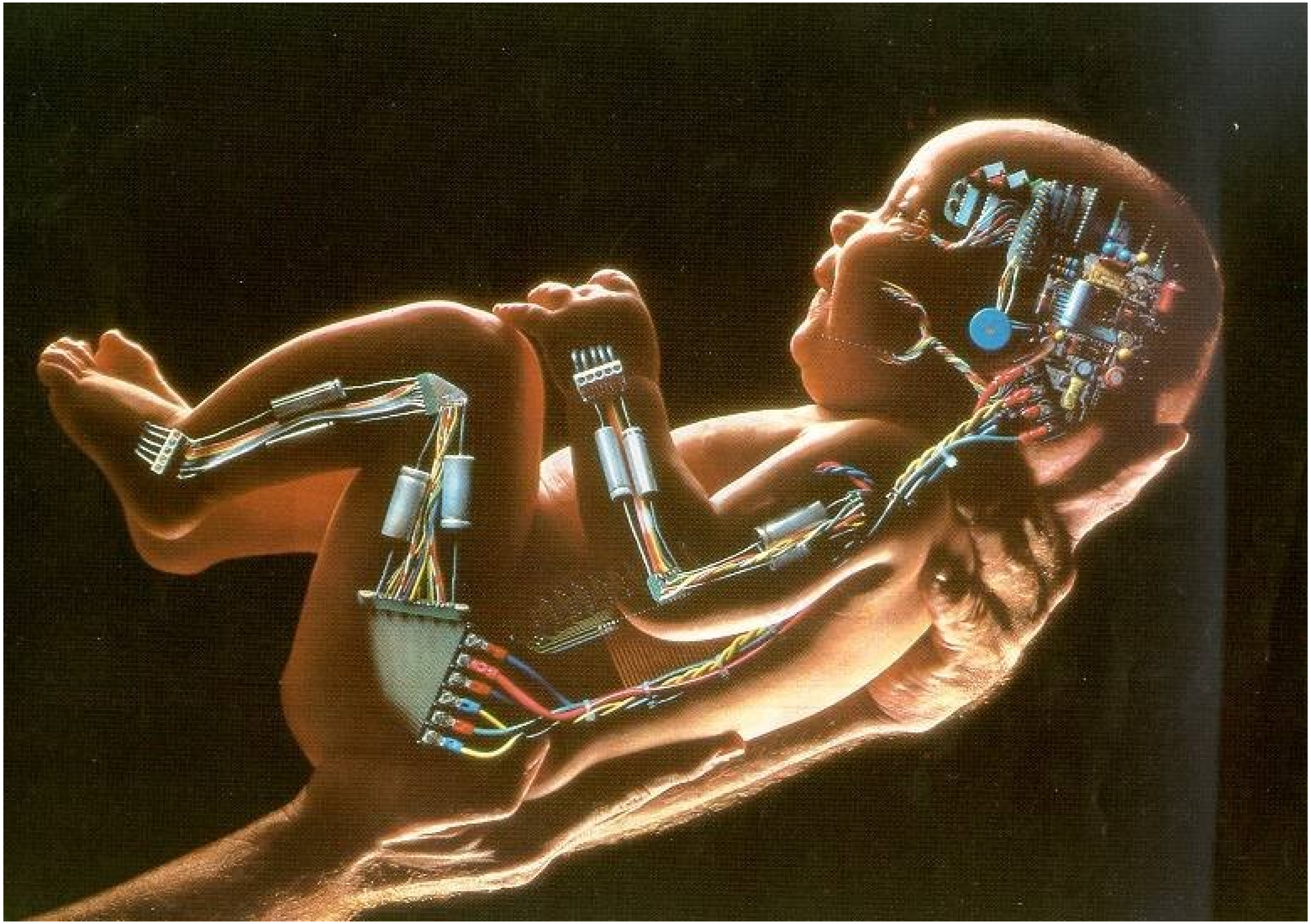
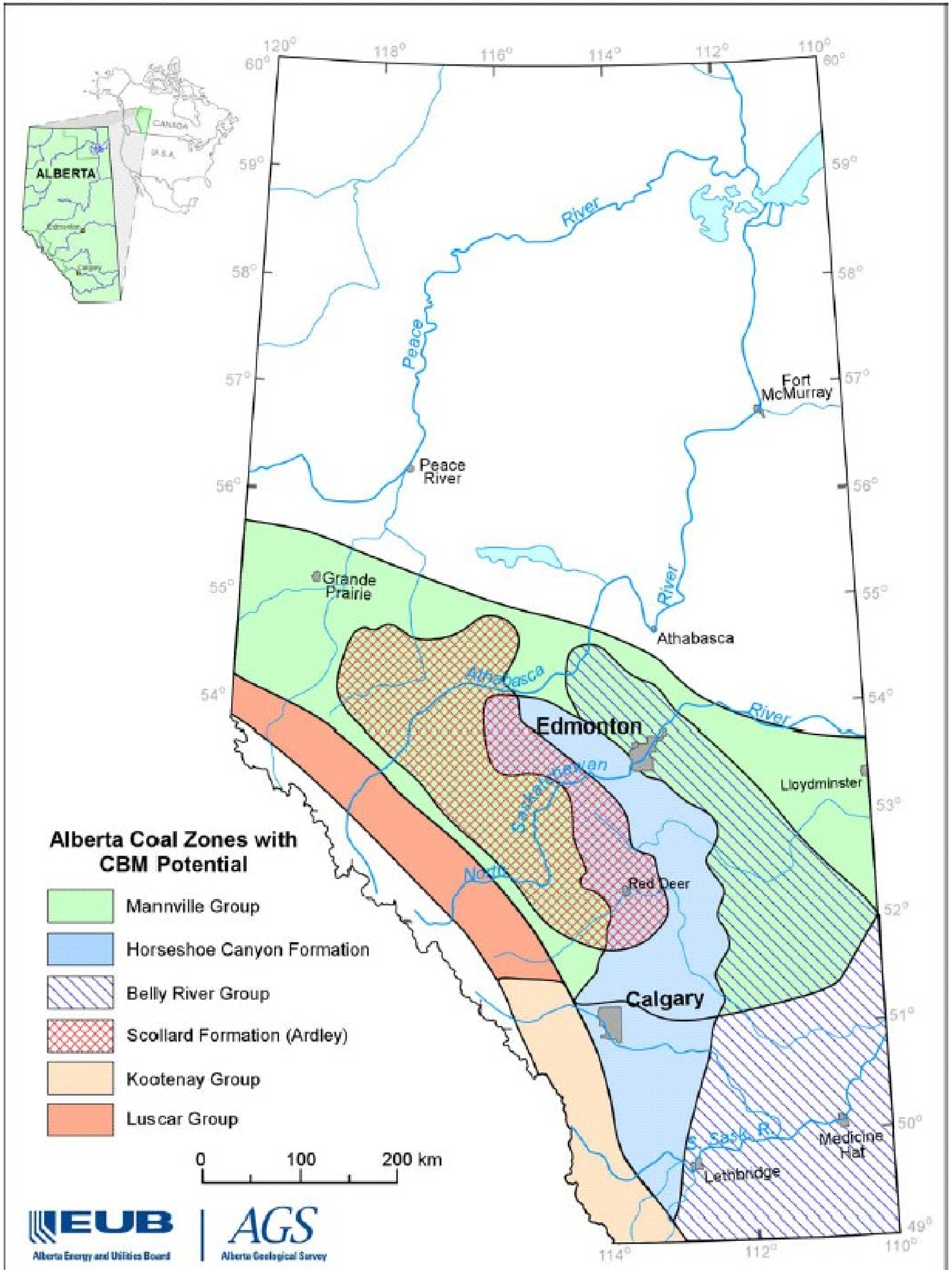
MANNVILLE COALBED METHANE PLAY A TECHNOLOGY DRIVEN RESOURCE IN ITS INFANCY





Alberta Coal Zones with CBM Potential
Mannville Group
Horseshoe Canyon Formation
Belly River Group
Scollard Formation (Ardley)
Kootenay Group
Luscar Group
0
100
200 km
EUB
Alberta Energy and Utilities Board
AGS
Alberta Geological Survey
ALBERTA
CANADA
U.S.A.
Peace River
Fort McMurray
Grande Prairie
Athabasca
Edmonton
Lloydminster
Red Deer
Calgary
Medicine Hat
Lethbridge
Peace
River
Athabasca
River
North Saskatchewan
S. Sask. R.
120°
118°
116°
114°
112°
110°
60°
59°
58°
57°
56°
55°
54°
53°
52°
51°
50°
49°

Interpretation of Mannville Gas Content Trends

- Depth to coal targets ranges from <900 m to 1600 m
- Permeabilities range from 3 to 4 md in the shallower targets to <1 md in the deeper targets
- Generally 2 – 5 seams (cum. thickness to 20m)
- Gas contents of the target seams ranges from less than 7 cc/g to more than 10 cc/g, depending on depth and geographic location (300 – 500 scf/ton)
- Gas-in-place ranges from less than 2 to >10 bcf/sec depending on gas content and coal seam thickness
- High salinity water needing disposal strategy
- Wet and dry coal regions
- Recovery of economic volumes of gas depends on successfully drilling and completing horizontal wells in the targeted coal seams as there is no evidence to date that vertical Mannville CBM wells are economic
- There is significant potential in the Mannville (70% of the estimated 500 tcf are in these coals)

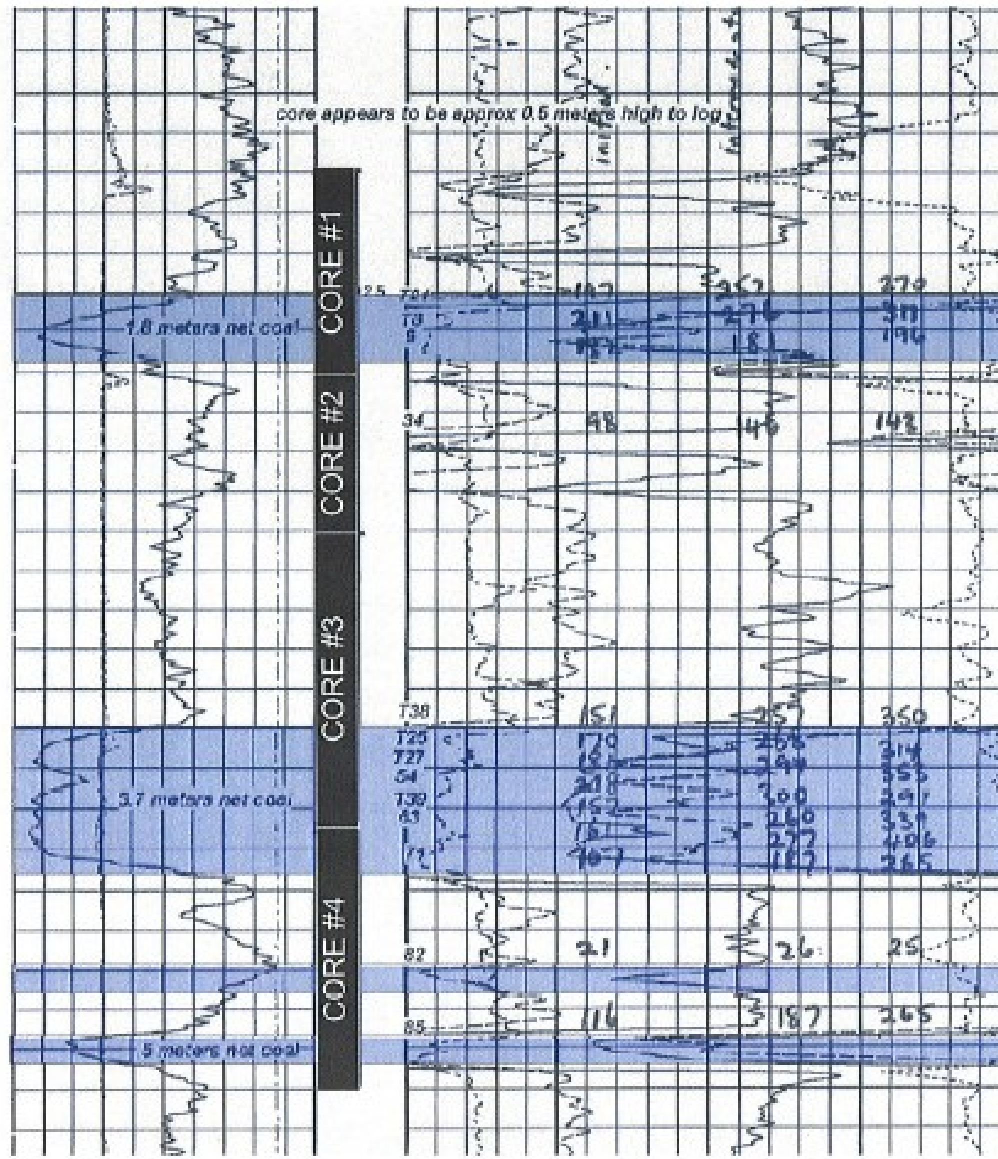
Log Correlation of Samples

<u>Seam #1 1025.0-1026.8 m (log depth)</u>
<u>Seam 1a</u> (1025.0-1026.2 m)
Average gas content = 291 scf/ton (343 scf/ton DAF)
Average ash content = 13.7%
<u>Seam 1b</u> (1026.2-1026.8 m)
Average gas content = 170 scf/ton (312 scf/ton DAF)
Average ash content = 45.1%

<u>Seam #2 1036.0-1039.5 m (log depth)</u>
Average gas content = 331 scf/ton (386 scf/ton DAF)
Average ash content = 12.3%

<u>Seam #3 – Carb Shale 1041.9-102.4 m (log depth)</u>
Average gas content = 25 scf/ton

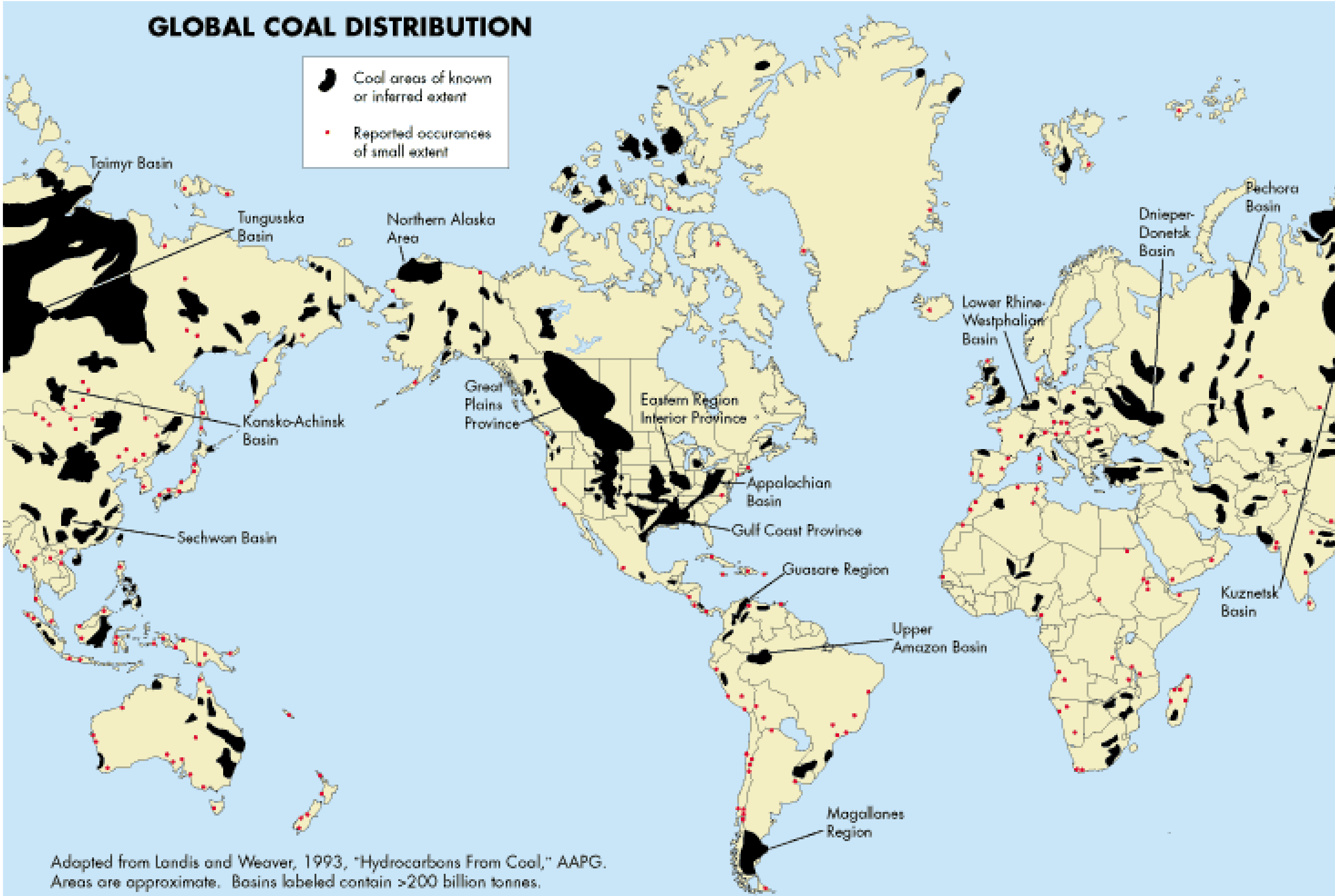
<u>Seam #3 1043.8-1044.2 m (log depth)</u>
Average gas content = 187 scf/ton (310 scf/ton DAF)
Average ash content = 39.1%



Measured and corrected gas contents (scf/ton) of coal core samples.

Raw Data										Corrected Data Gas Content
Seam #	Sample Type	Canister #	Depth (m)		Lost Gas (scf/ton)	Measured Gas (scf/ton)	Residual Gas (scf/ton)	Crushed Gas (scf/ton)	Gas Content (scf/ton)	Dry Ash Free (scf/ton)
			Top	Bottom						
1	core	T21	1024.8	1025.4	56.4	170.3	30.6	12.7	270.1	320.0
1	core	T8	1025.4	1026.0	64.0	183.7	35.6	28.0	311.4	365.6
1	core	9	1026.0	1026.3	32.7	126.9	22.9	13.9	196.4	353.4
1	core	34	1028.0	1028.3	21.4	99.7	21.9	\	143.0	270.4
2	core	T38	1035.3	1035.9	40.7	171.7	58.4	79.5	350.3	419.8
2	core	T25	1035.9	1036.5	47.4	181.3	42.2	43.3	314.3	356.0
2	core	T27	1036.5	1037.1	53.1	192.9	66.6	40.4	353.0	367.8
2	core	54	1037.1	1037.4	59.7	195.6	35.5	\	290.8	311.1
2	core	T39	1037.4	1038.0	47.7	164.7	65.7	60.5	338.6	387.2
2	core	63	1038.0	1038.3	47.6	176.3	71.8	110.4	406.2	424.4
2	core	71	1038.9	1039.2	32.5	118.1	45.0	69.5	265.1	435.6
3	core-shale	82	1041.5	1041.8	7.2	15.1	2.2	\	24.5	\
3	core	85	1043.3	1043.6	25.8	126.3	34.6	\	186.6	310.3

DEEP CBM ACTIVITY AND THE TECHNOLOGIES BEING EMPLOYED TO EXPLOIT THEM



Adapted from Landis and Weaver, 1993, "Hydrocarbons From Coal," AAPG.
Areas are approximate. Basins labeled contain >200 billion tonnes.

TYPES OF DEEP COALBED METHANE PLAYS

- **DRY COALS**
- **WET COALS**
- **PRESSURED COALS**
- **NON-PRESSURED COALS**

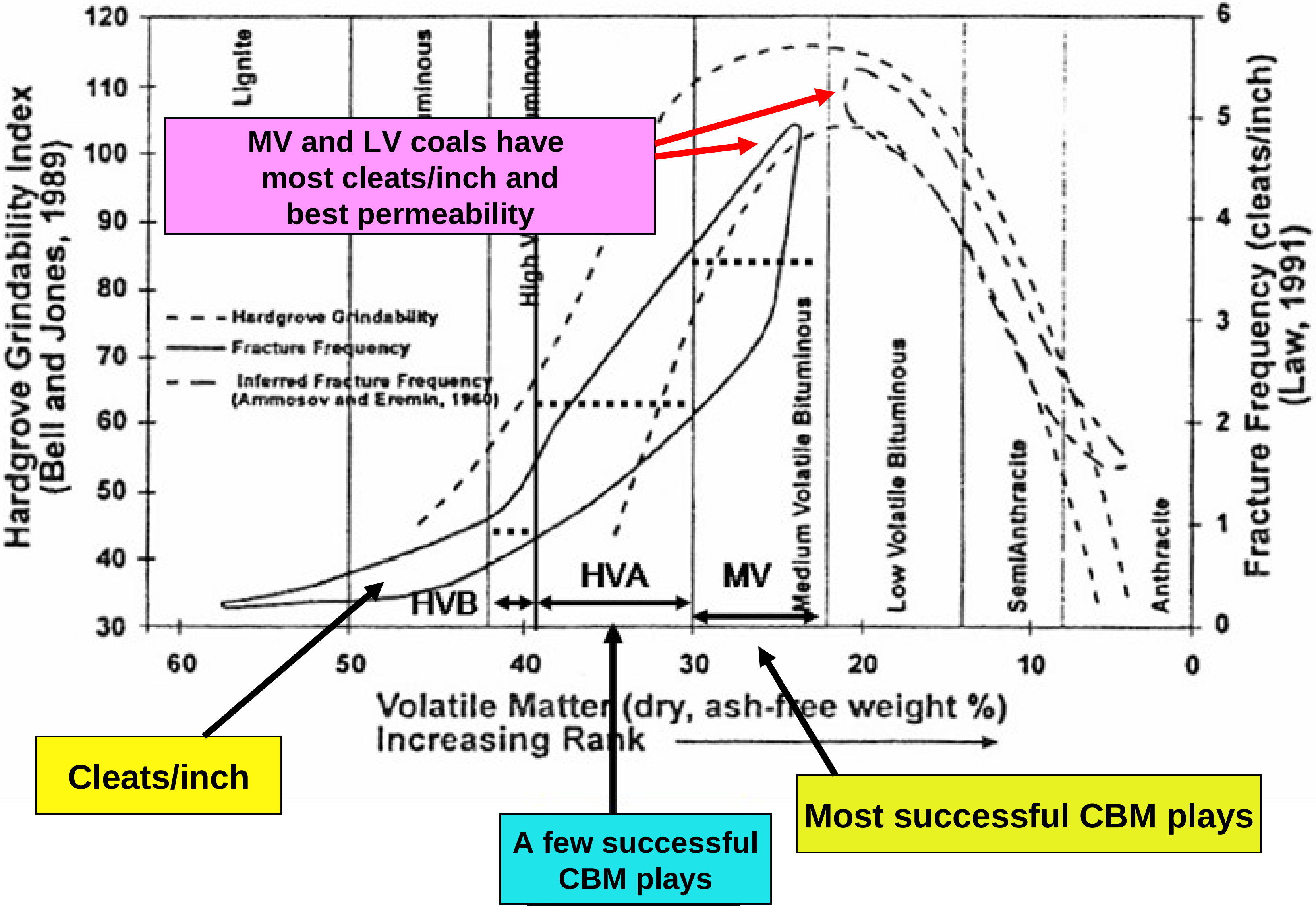
Depth and permeability: the problem

- Majority of successful CBM plays in the world are at depths < 1000m (3300 ft)
- An exception is White River Dome in Piceance basin, where depths are ~6000-7000 ft. This must be an area of perm enhancement.
- Most successful CBM plays have permeabilities 3-30 md, and these occur at depths < 1000 m

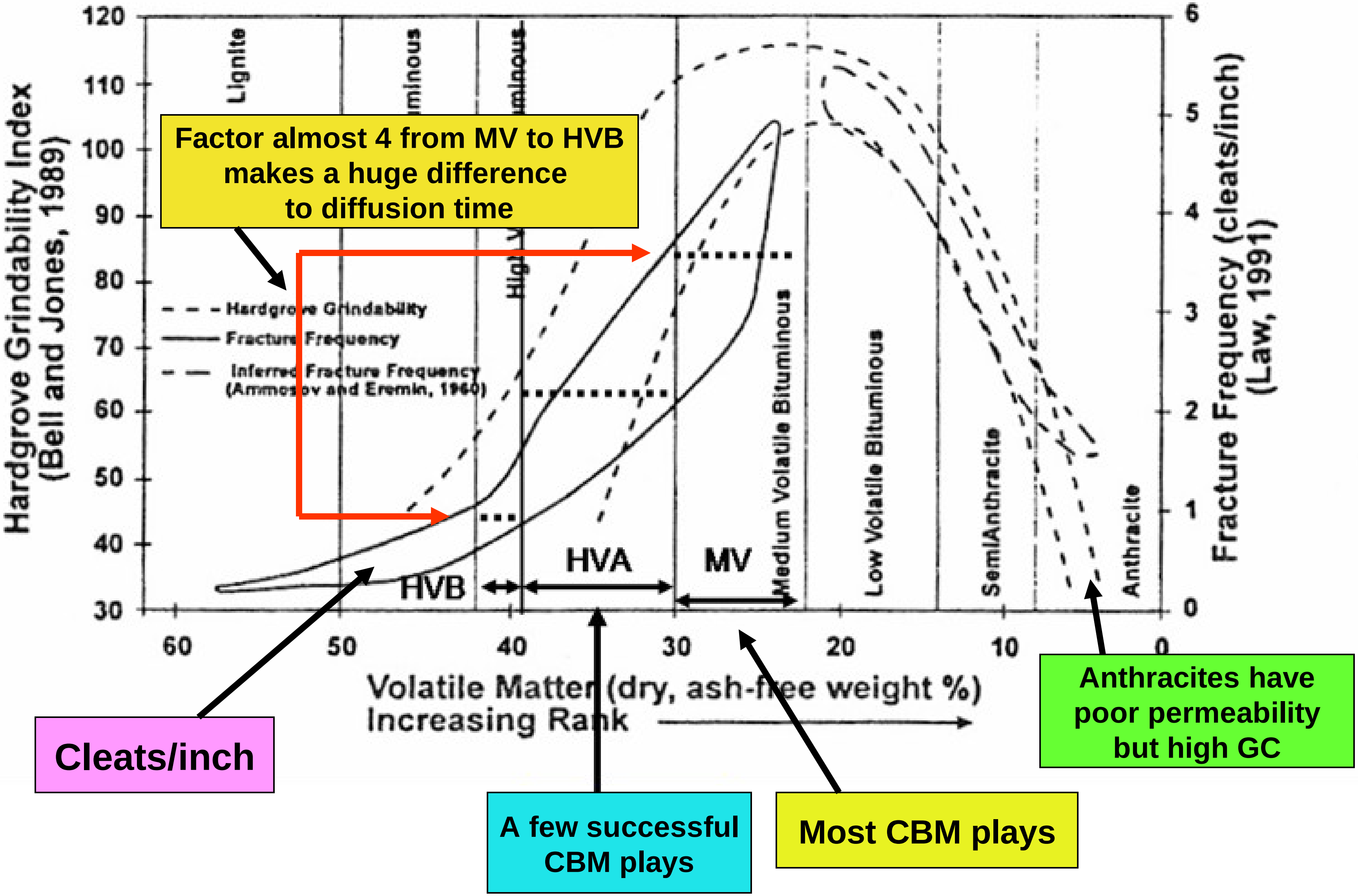
Exploiting Tight Coals <1 md

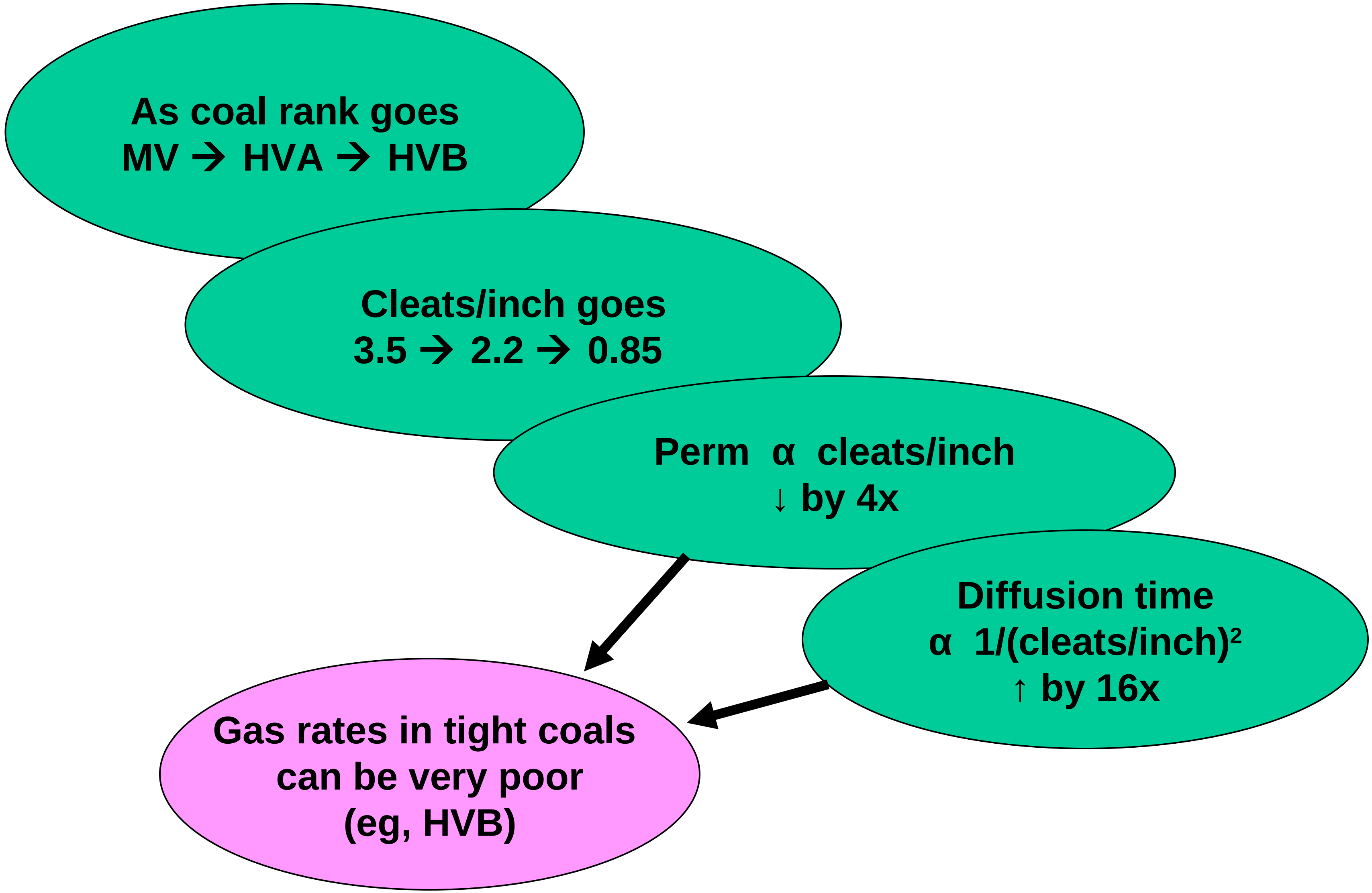
- Most CBM plays have permeability >3 md; exception is dry coal south of fairway (0.1-3 md)
- Hard to make an economic play for 0.1-1 md coals, without new stimulation technology
- These tight coals behave similar to tight gas sands (<20 μd):
  - water and gas rates decline rapidly, over several months (flush production from cleats)…..not economic
- Explanation:
  - desorption too slow to refill cleats because cleats are too far apart in low-perm coals <1 md
  - eg, cleat spacing is ~4x worse in HVB coals than in MV coals
  - this slows down desorption by 16x (a diffusive process)
  - And perm is worse by 4x ….double whammy!

Cleats per inch versus coal rank



The problem with HVB and Anthracites



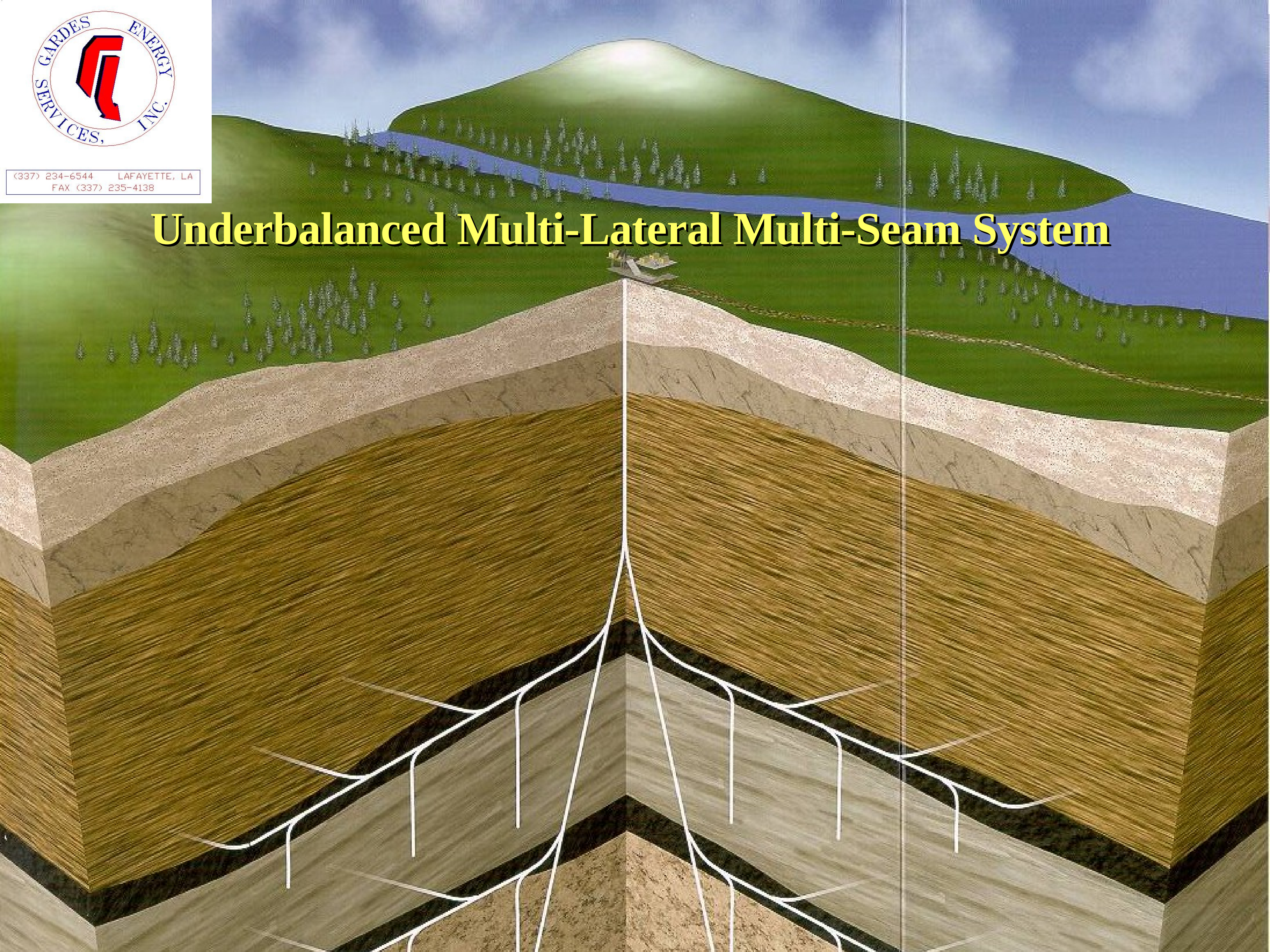

As coal rank goes
MV → HVA → HVB
Cleats/inch goes
3.5 → 2.2 → 0.85
Perm α cleats/inch
↓ by 4x
Diffusion time
α 1/(cleats/inch)^2
↑ by 16x
Gas rates in tight coals
can be very poor
(eg, HVB)

PERMEABILITY ENHANCEMENTS

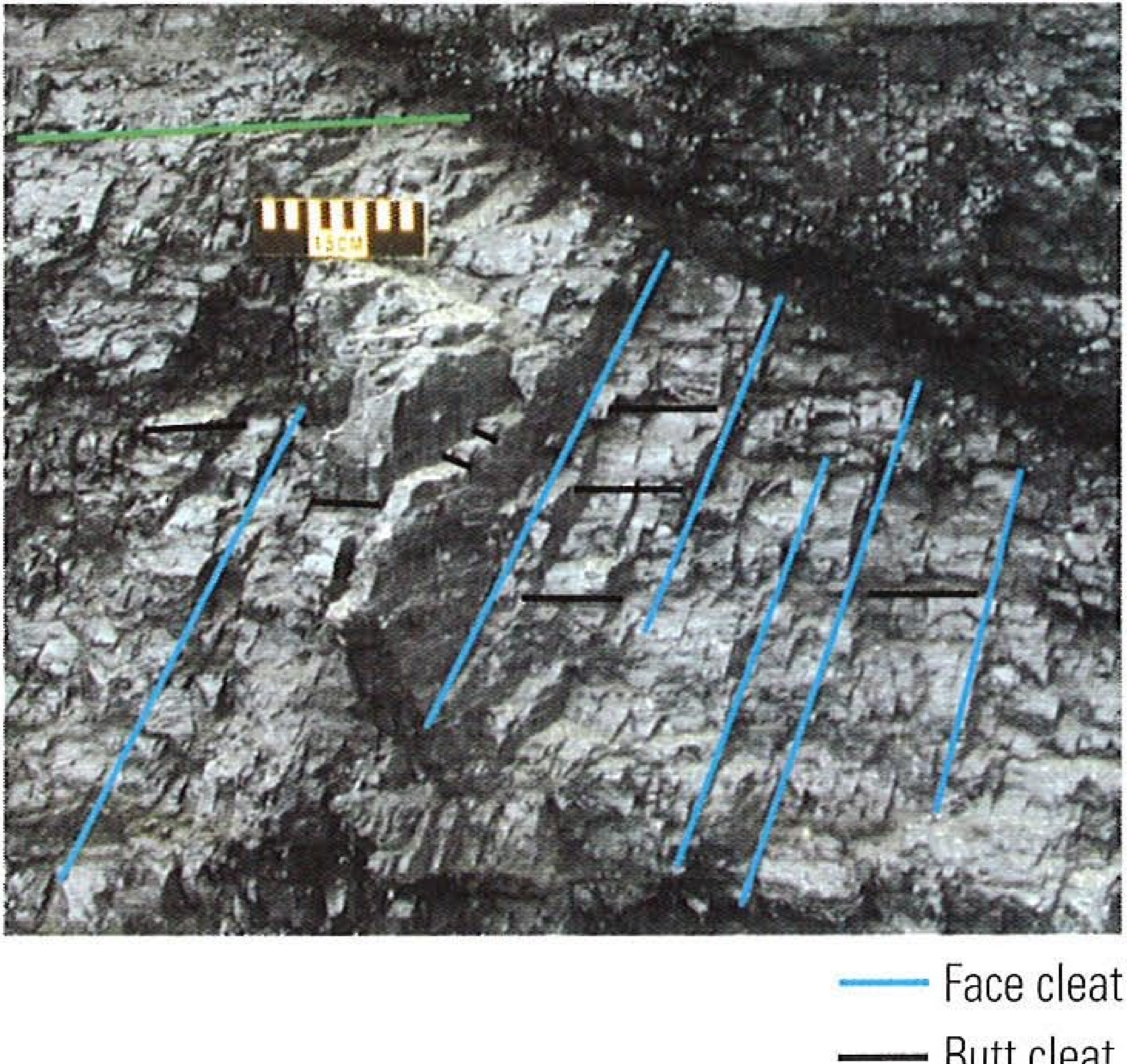
- Cleating occurs during coalification
- Tectonic Fracturing
  - Numerous stages
- Relaxed Stress conditions
- Stimulation Treatments
- Under Balanced Multi Lateral Multi Seam Drilling

GARDES ENERGY SERVICES, INC.
(337) 234-6544 LAFAYETTE, LA
FAX (337) 235-4138

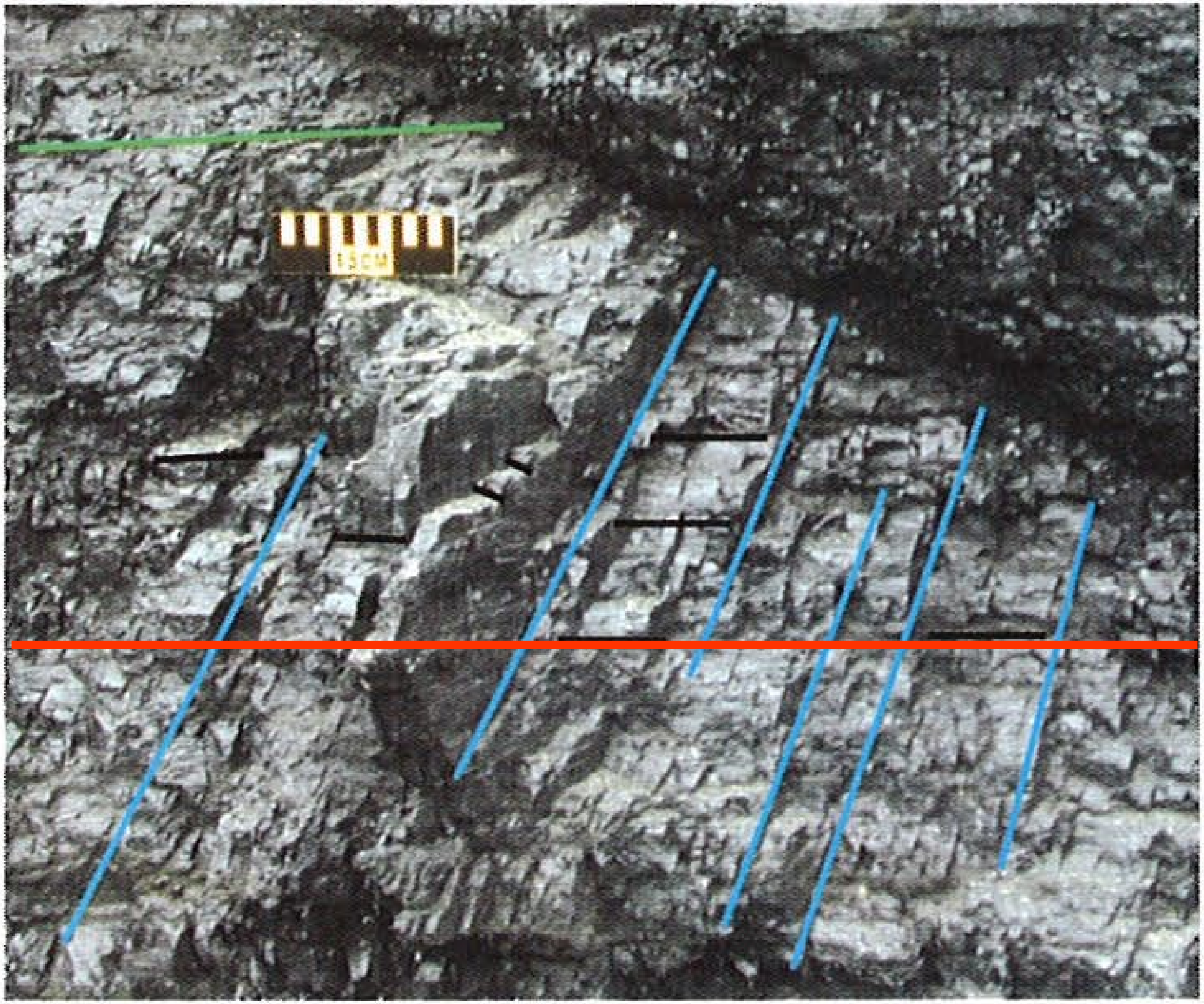
Underbalanced Multi-Lateral Multi-Seam System



Plains Coal



Plains Coal



Mechanical Butt Cleat

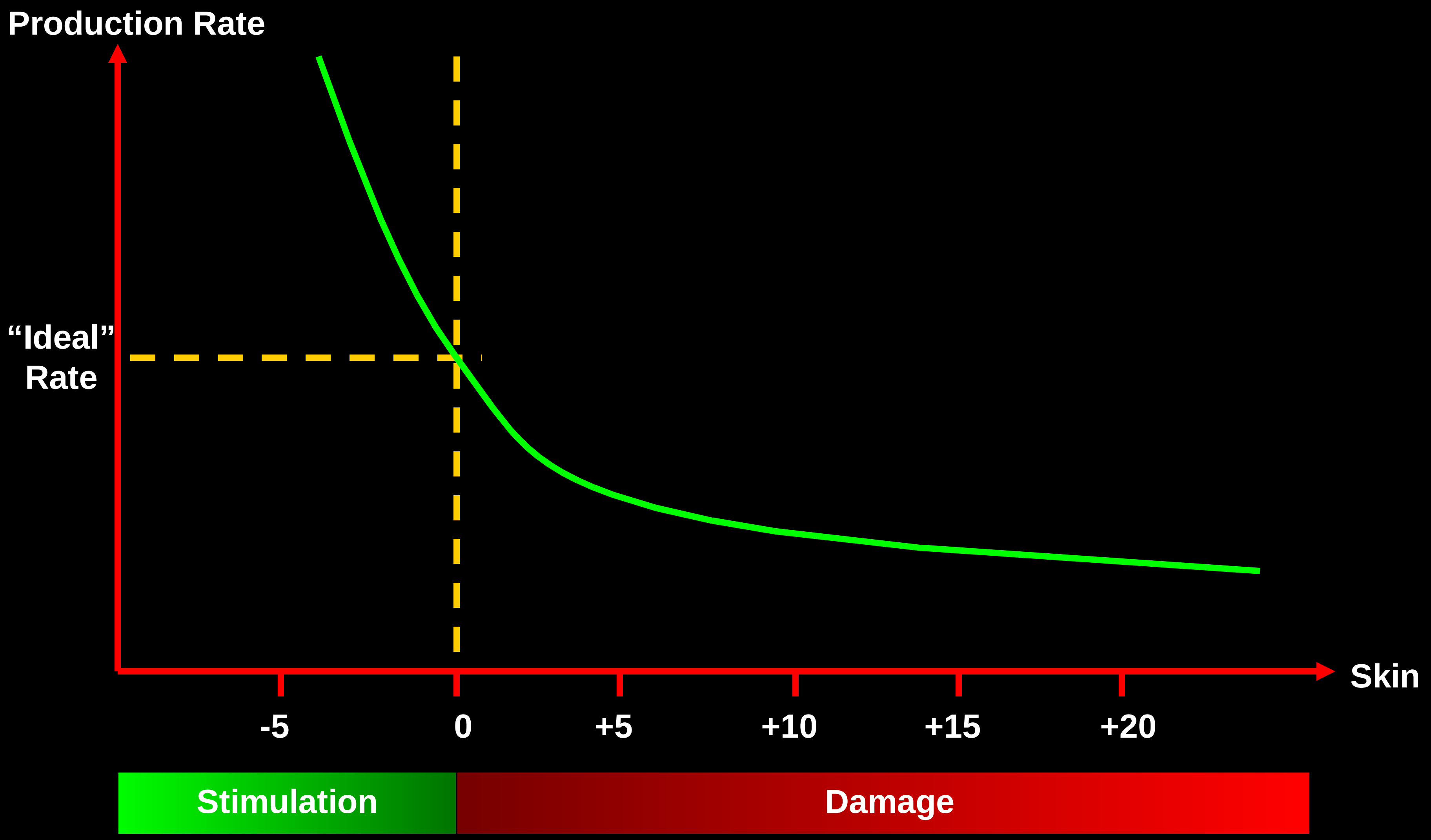
Face cleat

Butt cleat

Multi-Lateral Wellbore

- **“permeability enhancements may be the most significant benefit of Under Balanced Multi Lateral Multi Seam Drilling to enhance coalbed methane production. “**

Skin Factor Impact on Production Rate



MECHANISMS OF FORMATION DAMAGE IN COAL

1) **Chemical Absorption**

3) **Invasion of Fines**

Formation Damage in Under Pressured Zones due to Over Pressured Drilling Applications and Drill Mud Additives Cause Reduction and Damage to Coal Bed Methane Gas Recovery

- **"…it appears that even water containing low concentrations of friction reducing polymers can cause significant damage to coal permeability"**
  - **Puri, King & Palmer, 1991**

- **"Due to the possibility of extensive damage to coal permeability, it is recommended that all possible effort be made to avoid contacting the coal seam with fluids containing polymers, surfactants, biocides, friction reducers, or any other liquid chemicals."**
  - **Puri, King & Palmer, 1991**

SOURCE: SPE 21813

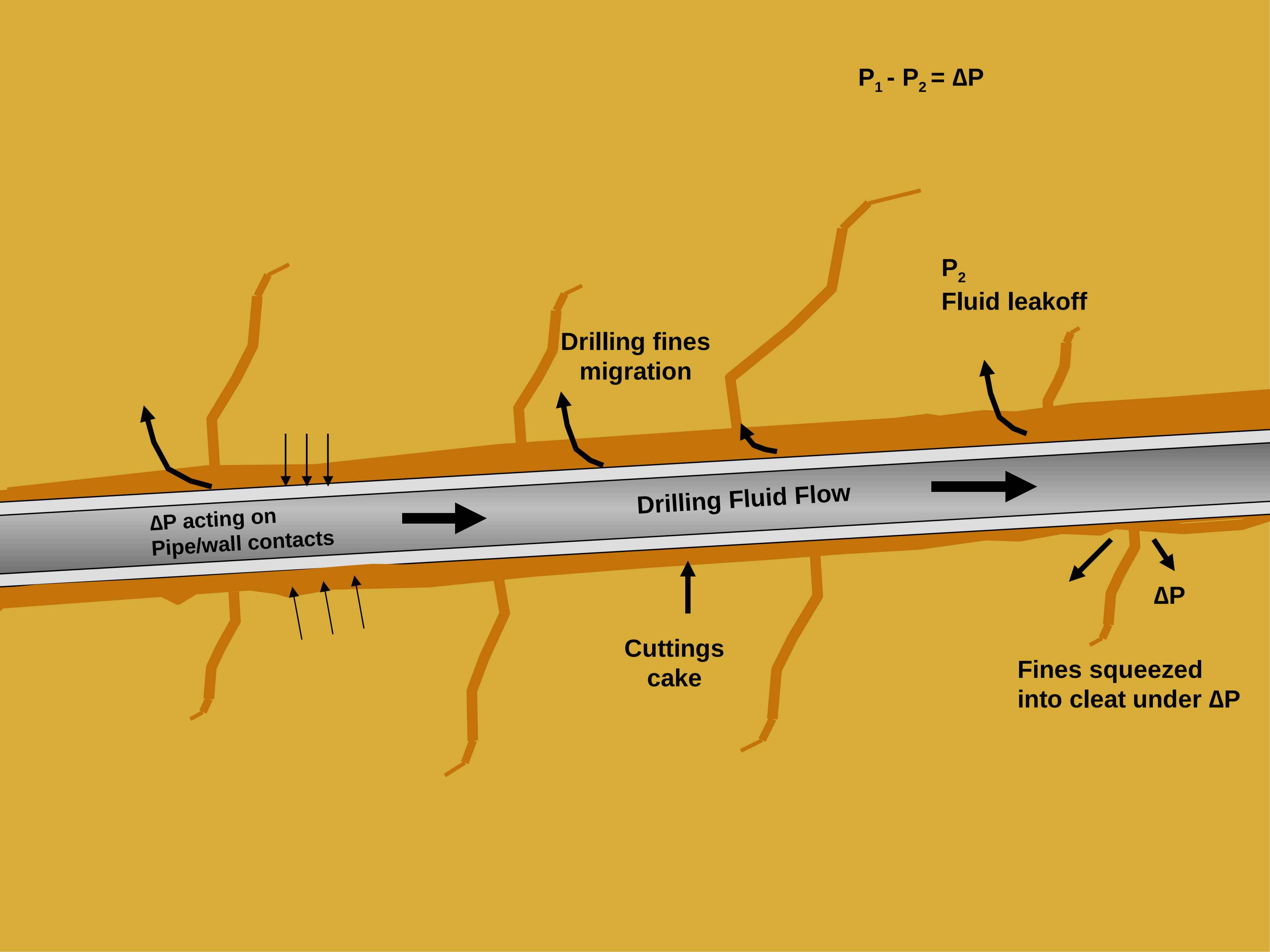
Routine Analysis of McRae Coal Seam Samples used in the Formation Damage Studies

ROUTINE CORE ANALYSIS

Sample No.	Air Permeability (mD)	Porosity (fraction)
SP 1	0.24	0.018
SP 2	6.62	0.028
SP 3	14.33	0.023
SP 4	14.79	0.028
SP 5	47.19	0.050
SP 6	110.96	0.036
SP 7	13.76	0.036
SP 8	20.71	0.038
SP 9	101.66	0.097
SP 10	5.31	0.021

Summary of Coalbed Methane Overbalanced Drilling Fluid Formation Damage Test Results

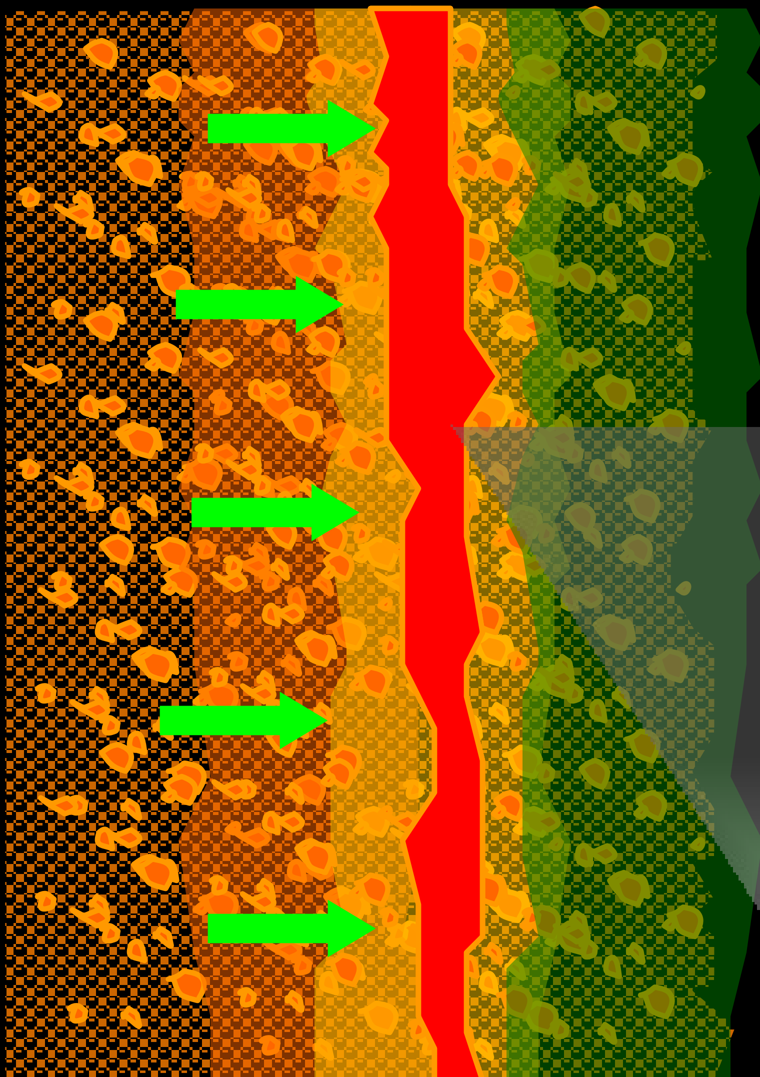
Sample No.	Fluid Tested	Routine Dry Air Perm (mD)	Poro sity Fract ion	Overbalanced Pressure (kPA)	Fluid Loss in 240 min (cc)	Initial Brine Perm (mD)	Final Brine Perm (mD)	Reduction by Mud Contact (%)
9	Pure P.A.C.	20.71	0.038	5000	37.1	3.32	0.739	-77.7
7	Xanthan Gun + P.A.C.	13.76	0.036	5000	3.9	1.38	0.332	-76.0
3	Xanthan Gum, pH=12	14.22	0.023	5000	4.6	.086	0.112	-87.0
4	Xanthan Gum, pH=7	14.78	0.028	5000	1.8	1.42	0.295	-79.2
5	Base Foaming Solution	47.19	0.050	1000	127.8	1.17	0.269	-77.0
7A	Xanthan Gum Field Mud	29	0.025	5000	20.6	5.14	1.39	-72.9
5A	Xanthan Gum + Fiber Bridging Agent	55	0.027	5000	5.3	8.94	1.23	-86.3
3A	Cationic Shale Inhibitor/HEC	21.5	0.020	5000	156.2	2.22	0.556	-74.9



P1 - P2 = ΔP
P2
Fluid leakoff
Drilling fines
migration
Drilling Fluid Flow
ΔP acting on
Pipe/wall contacts
Cuttings
cake
ΔP
Fines squeezed
into cleat under ΔP

Formation Damage
Building a Filter Cake

The Result is Porous Areas of Formations become Restricted or “Clogged” and are Unable to Flow or Produce to Their Full Potential.



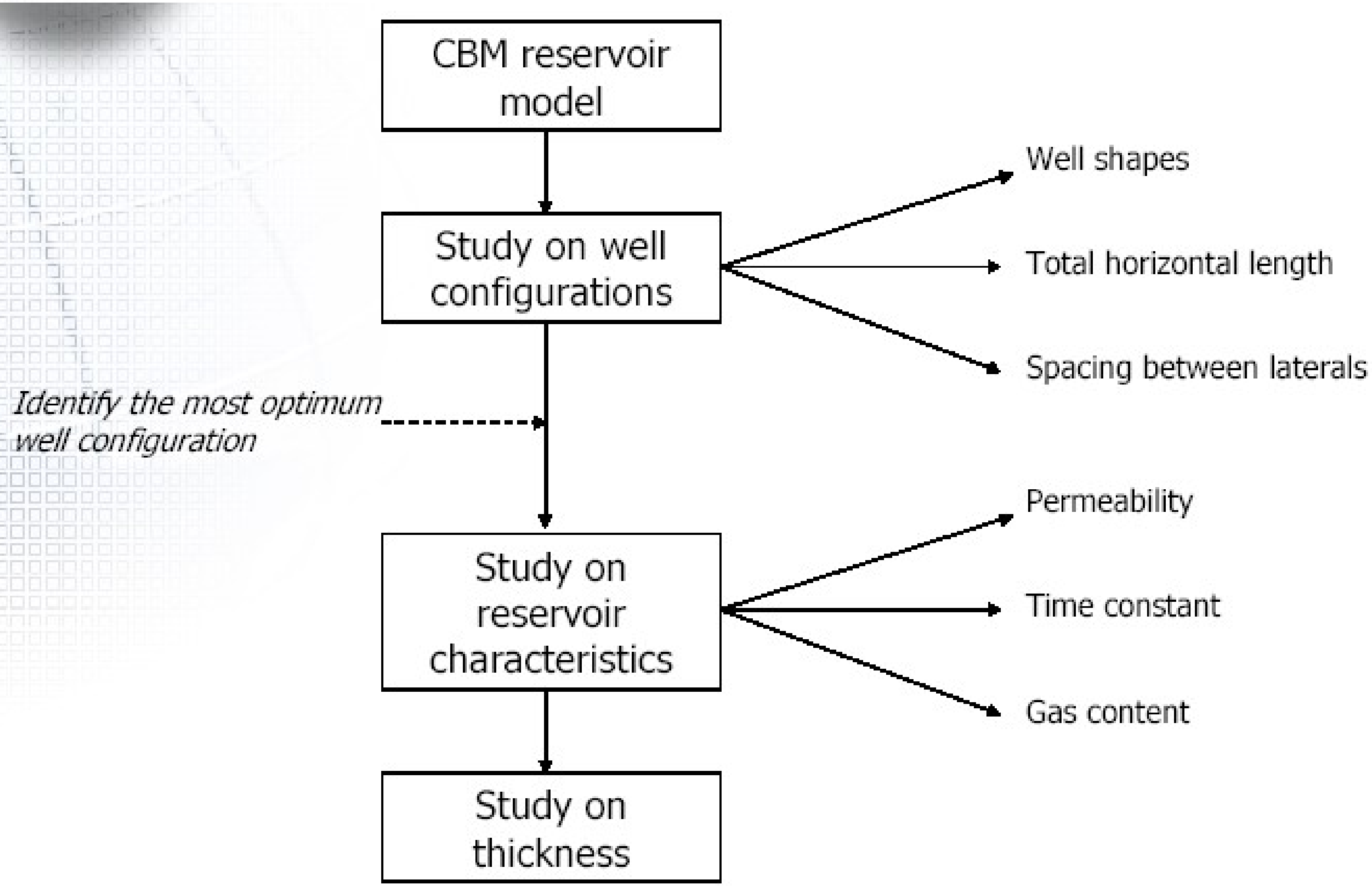
•Actual Core Photo Showing Formation Damage Compliments of COSMA

Three Contributions to Skin Factor in Horizontal Wells

- **Perm damage due to drilling mud (OB drilling)**
- **Perm loss due to coal fines plugging of cleats (OB drilling**
- **Perm loss due to hoop stress concentration (OB of UB drilling)**
- **Perm loss due to failure around well, and fines plugging**

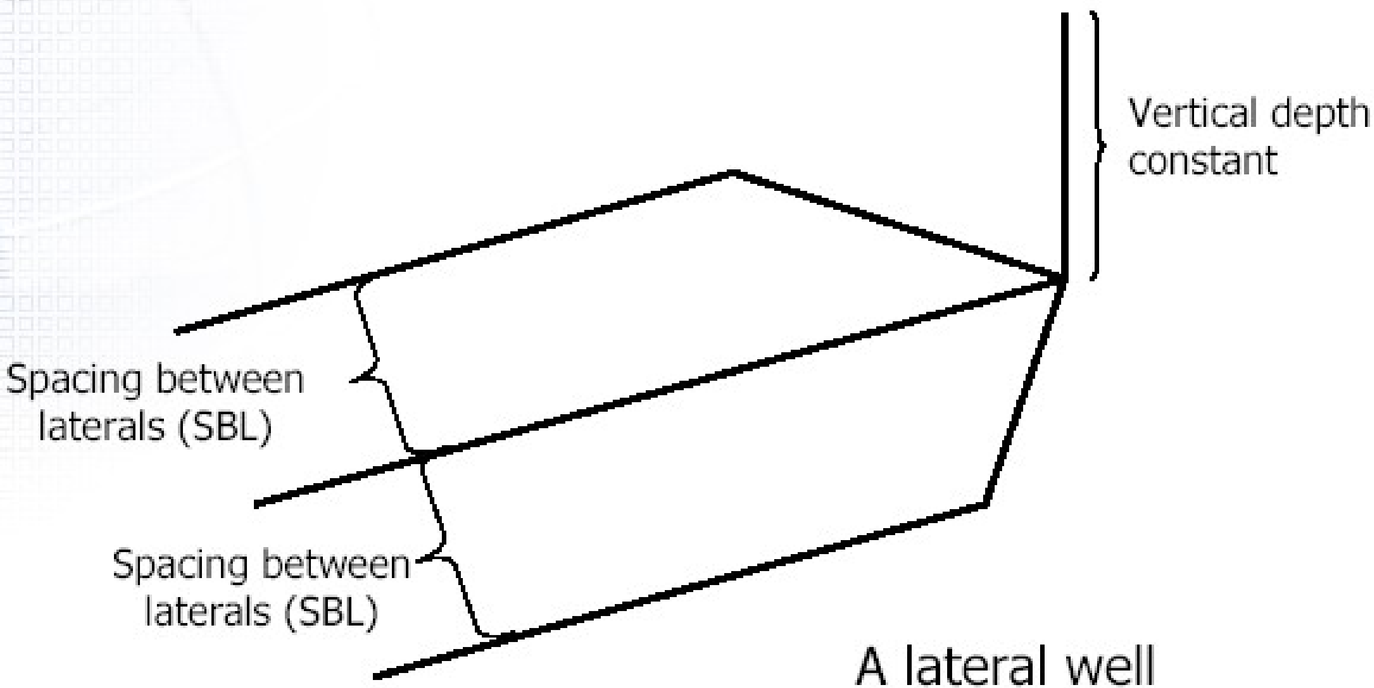
Horizontal/Multilateral Well Planning

Flow chart

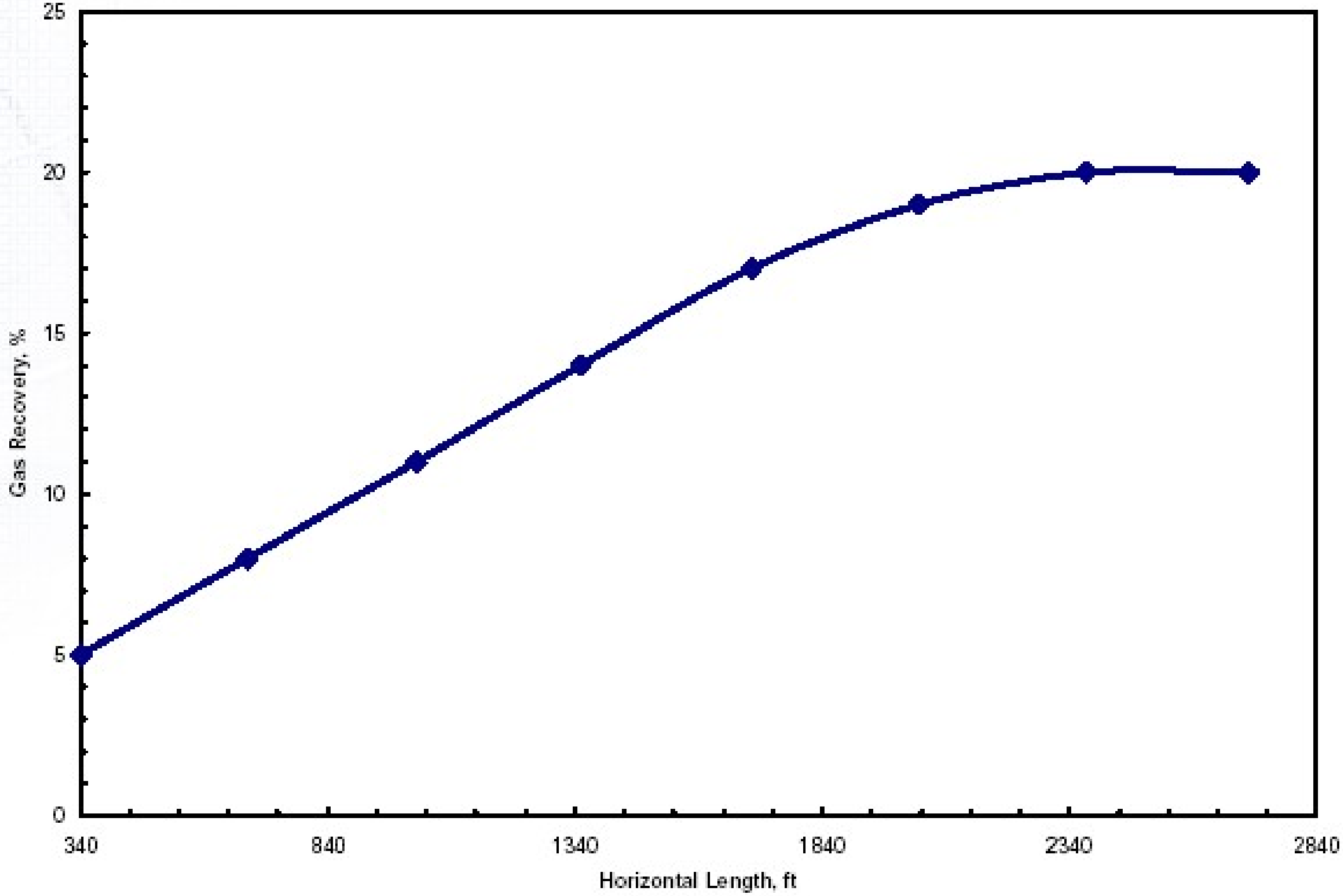

CBM reservoir model
Study on well configurations
Well shapes
Total horizontal length
Spacing between laterals
Identify the most optimum well configuration
Study on reservoir characteristics
Permeability
Time constant
Gas content
Study on thickness

Investigated Parameters

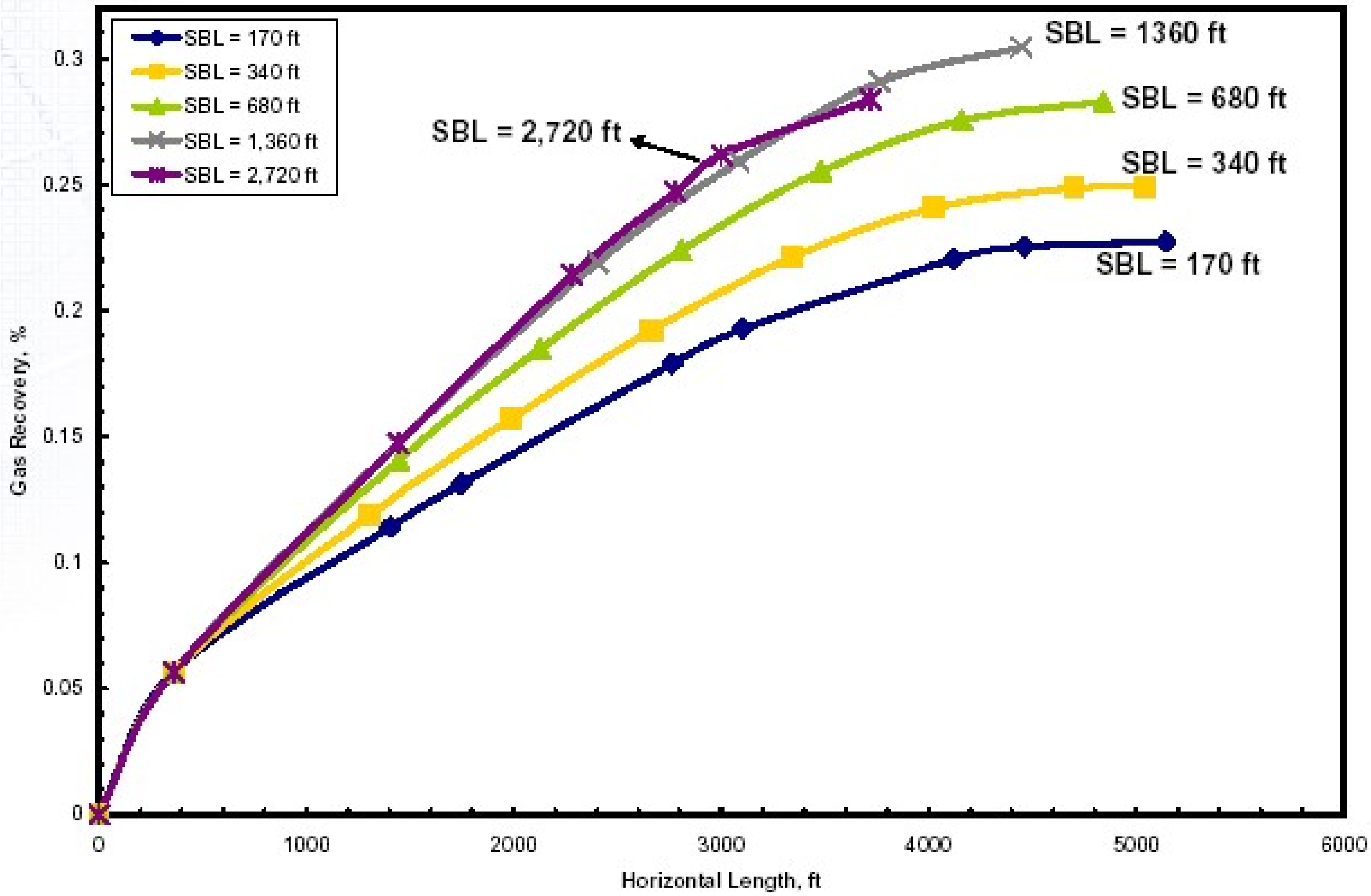
1. Total Horizontal Length (THL)
2. Spacing Between Laterals (SBL)



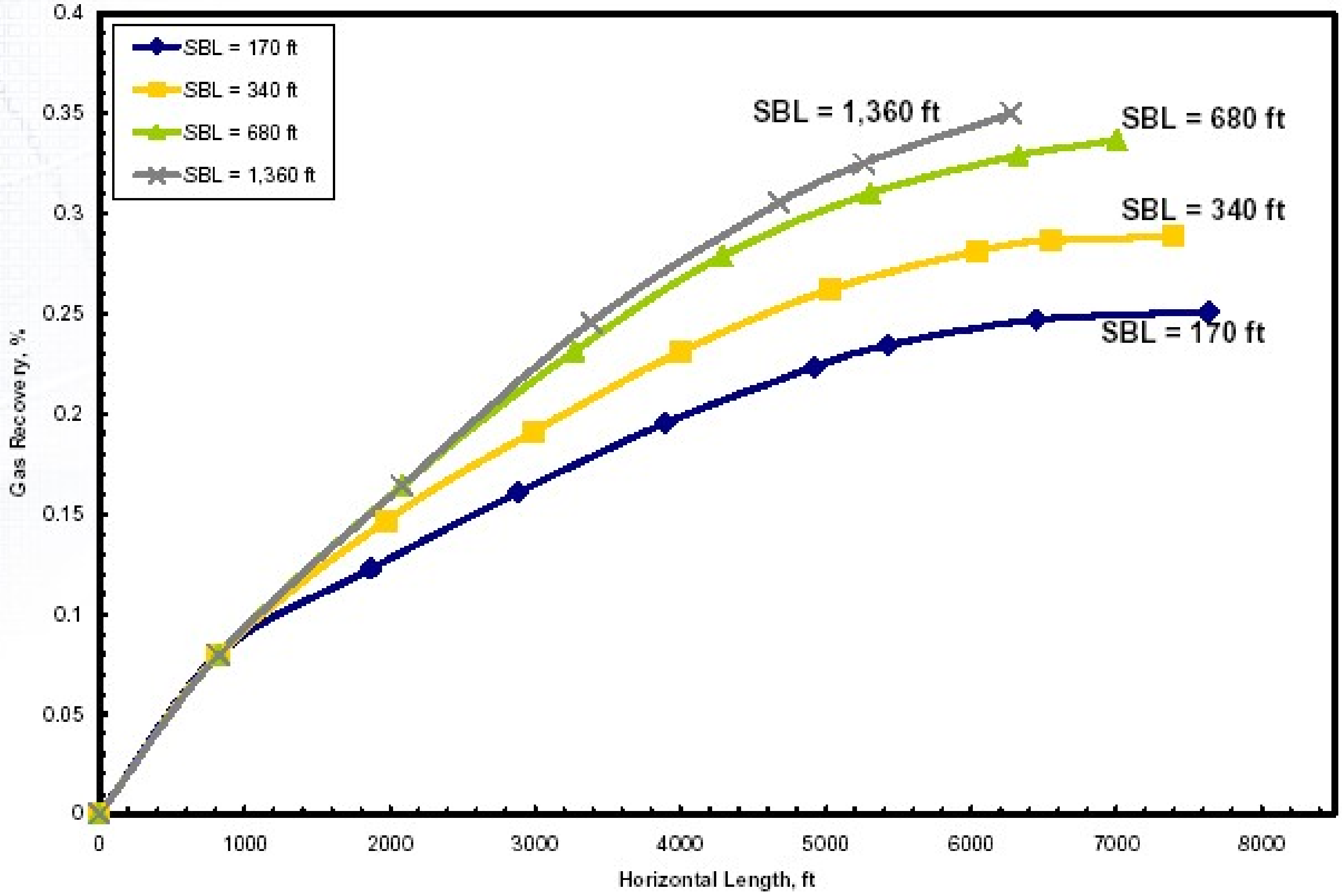
Single-lateral



Dual-lateral

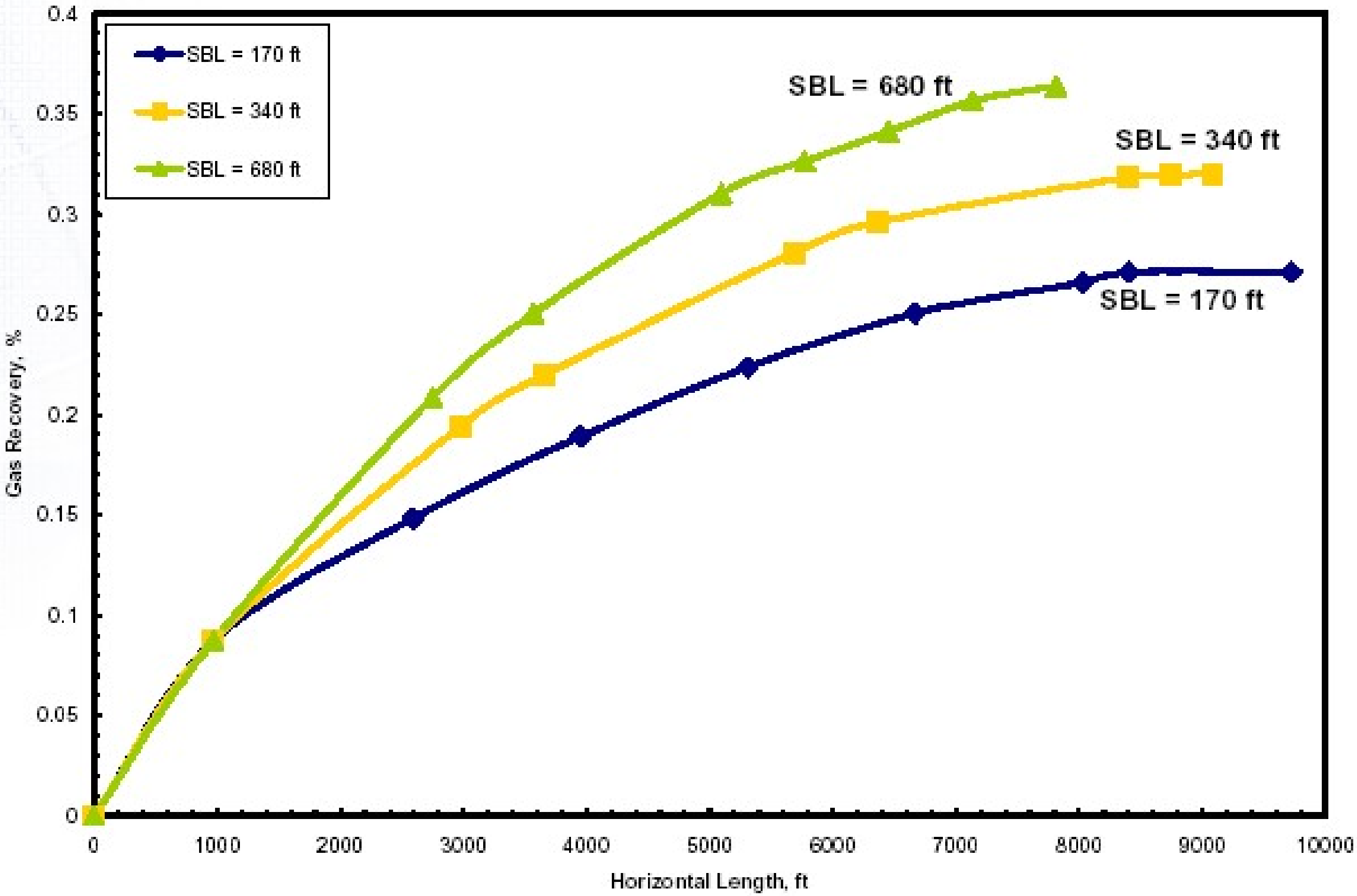


Tri-lateral

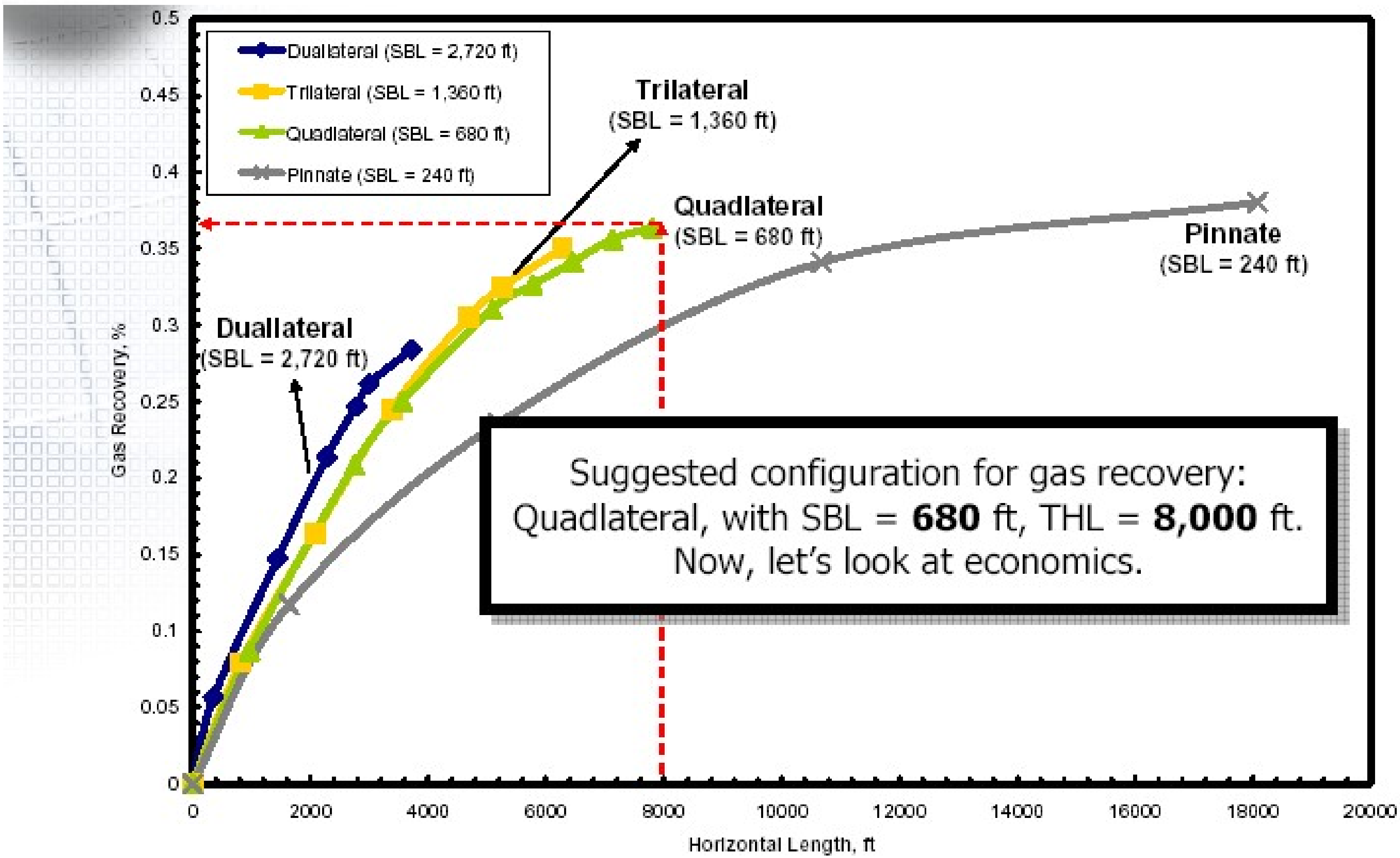


SBL = 170 ft
SBL = 340 ft
SBL = 680 ft
SBL = 1,360 ft
SBL = 1,360 ft
SBL = 680 ft
SBL = 340 ft
SBL = 170 ft
Gas Recovery, %
Horizontal Length, ft
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0
1000
2000
3000
4000
5000
6000
7000
8000

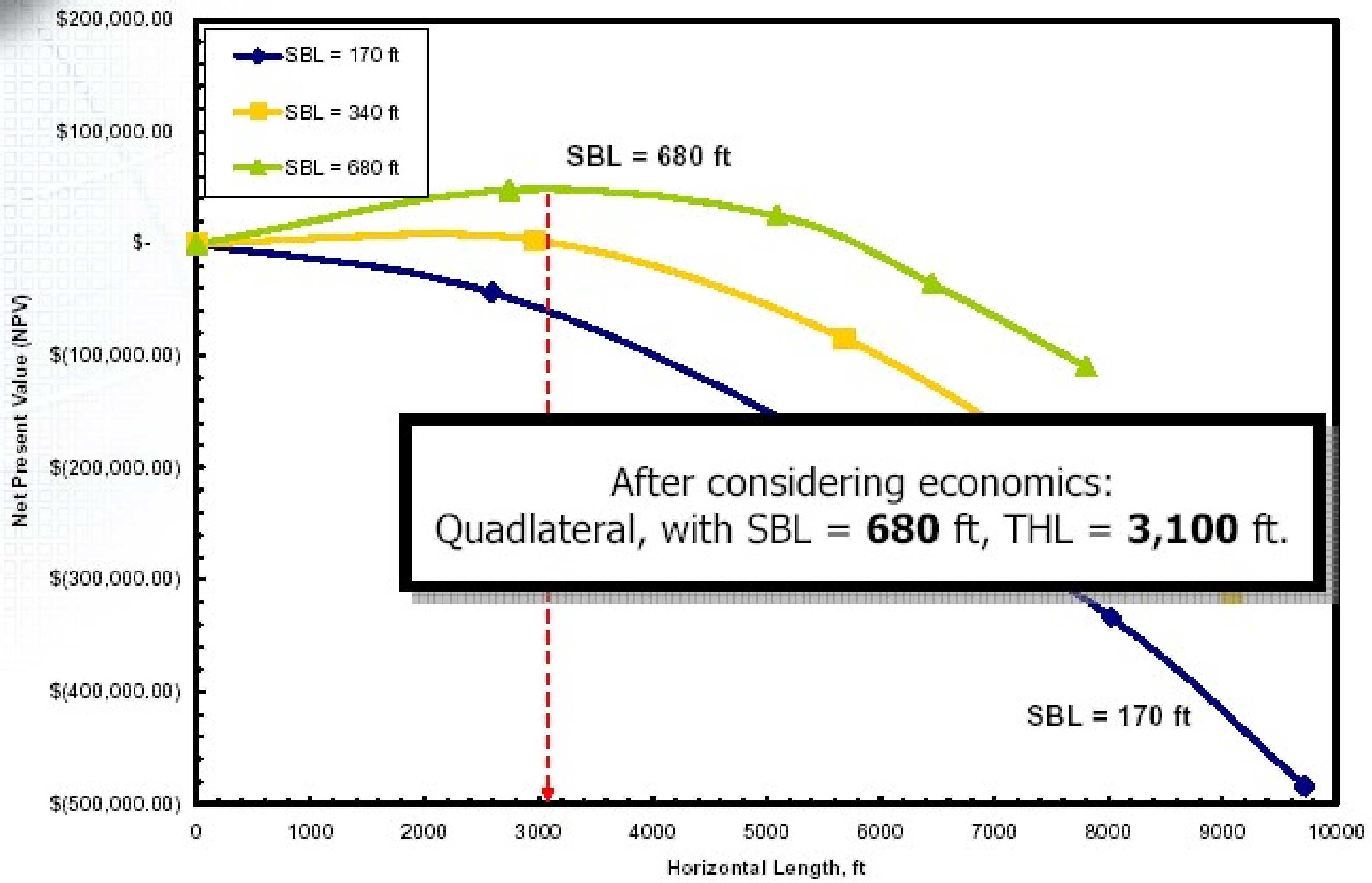
Quad-lateral



Best Producers Comparison



Quad-lateral Economics



Predicting Failure while Drilling: Horizontal Well Stability

GeoMechanics International, Inc.

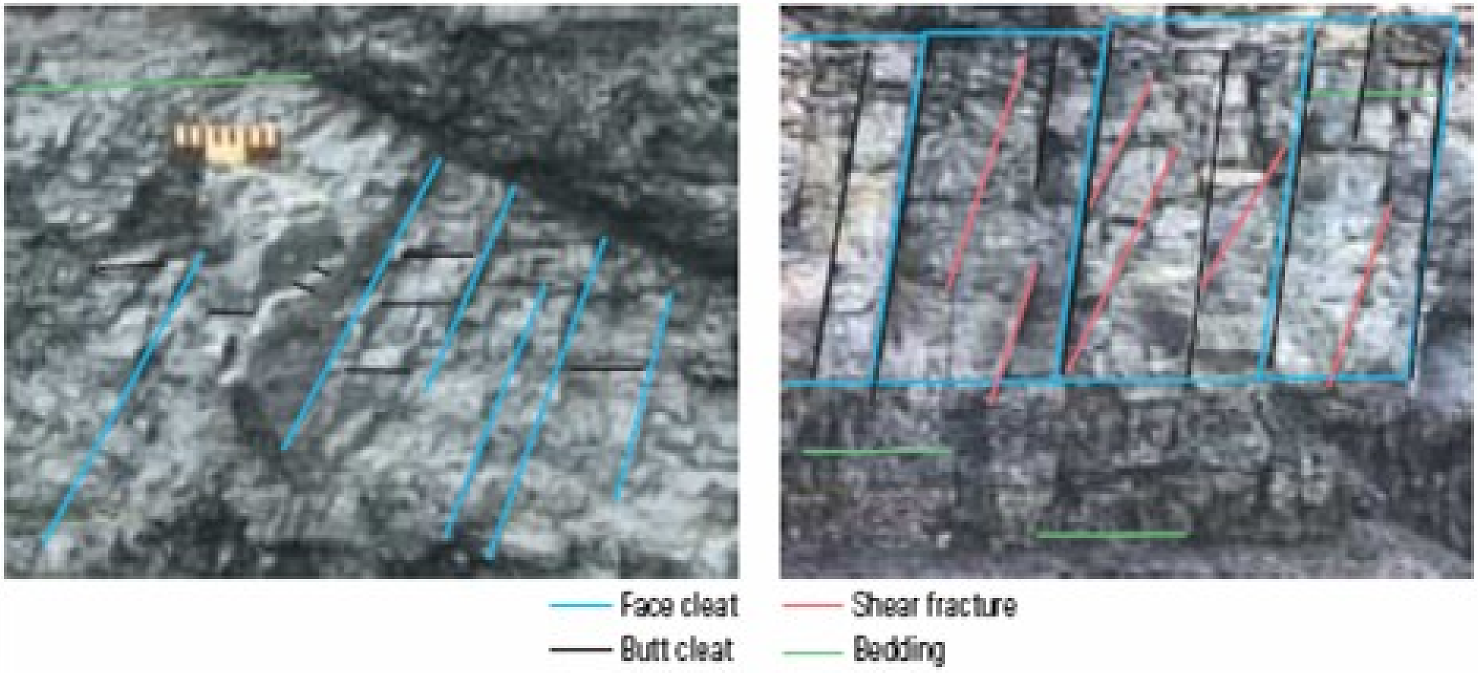
GeoMechanics for CBM Drilling, Completion and Production

Julie Trotta & Peter O'Conor

09/04/07

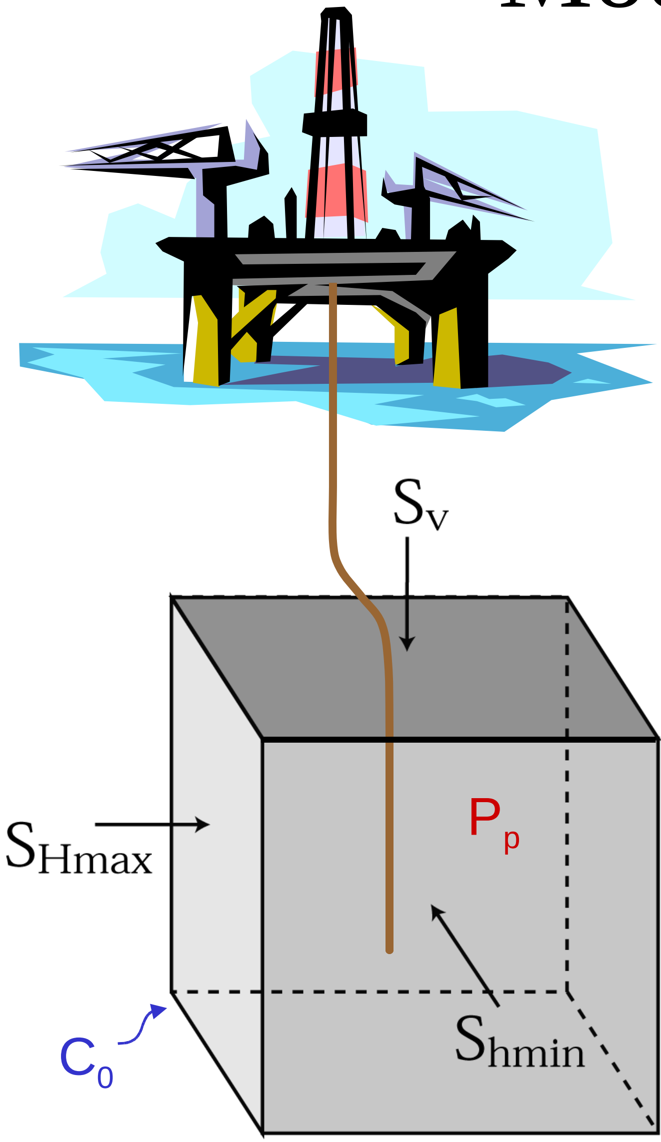
Coal Bed Methane Symposium
Presentation Outline

- Introduction to Geomechanics
- Coal Properties and Geomechanics
- Designing a Drilling Program for Coal Bed Methane
-



Introduction to Geomechanics

Foundation of the Geomechanical Model



The Principal Stress Tensor

Description of a geomechanical model for a reservoir involves detailed knowledge of

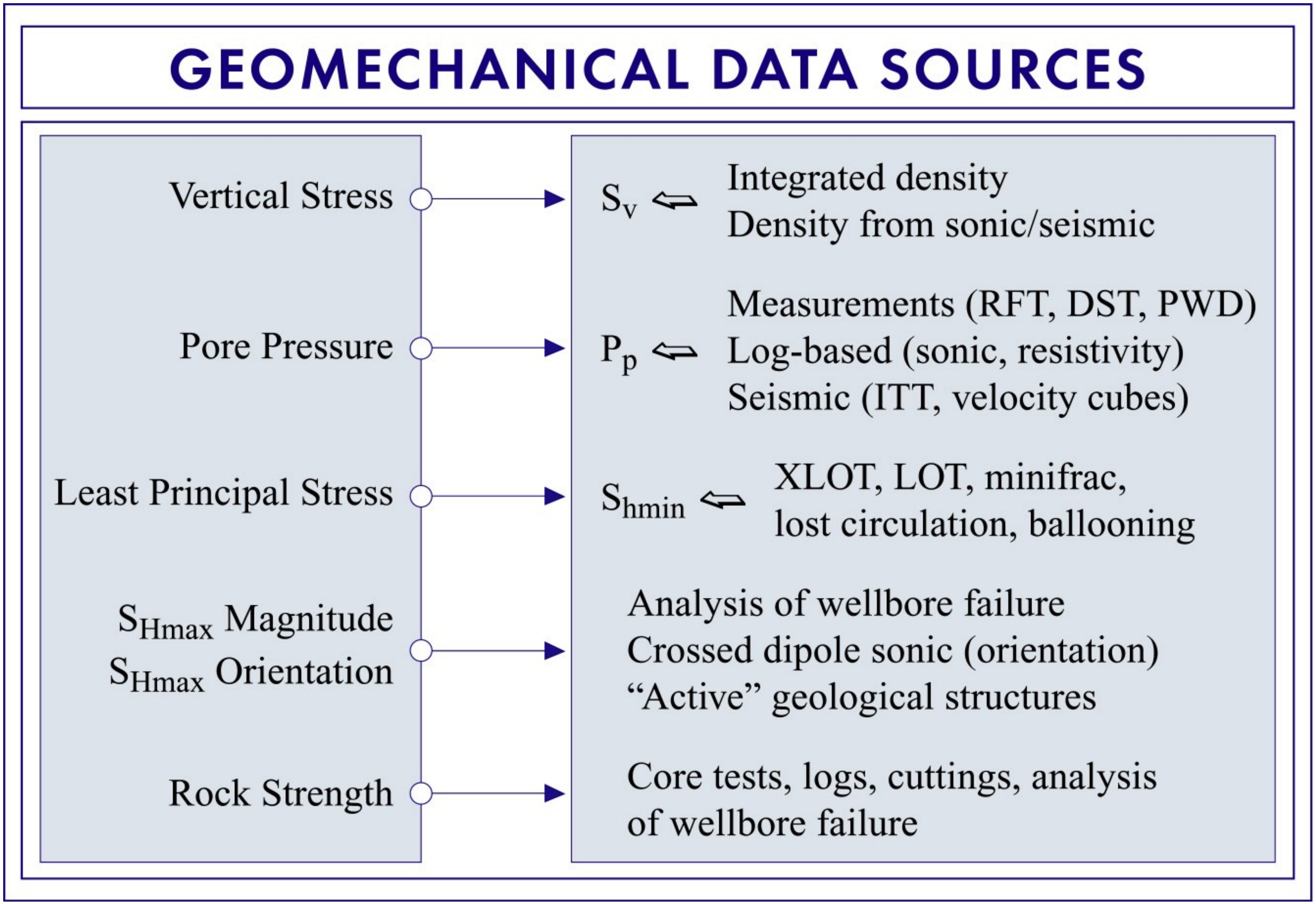
- **In situ stress orientations**
- **In situ stress magnitudes**
- **Pore pressure**
- **Rock Mechanical Properties**

Other considerations: Mud Chemistry, Weak Bedding Planes, Fractures, Thermal Effects

S_v	– Vertical Stress
S_{Hmax}	– Maximum Horizontal Stress
S_{hmin}	– Minimum Horizontal Stress
P_p	– Pore Pressure
C_0	– Unconfined Compressive Rock Strength (UCS)

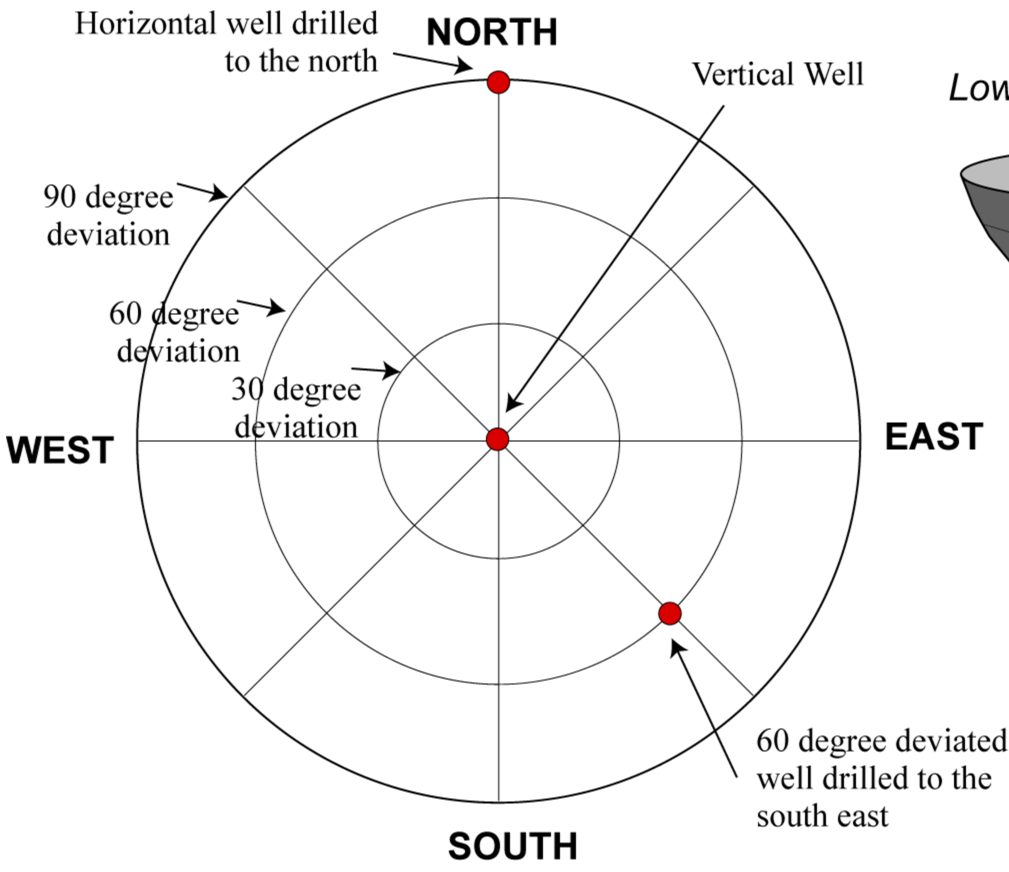
Rock Properties – Cohesion, Friction, Elastic Moduli

Building a Geomechanical Model

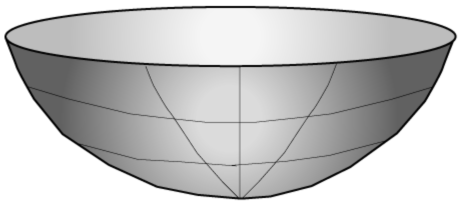


Wellbore Stability Diagrams

Lower Hemisphere Stereo Plot



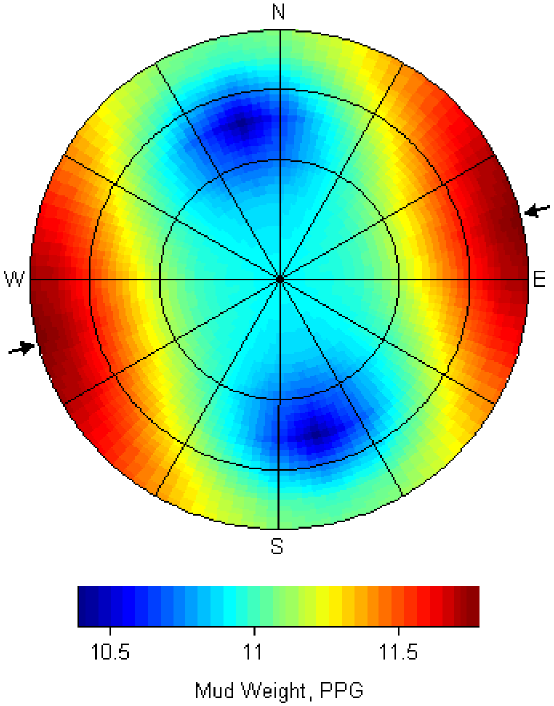
Lower hemisphere projection



Tendency for Breakout Development in Different Stress Regimes

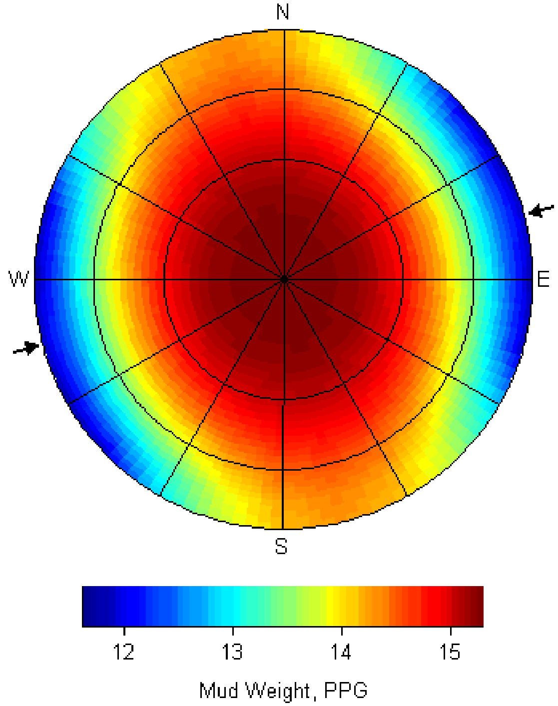
Stress Regime, Trajectory and Mud Weight all Impact Stability

Normal



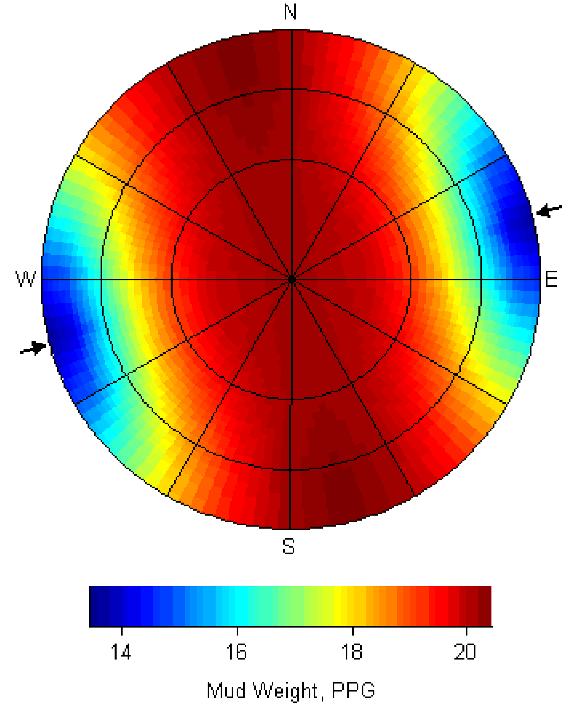
$S_{hmin} < S_{Hmax} < S_v$

Strike-Slip



$S_{hmin} < S_v < S_{Hmax}$

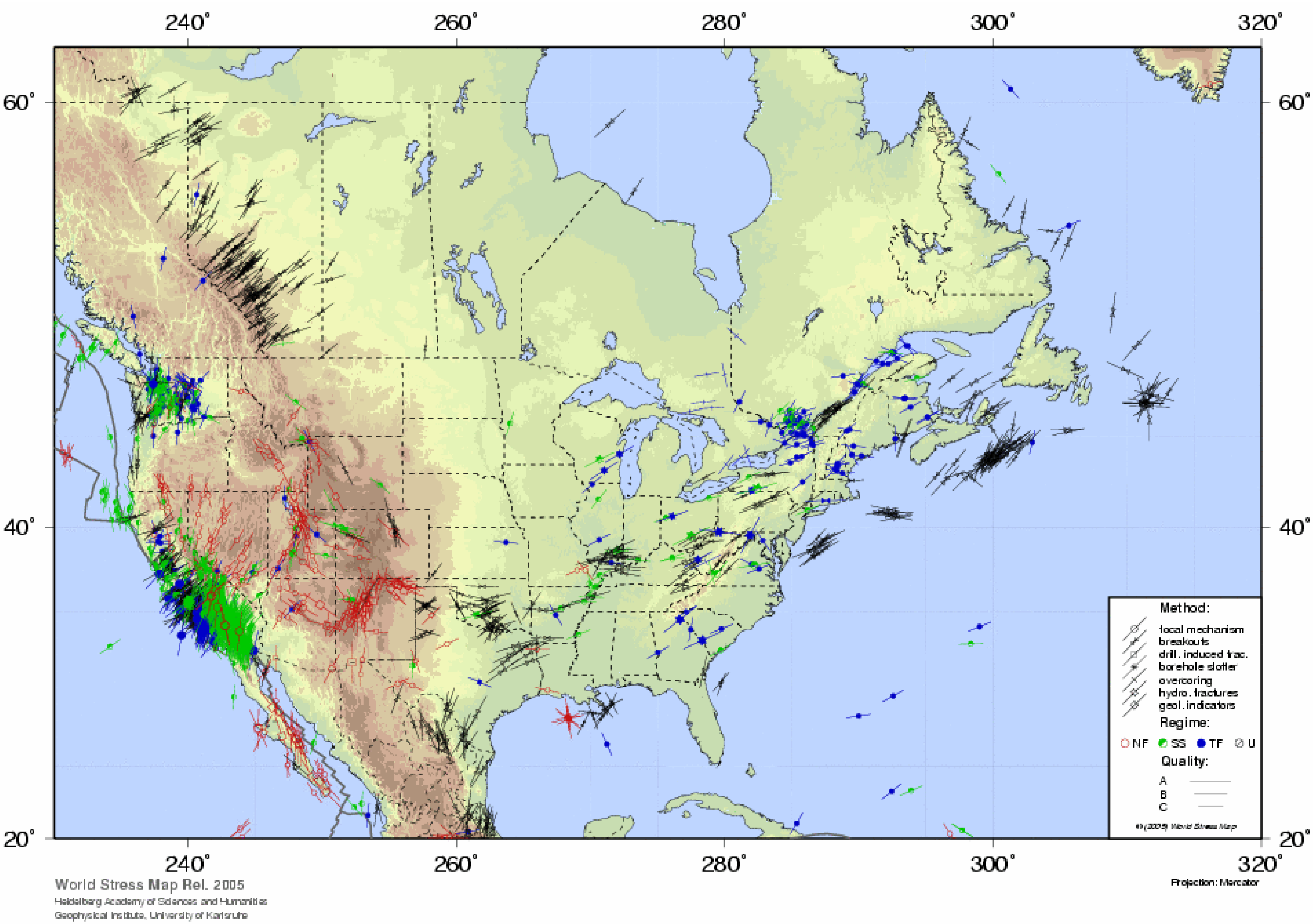
Reverse



$S_v < S_{hmin} < S_{Hmax}$

Area of Manville coals will be either strike-slip reverse faulting

World Stress Map – North America

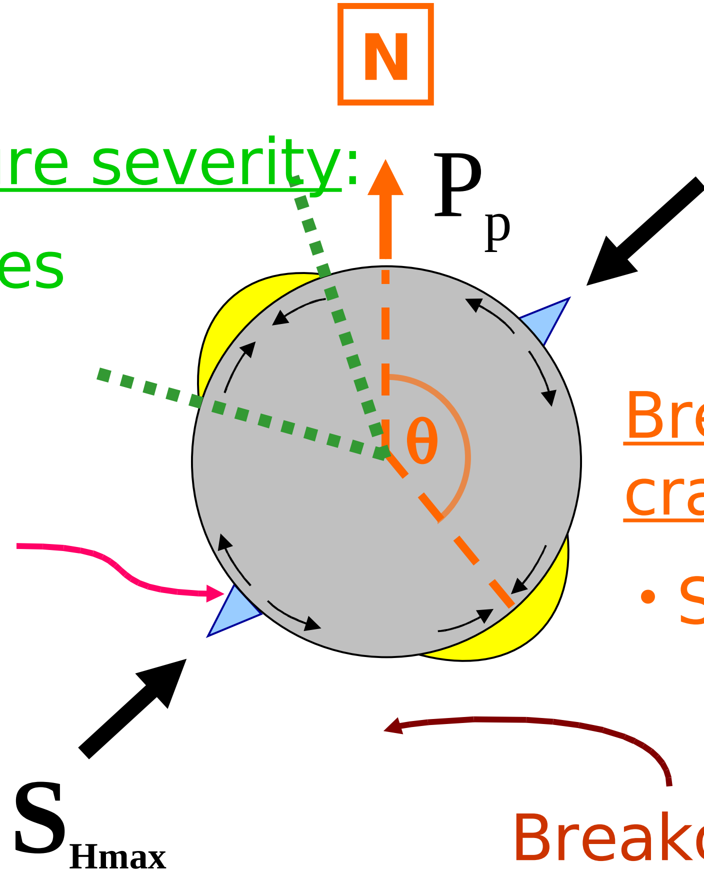


Observations of Borehole Failure to Constrain the Stress State

The mechanical interaction of the borehole in a given litholo
with the current stress field governs borehole failure – henc
borehole stability.

Breakout width/failure severity:

- Stress magnitudes
- Rock strength



Tensile cracks

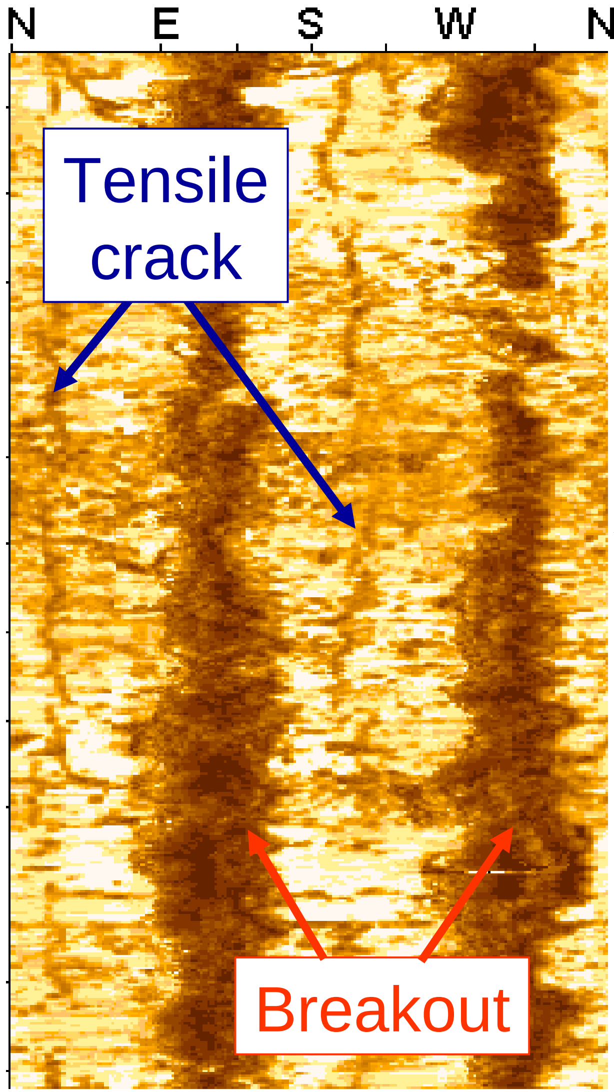
Breakouts

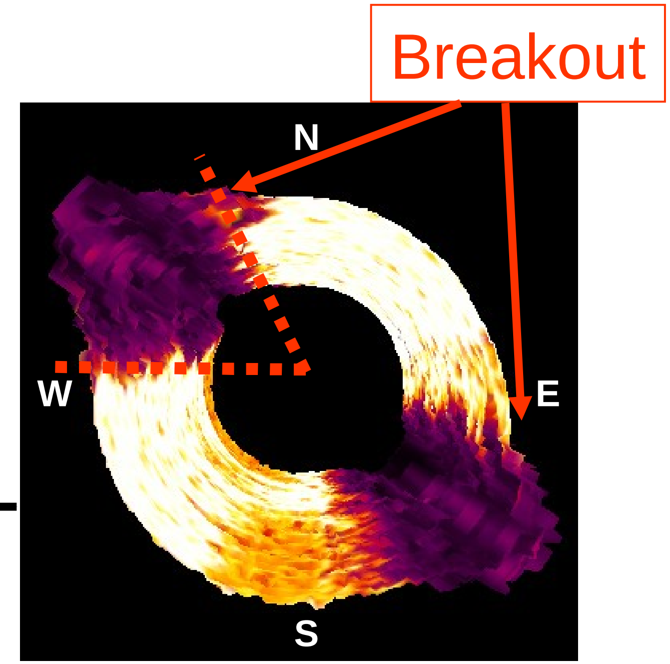
Breakout or tensile crack azimuth:

- Stress orientation

Example of Wellbore Failure

This well is failing simultaneously in compression and in tension





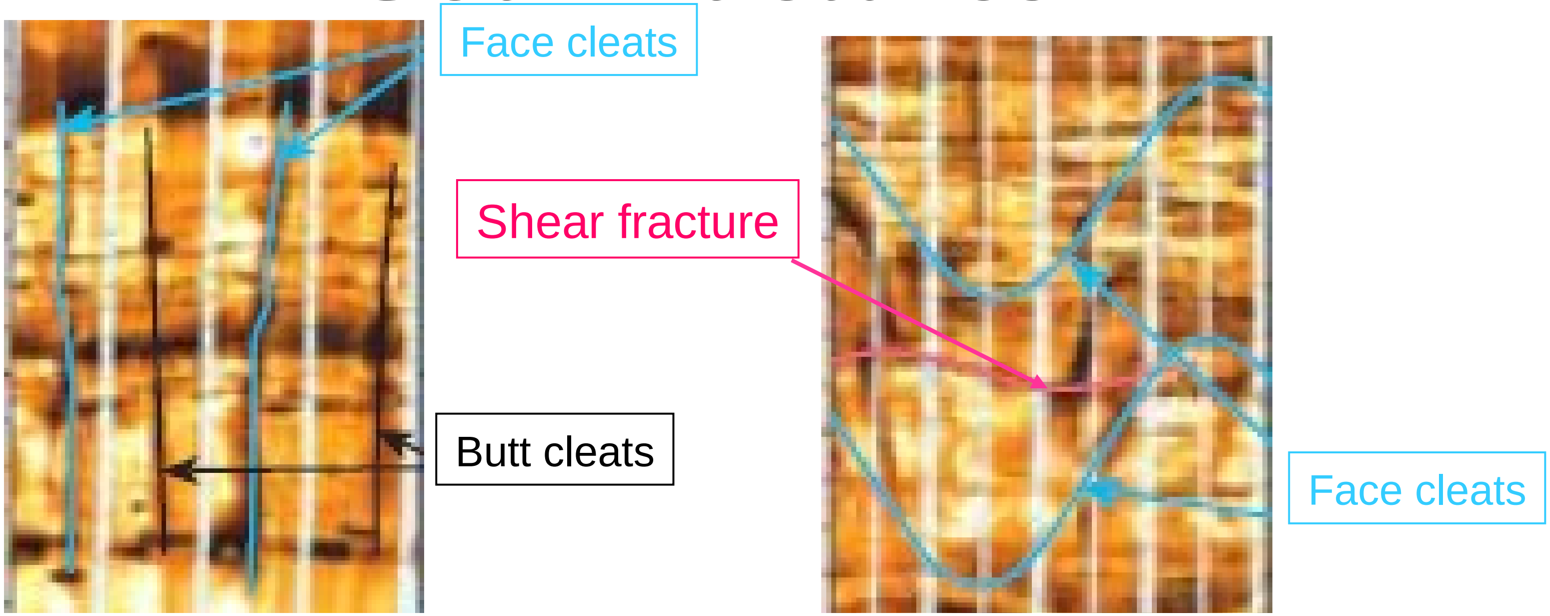
<u>Important</u>: This failure is often *not* catastrophic and does *not* adversely affect drilling.

Coal Properties

Comments on the unique properties and complications of coal

1. Coals are commonly (but not always) extensively fractured.
2. Coals are often inter-bedded within shales or sands which could be weaker or stronger and the shales can be strongly anisotropic.
3. Coals can have anomalous stresses compared to surrounding rocks.
4. This can lead to difficult drilling conditions and difficulties designing fracture completions.

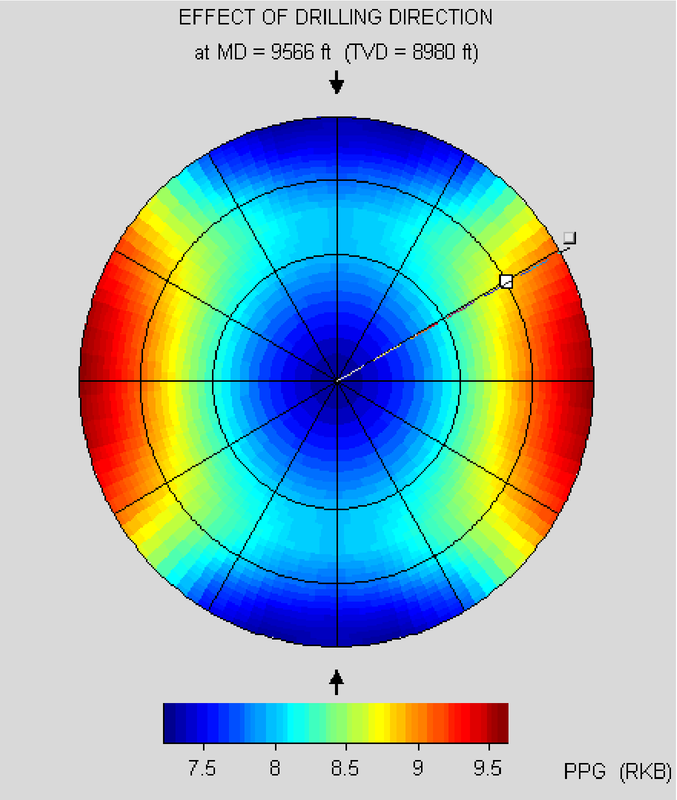
Coal fractures



- Drilling and completions programs need to take the fractures into account

After: Anderson et al., 2003

Blocky Cavings ('Rubble')

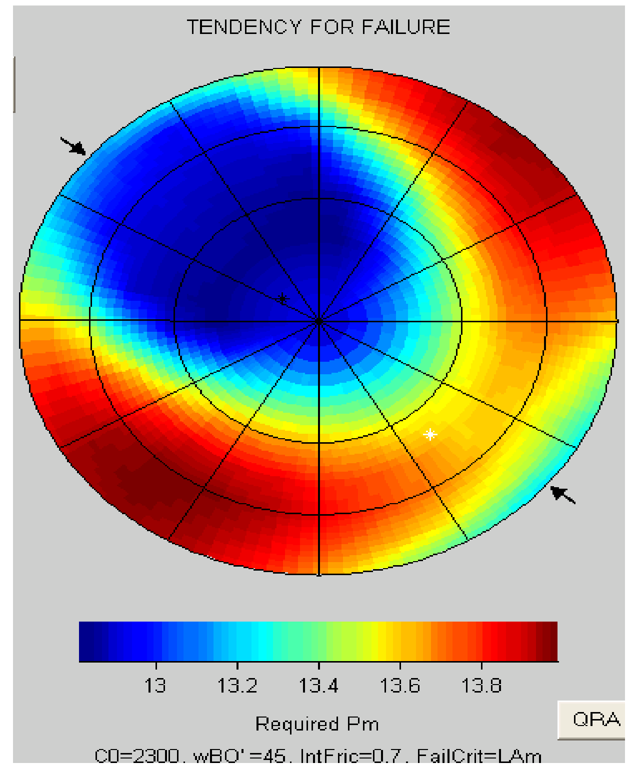


Failure: Due to Stress and Time-Dependent Mud Penetration into Fractures (e.g., Fractured Rocks, Around Salt, Along Faults)

Mud Type: OBM worse than WBM

Solutions: Adjust Mud Weight, Change Mud Type, Prevent Mud Penetration

Platy/Tabular Cavings



Failure: Due to Formation Strength Anisotropy (weakly bedded or fissile)

Mud Type: OBM or WBM

Solutions: Raise Mud Weight, Increase Angle-of-Attack to bedding

Published Coal Strength Information

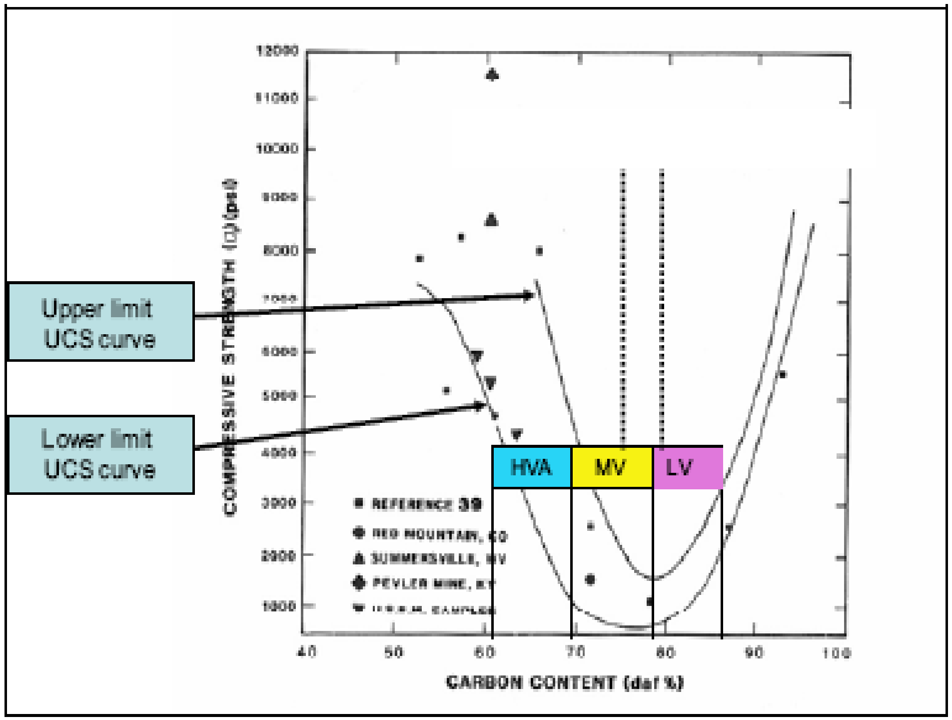
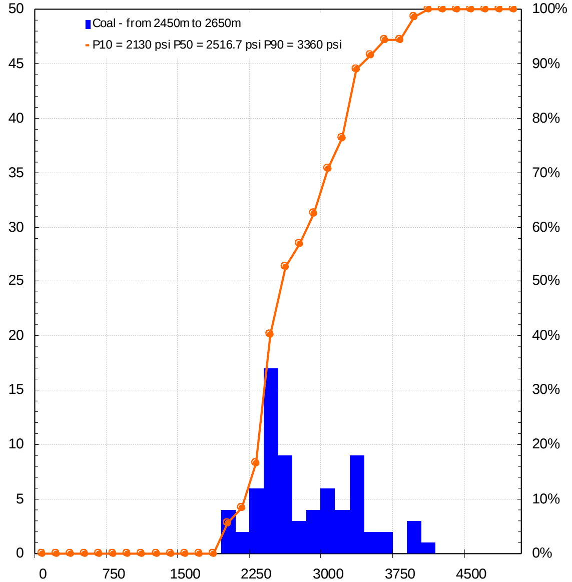
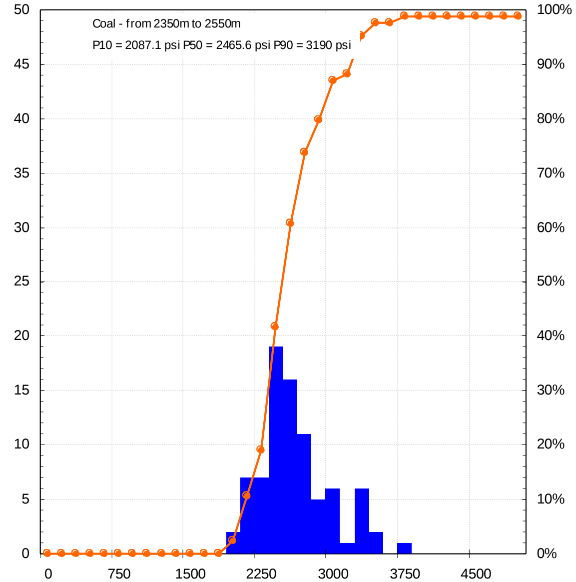


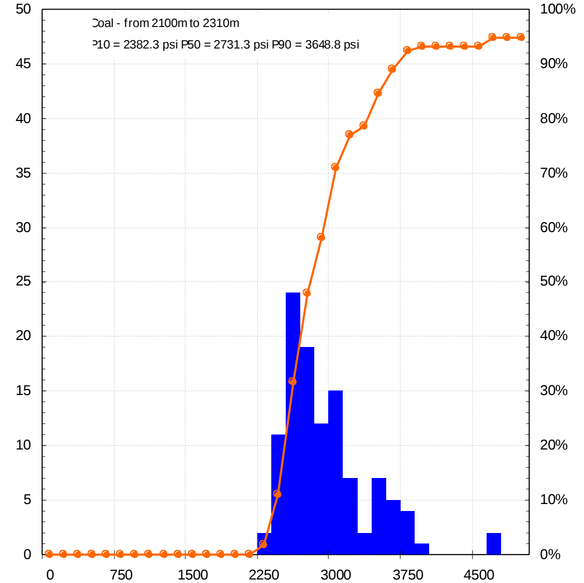
Figure 1. Band of UCS from core tests versus coal rank, and HGI measurements (adapted from refs. 7, 8). Note: carbon content = 100 – volatile matter (daf)

Examples of Coal Strength Histograms

Coal UCS ranges from 1700 to more than 3100 psi



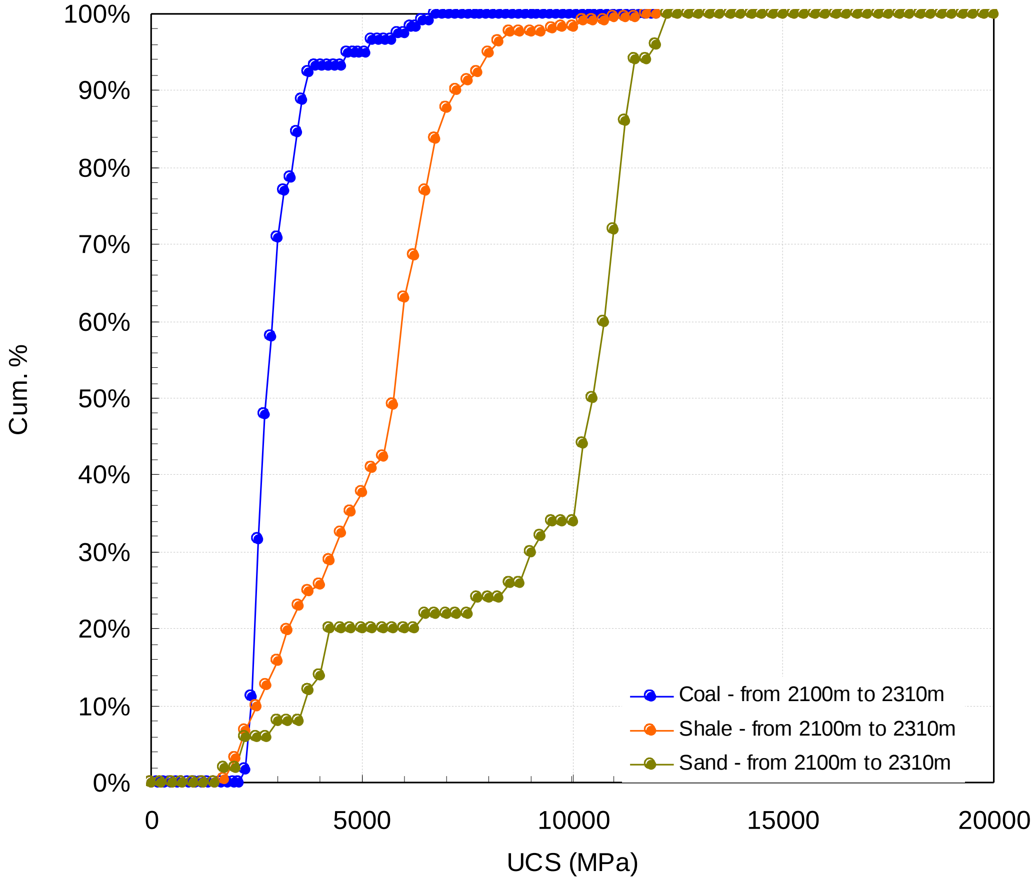




You can develop log-based correlations to calculate strength based on core test results.

Coal UCS is similar in all three wells but one well has no coals weaker than 2250psi.

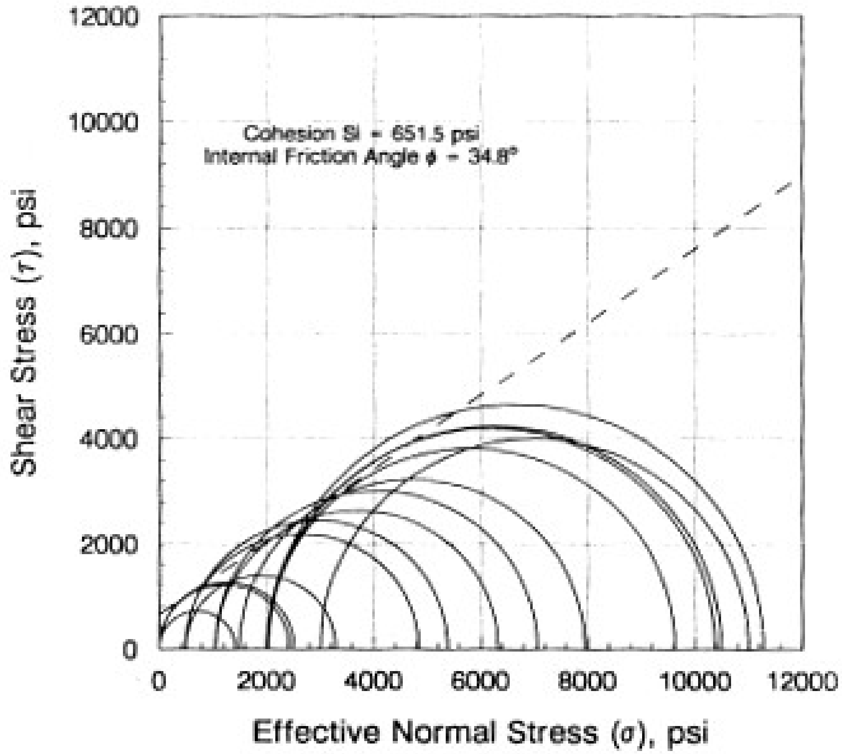
Example of Strength vs. Lithology

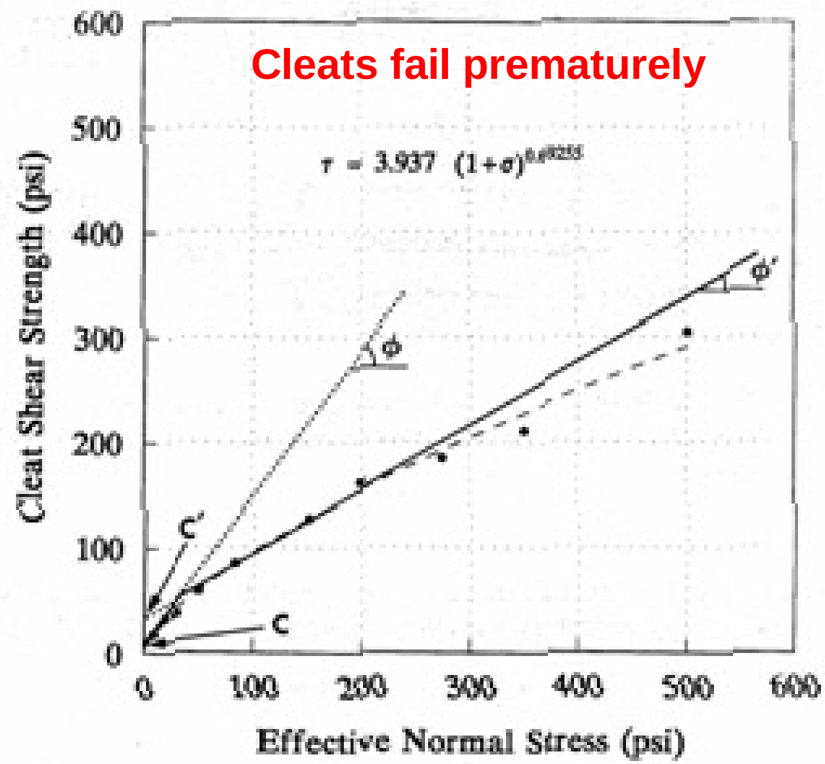


- Coal is the weakest lithology (not always the case)
- Sands are the strongest lithology
- Shales have intermediate strengths (UCS ~3000-7000 psi)
- Shales are differentiated from sands based on a GR cutoff, after filtering out coals

Examples of Coal strength properties

Intact properties Properties of cleats



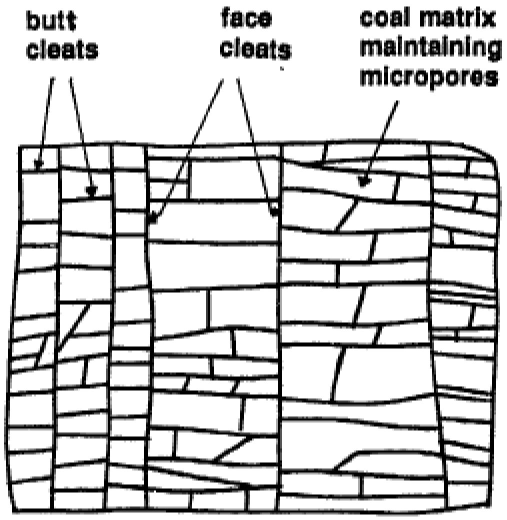


From: GRI Report

Traditional triaxial tests <u>can</u> over estimate the strength of coals if highly fractured because cleats fail prematurely.

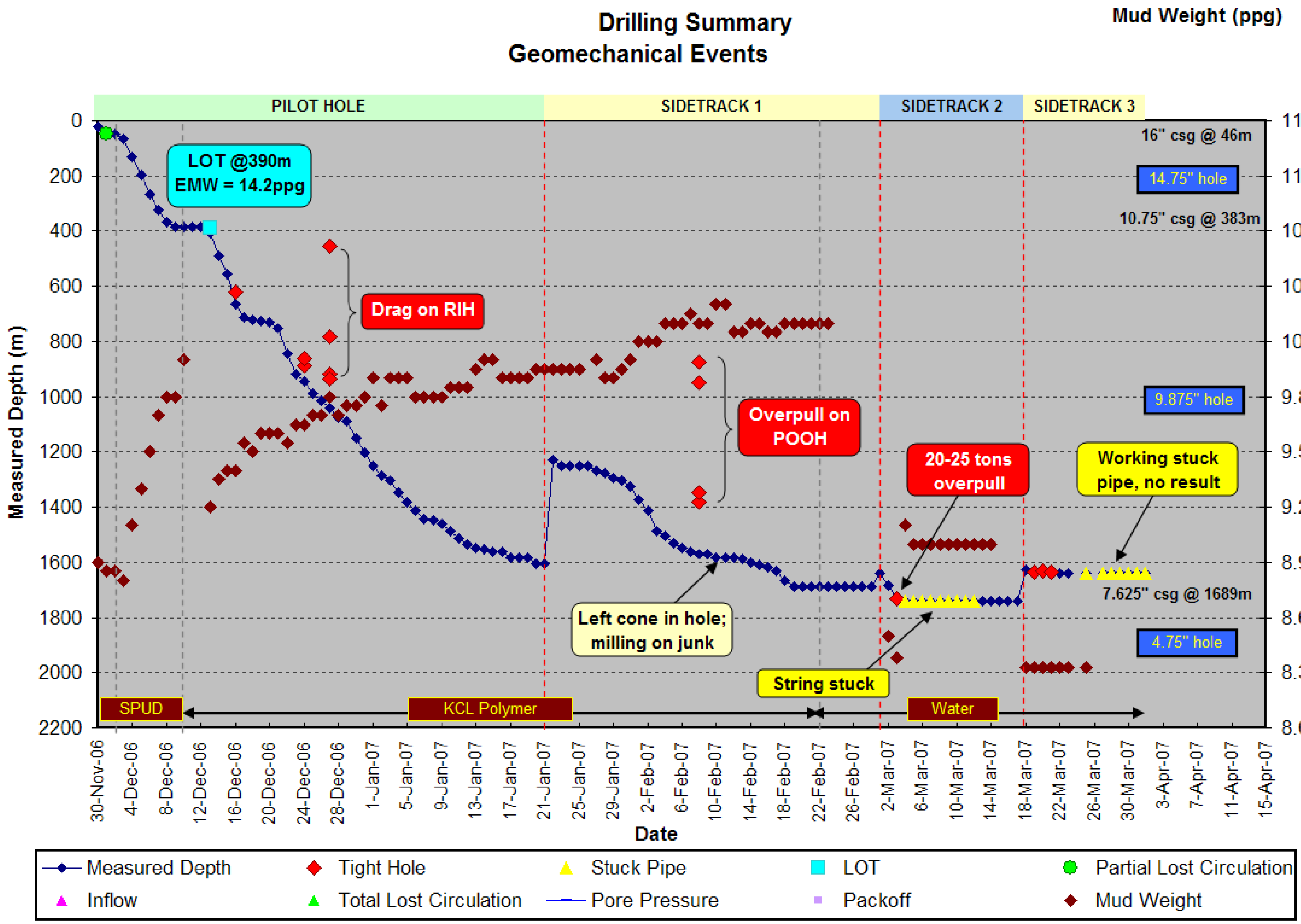
Drilling

- While coal can be quite strong, weak fractures can fail prematurely producing rubble.
- Open fractures can contribute to losses with mud weights below the fracture gradient
- These, and stress differences relative to surrounding rock, can result in narrow mud windows.
- BUT – coal has very low density, so hole cleaning of fines is easier with low mud densities than for other rocks

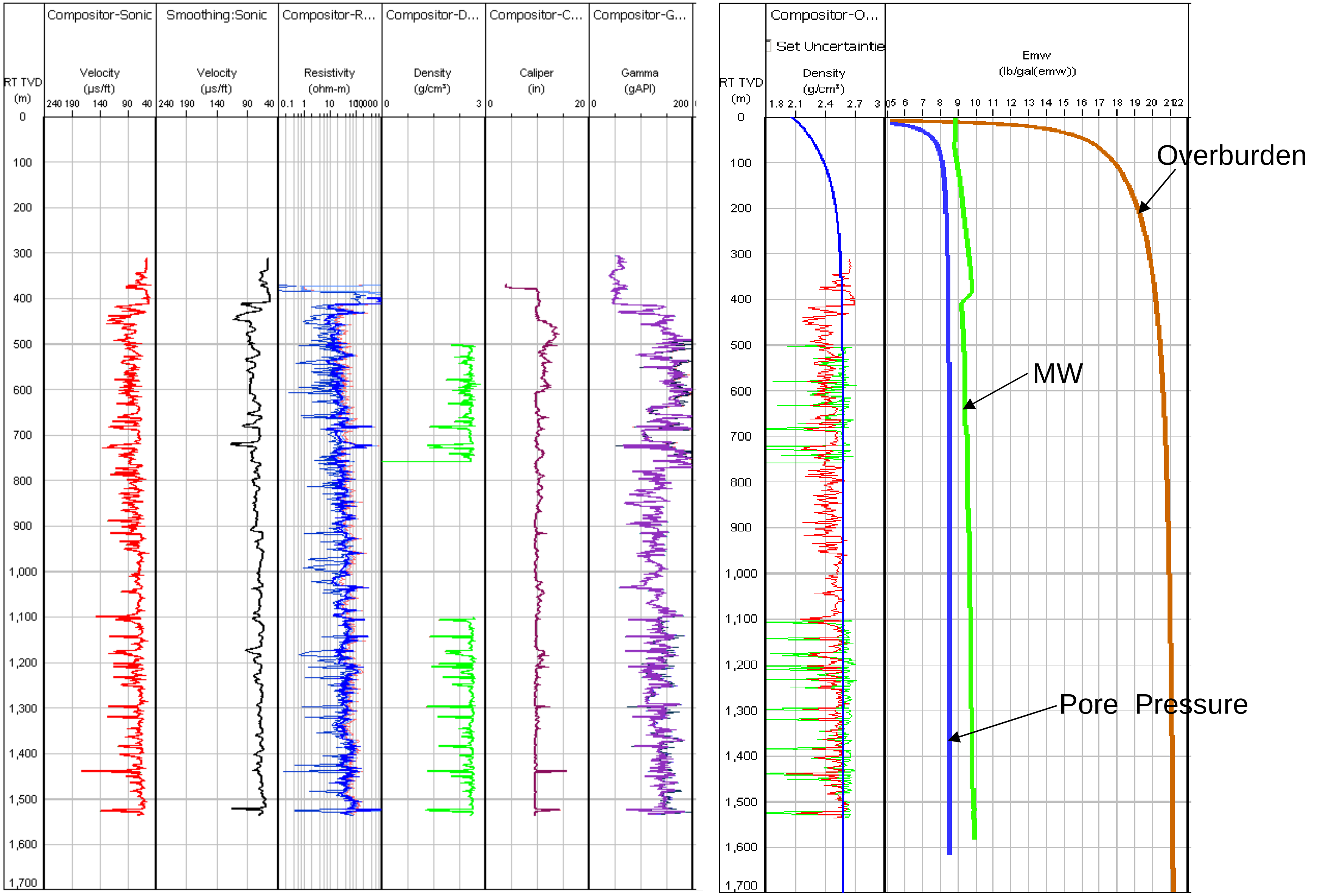


Designing a Drilling Program for Coal Bed Methane

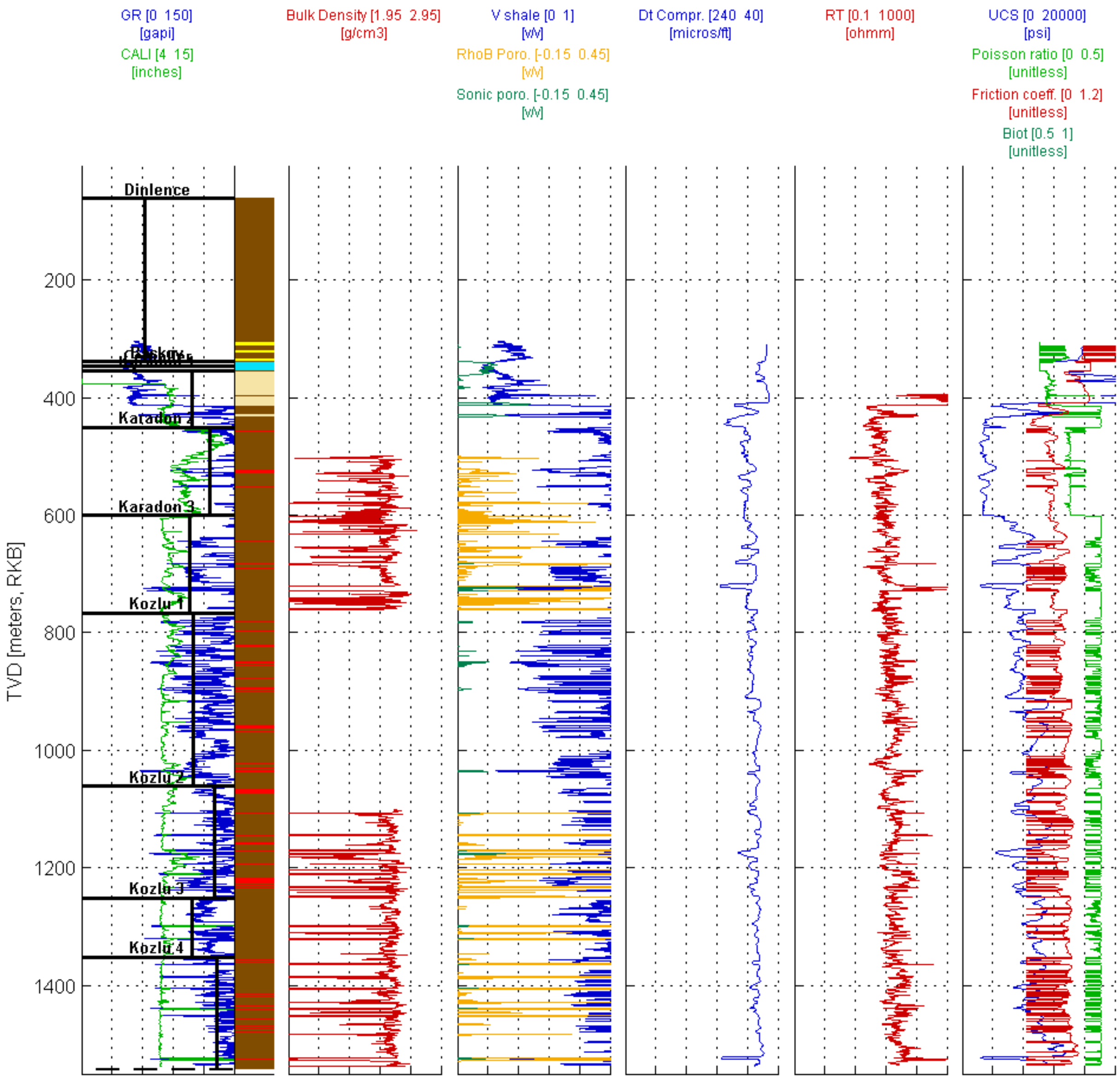
Example Drilling Experiences



Example Pore Pressure and Overburden

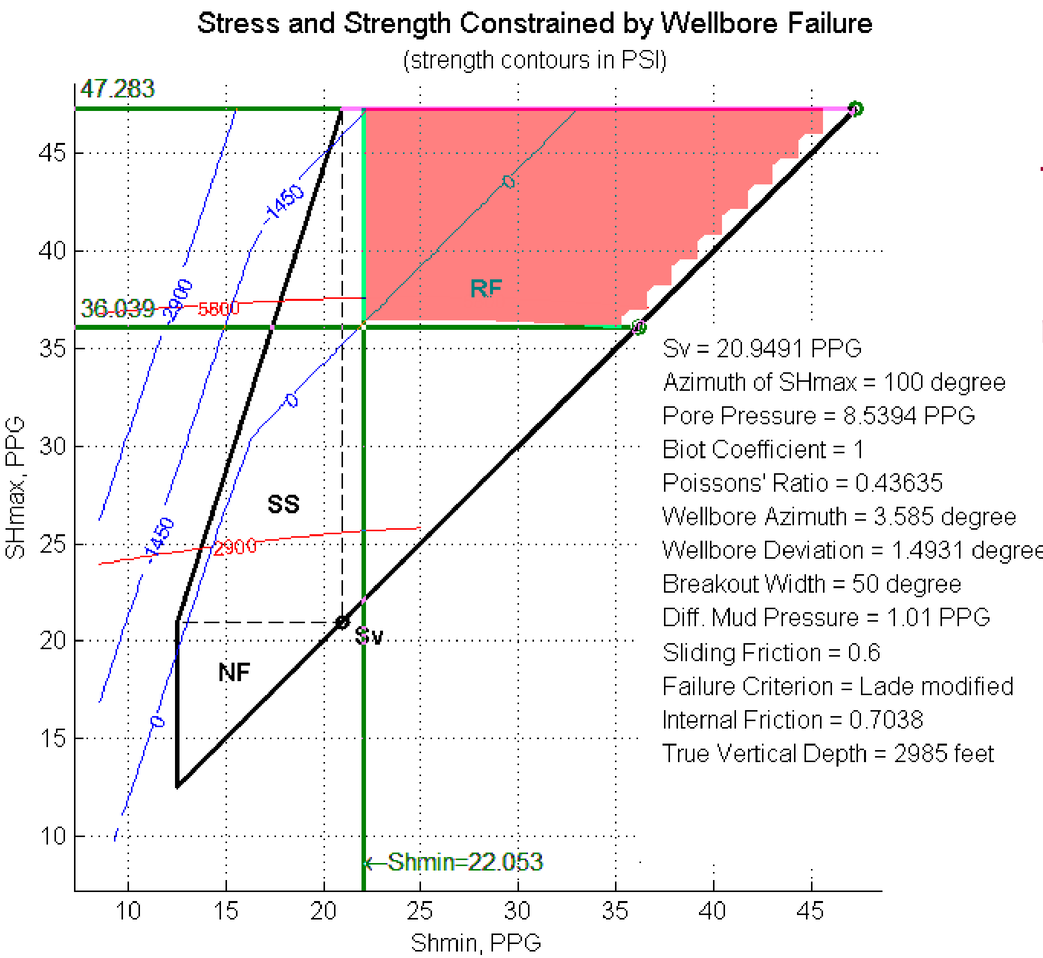


Example Rock Properties



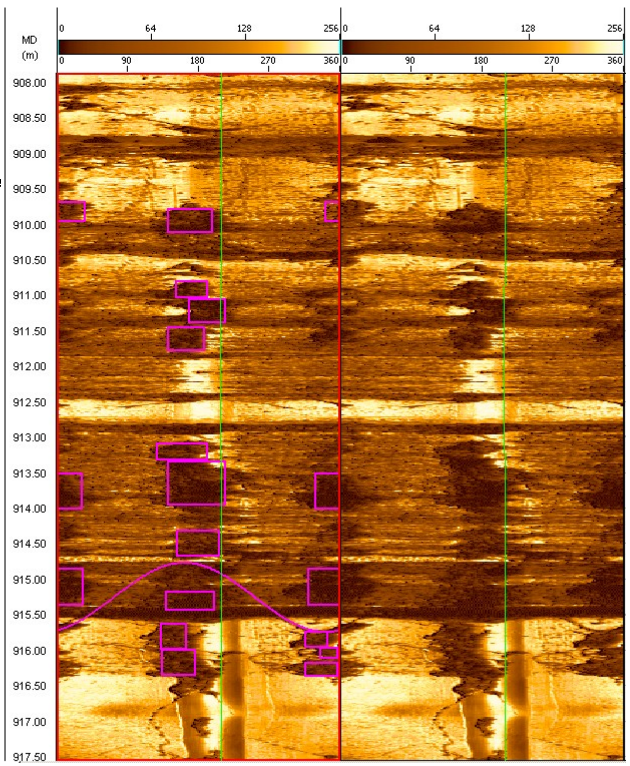
- Rock mechanical properties are derived from empirical correlations

Constraining the Magnitude of Shmin and SHmax

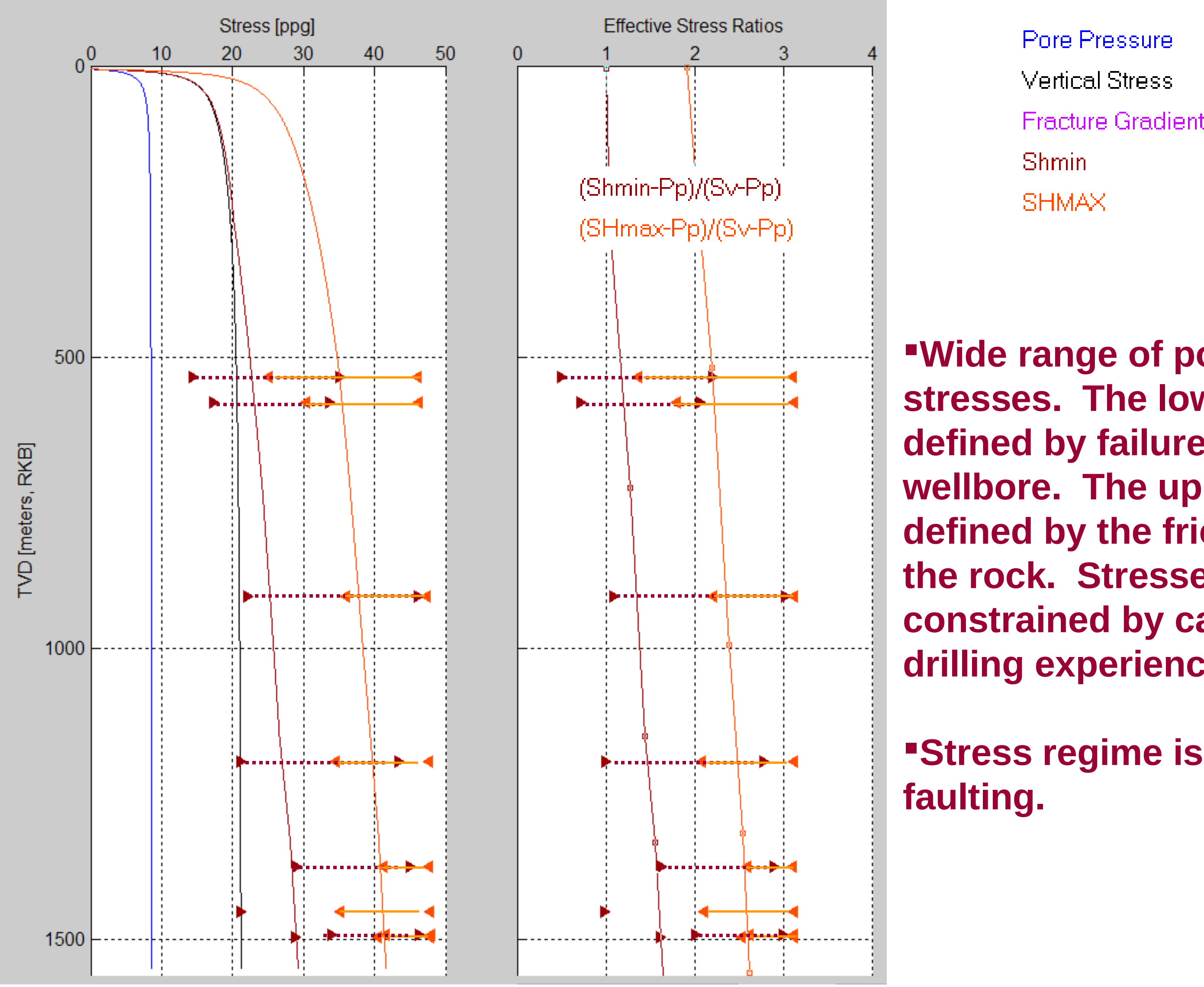


Breakouts in coal @ 910m indicate:
36 ppg < SHmax < 47.3 ppg
22 ppg < Shmin < 46 ppg

- **Modified Lade Failure Criterion.**
- **Stress regime is reverse faulting.**
- **5500-11000psi rock strength range in this interval.**



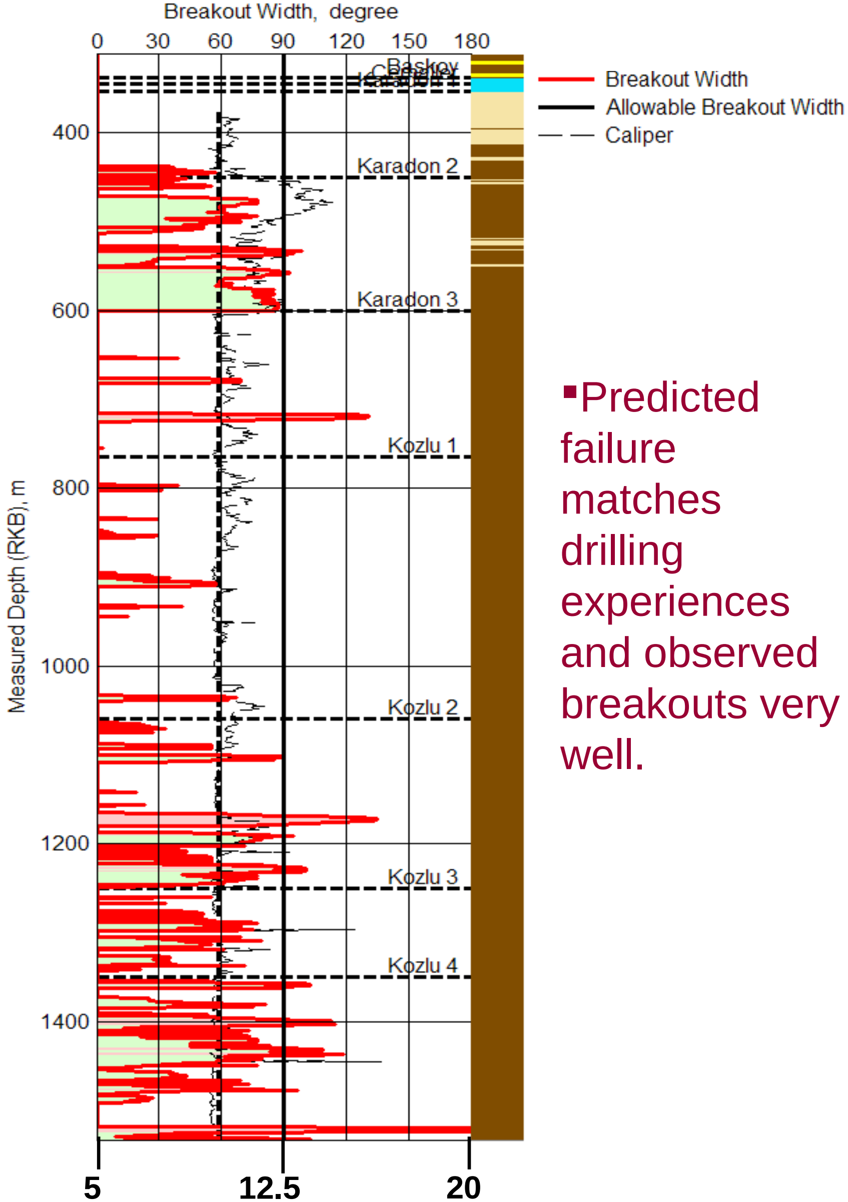
Example Stress Profile



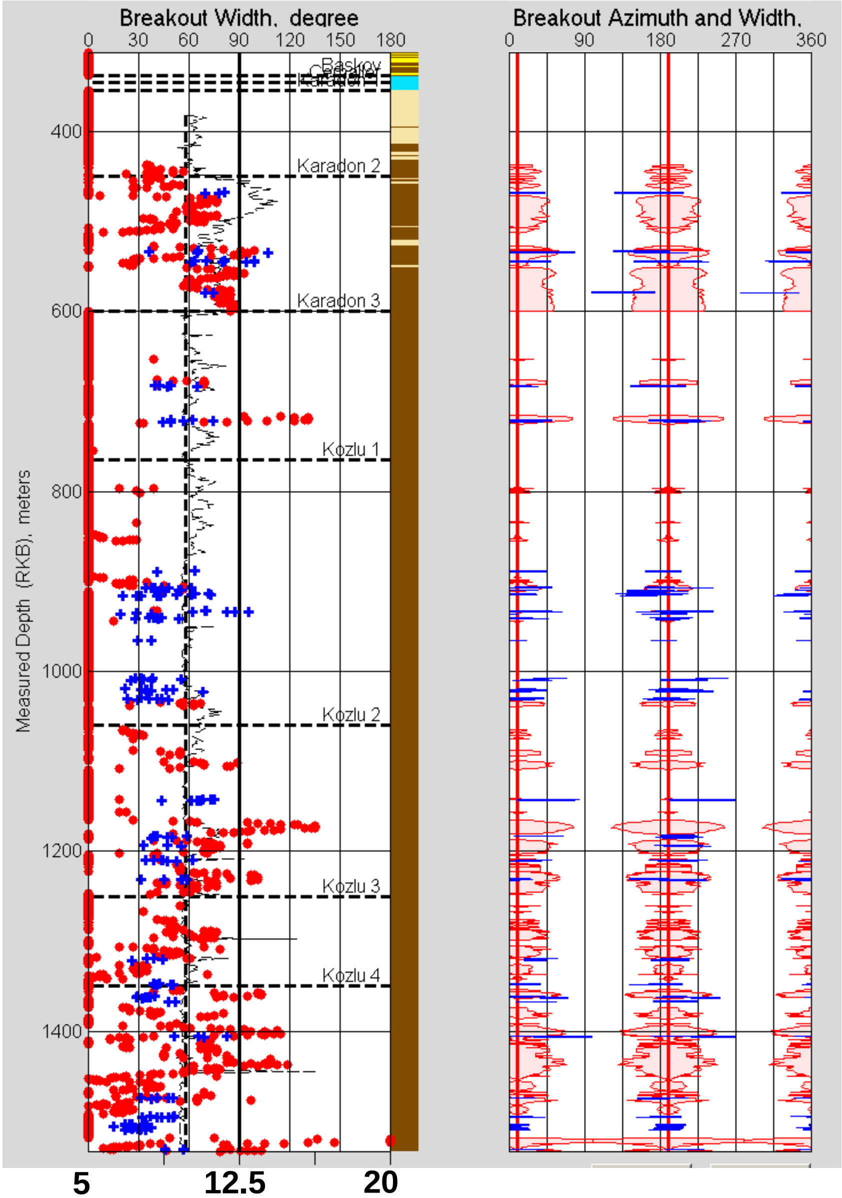
- Wide range of possible stresses. The lower limit was defined by failure in observed in wellbore. The upper limit was defined by the frictional limit of the rock. Stresses were further constrained by calibrating to drilling experiences.

- Stress regime is reverse faulting.

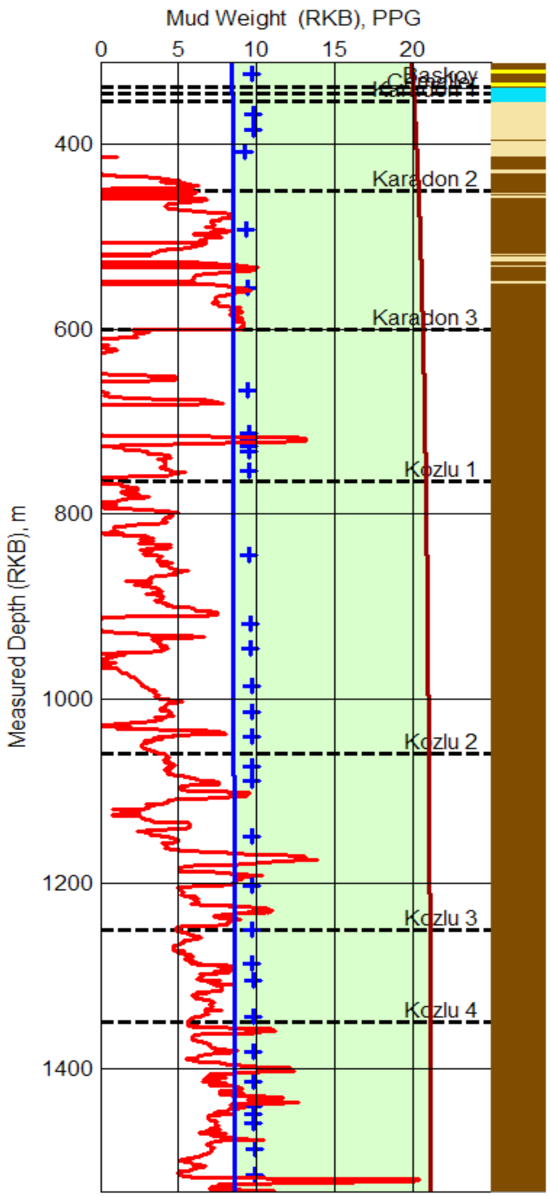
Predicted Failure and Model Verification Pilot Well



- Predicted failure matches drilling experiences and observed breakouts very well.



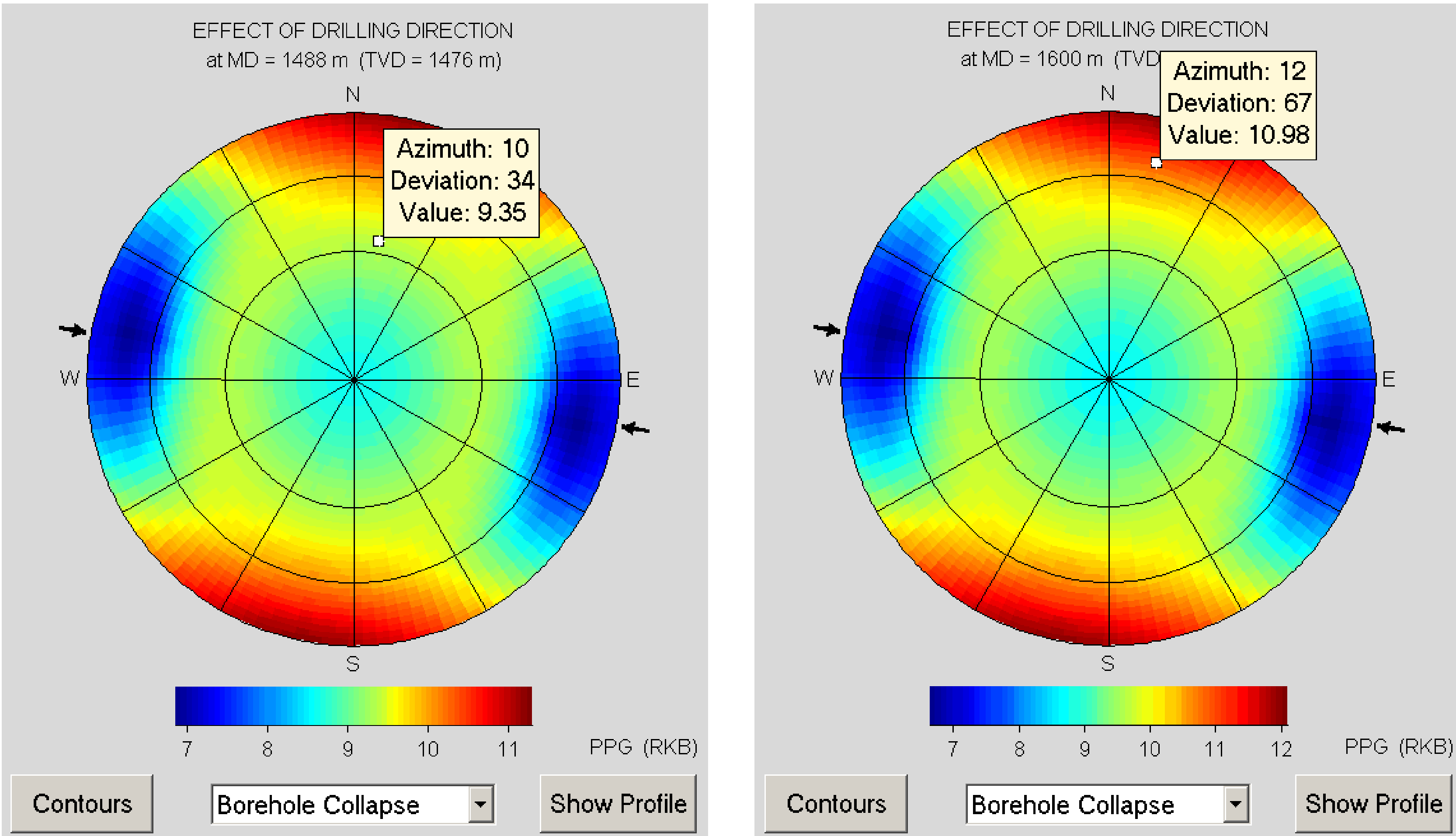
Predicted Mud Weight Windows
Pilot Well



- Maximum of borehole collapse pressure/pore pressure is the lower bound of the mud weight window

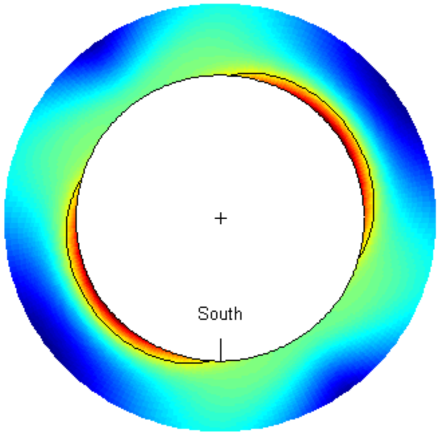
- Used vertical stress as upper bound of mud weight window

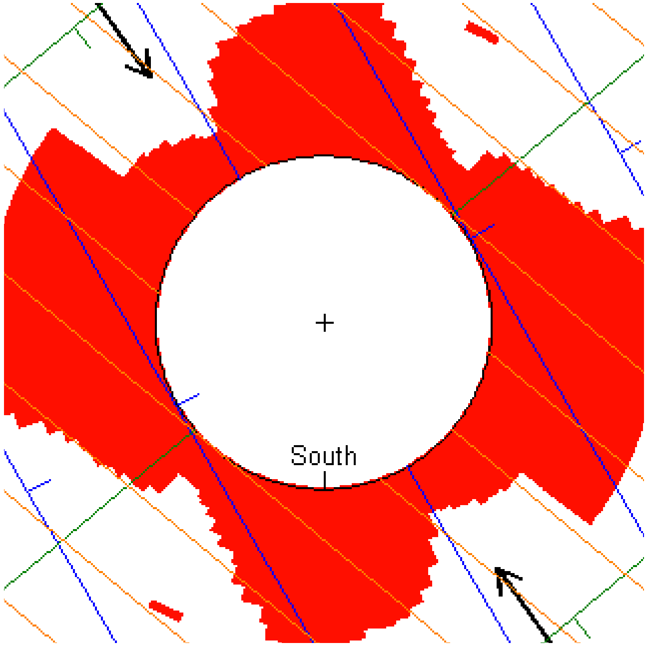
Effect of Drilling Direction - Sidetrack



- **Drilling horizontally in the direction of SHmax requires the least mud weight for stability.**

Premature failure of fractured coal

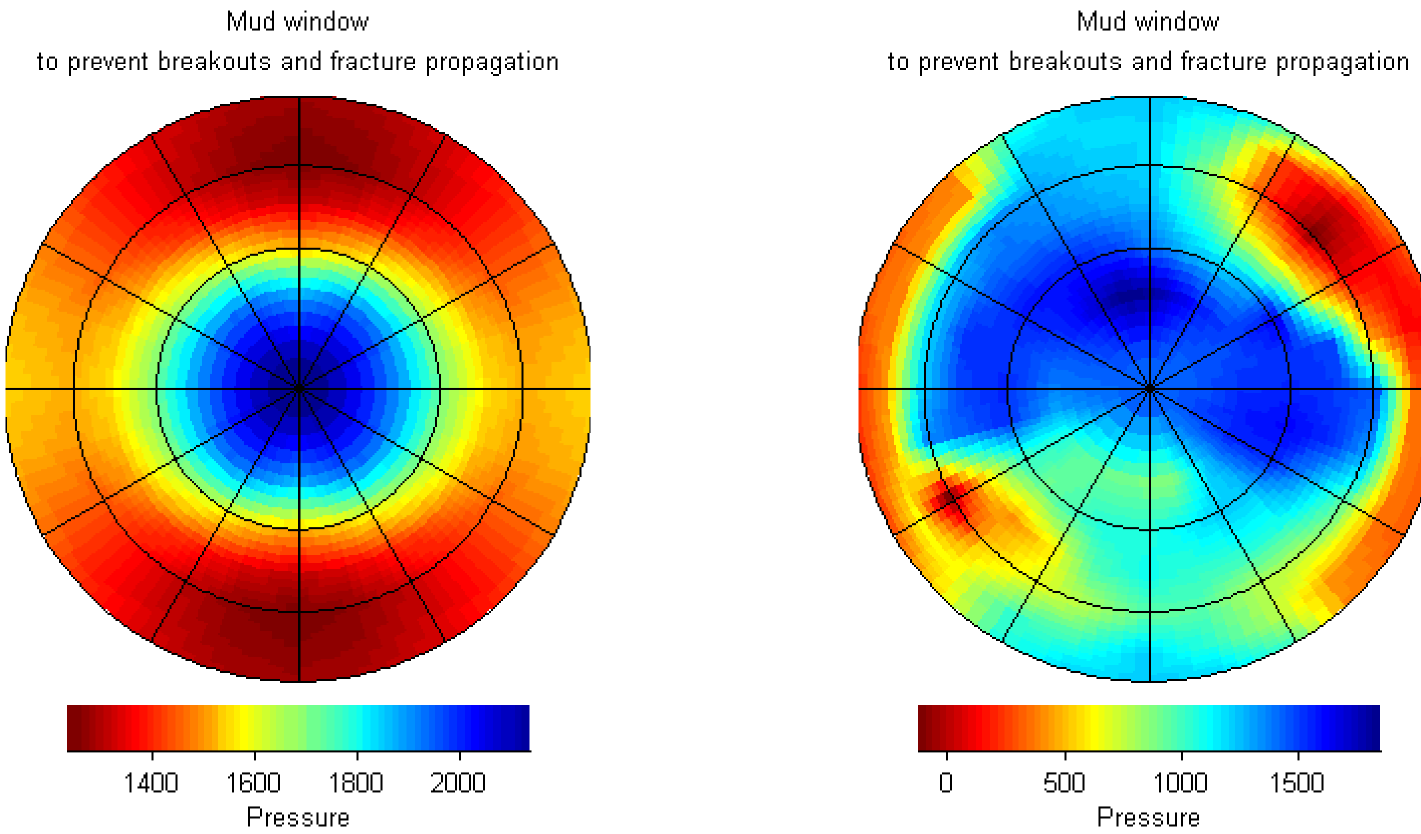




If not fractured, there is little risk of instabilities while drilling. Some coals are quite strong.

When fractured, large zones of instability develop due to premature failure of along cleats and fractures

Example of Mud window in fractured coal

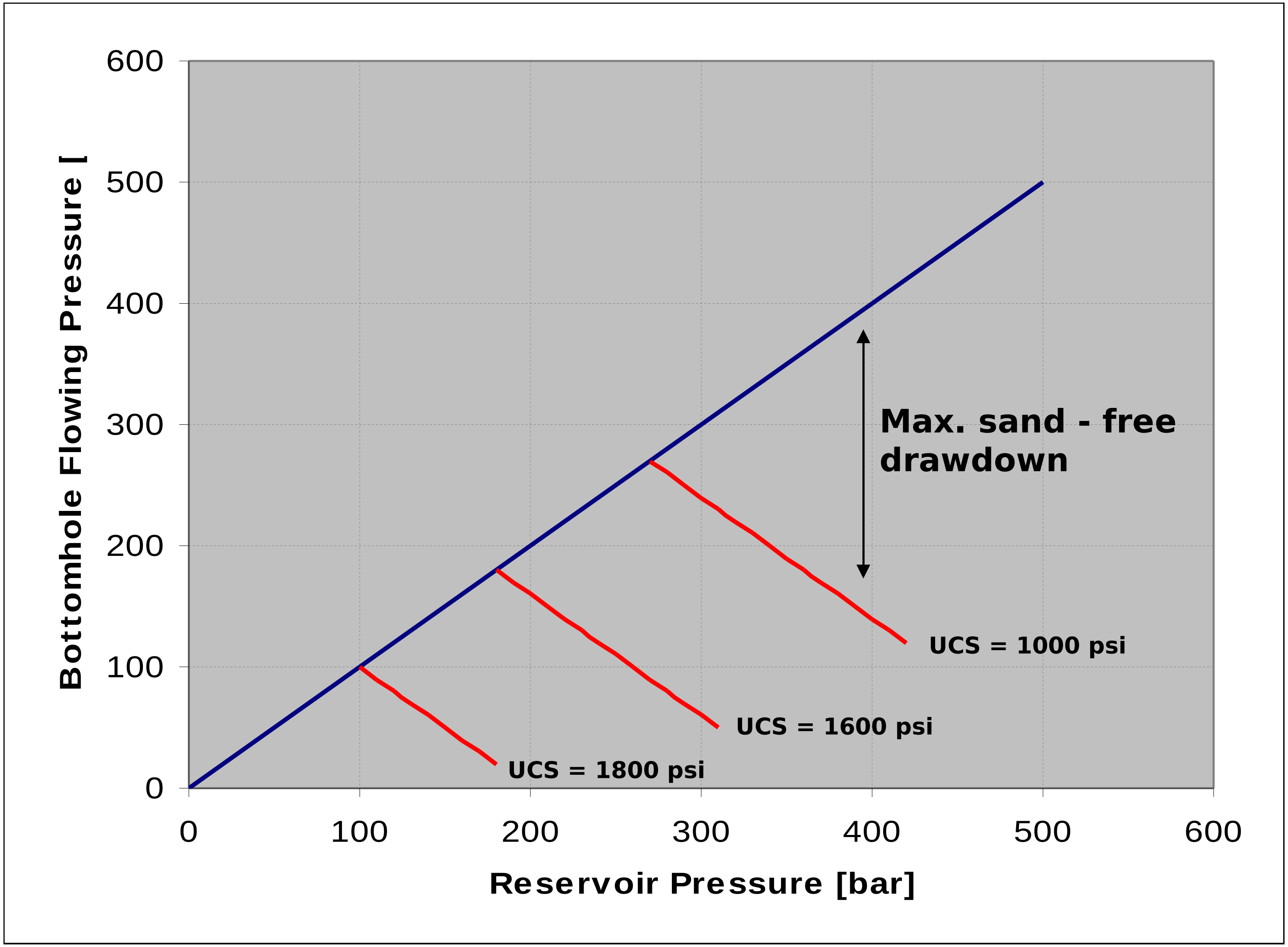


When unfractured, low mud weights can stabilize the wellbore and larger mud windows result.

In fractured coal, premature failure of fractures require high mud weights, resulting in small mud windows and a high risk of instability, as well as losses.

Stability of Openhole Completion

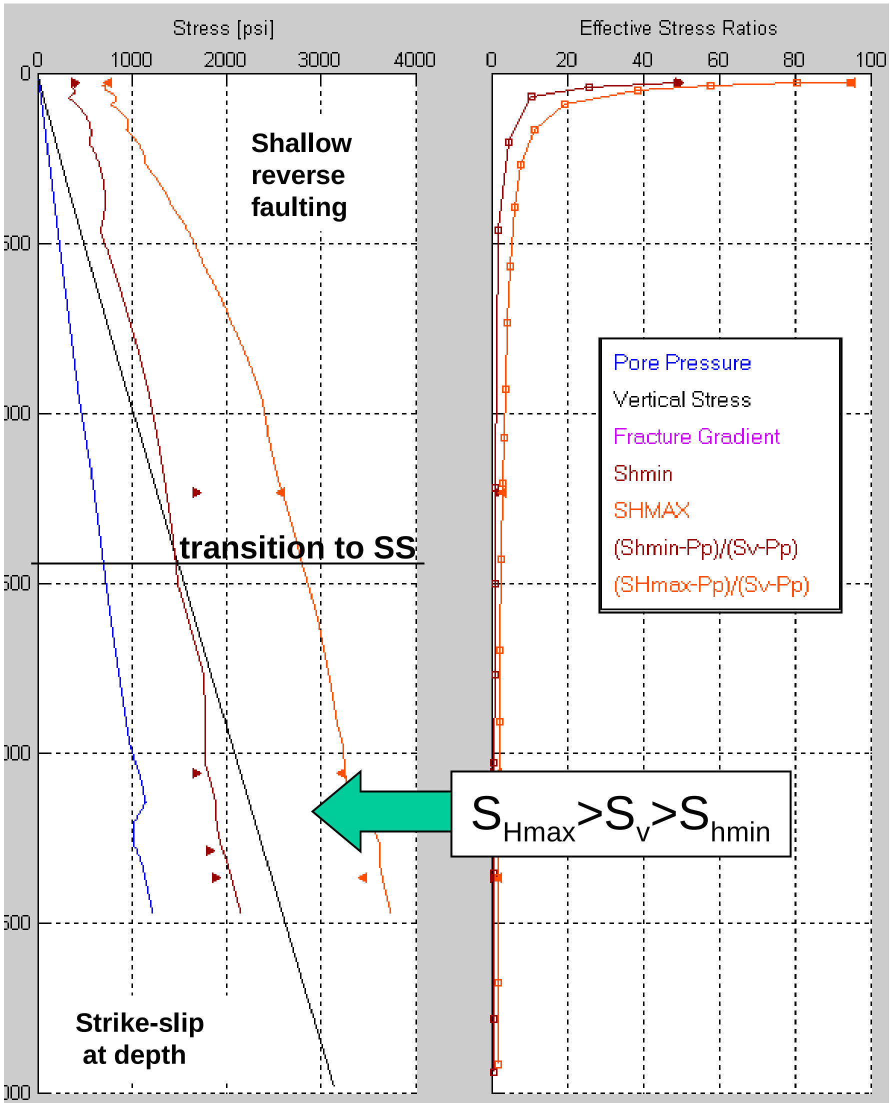
Onset of Sand Production



Approach

- Drawdown is modeled using a poroelastic analysis for:
  - Two horizontal well orientations (drilled parallel and perpendicular to SHmax)
  - Two stress path scenarios:
    - dSH/dP=0, dSv/dP=0 (no stress change with depletion)
    - dSH/dP=1; dSv/dP=0 (horizontal stress change is equal to the pore pressure change)
  - Drawdown limit is the BHFP that causes failure to extend more than 10% into the rock away from the well
  - Required strengths will vary if this is changed, but relative changes with RP will be approximately the same

Geomechanical Model



Pp- constrained using mud weights and pressure buildup test results

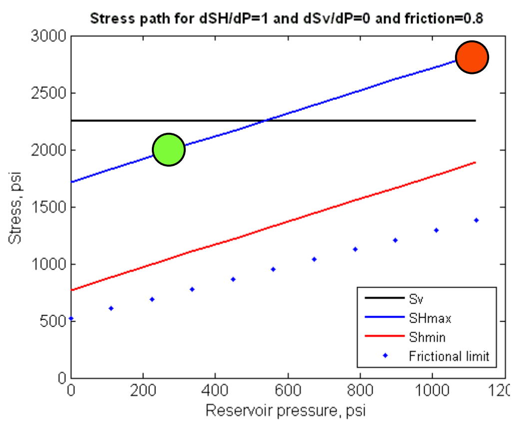
S_{hmin} ~ 0.83 psi/ft (below x000 ft) based on a compilation of LOT and minifrac data. Higher values are required to explain observed wellbore failure features at shallow depths

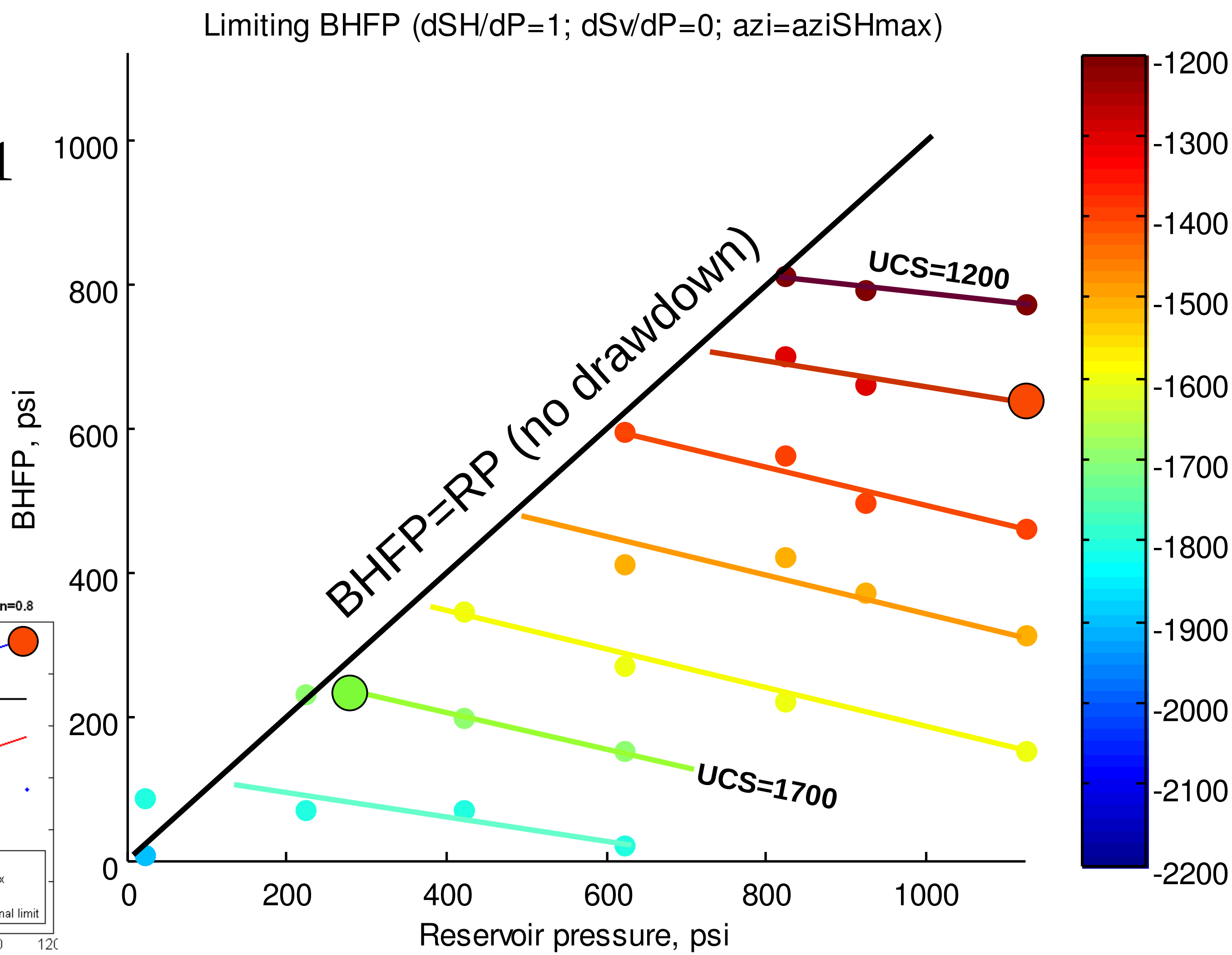
Sv- pseudo-density from sonic log

S_{Hmax}- below 2000 ft, SFIB modeling.

BHFP vs RP – Well Drilled Towards SHmax

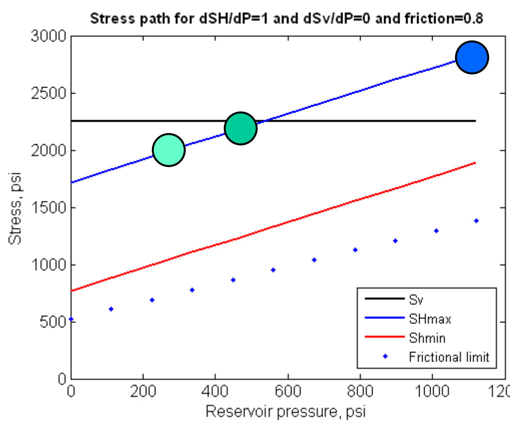
- dSH/dP=1
- dSv/dP=0

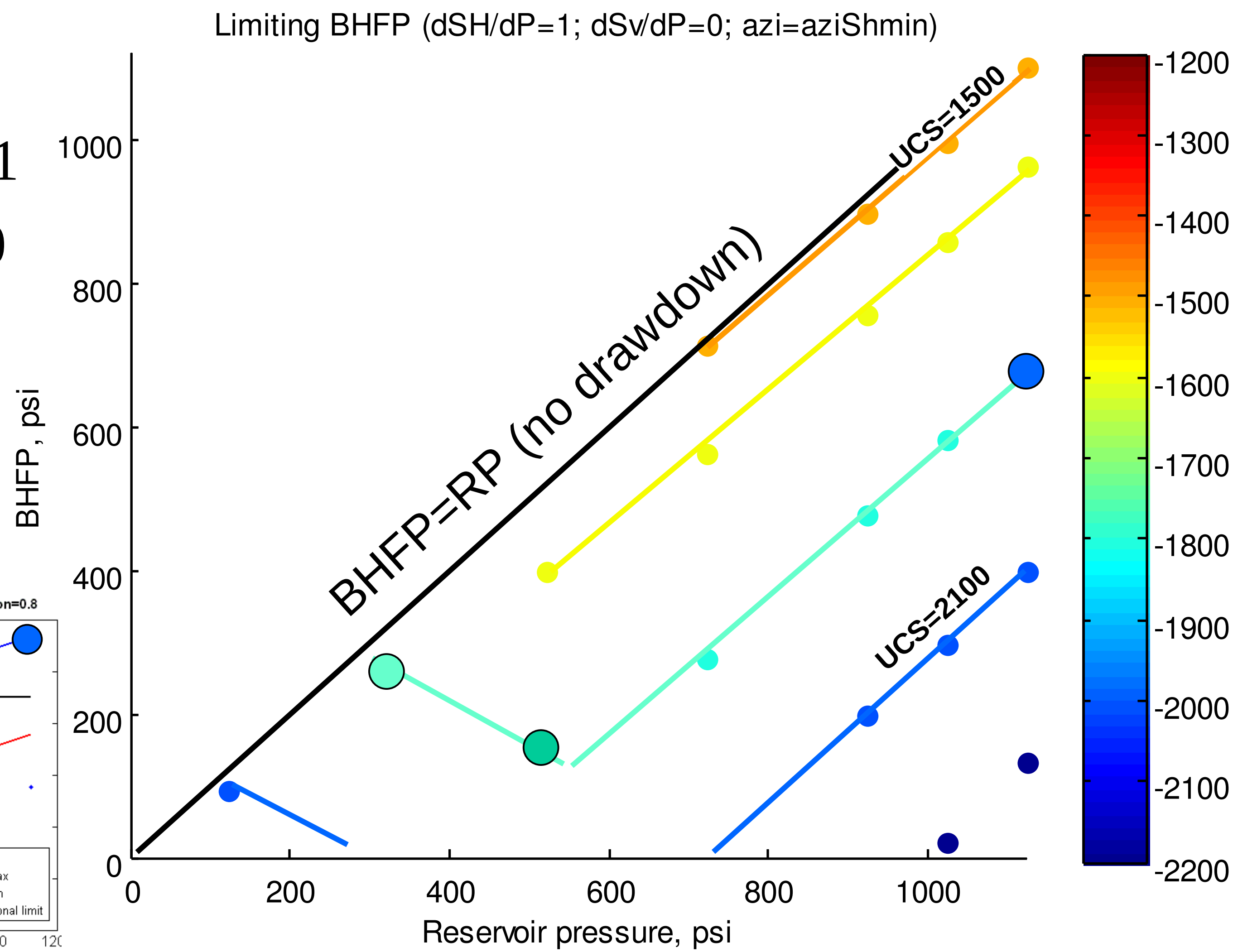




BHFP vs RP – Well Drilled Towards Shmin

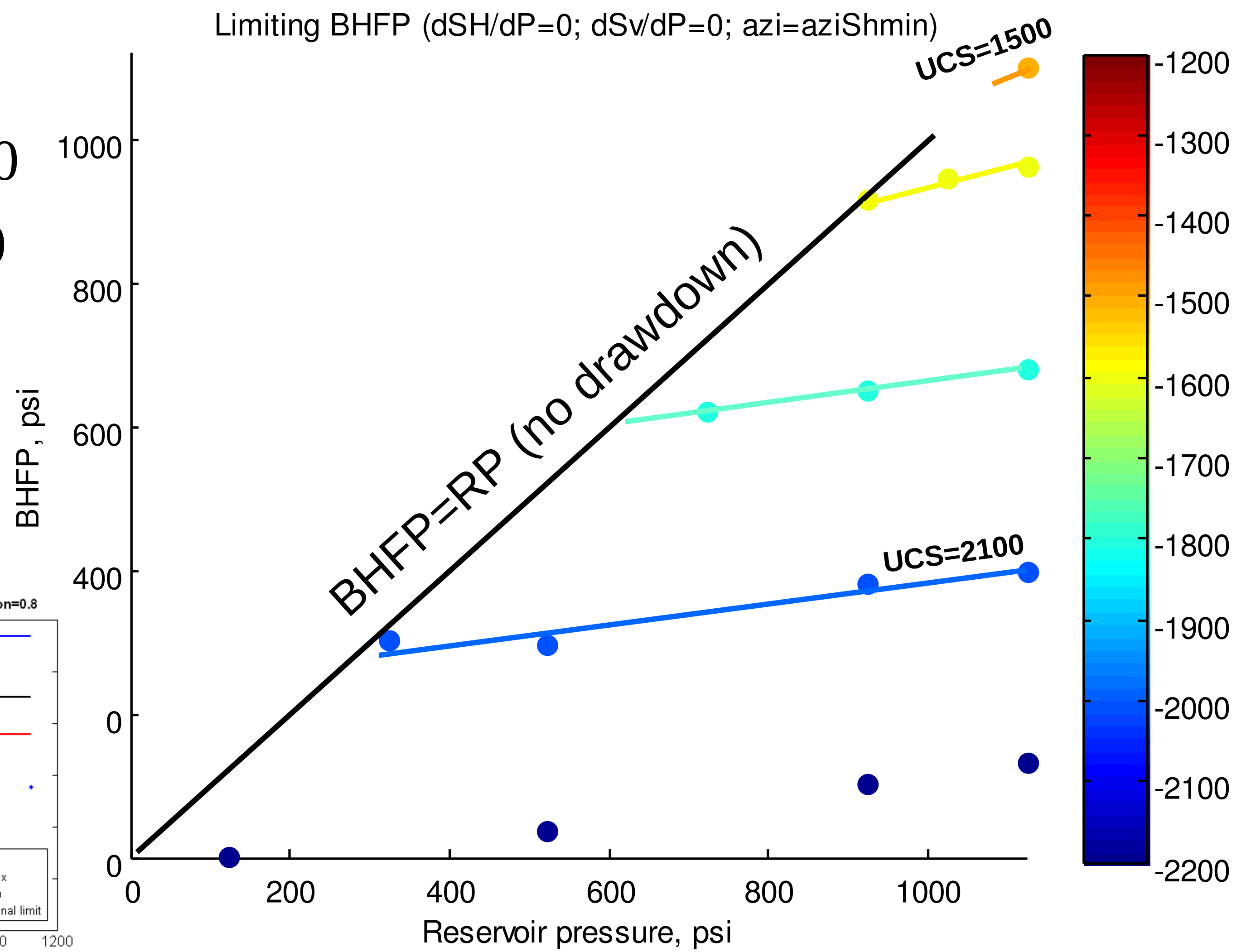
- dSH/dP=1
- dSv/dP=0

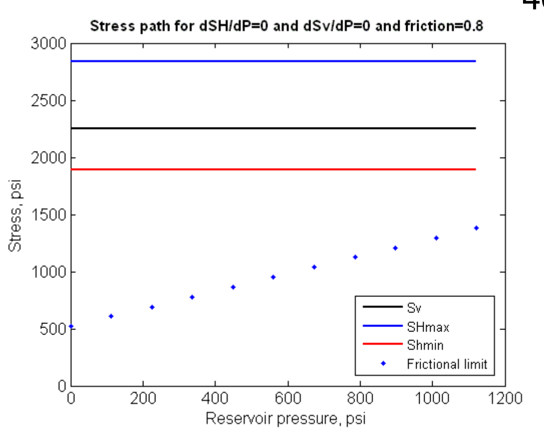




BHFP vs RP – Well Drilled Towards Shmin

- dSH/dP=0
- dSv/dP=0

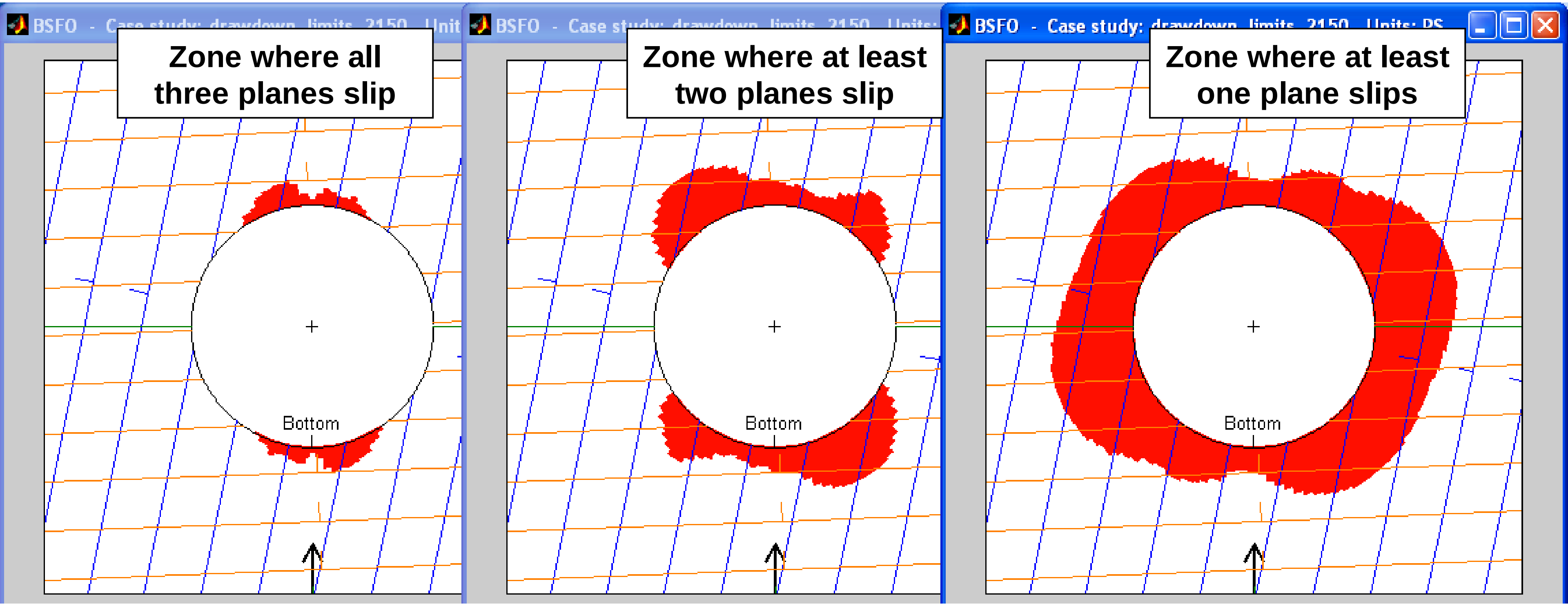




Key Points

- Wells drilled towards SHmax are initially much stronger than those drilled towards Shmin
- As depletion occurs, the critical safe BHFP depends on the stress path
- For some stress paths, wells can rapidly destabilize after a period of constant critical safe drawdown
- Late in the life of the reservoir, wells drilled towards Shmin could become nearly as stable than those drilled towards SHmax

Is it possible to enhance productivity by activating near-well slip on cleats?



Likely zone of block failure

Possible failure zone

Potential zone of enhanced permeability

Cohesion 30 psi. Sliding friction 0.58

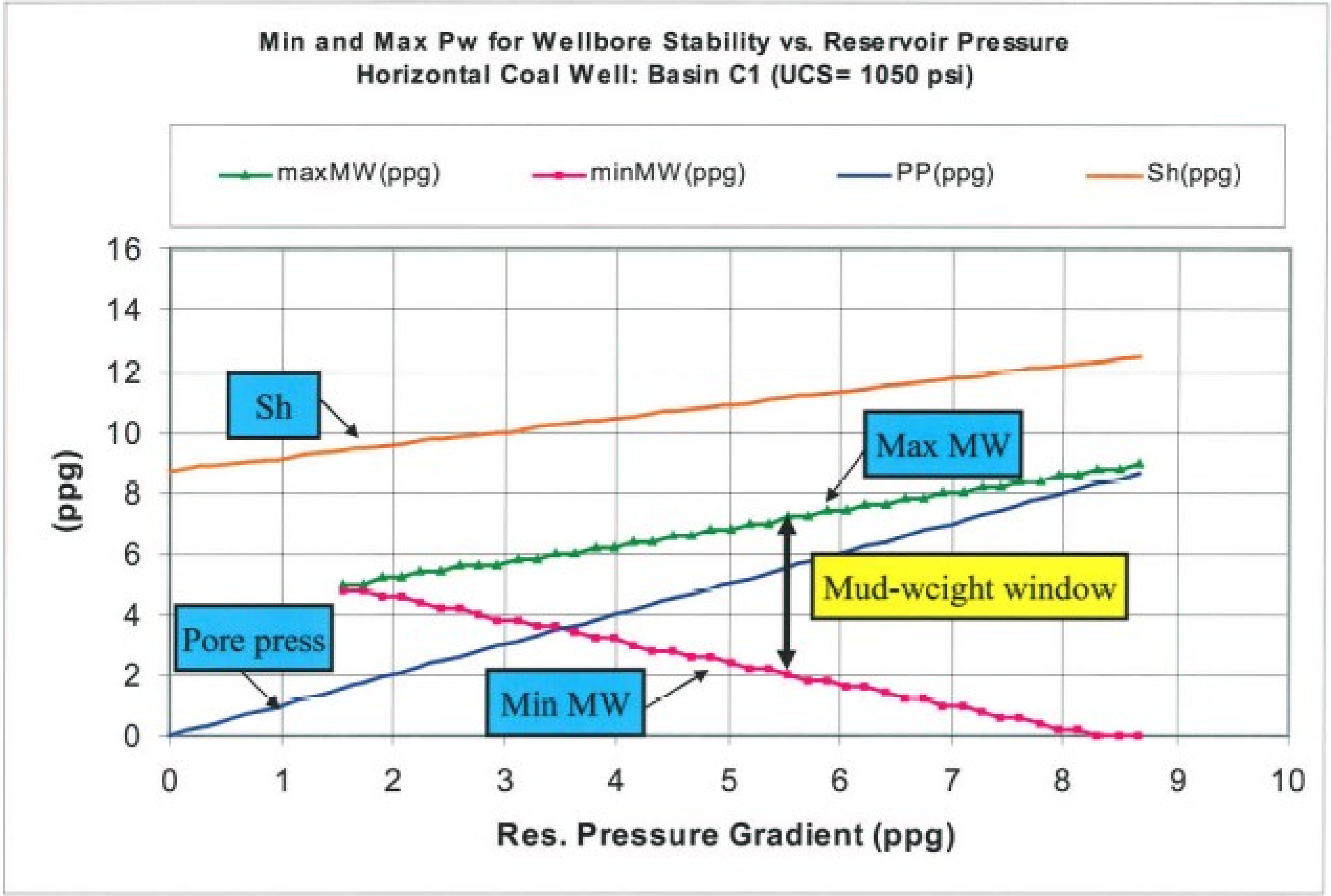
Summary

- The geomechanical concepts presented here can be used to design drilling programs (mud weight windows) to minimize the formation damage, but requires an understanding of the properties of both intact rocks and cleated rocks.
- Horizontal wells drilled towards SHmax in the foothills of the Canadian Rockies are more likely to be stable than those drilled in the direction of Shmin.
- Deciding whether or not to do openhole completion requires knowing the current stress state as well as how the stresses will change over time.
- It may be possible to enhance near-well permeability by activating slip on cleats (cavity completions) but there is a risk of causing catastrophic failure.

Safe mud-weight window for horizontal wells in CBM basins of USA

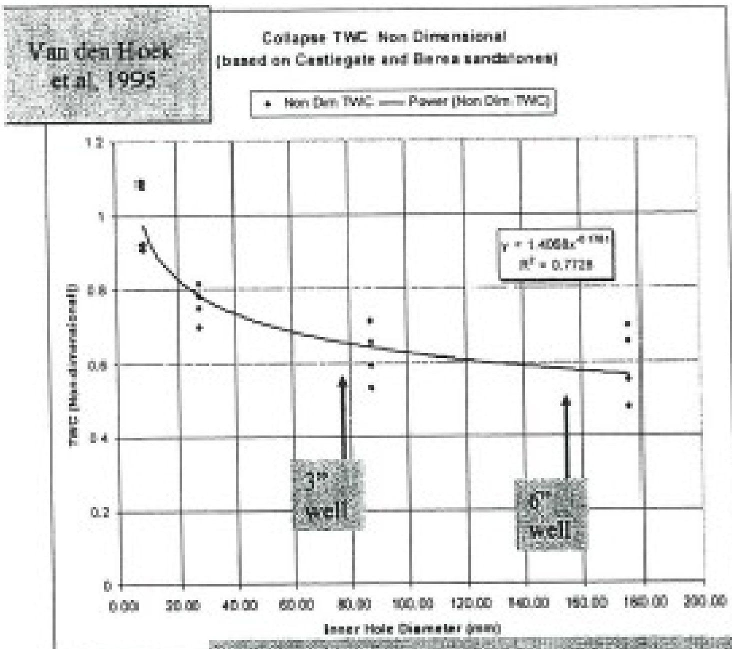
Basin & depth (ft)	Min Hor. Stress (ppg)	LV or MV Coals (UCS = 490 psi) min MW (ppg)	LV or MV Coals (UCS = 490 psi) max MW (ppg)	HVA Coals (UCS = 1050 psi) min MW (ppg)	HVA Coals (UCS = 1050 psi) max MW (ppg)	UCS = 2050 psi min MW (ppg)	UCS = 2050 psi max MW (ppg)	HVB Coals (UCS = 4800 psi) min MW (ppg)	HVB Coals (UCS = 4800 psi) max MW (ppg)
A1 (1000)	13.27	0.00	8.80	0.00	10.40	0.00	13.20	0.00	13.20
A2 (1500)	12.69	0.00	7.80	0.00	9.40	0.00	11.80	0.00	12.60
B1 (1900)	15.39	0.00	12.80	0.00	13.60	0.00	15.20	0.00	15.20
B2 (2100)	15.00	0.00	12.20	0.00	13.20	0.00	14.80	0.00	14.80
C1(2700)	12.50	NO SAFE WINDOW		0.00	9.00	0.00	10.60	0.00	12.40
C2 (2900)	12.12	NO SAFE WINDOW		NO SAFE WINDOW		0.00	9.80	0.00	11.80
D1 (4500)	14.62	NO SAFE WINDOW		0.00	12.60	0.00	13.60	0.00	14.60
D2 (4800)	14.04	NO SAFE WINDOW		3.60	12.00	0.00	12.80	0.00	13.80
E1 (7200)	15.83	9.40	14.40	0.00	14.80	0.00	15.20	0.00	15.80
E2 (7400)	15.53	13.80	14.00	0.00	14.20	0.00	14.80	0.00	15.40
Overburden = 19.23 ppg = 1 psi/ft									
Reservoir Pressure = 8.65 ppg = 0.45 psi/ft									

Effect of reservoir depletion on WBS--Basin C1, HVA Coals



**A practical question:
are smaller-diameter horizontals
more stable than
larger-diameter horizontals?**

Are 6" horizontals weaker than 3" horizontals?



TWC ID (in)	TWC ID (mm)	Non-Dimensional TWC
0.28	7.06	1.00
1.00	25.40	0.80
2.00	50.80	0.70
3.00	76.20	0.66
4.00	101.60	0.62
5.00	127.00	0.60
6.00	152.40	0.58
7.00	177.80	0.56
8.00	203.20	0.55
9.00	228.60	0.54
10.00	254.00	0.53
11.00	279.40	0.52
12.00	304.80	0.51
13.00	330.20	0.51
14.00	355.60	0.50
15.00	381.00	0.49
16.00	406.40	0.49
17.00	431.80	0.48
18.00	457.20	0.48
19.00	482.60	0.47
20.00	508.00	0.47

For sandstones: thick-wall cylinder (TWC) strength decreases from 3" well to 6" well by 11%

How does this effect wellbore stability during drilling or production?

- During production, a 6” horizontal is predicted to collapse earlier than a 3” horizontal

- For example for an HVA coal at 2800 ft, maximum allowable depletion (before collapse) is reduced by almost a third

- A similar situation is expected to apply for wellbore stability during drilling…especially when drilling underbalanced

- The strength reduction could be even greater than 11% for coals, since they are naturally fractured (cleats)

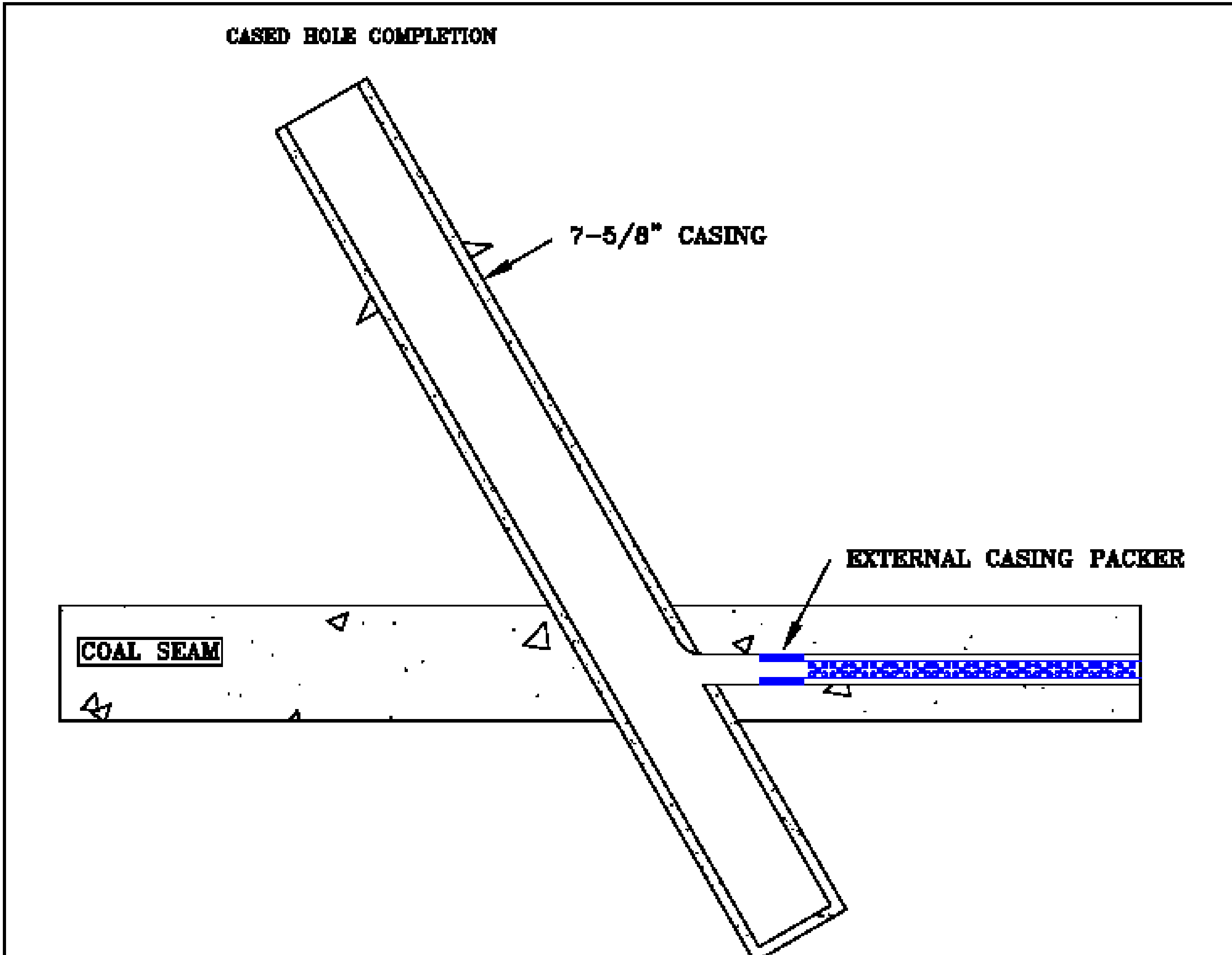
Summary

- A 3” well is stronger and therefore more stable than a 6” well, and less likely to fail or collapse
- A 6” well gives negligible improvement in gas rate over a 3” well when water is being produced
- A liner is nearly always recommended in coals
- Therefore the best horizontal well is the smallest diameter well that can accept a liner (note: it will be more difficult to install a liner into a smaller diameter well, due to friction effects)
- For wells with undulations, gas rate is larger for the 2000 ft well than for a 6000 ft well (but less than for a flat well)
- Downdip wells produce much less than flat well at low reservoir pressures

Advantages of Liner in Horizontal Wells

- It appears more wells have been lined than not
- The danger of unlined horizontals is wellbore collapse due to depletion:
- Or if the wellbore intercepts (1) weak shales (2) unmapped faults

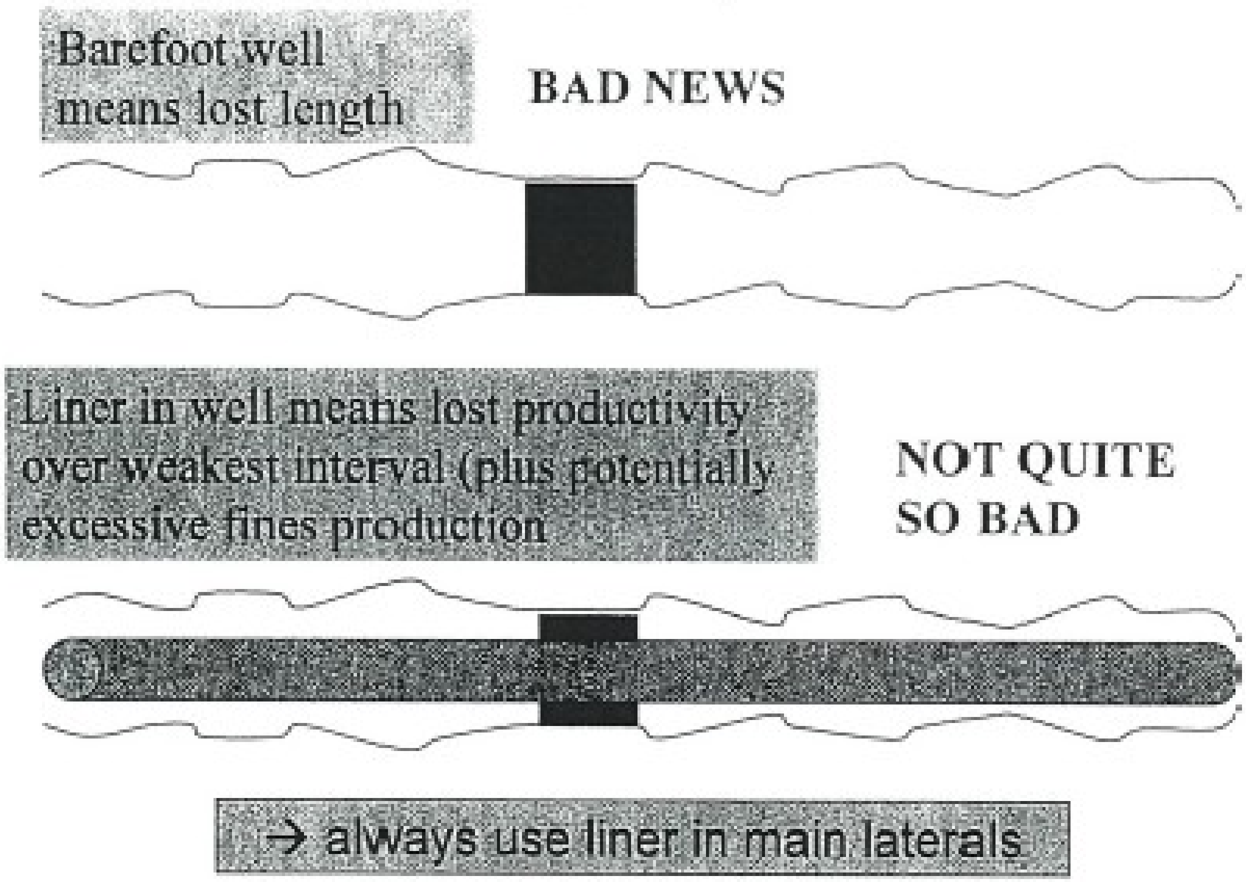
- A liner is insurance against the possibility of wellbore collapse for any reason, and is recommended for most coals (at least the main laterals)


CASED HOLE COMPLETION
7-5/8" CASING
EXTERNAL CASING PACKER
COAL SEAM

Liner Specs in Horizontals

- Pre-perforated liner used in Arkoma:
  - cheaper than slotted
  - perfs too large and let too many fines through → plug pumps and tubulars
- Slotted liners used in Mannville
- But coal fines have very wide PSD, and will plug anything and everything (including slots)
- Slots in weak sandstones work best in well-sorted sands → slots should not work well in coals0
- Best practice: design liners for CBM with 1 mm holes and 3% hole area. 1 mm holes = 2 x slot width

What if Horizontal Well does Collapse during Depletion?



Fine Problems

- Endemic in Powder River
- Fines are a common problem San Juan, Uinta, and Raton basins
- Horizontals in Arkoma have pump plugging problems late in life
- Affects peak flowrate and decline in San Juan basin
- One large CBM operator in the San Juan basin has reported that coal fines are becoming more of a problem:
  - They are building up at the bottom of wells because late-life flowrates are too low to lift them
  - Some liners have been pulled from vertical wells and found to be plugged.
  - Fines production should increase with depletion, and so the situation can only get worse

Fines Prediction Equation
(borrowed from sanding literature)

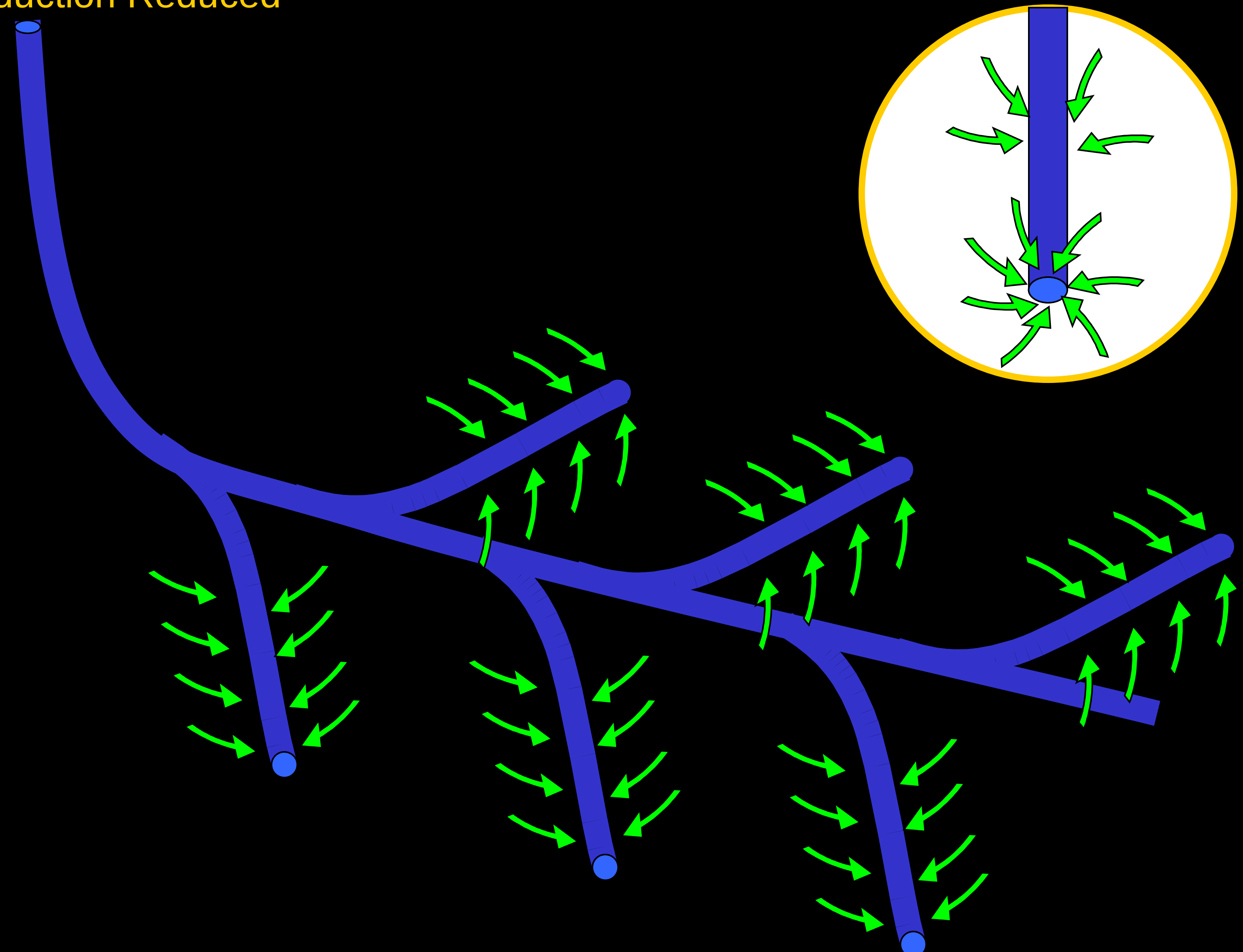
- **CBHFP = $(3S_1 - S_2 - U - AP) / (2 - A)$**

$$A = \frac{(1 - 2v)}{(1 - v)} \, a \quad a = (1 - K_R / K_S)$$

  - **CBHFP = critical bottomhole flowing pressure (threshold for coal fines)**
  - **If BHFP lower than CBHFP, expect fines at surface**
  - S_1 = max stress acting perpendicular to hole
  - S_2 = minimum stress acting perpendicular to hole
  - TWC = a * UCS ^ b
  - U = 3.1 * TWC
  - P = current reservoir pressure

ΔP Flow in Multilateral

- Fluid Velocity Reduced
- Fine Production Reduced



Underbalanced Multilateral Drilling

LETS DISCUSS HOW IT WORKS

- CONTINUOUS CIRCULATION vs. JOINTED PIPE
- MULTI-SEAM COMPLETIONS
- MANAGED PRESSURE DRILLING
- GEOSTEERING
- FRACTURE STIMULATING OF UNDERBALANCED MULTI-LATERAL WELLS
- SUMPED PUMPING

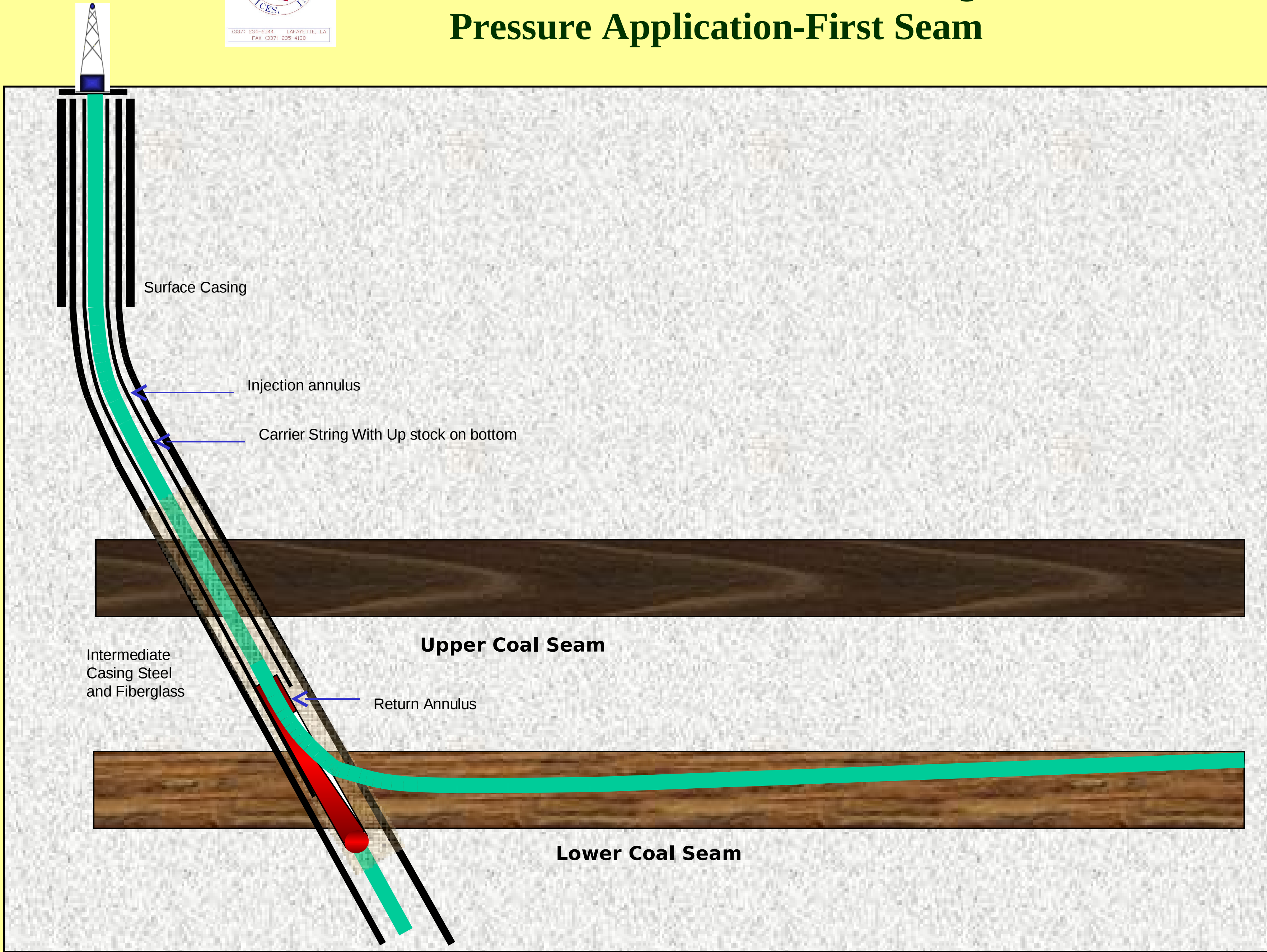
Gardes Upstock®

Images

Upstock® with carrier string and drill bit (side view).

Upstock® with carrier string and drill bit (profile view).

Horizontal Underbalanced Managed Pressure Application-First Seam



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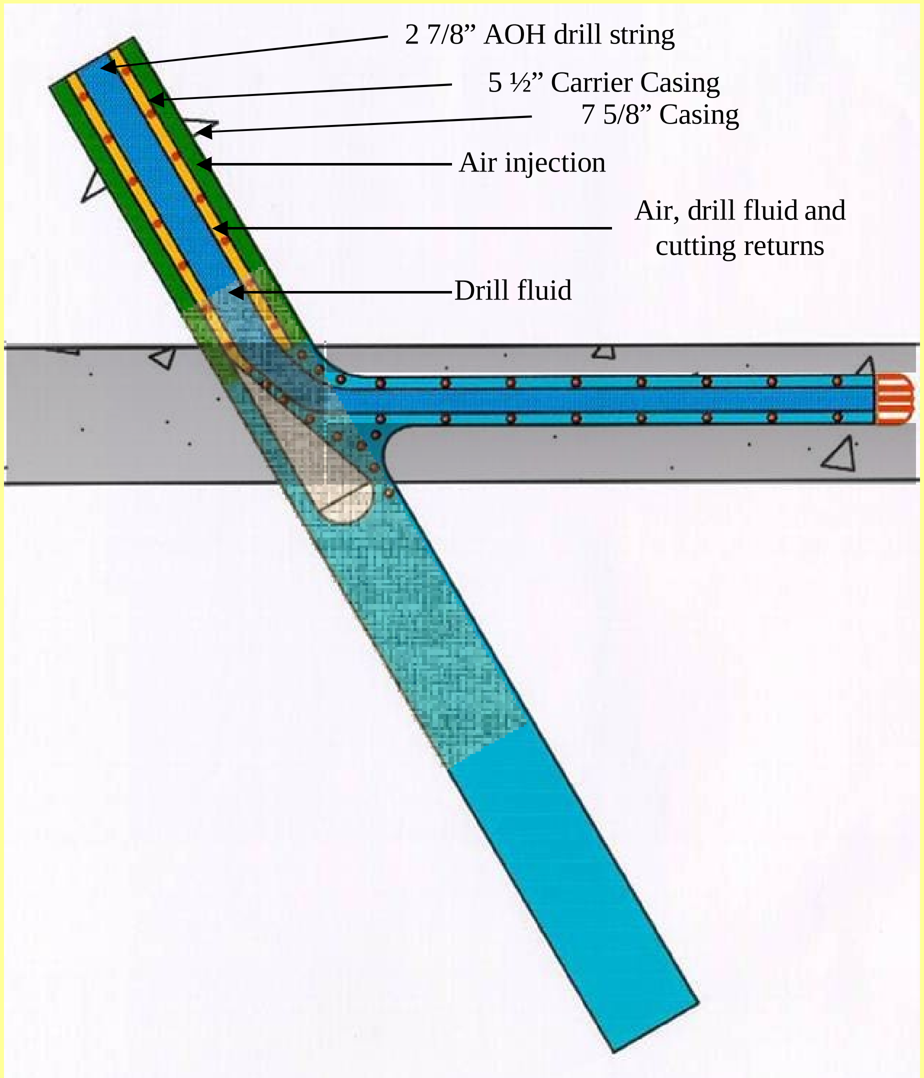
FAX (337) 235-4138

Underbalanced Managed Pressure Drilling



Drilling Coal Seam:

Drill Coal seam while injecting air down the 7 5/8” and 5 ½” annulus with drill fluid down 2 7/8” drill string. Both injection mediums and cuttings will meet at window and return to surface via the 5 ½” and 2 7/8” annulus.

Injection rates should start out as per the pre flow model data and adjusted according to down hole MWD pressure sensors in order to keep the well under balanced.

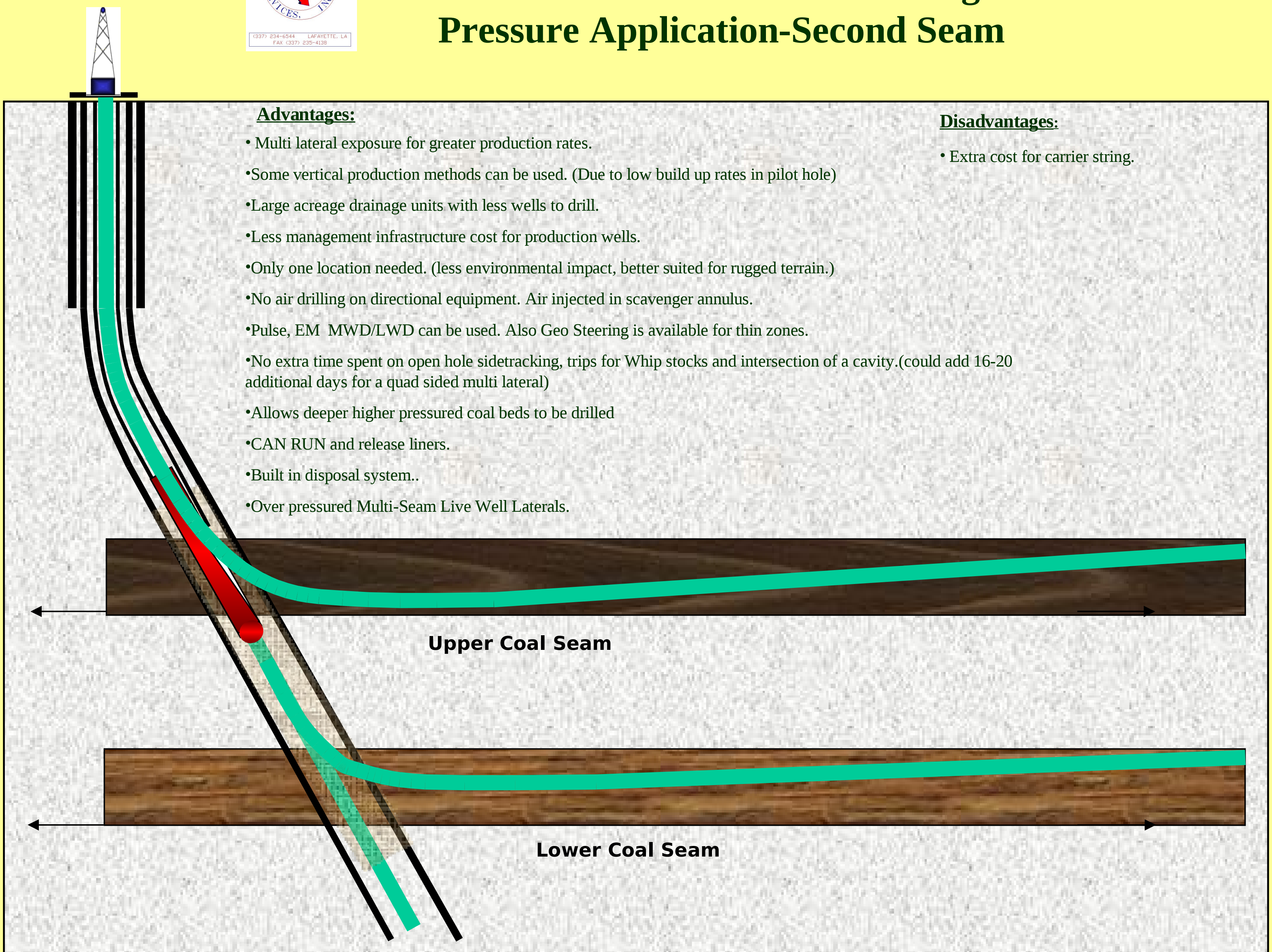
Horizontal Underbalanced Managed Pressure Application-Second Seam

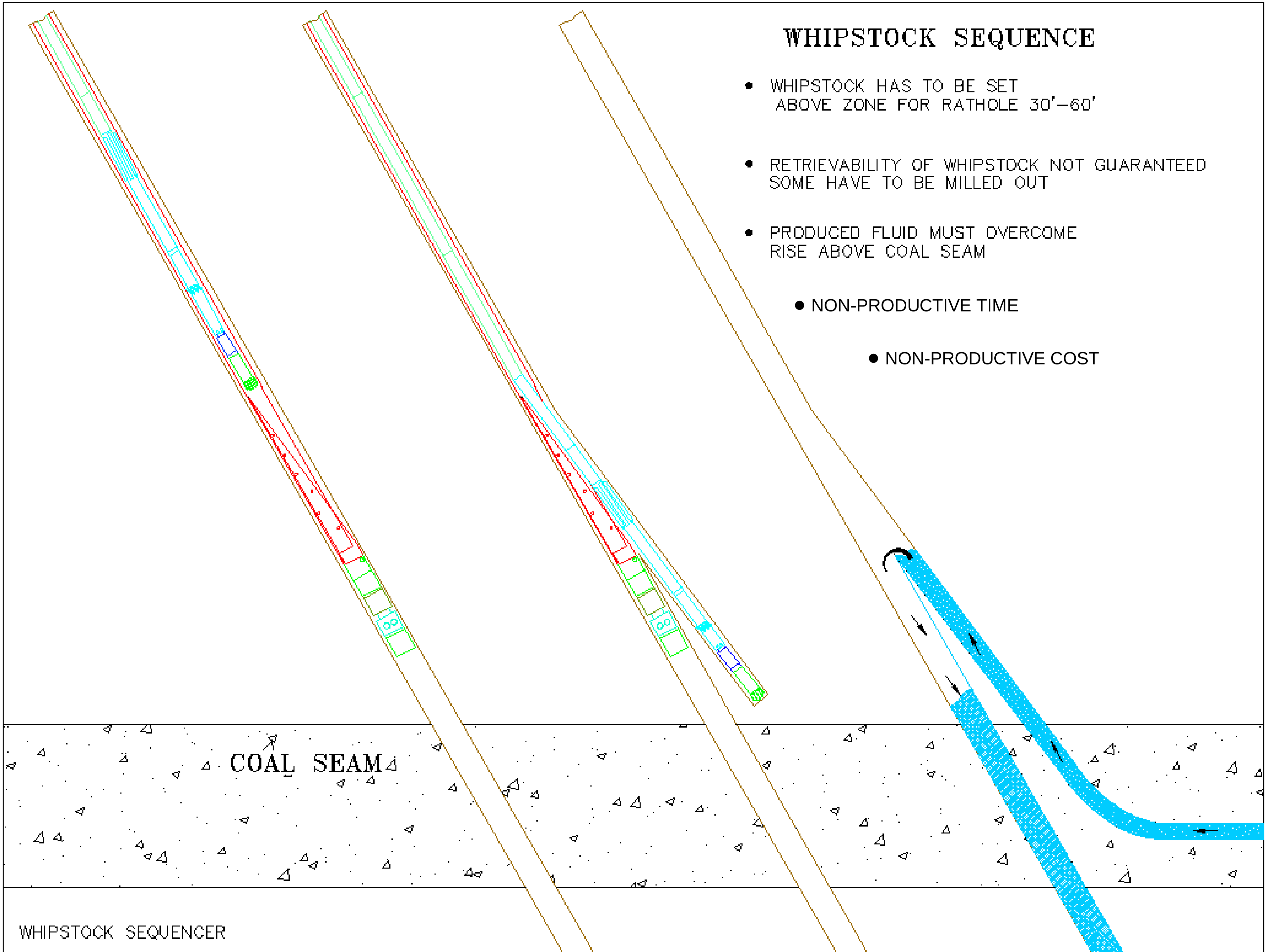
Advantages:

- Multi lateral exposure for greater production rates.
- Some vertical production methods can be used. (Due to low build up rates in pilot hole)
- Large acreage drainage units with less wells to drill.
- Less management infrastructure cost for production wells.
- Only one location needed. (less environmental impact, better suited for rugged terrain.)
- No air drilling on directional equipment. Air injected in scavenger annulus.
- Pulse, EM MWD/LWD can be used. Also Geo Steering is available for thin zones.
- No extra time spent on open hole sidetracking, trips for Whip stocks and intersection of a cavity.(could add 16-20 additional days for a quad sided multi lateral)
- Allows deeper higher pressured coal beds to be drilled
- CAN RUN and release liners.
- Built in disposal system..
- Over pressured Multi-Seam Live Well Laterals.

Disadvantages:

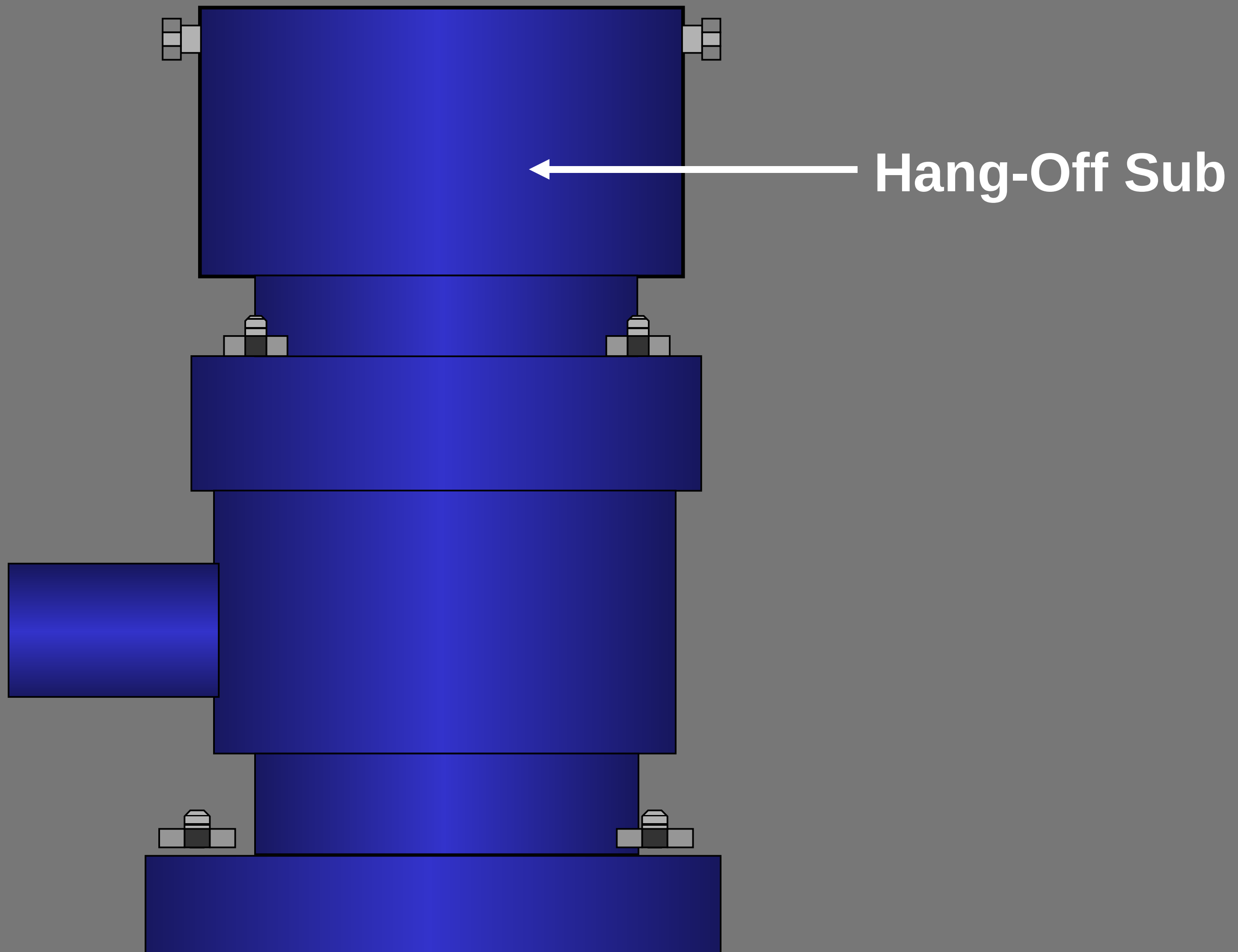
- Extra cost for carrier string.

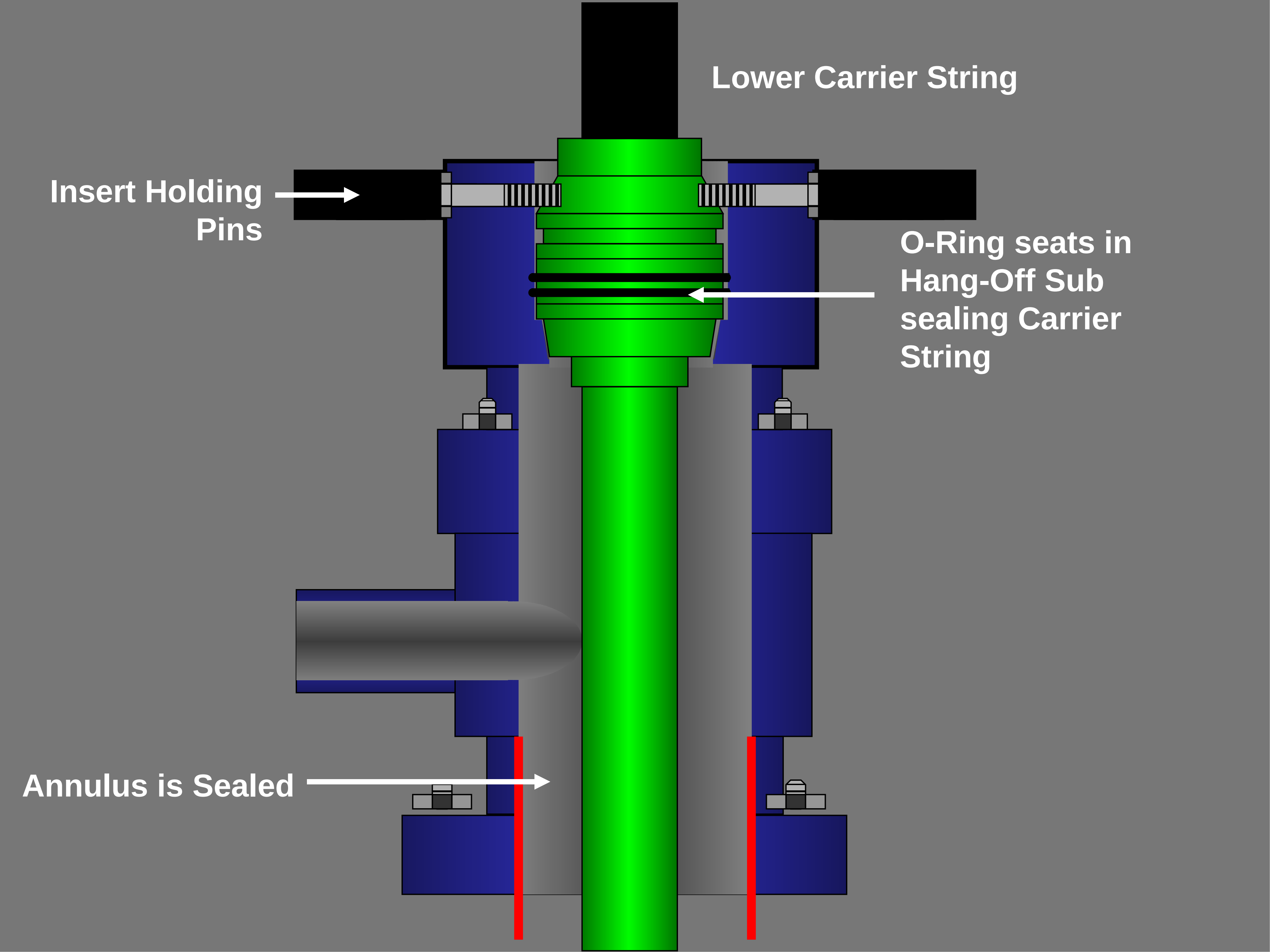


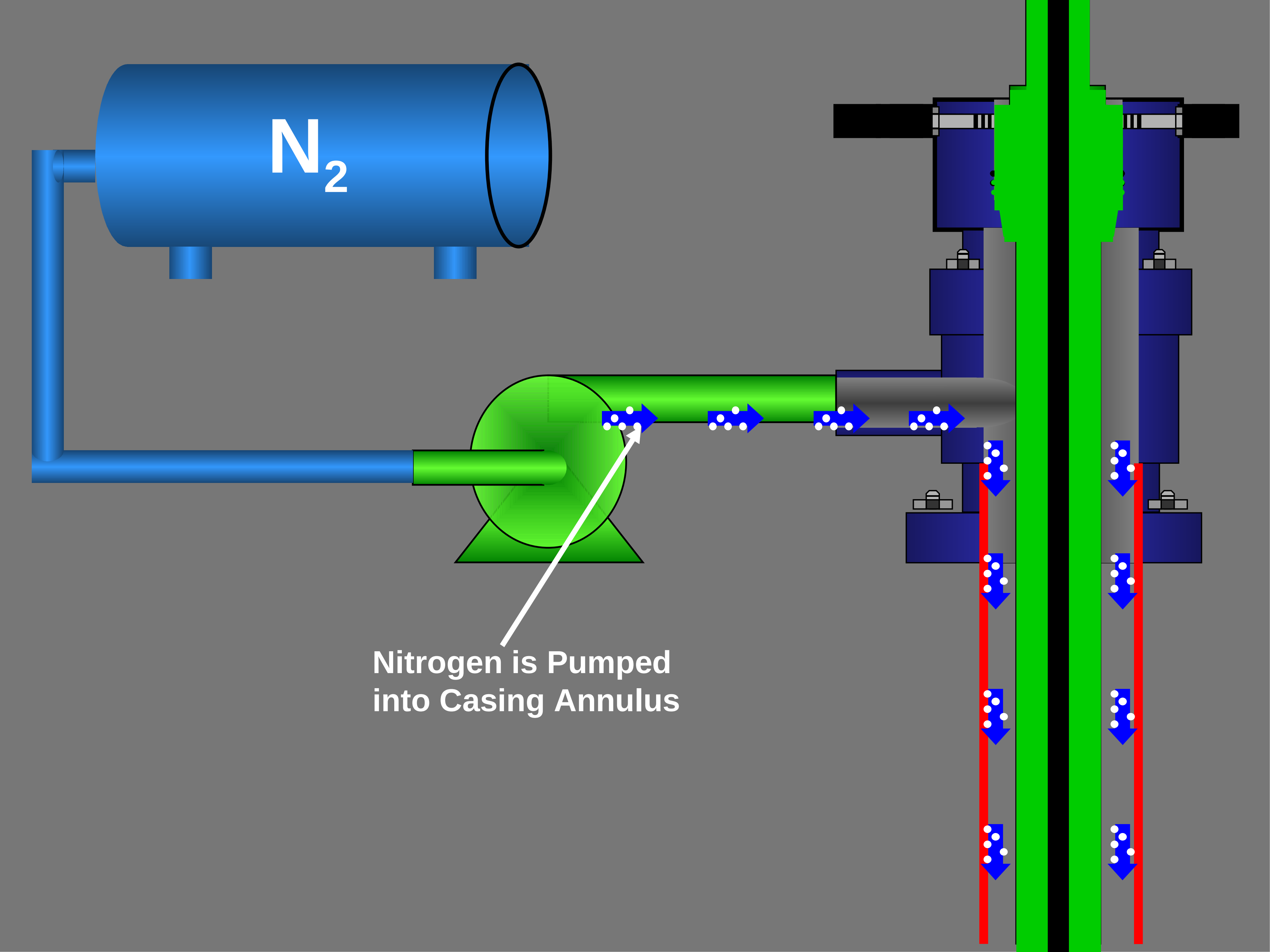

WHIPSTOCK SEQUENCE
• WHIPSTOCK HAS TO BE SET ABOVE ZONE FOR RATHOLE 30'–60'
• RETRIEVABILITY OF WHIPSTOCK NOT GUARANTEED SOME HAVE TO BE MILLED OUT
• PRODUCED FLUID MUST OVERCOME RISE ABOVE COAL SEAM
• NON-PRODUCTIVE TIME
• NON-PRODUCTIVE COST
COAL SEAM
WHIPSTOCK SEQUENCER

Schaffer double ram, annular BOP and rotating head

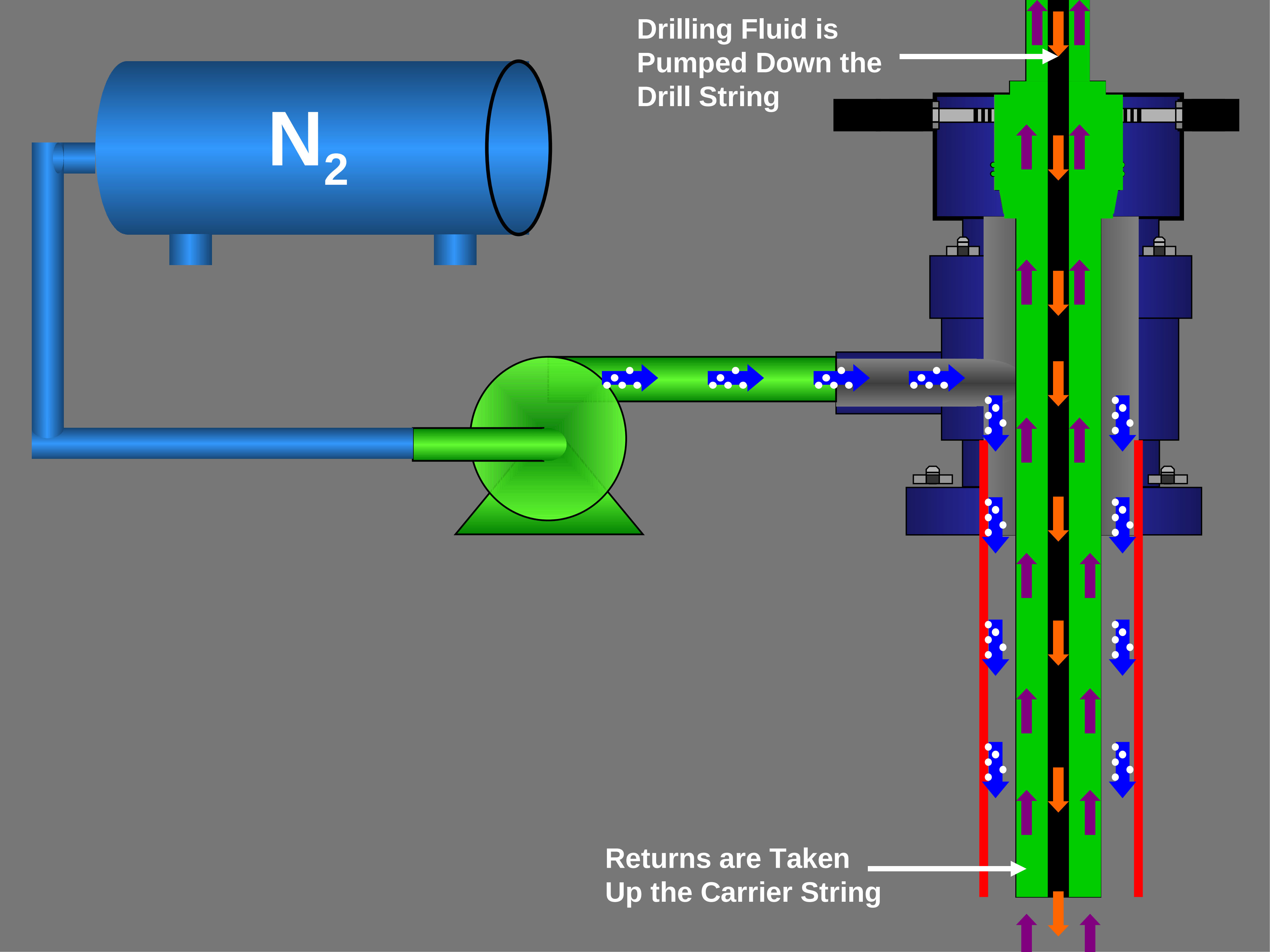
Well Head configuration at setting 5 ½ casing


Hang-Off Sub


Lower Carrier String
Insert Holding Pins
O-Ring seats in Hang-Off Sub sealing Carrier String
Annulus is Sealed



N2
Nitrogen is Pumped
into Casing Annulus


Drilling Fluid is
Pumped Down the
Drill String
N2
Returns are Taken
Up the Carrier String

Wood Group Pressure Control

SH-2 UB/Friction Wellhead System Installation Sequence

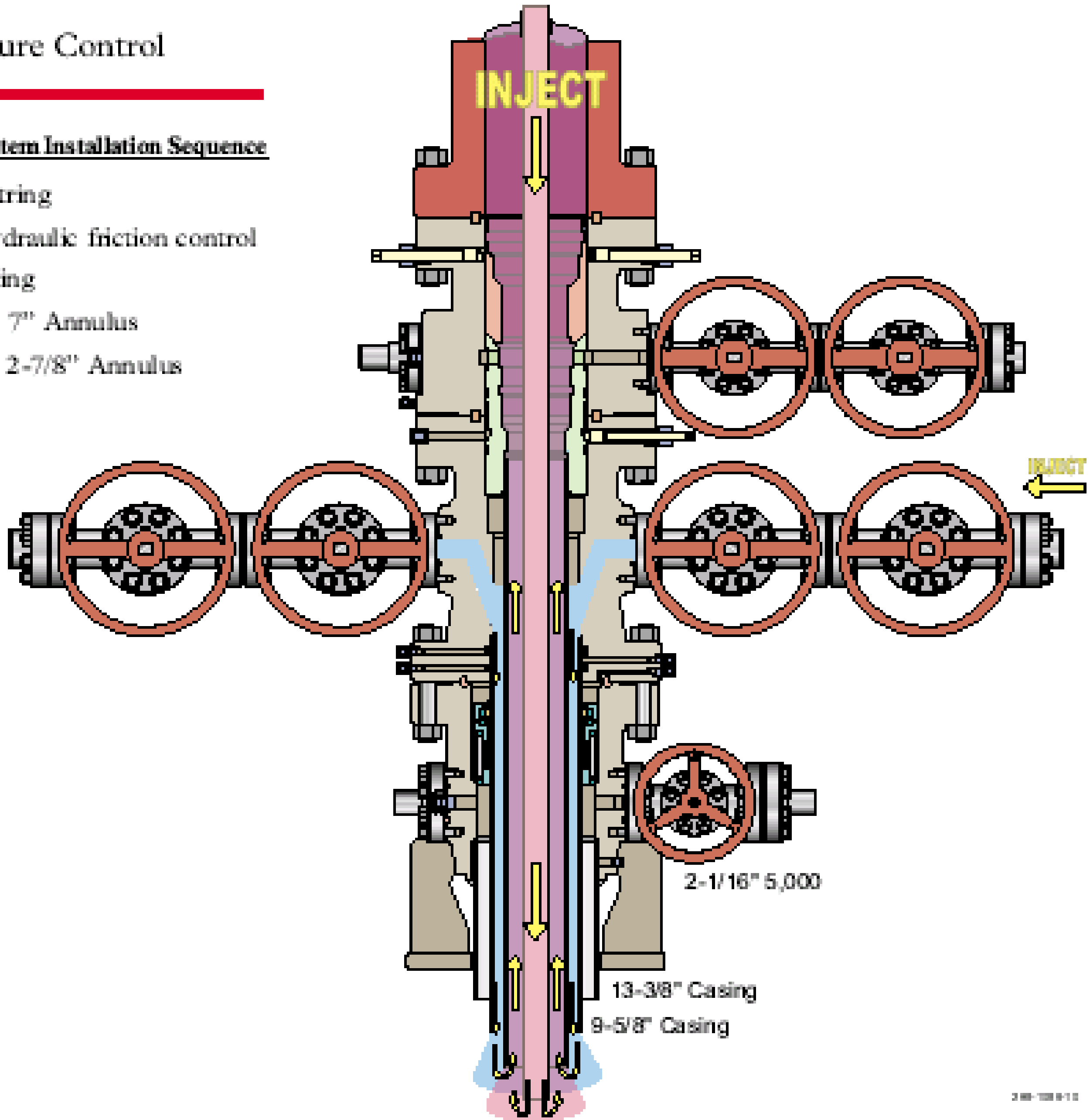
Stage 9. Run 2-7/8" Drill String

Drill Underbalanced with hydraulic friction control

– Inject Fluid down Drill String

– Inject Fluid down 9-5/8" x 7" Annulus

– Co-mingle returns up 7" x 2-7/8" Annulus



Continuous Circulation Concentric Casing System

- During connections the established standpipe injection volume used while drilling is added to the concentric casing injection volume on the back side, so the ECD remains constant eliminating the Bottom Hole Pressure surges associated with drill pipe connections.

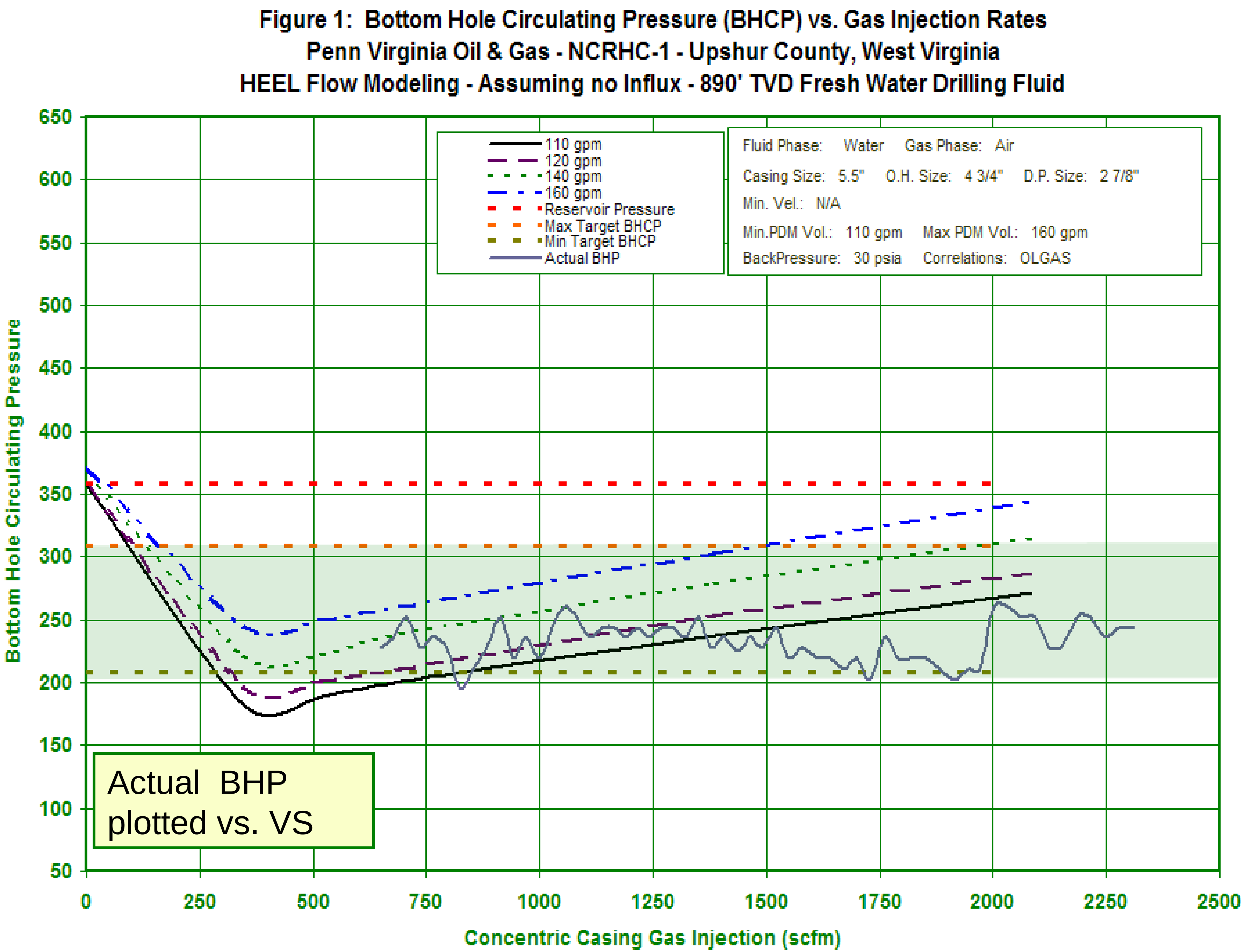
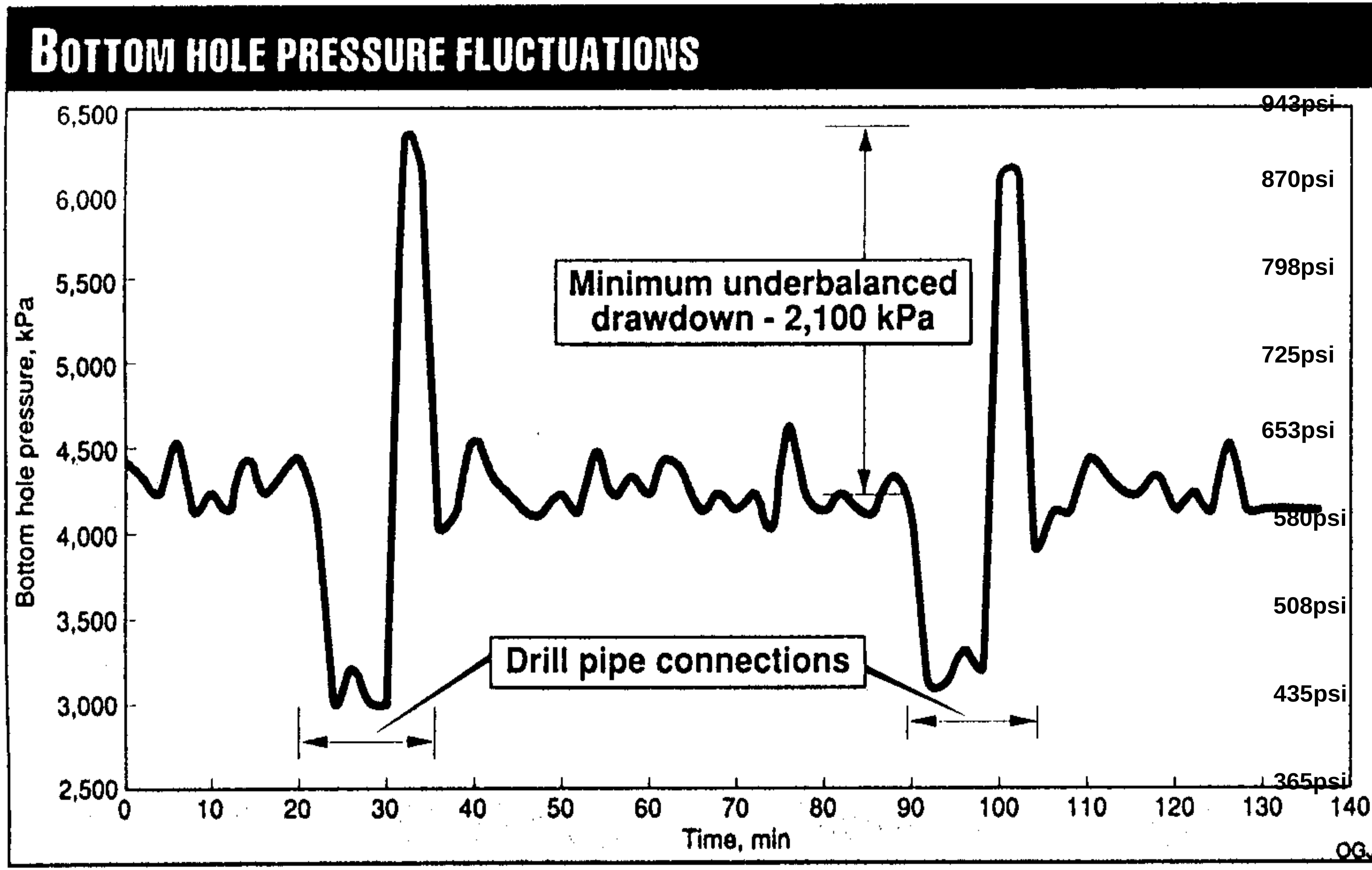


Figure 1: Bottom Hole Circulating Pressure (BHCP) vs. Gas Injection Rates
Penn Virginia Oil & Gas - NCRHC-1 - Upshur County, West Virginia
HEEL Flow Modeling - Assuming no Influx - 890' TVD Fresh Water Drilling Fluid
110 gpm
120 gpm
140 gpm
160 gpm
Reservoir Pressure
Max Target BHCP
Min Target BHCP
Actual BHP
Fluid Phase: Water Gas Phase: Air
Casing Size: 5.5" O.H. Size: 4 3/4" D.P. Size: 2 7/8"
Min. Vel.: N/A
Min.PDM Vol.: 110 gpm Max PDM Vol.: 160 gpm
BackPressure: 30 psia Correlations: OLGAS
Actual BHP plotted vs. VS
Bottom Hole Circulating Pressure
Concentric Casing Gas Injection (scfm)
650
600
550
500
450
400
350
300
250
200
150
100
50
0
250
500
750
1000
1250
1500
1750
2000
2250
2500

Continuous Circulation Concentric Casing Drilling Advantages

- ❖ Bottom Hole Pressure remains constant with no pressure oscillations during connections
- ❖ 2 Phase fluid circulation allows for all types of guidance and logging MWD’s to be run
- ❖ Significant formation damage to the cleat/fracture system by induced mud loss and polymer/chemical absorption is eliminated



This figure shows the actual bottom hole pressure fluctuations on the Brazil well-1 FR-1-SC. The pressure spikes were during a connection of a joint of drill pipe while drilling under balanced thru the 2822' to 2900' TVD section. The lower pressure readings were logged during the shut off of air and mud injection primarily due to frictional losses. The high spikes were due to the start up of the air and mud injection primarily due to fluid acceleration. The formation pressure was established at 638psi at the 2822'-2900' TVD section. The only time it stayed close to that range was during the drilling process.

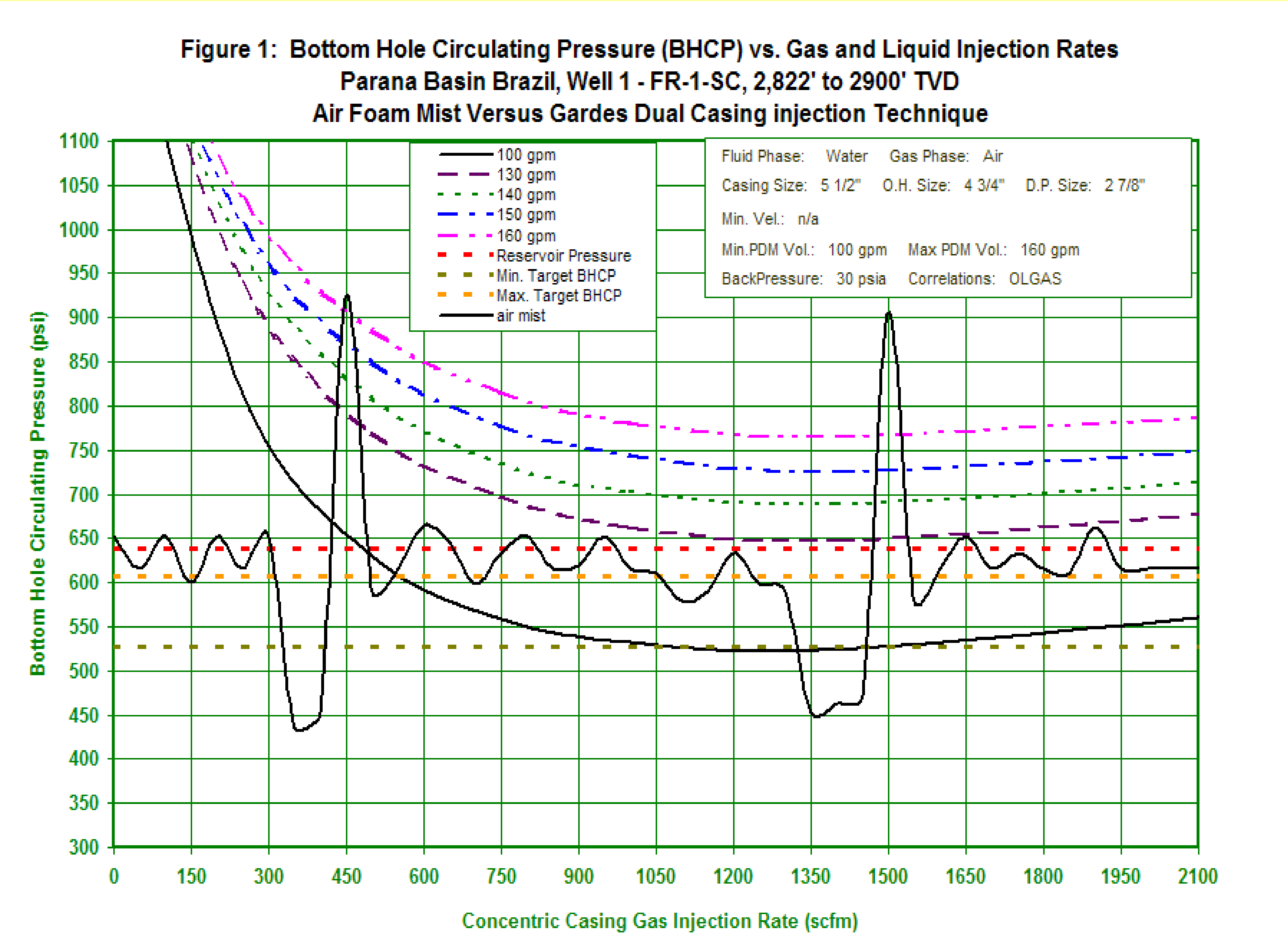
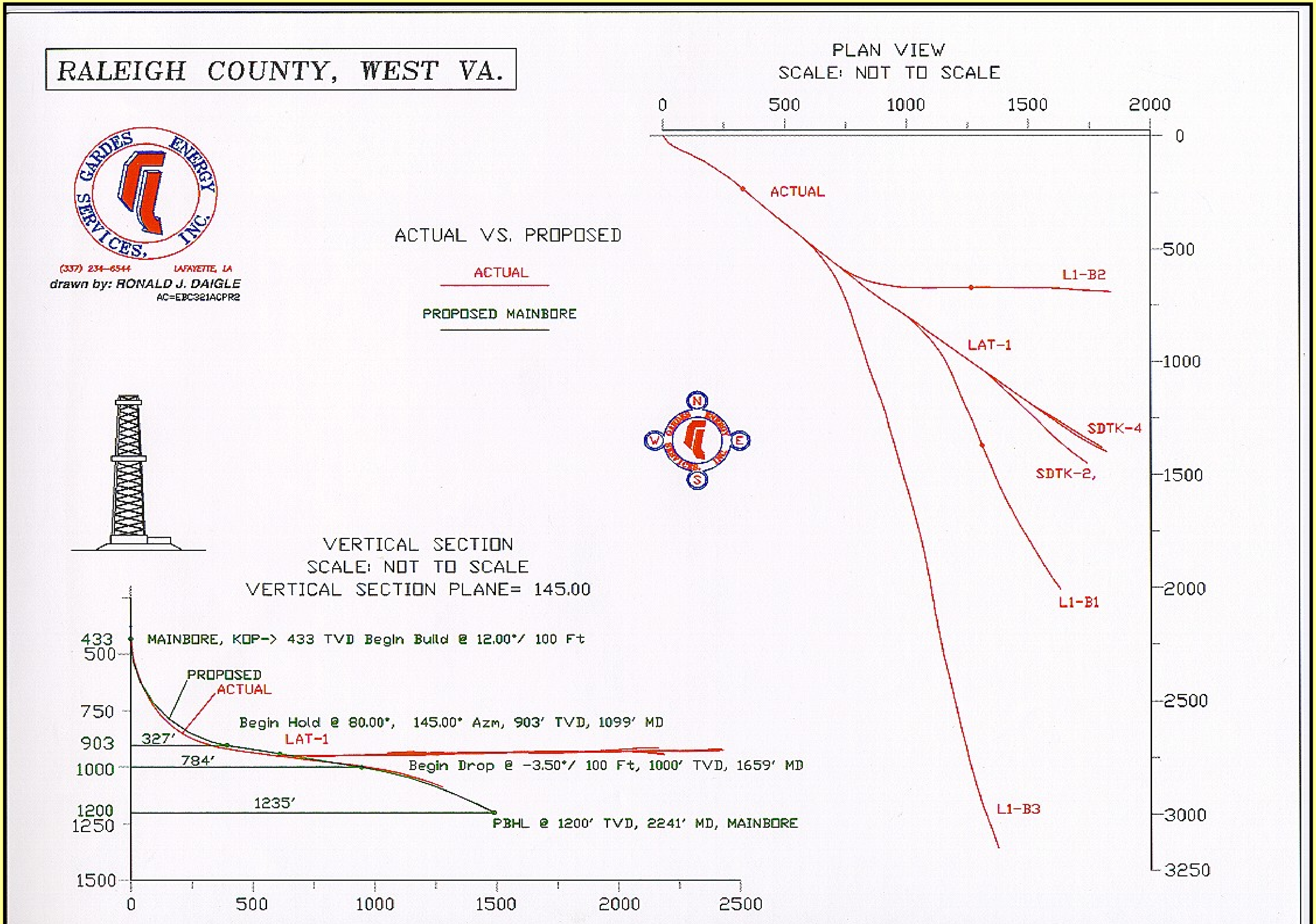


Figure 1: Bottom Hole Circulating Pressure (BHCP) vs. Gas and Liquid Injection Rates
Parana Basin Brazil, Well 1 - FR-1-SC, 2,822' to 2900' TVD
Air Foam Mist Versus Gardes Dual Casing injection Technique
100 gpm
130 gpm
140 gpm
150 gpm
160 gpm
Reservoir Pressure
Min. Target BHCP
Max. Target BHCP
air mist
Fluid Phase: Water Gas Phase: Air
Casing Size: 5 1/2" O.H. Size: 4 3/4" D.P. Size: 2 7/8"
Min. Vel.: n/a
Min.PDM Vol.: 100 gpm Max PDM Vol.: 160 gpm
BackPressure: 30 psia Correlations: OLGAS
Bottom Hole Circulating Pressure (psi)
Concentric Casing Gas Injection Rate (scfm)
1100
1050
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
0
150
300
450
600
750
900
1050
1200
1350
1500
1650
1800
1950
2100

GEOSTEERING

- **The Art of Staying in the Coal**

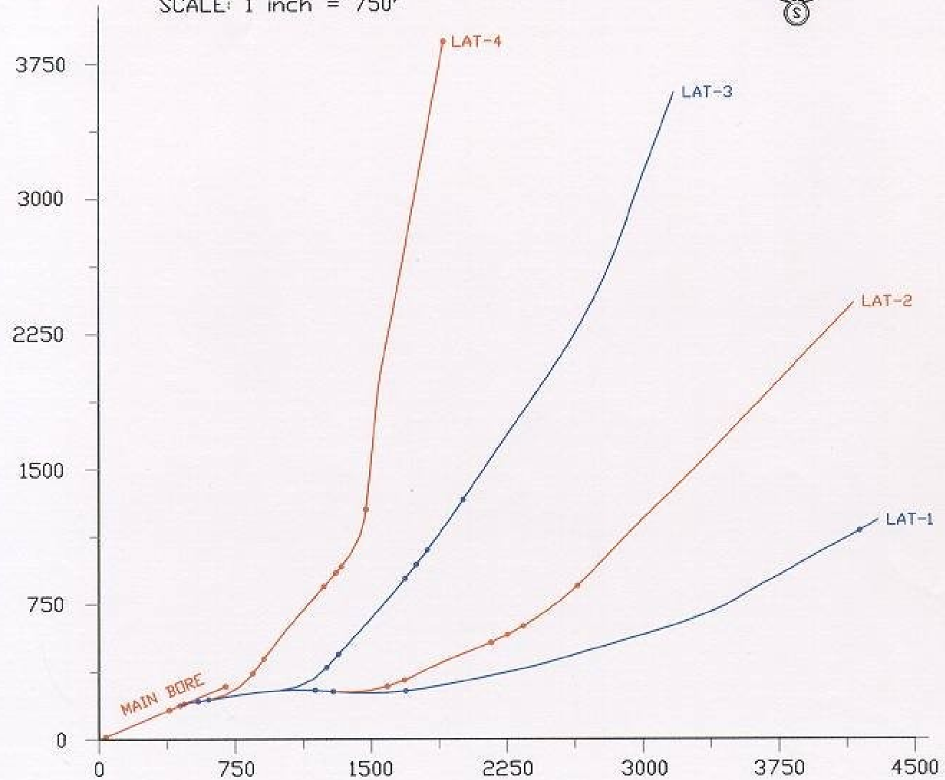
Actual HML Coal Bed Methane Well



PROPOSED 3/16/04

PENN-VIRGINIA, DOMINIONS JV
WELL- NCRHC-1
UPSHUR COUNTY
WEST VIRGINIA, USA

PLAN VIEW
SCALE: 1 inch = 750'

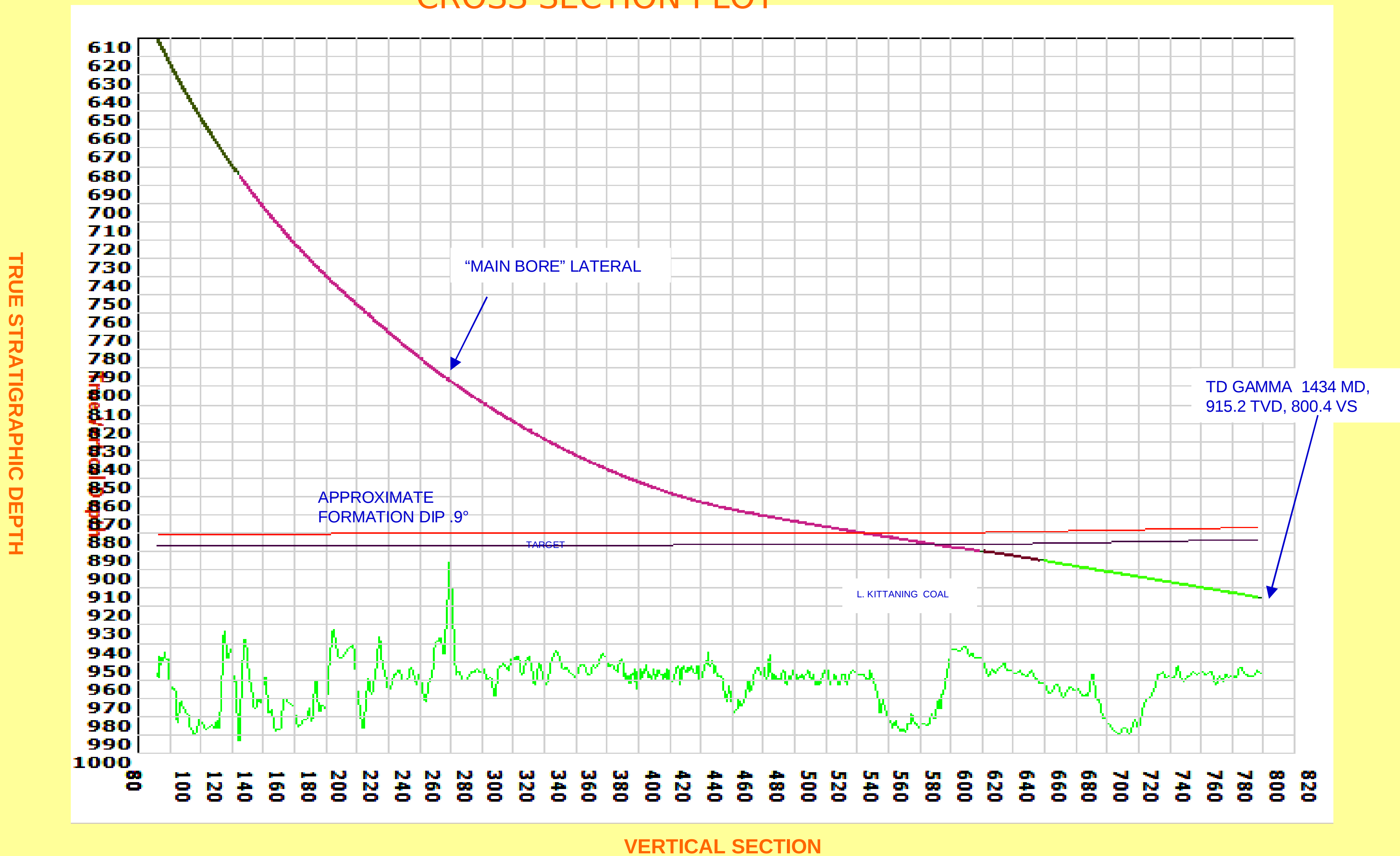


VERTICAL SECTION
SCALE: 1 inch = 1000'
VERTICAL SECTION PLANE= 67.00

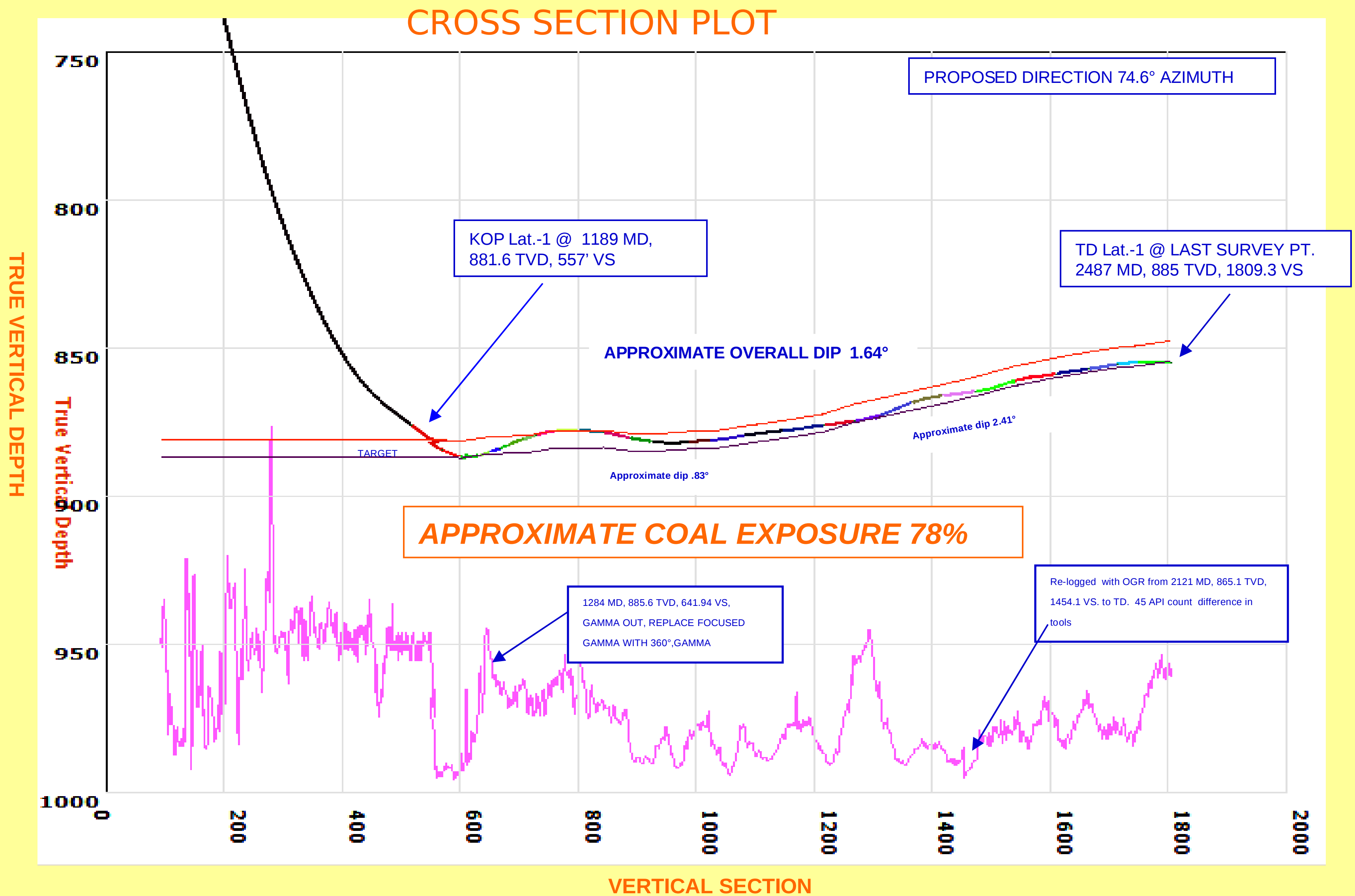
(337) 234-6544 LAFAYETTE, LA
drawn by: RONALD J. DAIGLE
AC=PENNVINKITTANINGR4-1, W=PVDJVHC1, C1-C5

PENN VIRGINA OIL AND GAS
NCRHC-1 MAINBORE
BARBOUR COUNTY, WV

CROSS SECTION PLOT

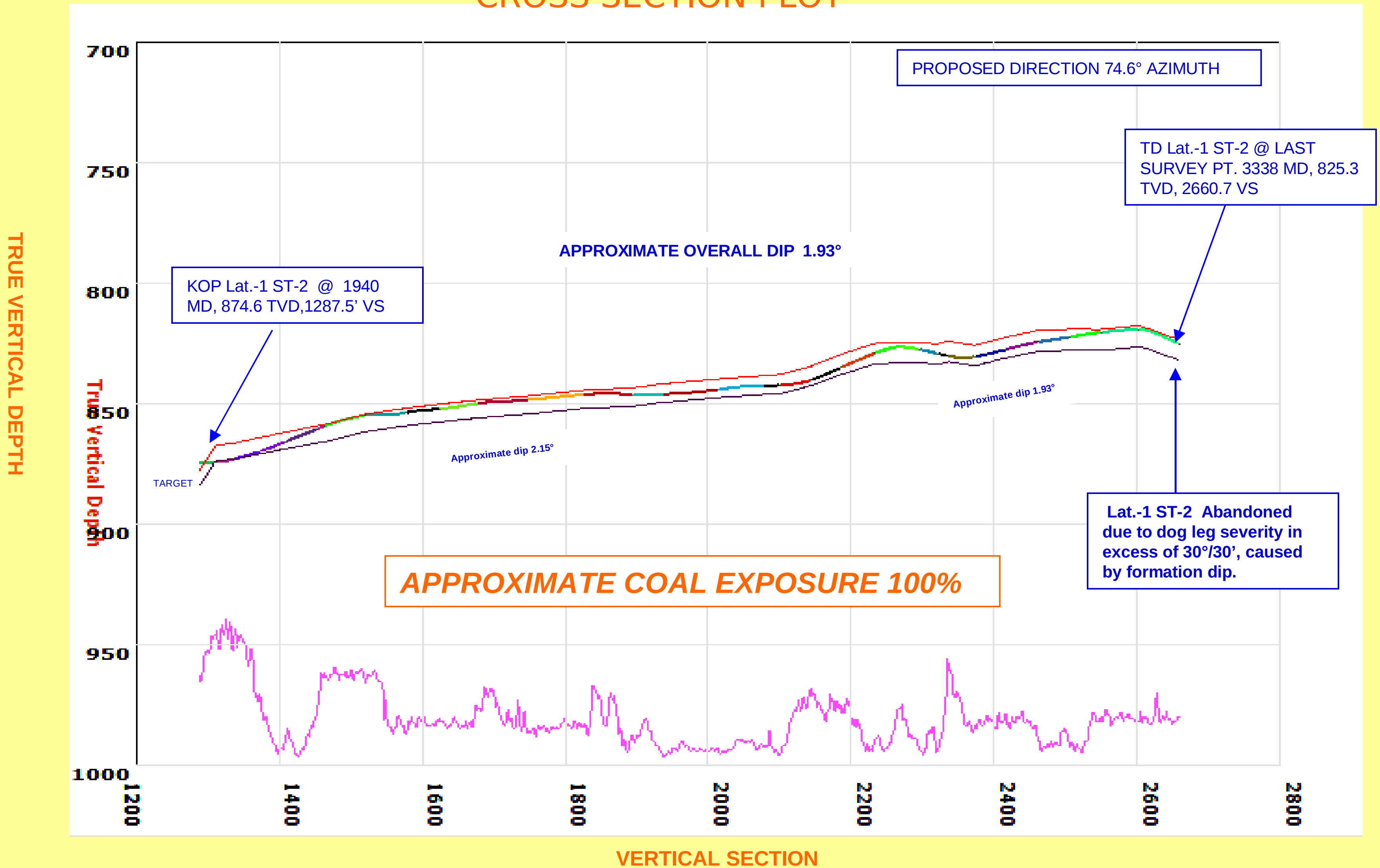


PENN VIRGINA OIL AND GAS
NCRHC-1 LATERAL 1
BARBOUR COUNTY, WV



PENN VIRGINIA OIL AND GAS
NCRHC-1 LATERAL 1 ST-2
BARBOUR COUNTY, WV

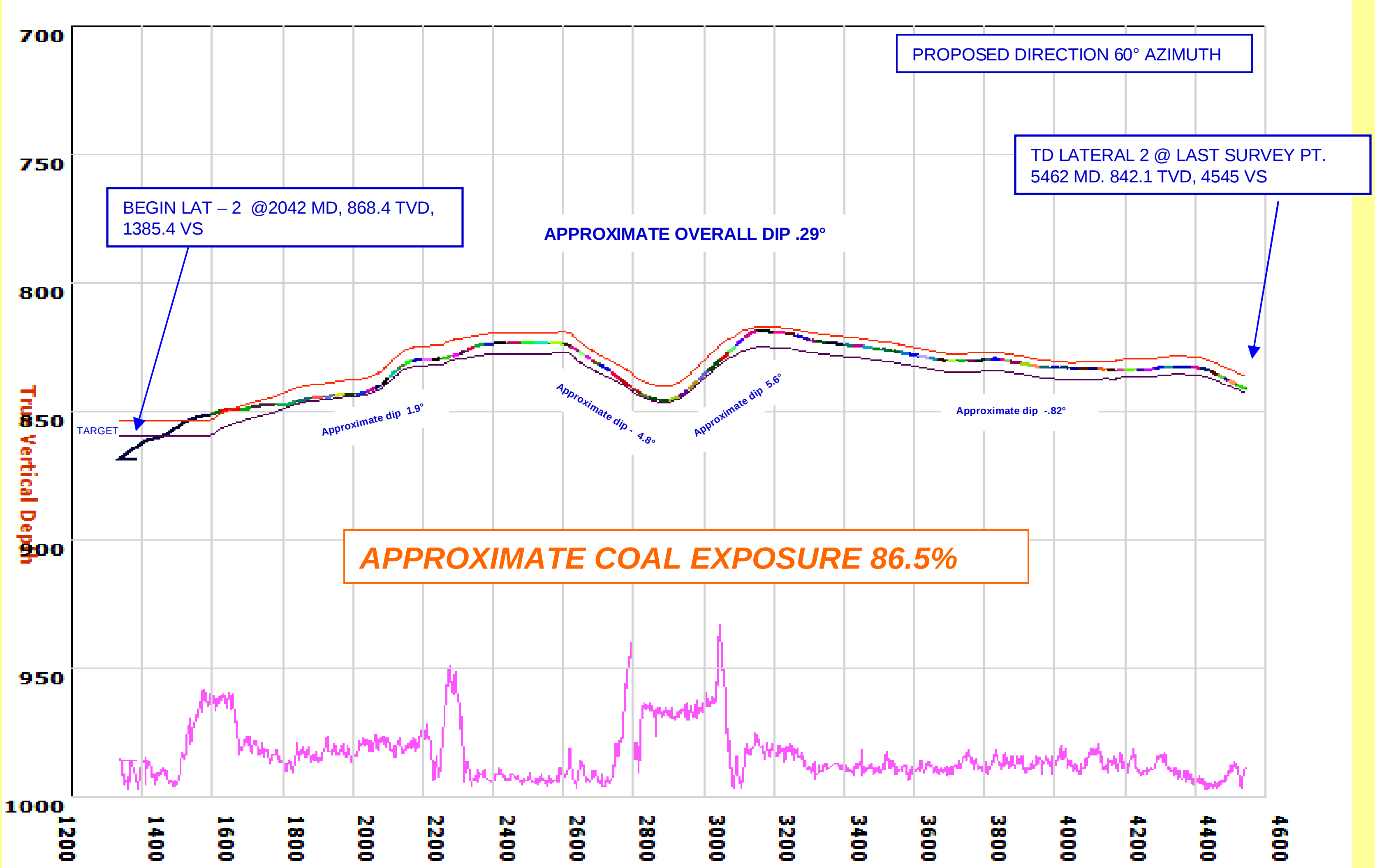
CROSS SECTION PLOT



PENN VIRGINA OIL AND GAS
NCRHC-1 LATERAL 2
BARBOUR COUNTY, WV

CROSS SECTION PLOT

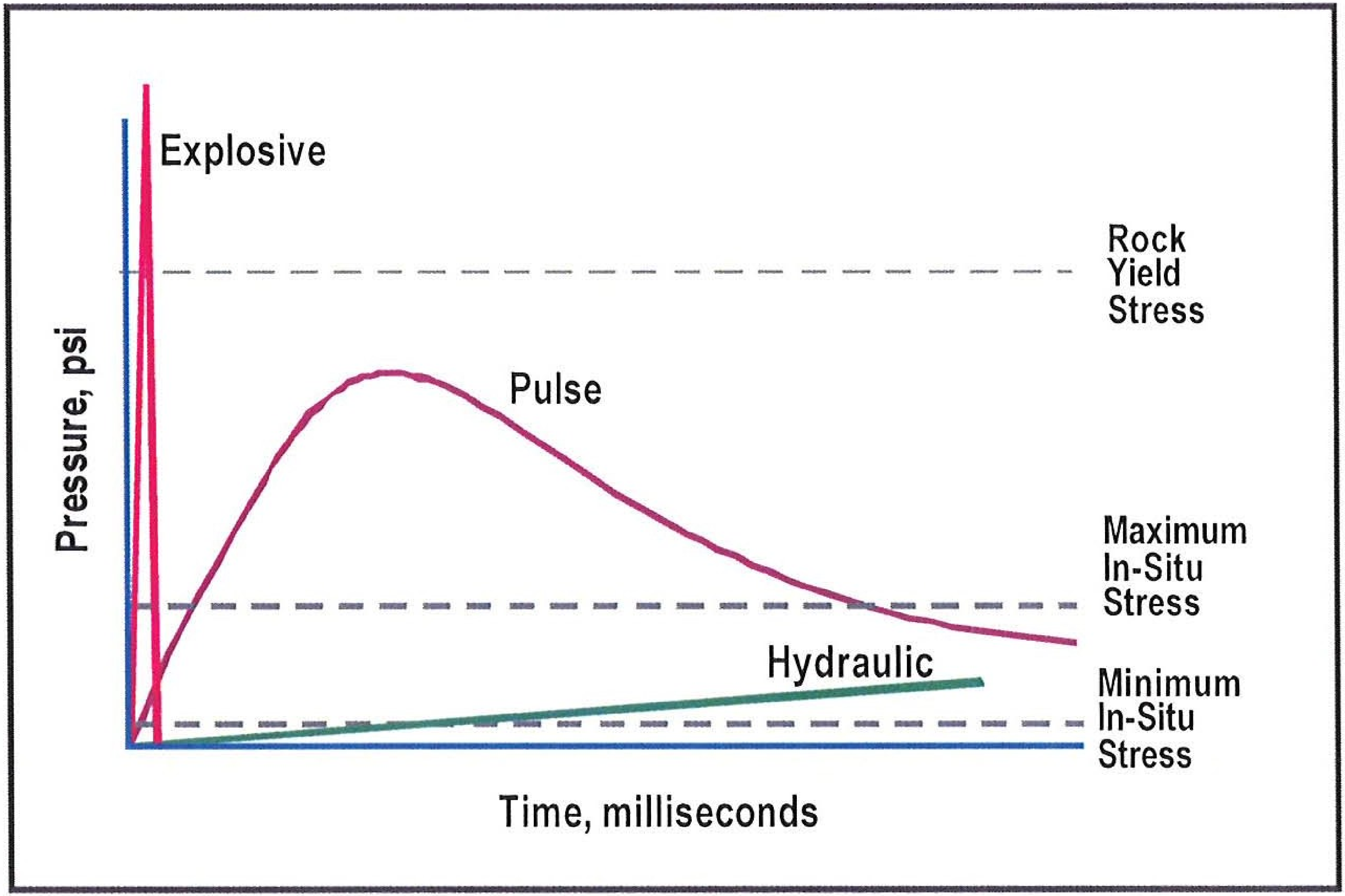
TRUE VERTICAL DEPTH



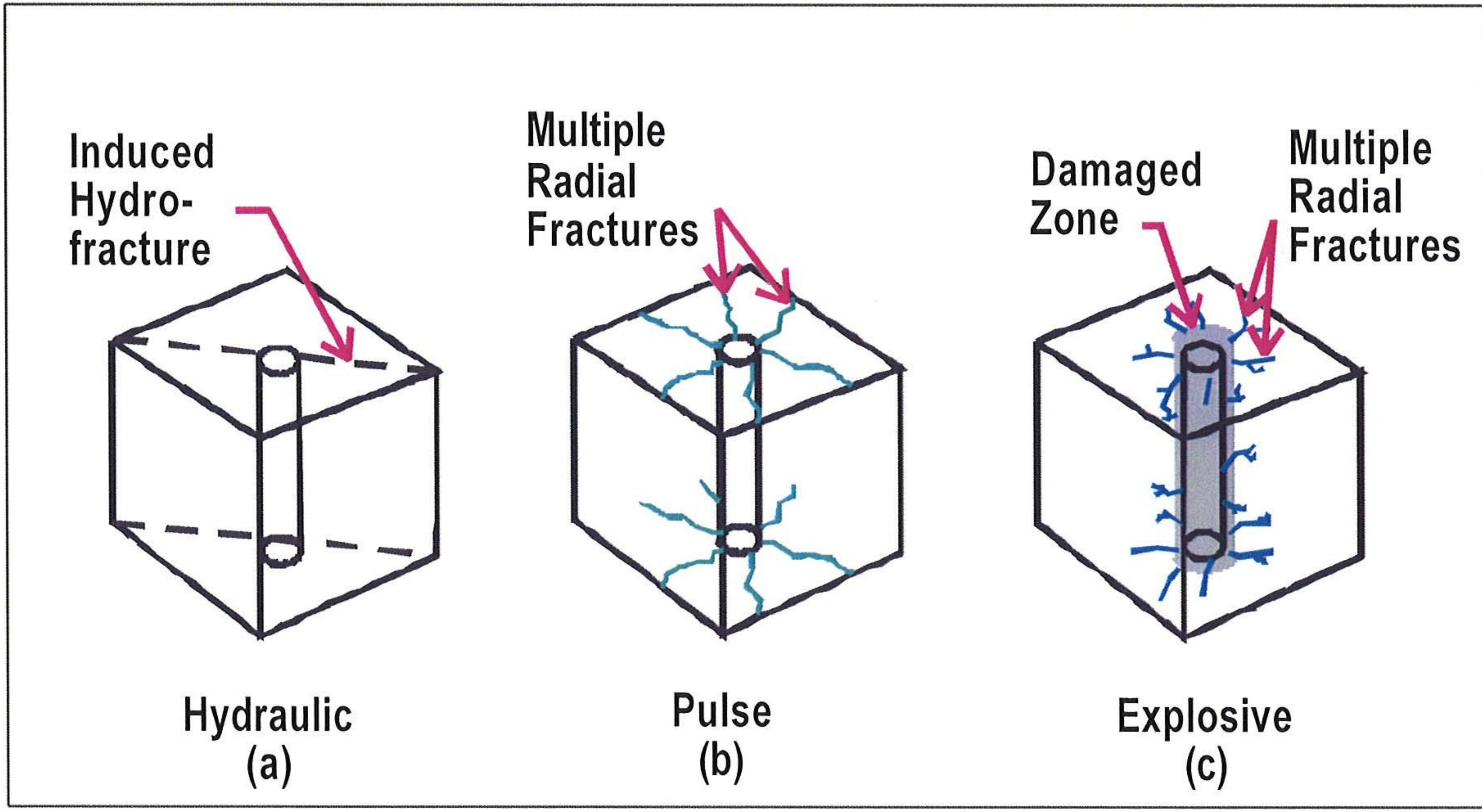
VERTICAL SECTION

FRACTURE STIMULATION

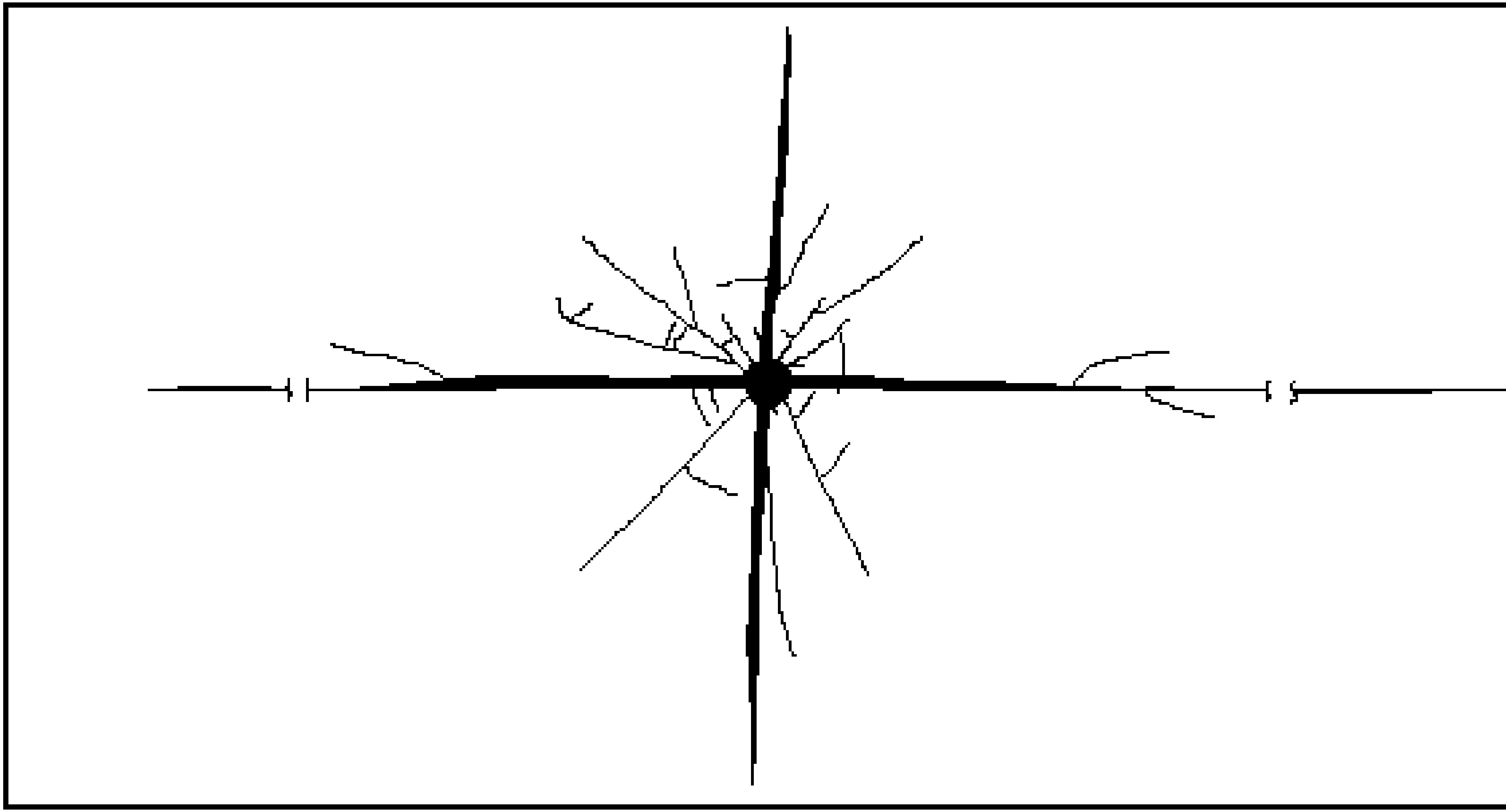
- STIMULATE MULTI-LATERAL PATTERN
  - NITROGEN HIGH RATE
  - CO_2 SYSTEM
- STIMULATE VERTICAL WELLS BETWEEN MULTI-LATERAL PATTERN



Comparison of Pressure Histories for Rock Fracturing Techniques



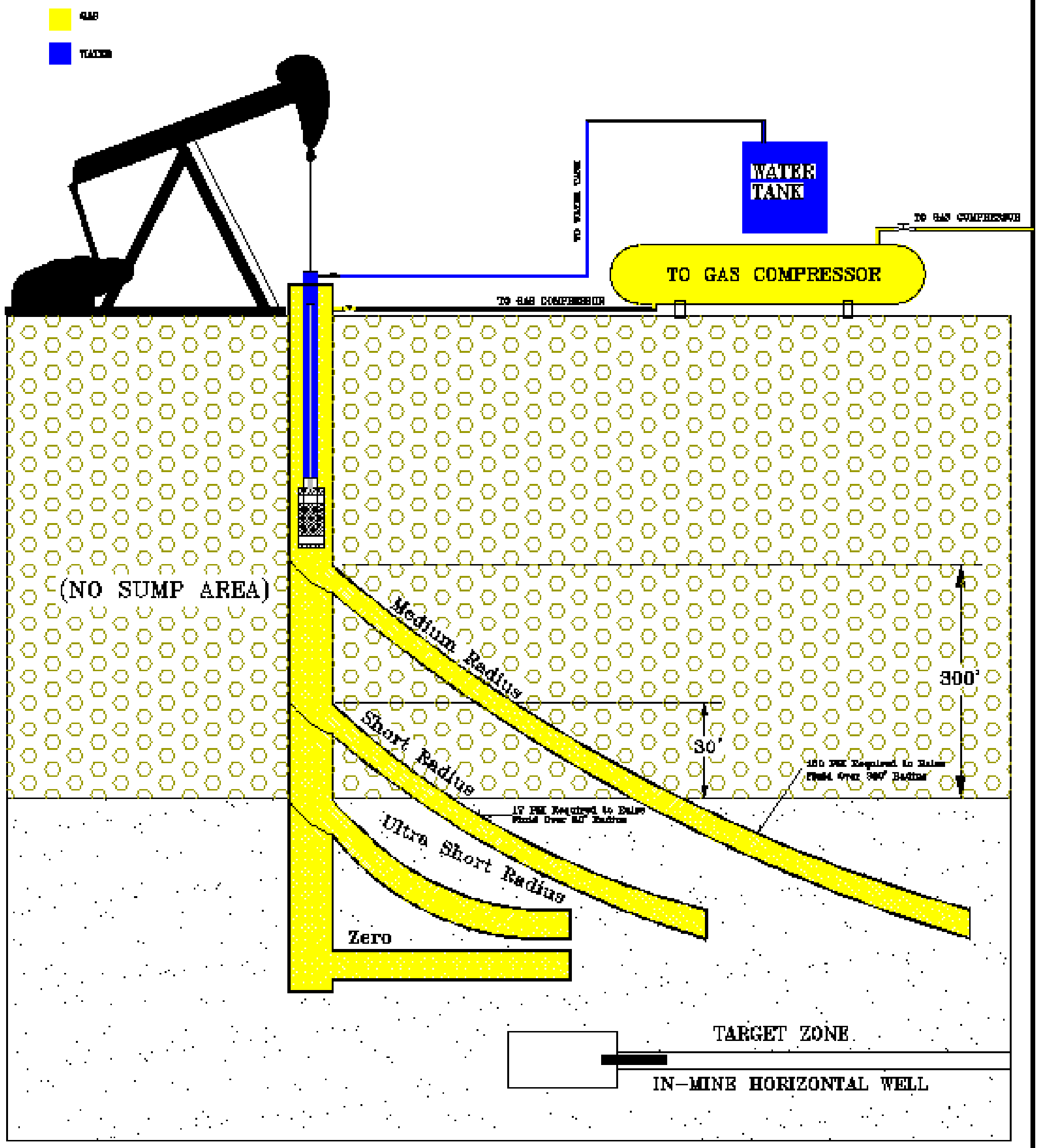
Comparison of Created Fracture Geometries for Rock Fracturing Techniques

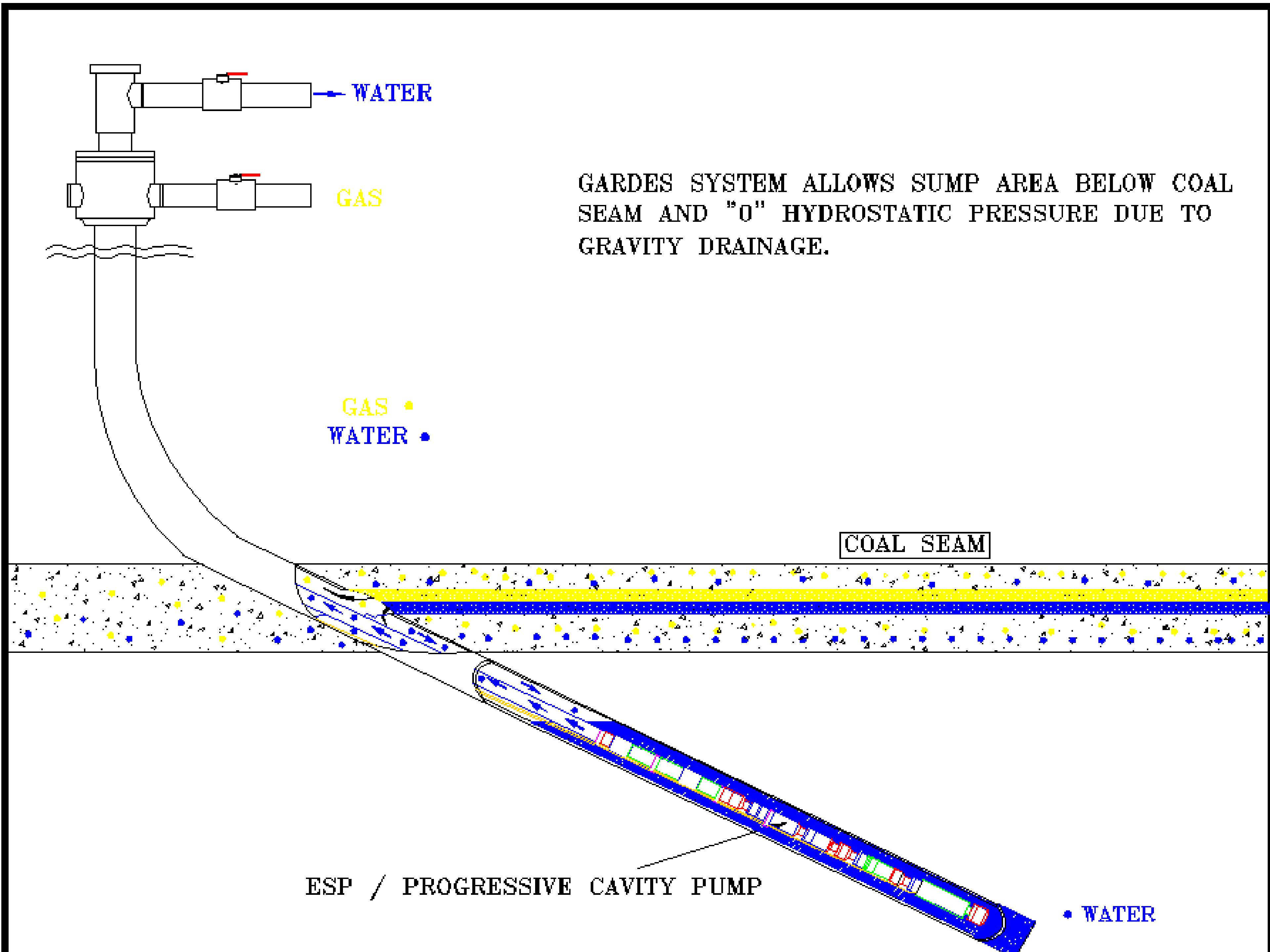


Conceptual Model of Pulse Fracturing Results

CONVENTIONAL HORIZONTAL DRILLING METHODS
REQUIRE PUMP TO BE PLACED ABOVE CURVE
CAUSING HYDROSTATIC PRESSURE ON COAL SEAM

17 PSI Required To
Raise Fluid Over A 30' Radius
130 PSI Required To
Raise Fluid Over A 300' Radius




WATER
GAS
GARDES SYSTEM ALLOWS SUMP AREA BELOW COAL SEAM AND "0" HYDROSTATIC PRESSURE DUE TO GRAVITY DRAINAGE.
GAS
WATER
COAL SEAM
ESP / PROGRESSIVE CAVITY PUMP
WATER

WHAT IS THE FUTURE DEVELOPMENT STATEGY OF THE MANNVILLE PLAY

- Multi-seam / multi-lateral wells
- Inert gas fracture stimulated multi-lateral wells
- Under formation pressure drilling with clear non-damaging fluids
- Sumped ESP’s

We would like to give a special thanks to the following for their contribution to this slide presentation.

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  Higgs – Palmer Technologies

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  GeoMechanics International