.5 ft/day in coal; in rest of hole very low except at or above 60 feet deep
Notes	Tertiary lineament in crossing area	1 Primary and 2 Tertiary lineaments within 0.5 miles - no effect	Found correlation between high angle fractures in core and ATV with lineament orientations and principal horizontal stress in area	Water levels in holes all lower than stream level implies downward gradient (losing stream)	very few high angle fractures in core
Results	high water inflow potential; potential adverse effects to stream and aquifer	no significant water inflow expected	below 120 feet deep, K is low; water inflow not expected to be problem	decent rock strength, but potential for significant adverse hydrogeologic conditions; numerous bedding plane separations with higher K, but lack of vertical fractures detected; eliminate 4-way intersections; limit cut depth	rock strata below 60 ft is very low K; but strata are weak and must be well supported because small movement could induce large increase in inflow
Recommendations	minimize number of entries; eliminate 4-way intersections; limit cut depth to 10 ft or less; use mesh/screens; use fully grouted bolts and cable bolts; pre-grout from surface and in-mine grouting	Remove 1 ft of immediate floor during mining; mine draw rock and rider coal to increase roof stability; use mesh/screens; use fully grouted bolts and cable bolts; reduce number of entries to 4; increase pillar size; eliminate 4-way intersections; no grouting necessary but have plan in place	use mesh/screens; minimize number of entries, intersections, and cross-cuts; use fully grouted bolts; no grouting recommended but have plan in place	use fully grouted bolts, cable bolts, and possibly steel sets or trusses; reduce bolt spacing; reduce entry width; use mesh/screens; apply sealant to deal with moisture sensitive strata; Intense grouting recommended (both pre-grouting from surface and in-mine)	increase pillar size to assist with floor instability; reduce entry width; use fully grouted bolts and cable bolts; eliminate 4-way intersections; do not leave roof unsupported for any length of time; pre-grouting from surface not recommended (not practical due to low K); in-mine grouting recommended to strengthen weak strata

Conclusions

- **Low cover depths, increased fracturing, and presence of significant water** = **adverse conditions**
- Stream crossing studies:
  - multi-disciplinary
  - characterize the subsurface through which a mine will attempt to advance, and
  - identify the potential issues before the mining occurs
  - Provide road map for grouting activities
- **Benefits:**
  - increased miner safety,
  - increased likelihood of a successful crossing,
  - decreased mining and ground control costs in the crossing area, and
  - decreased potential for damage to the stream or nearby water wells

This paper is intended to inform mine operators of the key components and advantages of completing stream crossing evaluations.

ACKNOWLEDGEMENTS

The content for this paper was compiled and used over the course of decades by a team of Marshall Miller & Associates professional geologists and engineers. These individuals include Gerry Enigk (Mining Engineer), John Feddock (Mining Engineer), Scott Keim (Geologist), Ron Mullennex (Hydrogeologist), Scott Nelson (Geologist), and Mark Smith (Hydrogeologist and Downhole Logging Geophysicist). The practical knowledge has been passed on to the authors through project work and hands-on experience.

Thank you! Any questions?