Society of Petroleum Evaluation Engineers
Rocky Mountain Chapter
April 18, 2017

Using The Rectangle Method to Evaluate Drainage For Horizontal Wells

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Gene R. George & Associates, Inc.

Square Pegs and Round Holes

Geometrical Considerations

Relating Drainage Patterns to The Public Land Survey System

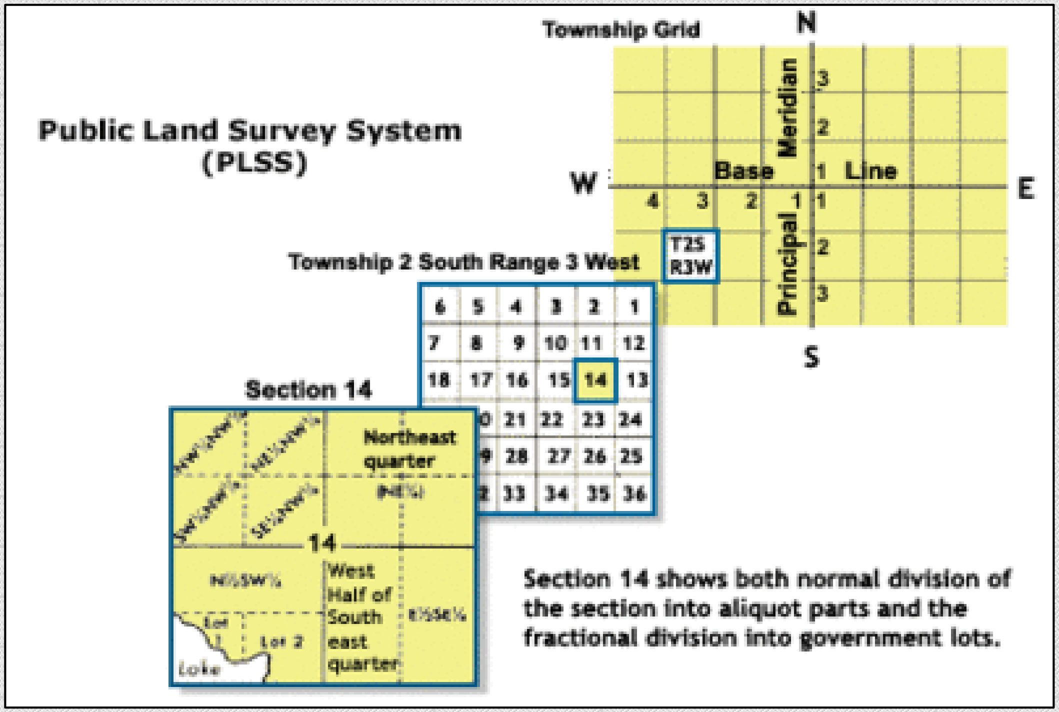
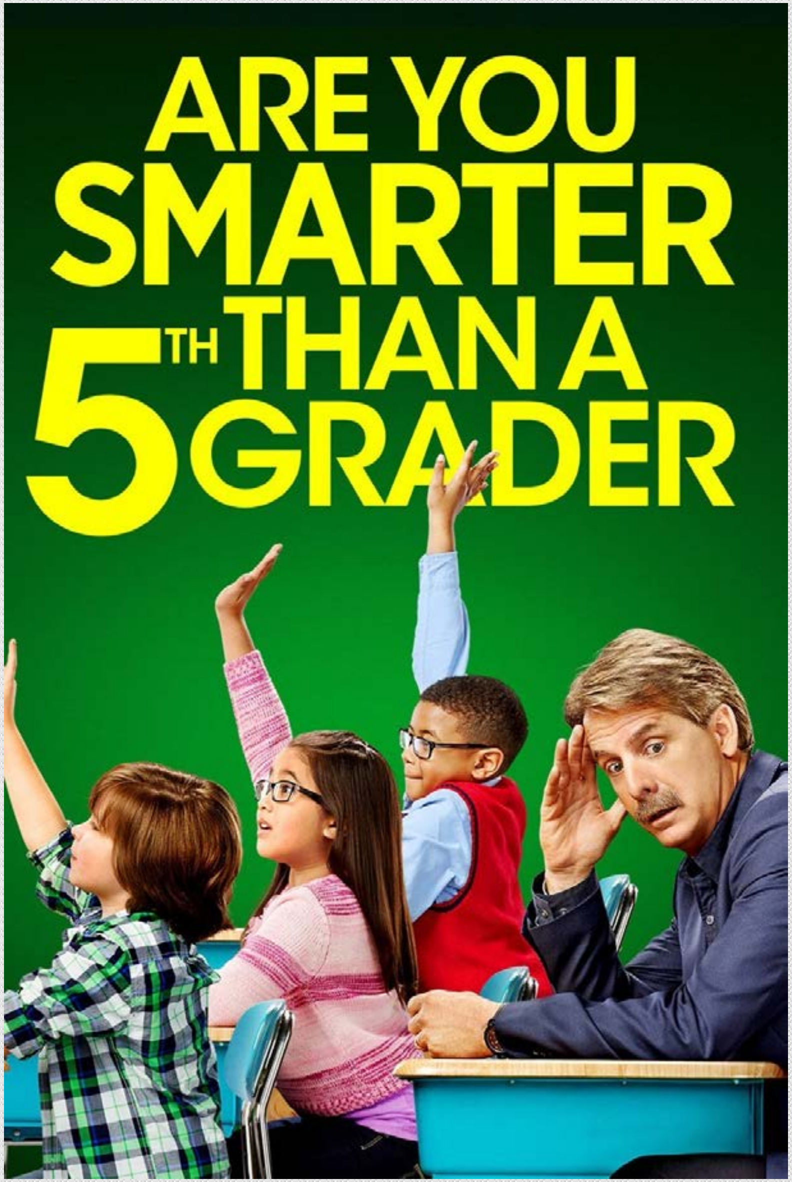
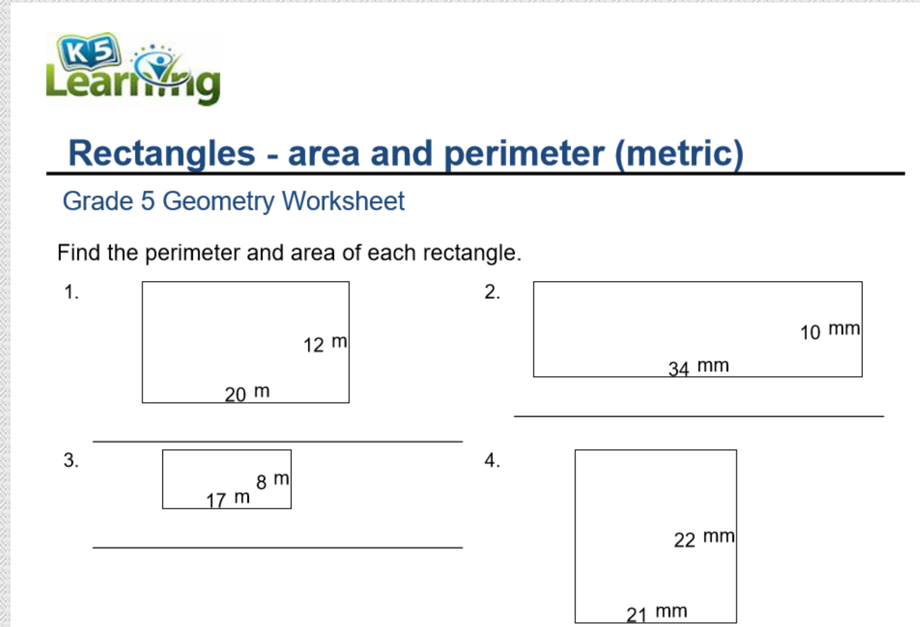


Image from Wikipedia



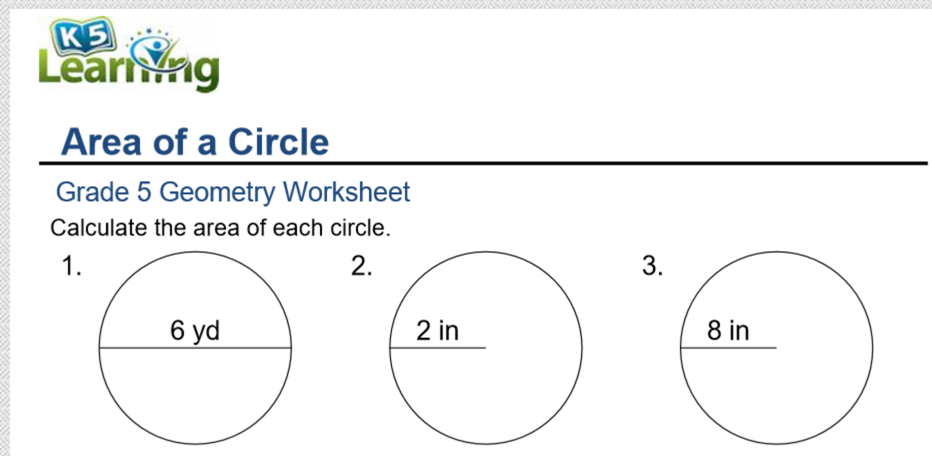

K5 Learning

Rectangles - area and perimeter (metric)

Grade 5 Geometry Worksheet

Find the perimeter and area of each rectangle.

Area = Base X Height


K5 Learning

Area of a Circle

Grade 5 Geometry Worksheet

Calculate the area of each circle.

Area = Pi R^2

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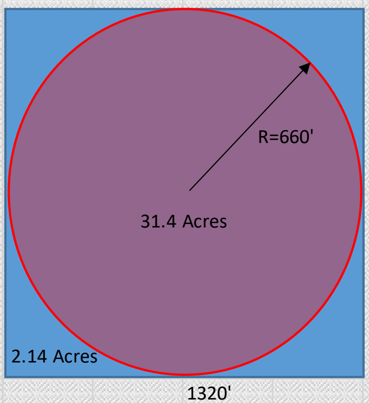
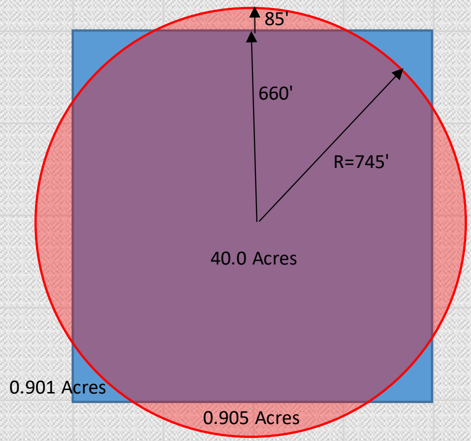
VERTICAL WELL DEVELOPMENT - 40 ACRE EXAMPLE

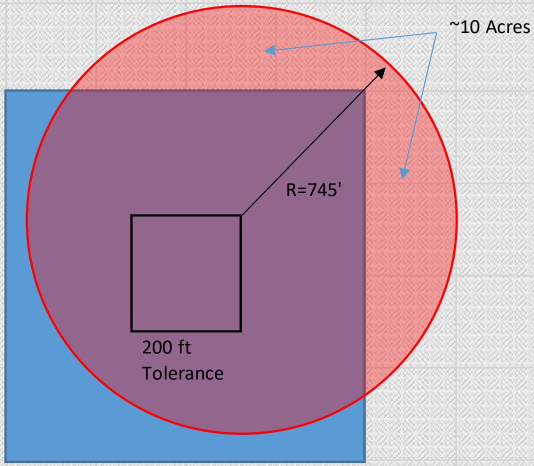
40-Acre Qtr Qtr



40-Acre Square and 40-Acre Circle



Effect of 200 Ft Drilling Tolerance



$A=piR^2=pi(660)^2/43560 = 31.4$ Acres

A=W*H=1320*1320/43560 = 40.0 Acres

(40.0-31.4) = 8.6 Acres
8.6/4 = 2.15 Acres

8.6/40 = 22% Undrained

$A=piR^2=pi(745)^2/43560 = 40.0$ Acres

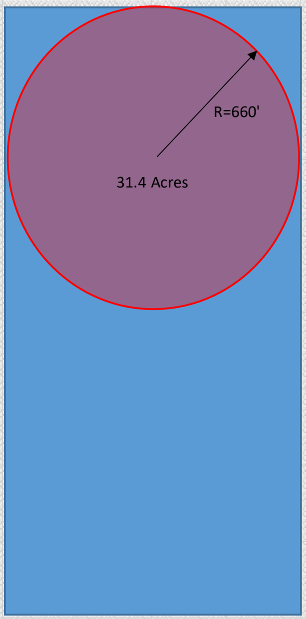
A=W*H=1320*1320/43560 = 40.0 Acres

(0.901*4)/40= 9% Undrained
(745-660)/660= 13%

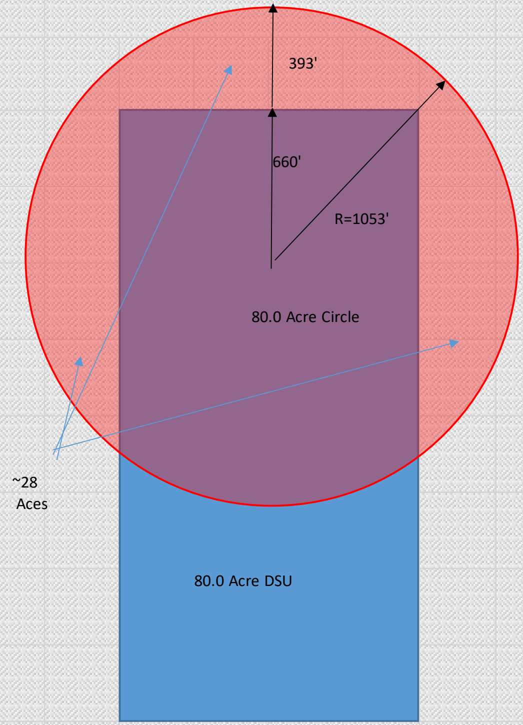
10/40= 25%
(745-460)/660= 43%

VERTICAL WELL DEVELOPMENT - 80 ACRE EXAMPLE

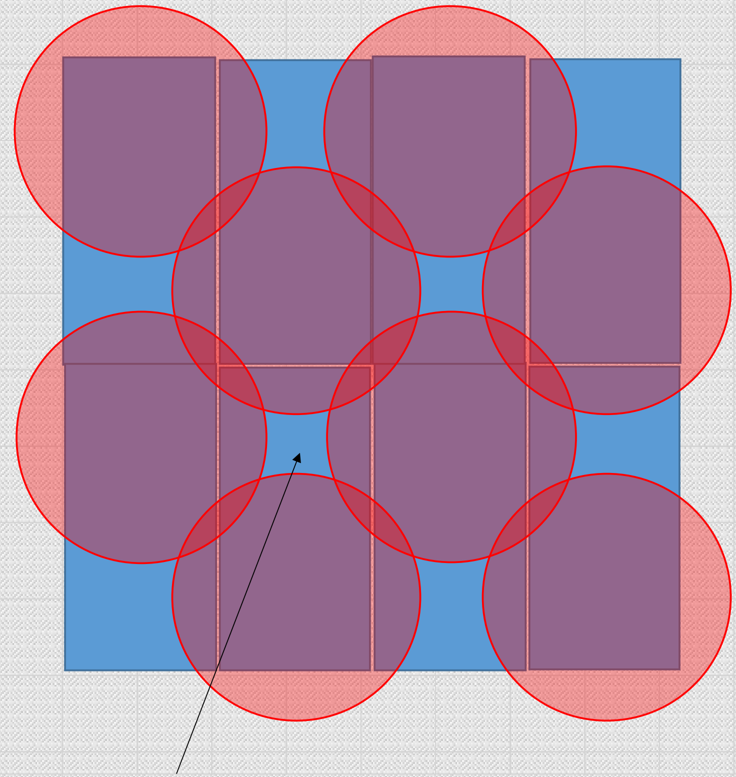
80-Acre Stand-up CBM DSU



80-Acre DSU with 80-Acre Circle



1/2 Scale - 8 DSUs = One Section



$A=piR^2=pi(660)^2/43560$ = 31.4 Acres

A=(W*H)=(1320)*(2640)/43560 = 80.0 Acres

(80.0-31.4) = 48.6 Acres

48.6/80 = 61% Undrained

$A=piR^2=pi(1053)^2/43560$ = 80.0 Acres

A=(W*H)=(1320)*(2640)/43560 = 80.0 Acres

28/80 35 %

(1053-660)/660= 60%

Continuous, overlapping patterns reduce undrained acreage to a "small" area

BLM Manual:

$$A_h = [OOIP \times FVF]/[(7{,}758\ bbls/ac\text{-}ft) \times Net\ Pay \times Porosity \times (1-S_w)*RF]$$

Where,
A_h = Area drained by horizontal well (acres)
OOIP = Original oil-in-place in area drained by the well (stbo)
FVF = Formation Volume Factor (reservoir barrels/stock-tank barrels)
Net Pay = Average net pay thickness (feet)
Porosity = Average reservoir porosity (fraction)
Sw = Water saturation (fraction)
RF = Recovery Factor

The radius of drainage "R_d" of a horizontal well in an isotropic reservoir is calculated by the following formula:

$$R_d = [-2 \times L + \sqrt{[(2 \times L)^2 - (4 \times \pi \times (-A_h \times 43{,}560))]}]/[2 \times \pi]$$

Where,
R_d = Radius of horizontal well drainage (feet)
L = Length of the open horizontal wellbore in reservoir (feet)
π = Pi (3.14159)
A_h = Area of horizontal well drainage (acres)

$$R = \left(\frac{-2L + \sqrt{(2L)^2 - (4\pi(-A\,43560))}}{2\pi} \right)$$

$$2\pi R = -2L + \sqrt{(2L)^2 + 4\pi A(43560)}$$

$$2\pi R + 2L = \sqrt{(2L)^2 + 4\pi A(43560)}$$

$$(2\pi R + 2L)^2 = (2L)^2 + 4\pi A(43560)$$

$$\frac{(2)^2(\pi R + L)^2}{2^2} = \frac{(2L)^2}{2^2} + \frac{2^2\pi A(43560)}{2^2}$$

$$(\pi R + L)^2 = L^2 + \pi A(43560)$$

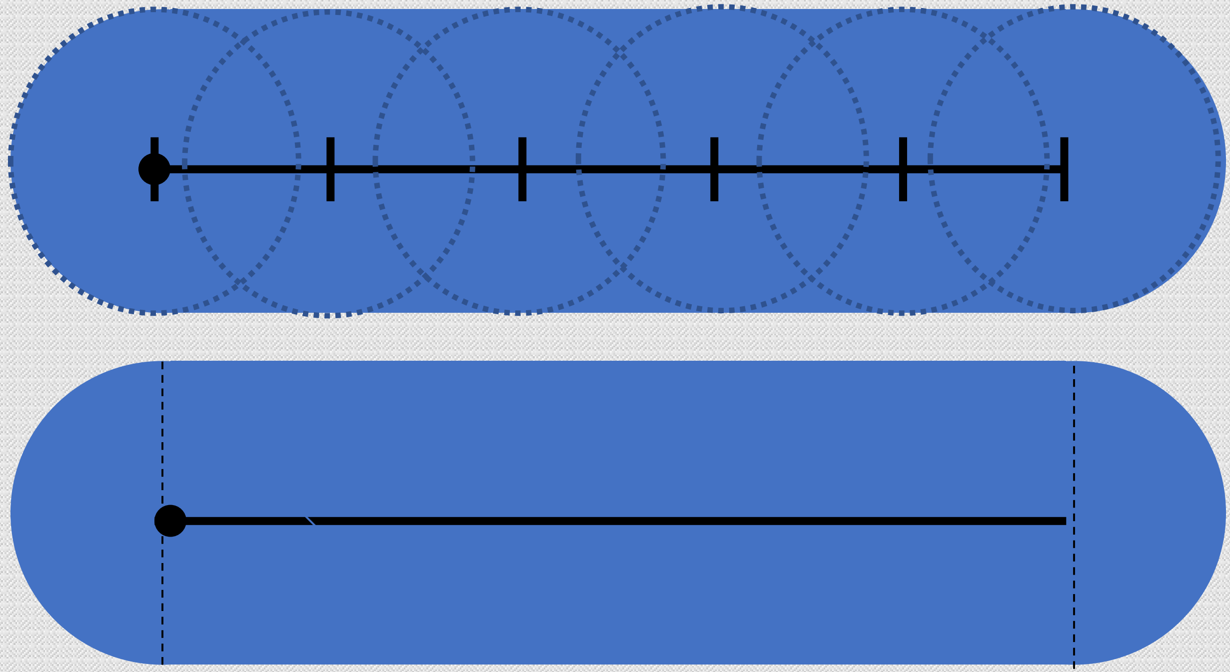
$$(\pi R)^2 + 2\pi RL + L^2 - L^2 = \pi A(43560)$$

$$\frac{\pi^2 R^2}{\pi} + \frac{2\pi RL}{\pi} = \frac{\pi A(43560)}{\pi}$$

$$\pi R^2 + 2RL = A(43560)$$

Thus the BLM manual is using a Joshi Method 1

Joshi Model (Method 1)



4000’ Lateral with 6 stages of 100’ X_f transverse Fractures

Joshi Method 1 (Area = Pi R^2 + 2*R*L)

Where R is the radius of a vertical well with a circular drainage area

A good approximation for longitudinal hydraulic fractures or for wells with a large drainage area and short transverse hydraulic fractures (isotropic conditions)

Assuming that each end of the horizontal well is represented by a vertical well that drains an area of a half circle with a radius of b, Joshi (1991) proposed the following two methods for calculating the drainage area of a horizontal well.

Method I

Ovoid

Joshi proposed that the drainage area is represented by two half circles of radius b (equivalent to a radius of a vertical well r_{ev}) at each end and a rectangle, of dimensions L(2b), in the center. The drainage area of the horizontal well is given then by:

$$A = \frac{L(2b) + \pi b^2}{43{,}650} \quad (7\text{-}45)$$

Note typo – should be "43560"

where A = drainage area, acres
L = length of the horizontal well, ft
b = half minor axis of an ellipse, ft

Method II

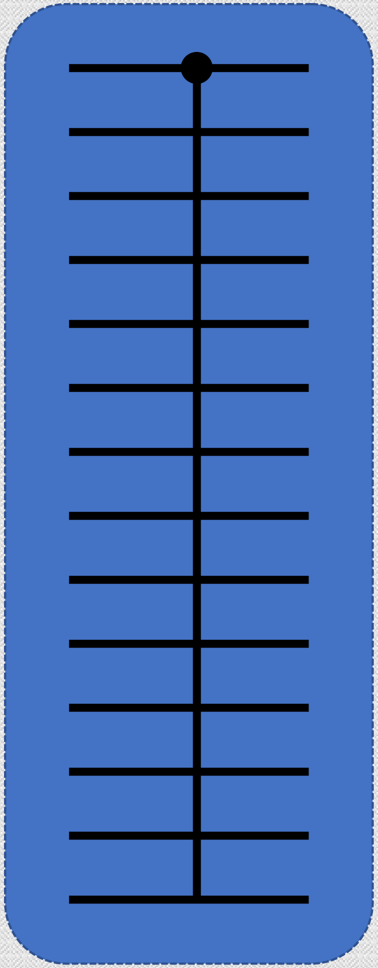
Ellipse

Joshi assumed that the horizontal well drainage area is an ellipse and given by:

$$A = \frac{\pi ab}{43{,}560} \quad (7\text{-}46)$$

Ref: Reservoir Engineering Handbook, Tarek Ahmed

Rectangle Model



Smaller drainage areas, increased number of stages and longer transverse hydraulic fractures result in a more rectangular drainage area.

4000' Lateral with 14 stages of 500' X_f transverse Fracs

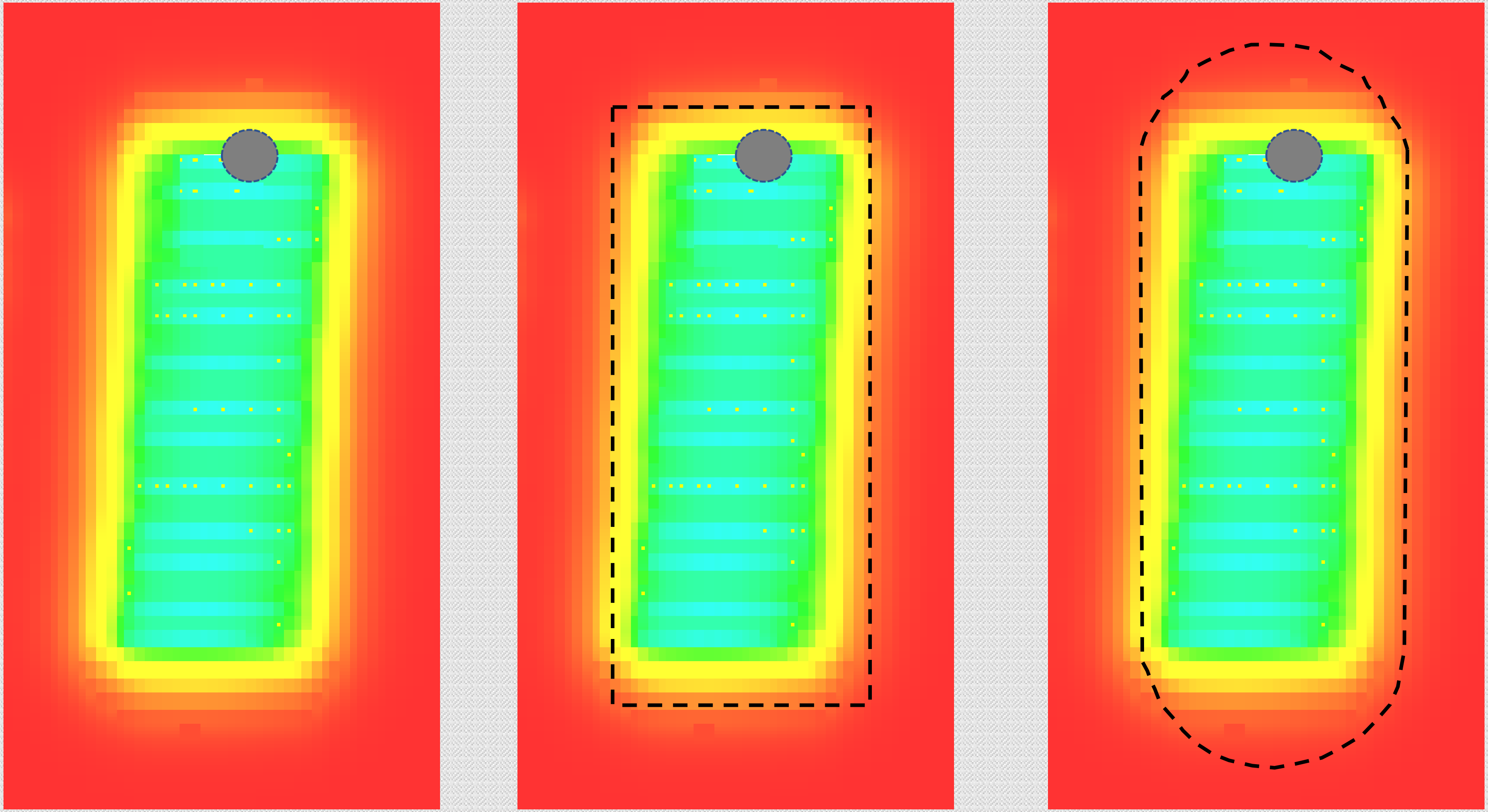
Reasons for Using Rectangle Method

1. Precedent for Geometric Model in the Regulatory History

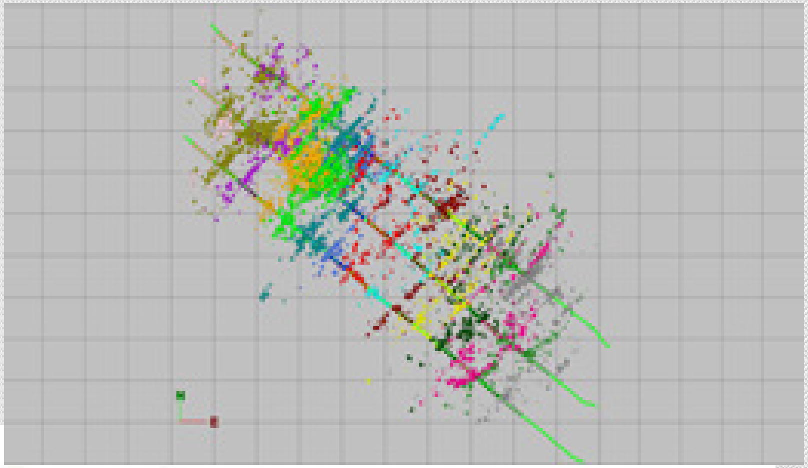
2. Mathematics that could be easily constructed or checked

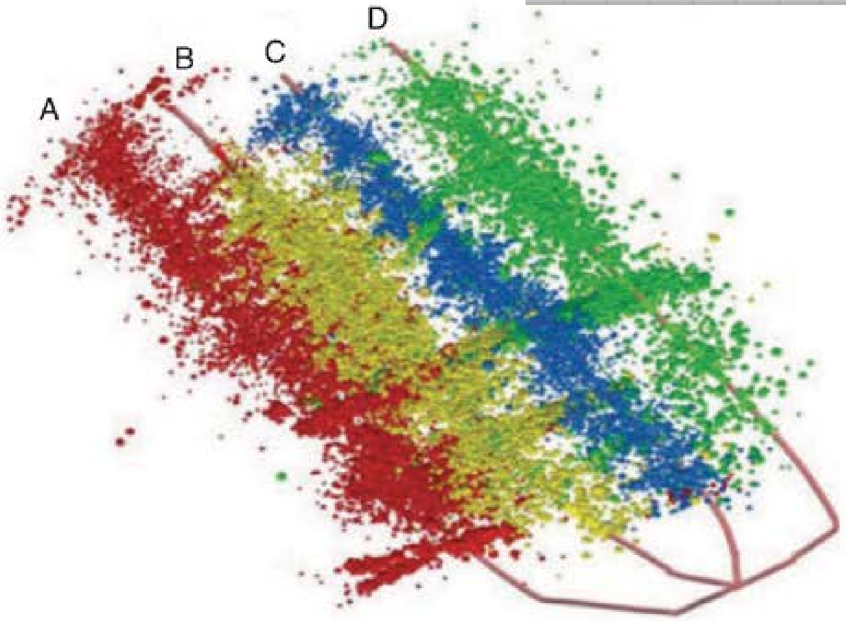
3. Better representation of Heel-Toe drainage patterns

3D Numerical Simulation



MicroSeismic Data





Microseismic imaging, such as this one of a four-well pad in the Eagle Ford, show that the stimulated rock goes far beyond the propped fractures near the wellbore. *Source: Paper SPE 174946.*

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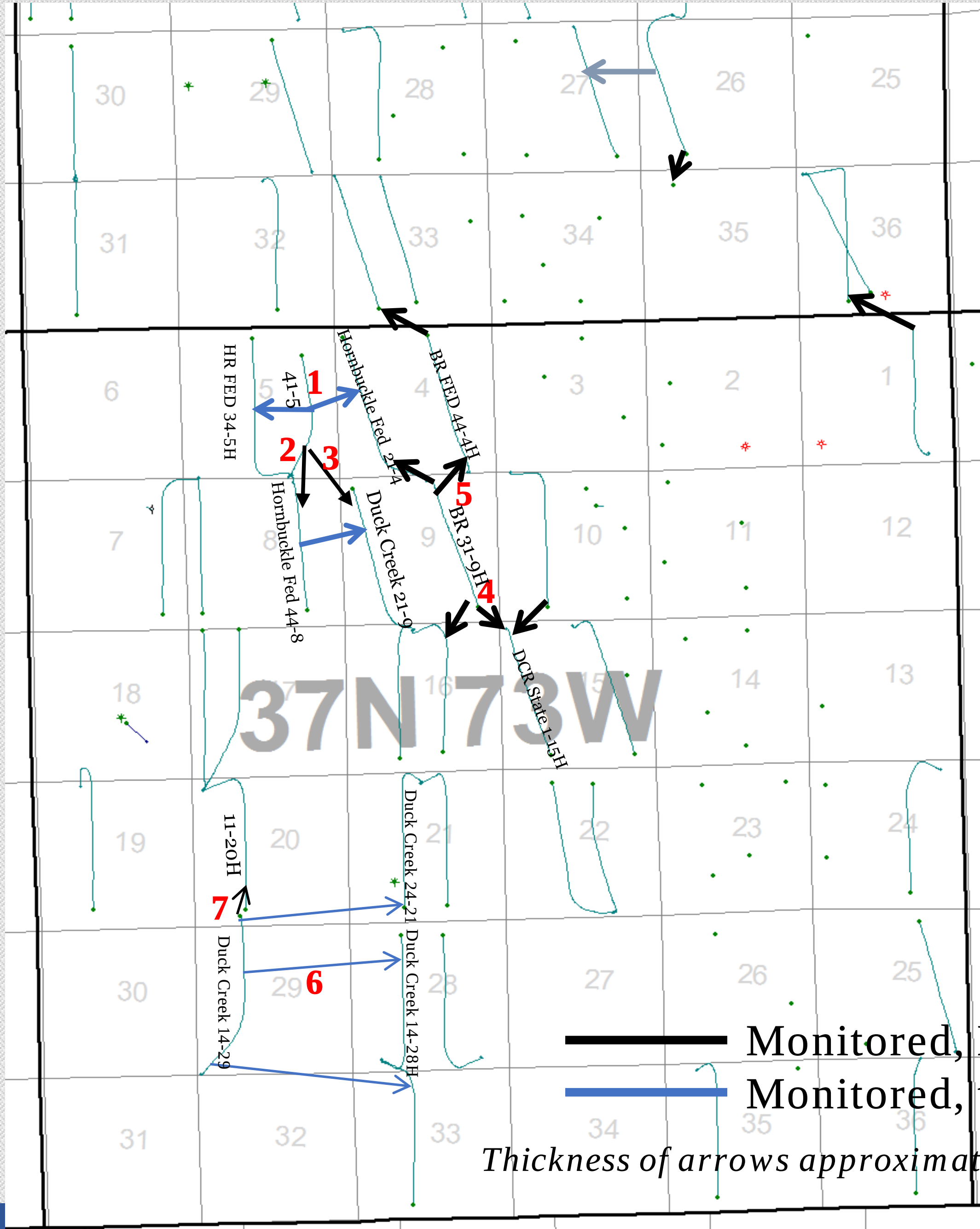
Samson Resources Company

WOGCC Docket No. 127-2014

Exhibit E-1

Anisotropy

Chemical Tracer Results



Monitored, No communication found

Monitored, tracers found, varying quantities

Thickness of arrows approximates relative scale

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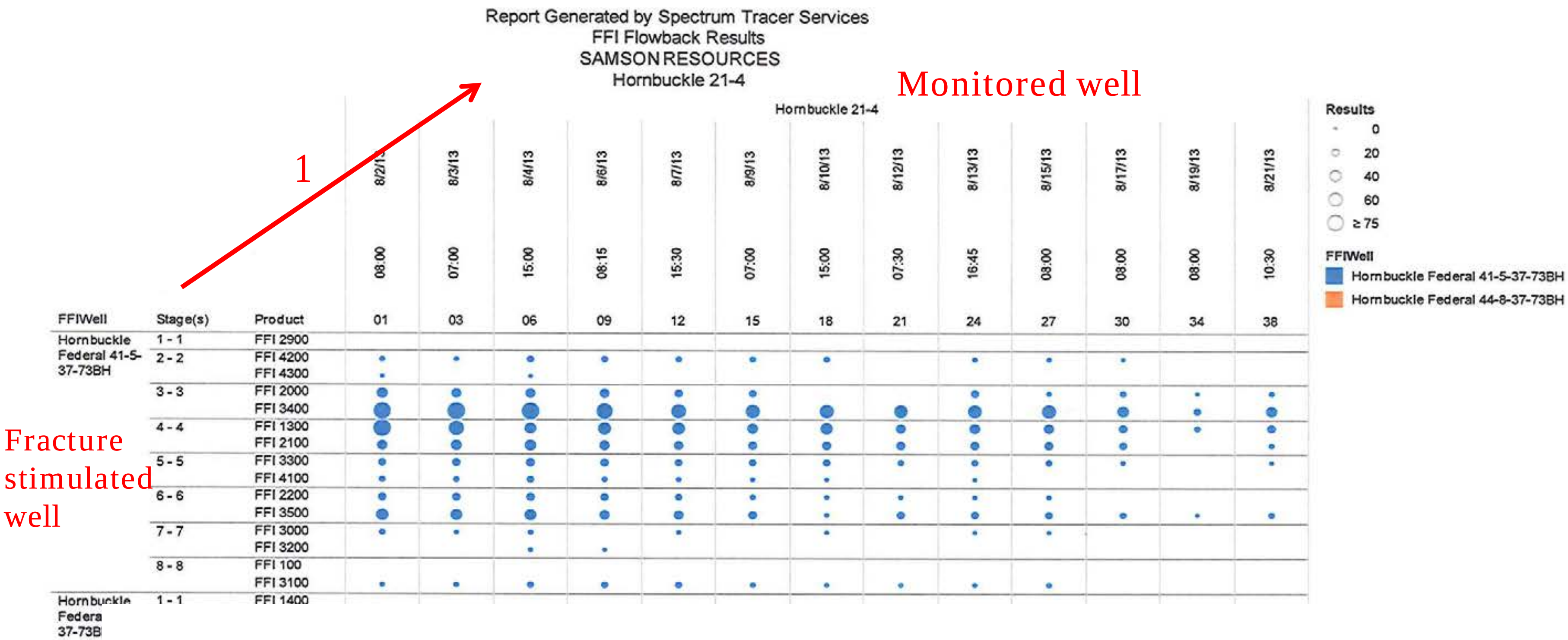
WOGCC Docket No. 127-2014

Exhibit E-2



Samson Resources Company
WOGCC Docket No. 127-2014
Exhibit E-3

Report Generated by Spectrum Tracer Services
FFI Flowback Results
SAMSON RESOURCES
Hornbuckle Federal 44-8-37-73BH

Monitored well

2

Fracture stimulated well

			Hornbuckle Federal 44-8-37-73BH								
			7/25/13			7/26/13	7/29/13	8/1/13	8/19/13	8/24/13	8/25/13
			02:00	10:00	22:00	11:00	14:00	14:00	12:00	18:00	16:00
FFIWell	Stage(s)	Product	01	03	06	09	12	15	18	20	22
Hornbuckle Federal 41-5-37-73BH	1 - 1	FFI 2900									
	2 - 2	FFI 4200									
		FFI 4300									
	3 - 3	FFI 2000									
		FFI 3400									
	4 - 4	FFI 1300									
		FFI 2100									
	5 - 5	FFI 3300									
		FFI 4100									
	6 - 6	FFI 2200									
		FFI 3500			•						
	7 - 7	FFI 3000									
		FFI 3200									
	8 - 8	FFI 100									
		FFI 3100		•							

Results
0
20
40
60
≥ 75

FFIWell
Hornbuckle Federal 41-5-37-73BH
Hornbuckle Federal 44-8-37-73BH

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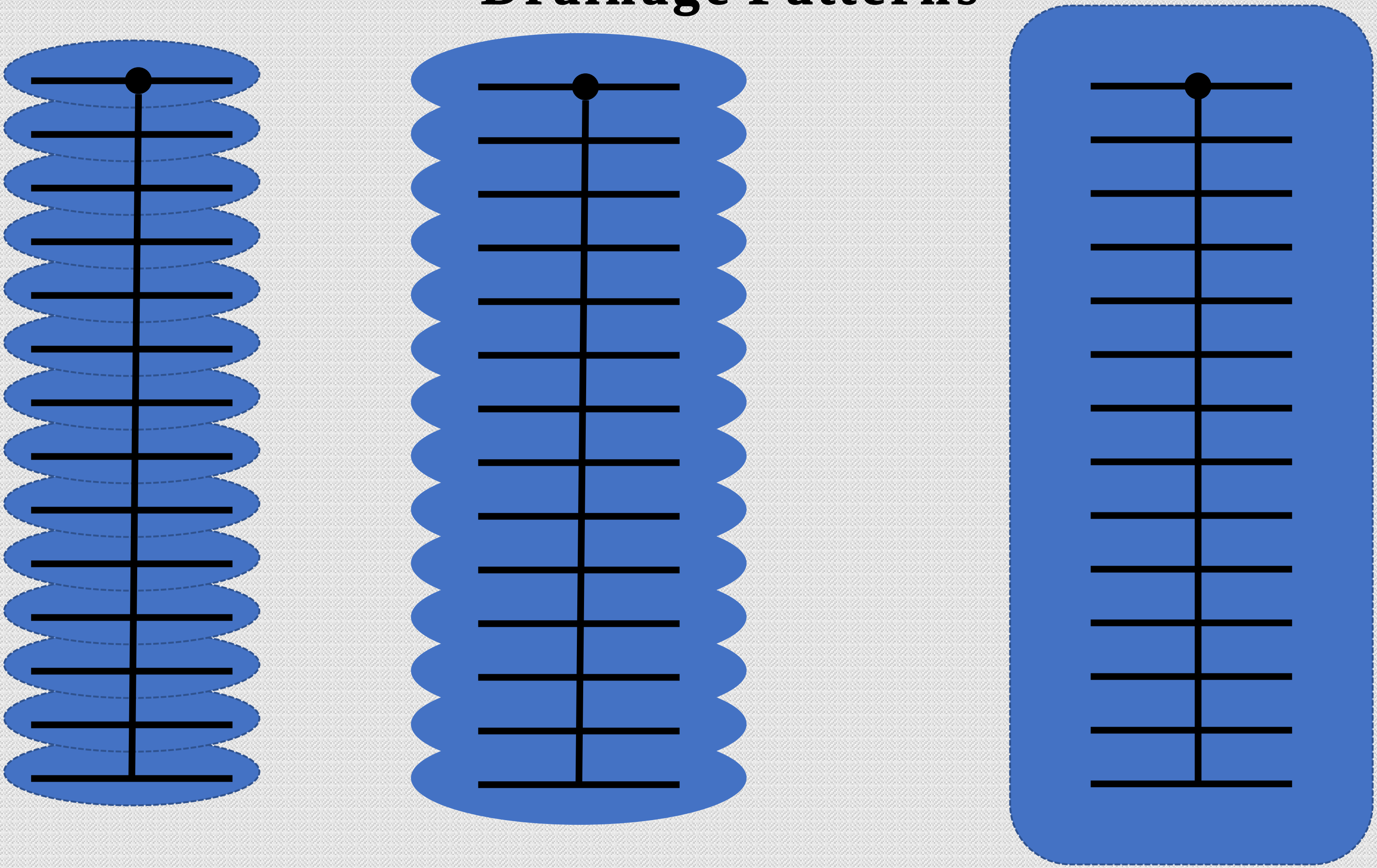
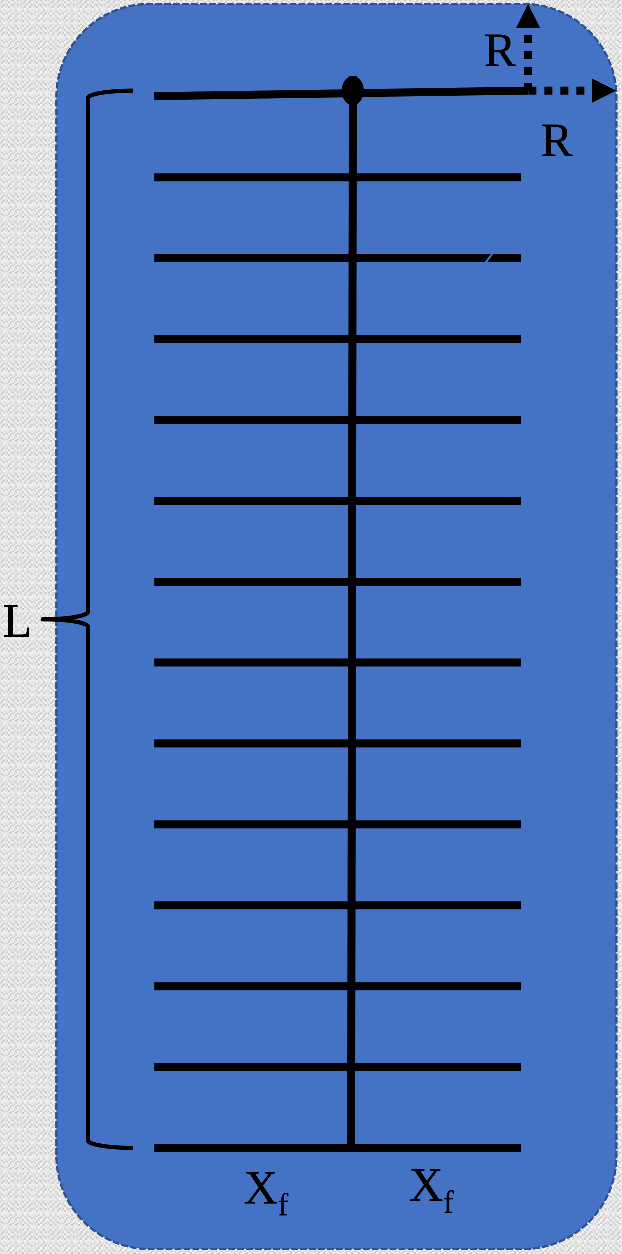
Rectangle Model – Approximates Late Time Drainage Patterns



Early Time
(4:1 Ellipse)

Middle Time
(4:1 Ellipse)

Late Time
(Ellipses merge to form a rectangular area)



Rectangle Model - Dimensions

R – Drainage Radius of a vertical well (unstimulated - without hydraulic fractures)

L – Lateral length

X_f – Hydraulic Fracture half length

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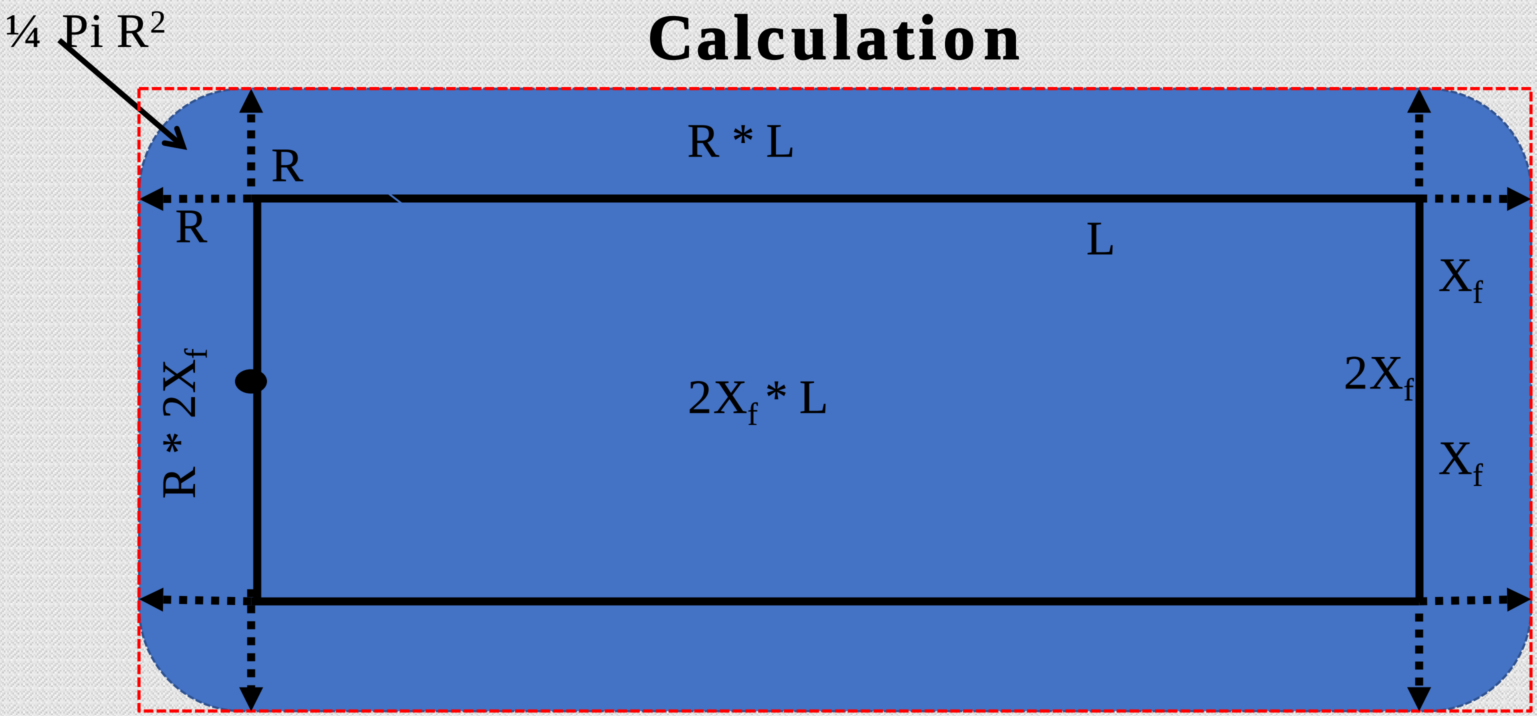
Rectangle Model – Drainage Area Calculation



Area = 4 (1/4 Pi R²) + 2*(R*L) +2*(R*2X_f) + (2X_f*L)

= Pi R² + 2*[(R*L) + (R*2X_f) + (X_f*L)]

Solving for R: R=(A/Pi-2* X_f *L/Pi+((L+2* X_f)/Pi)^2)^0.5-(L+2* X_f)/Pi

Approximate Area = (L+2R) * (2X_f +2R)

Solving for R: R=(((A/4)-(L*X_f/2)+((X_f/2+L/4)^2))^0.5)-X_f/2-L/4

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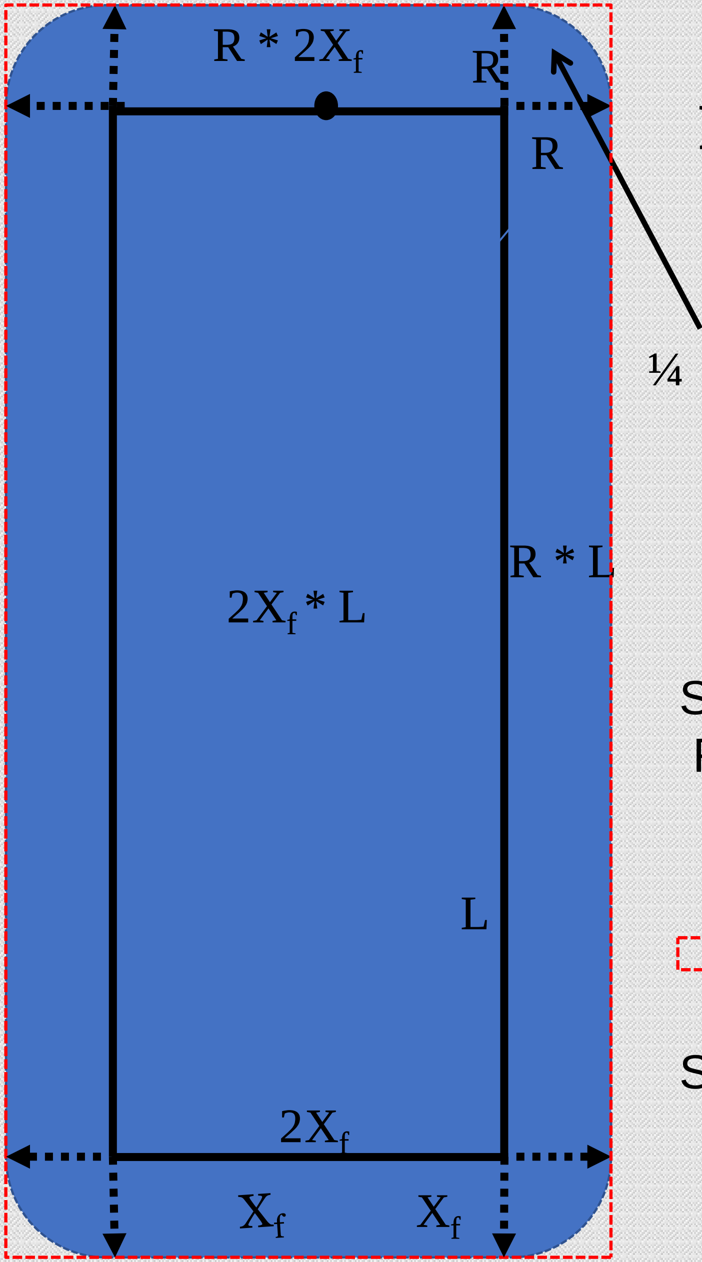
Rectangle Model – Drainage Area Calculation



$$\text{Area} = 4\,(1/4\ \text{Pi}\ R^2) + 2*(R*L) + 2*(R*2X_f) + (2X_f*L)$$
$$= \text{Pi}\ R^2 + 2*[(R*L) + (R*2X_f) + (X_f*L)]$$

Solving for R:

$$R=(A/\text{Pi}-2*X_f*L/\text{Pi}+((L+2*X_f)/\text{Pi})\text{^}2)\text{^}0.5-(L+2*X_f)/\text{Pi}$$

$$\text{Approximate Area} = (L+2R) * (2X_f + 2R)$$

Solving for R:

$$R=(((A/4)-(L*X_f/2)+((X_f/2+L/4)\text{^}2))\text{^}0.5)-X_f/2-L/4$$

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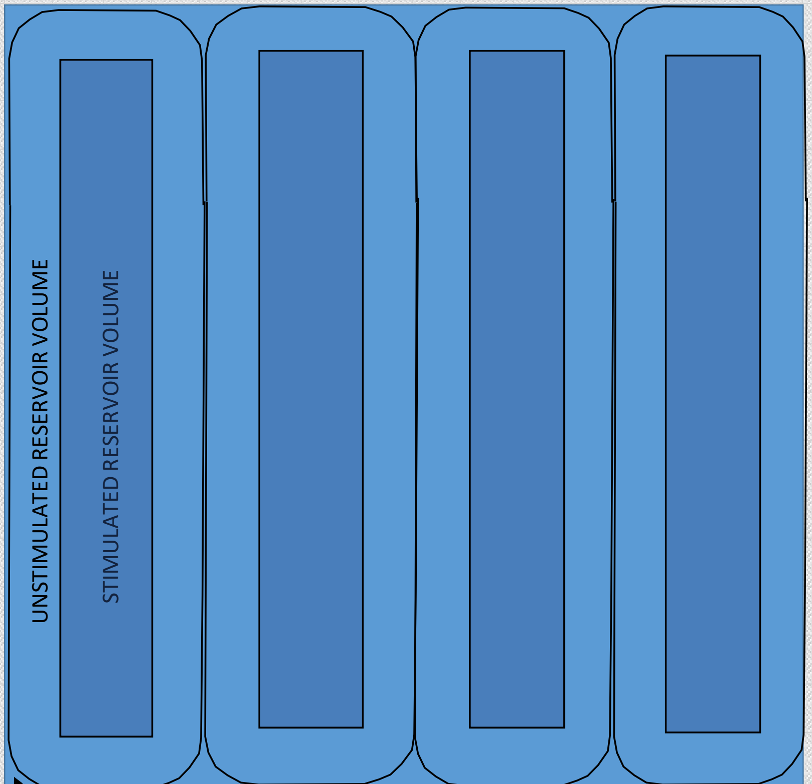
HORIZONTAL WELL DEVELOPMENT WITH N-S TRAJECTORIES - SANDSTONES AND SHALES

RECTANGLE METHOD



640-Acre DSU

0.54 Acres

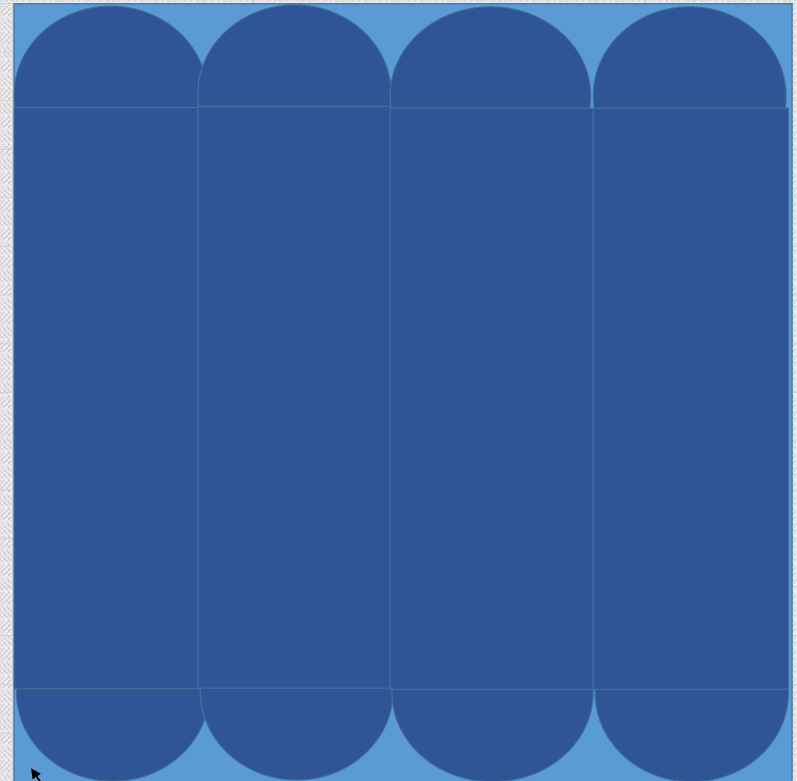
16*0.54 = 8.6 Acres

8.6/640 Acres = 1.3 % Undrained

For 1280:

8.6/1280 Acres = 0.7 % Undrained

JOSHI METHOD



640-Acre DSU

2.15 Acres

16*2.15 = 34.4 Acres

34.4/640 Acres = 5.4 % Undrained

For 1280:

34.4/1280 Acres = 2.7 % Undrained

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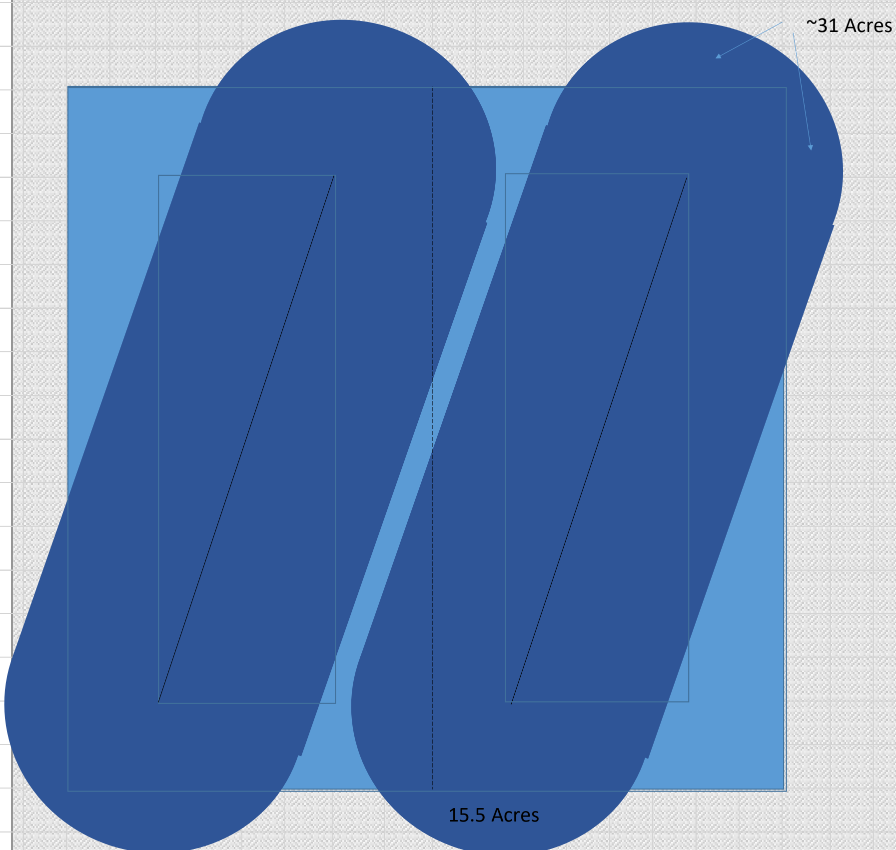
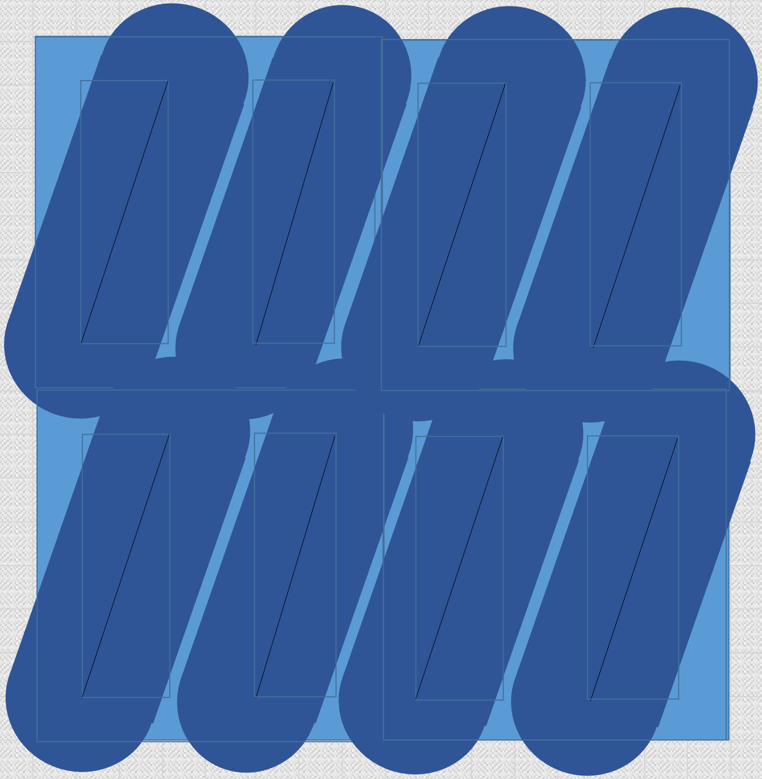
EARLY HORIZONTAL WELL DEVELOPMENT WITH DIAGONAL TRAJECTORIES - SANDSTONES

640-Acre DSU



1/2 Scale - Four 640-Acre DSUs



Joshi Area = Pi()R^2 + L*2R

320 Acres = (Pi()1162^2 + 4174*2*1162)/43560

(15.5+15.5+31+31)/640= **14.5 % Undrained**

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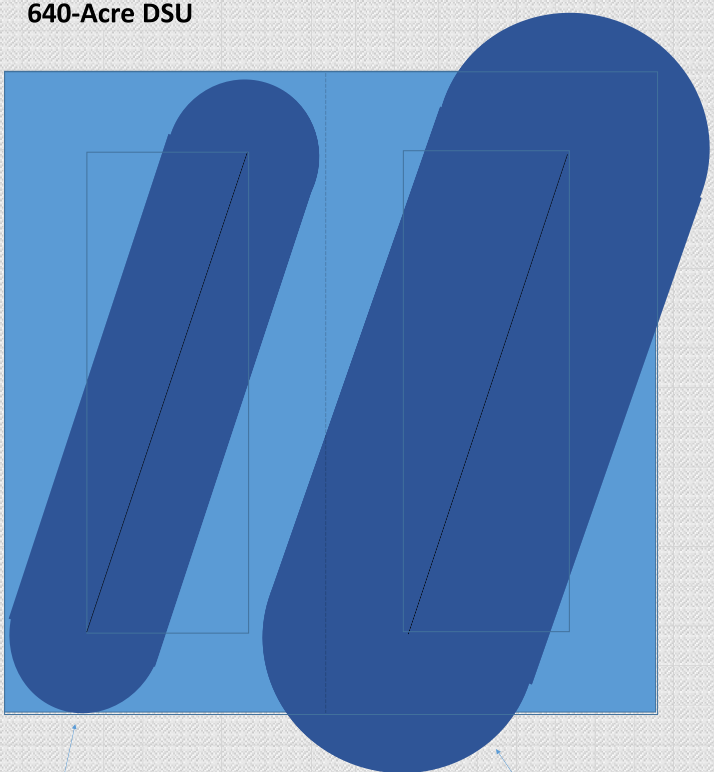
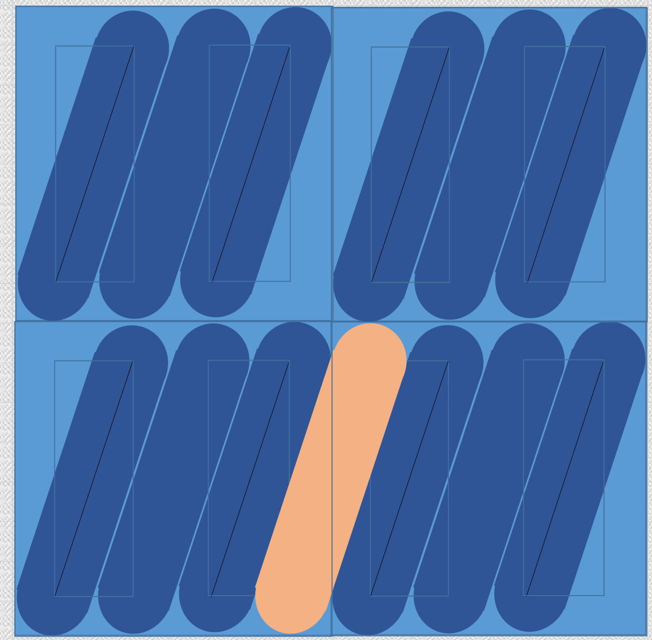
EARLY HORIZONTAL WELL DEVELOPMENT WITH DIAGONAL TRAJECTORIES - SHALES

640-Acre DSU



1/2 Scale - Four 640-Acre DSUs



Lease Line DSUs could be used to target undrained acreage

Undrained Percentages would be about 5%

Joshi Area = Pi()R^2 + L*2R

320 Acres = (Pi()1162^2 + 4174*2*1162)/43560

158 Acres = (Pi()660^2 + 4174*2*660)/43560

(320-158)/320 = 51 **% undrained**

(640-158*3)/640 = 26 **% undrained**

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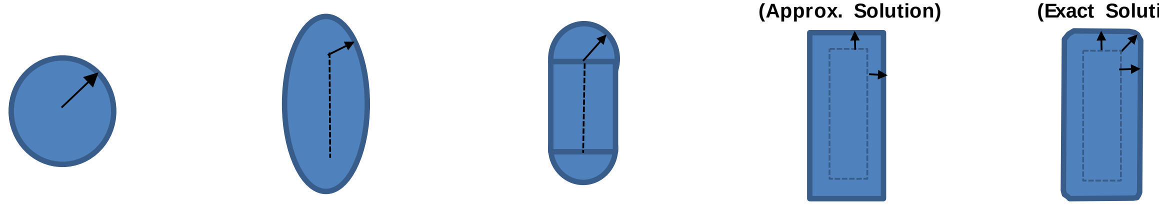
Drainage Geometry Comparison

Vertical Well	Horizontal Well	Horizontal Well	Horizontal Well	Horizontal Well
Circular Drainage Area	Joshi II - Elipse	Joshi I - Ovoid	Rectangle Method (Approx. Solution)	Rectangle Method (Exact Solution)



Well	Circle	4:1 Ellipse	Ovoid	Rectangle	Rectangle
Depth (FT - TVD)	8,000	8,000	8,000	8,000	8,000
Por - Porosity (%)	10.0%	10.0%	10.0%	10.0%	10.0%
Sw - Water Saturation (%)	40%	40%	40%	40%	40%
H - Net Pay (FT)	30	30	30	30	30
Boi - Oil Formation Volume Factor (RVB/STB)	1.28	1.28	1.28	1.28	1.28
EUR - Estimated Ultimate Recovery (MBO)	200	200	200	200	200
RF - Recovery Factor (%)	15%	15%	15%	15%	15%
OOIP - Original Oil in Place (MBO)	1,333	1,333	1,333	1,333	1,333
A - Drainage Area (Acres)	**122.2**	**122.2**	**122.2**	**122.2**	**122.2**
R_c - Drainage Radius (FT)	**1302**				
L - Lateral Length (FT)		4,360	4,360	4,360	4,360
R_e - Drainage Radius (FT)		**608**			
R_o - Drainage Radius (FT)			**515**		
X_f - Fracture Half Length				500	500
R_h - Drainage Radius (FT)				**87.1**	**87.7**
E-W Drainage Setback	**1302**	**608**	**515**	**587**	**588**
N-S Drainage Setback	**1302**	**608**	**515**	**87**	**88**

Rectangle Method - Variables

$$Area = Pi\ R^2 + 2*[(R*L) + (R*2X_f) + (X_f*L)]$$

$$Approximate\ Area = (L+2R) * (2X_f +2R)$$

Pi – 3.14

L – Lateral

- Toe Perf MD minus Heel Perf MD
- Toe Perf MD minus Heel Perf MD plus Frac Stage
- Sliding Sleeves – Toe Packer MD minus Heel Packer MD
- Any “out-of-zone” lateral corrections?

R – Unstimulated Radius

- Unstimulated vertical wells
- Stimulated vertical wells
- Reservoir simulation

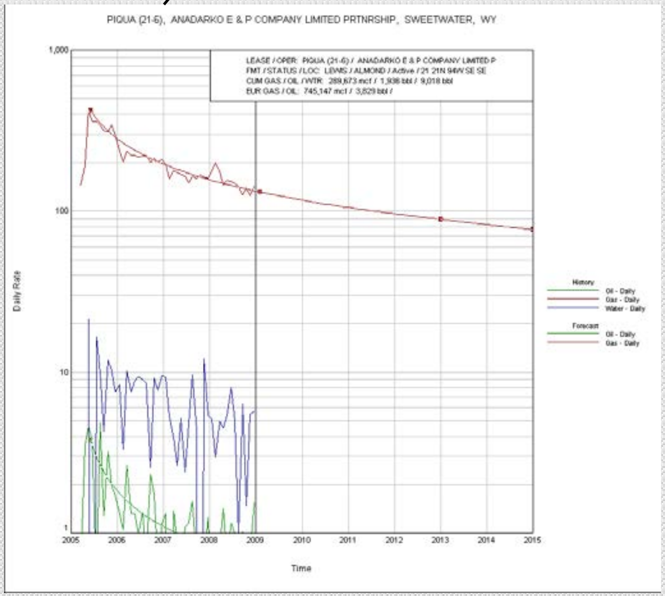
Xf – Fracture Half-Length

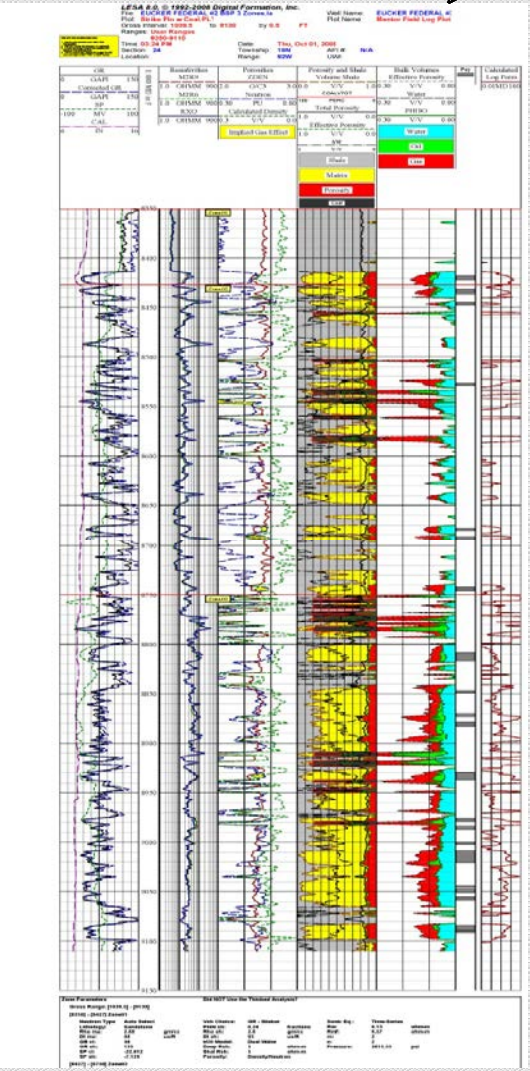
- Chemical Tracers
- Microseismic
- 2D Frac Models (Post-Frac and History Matched !!!)
- Reservoir Simulation

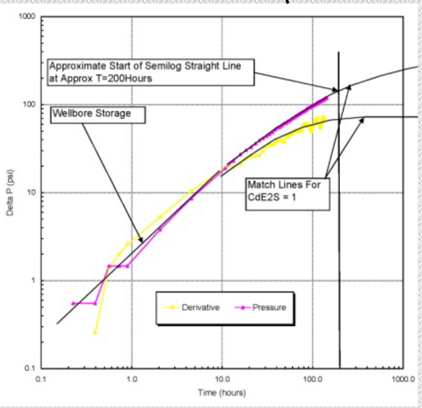
A – Area

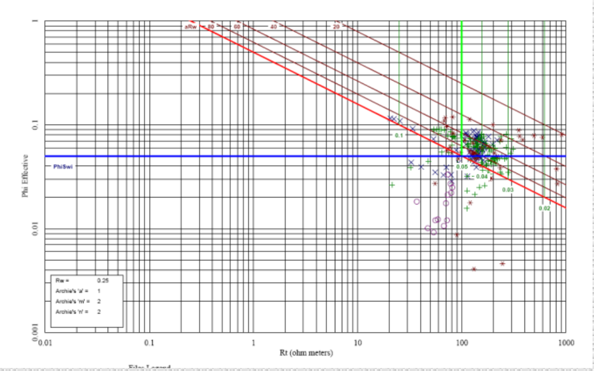
- Volumetrics or Simulation

Drainage Area = EUR/Recovery/(43560 x H x Phi x (1-Sw) x Bgi)









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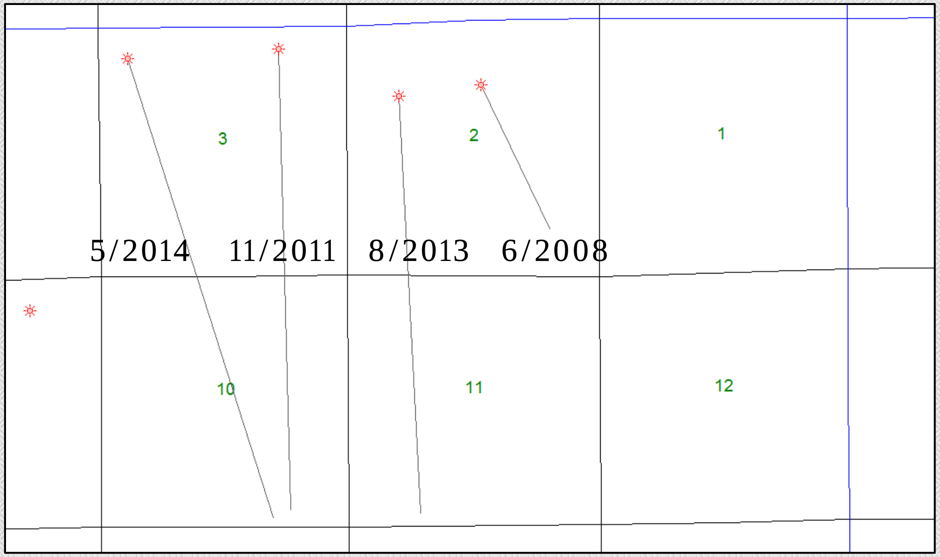
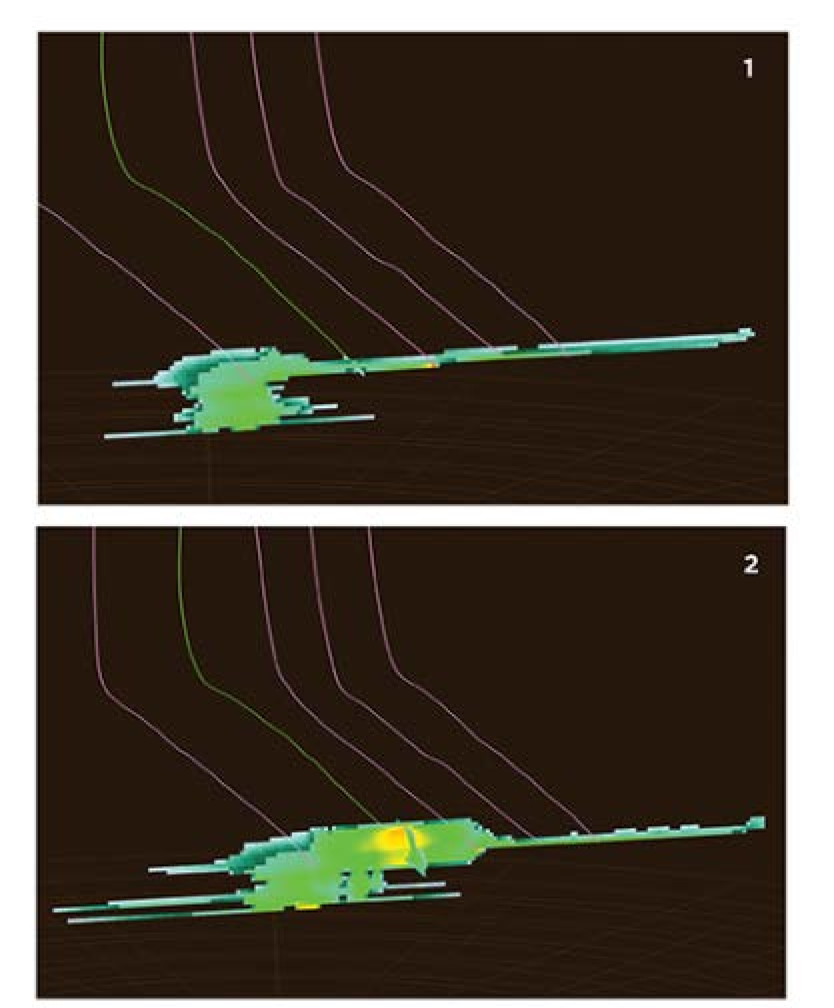
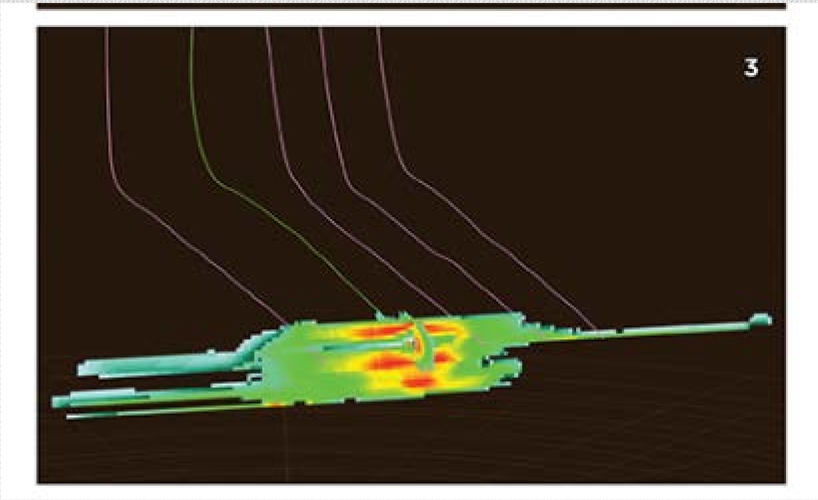
Frack Hits

100,000
10,000
1,000
100
Rate
2008
2010
2012
2014
2016
2018
2020
Time



3
2
1
10
11
12
5/2014
11/2011
8/2013
6/2008

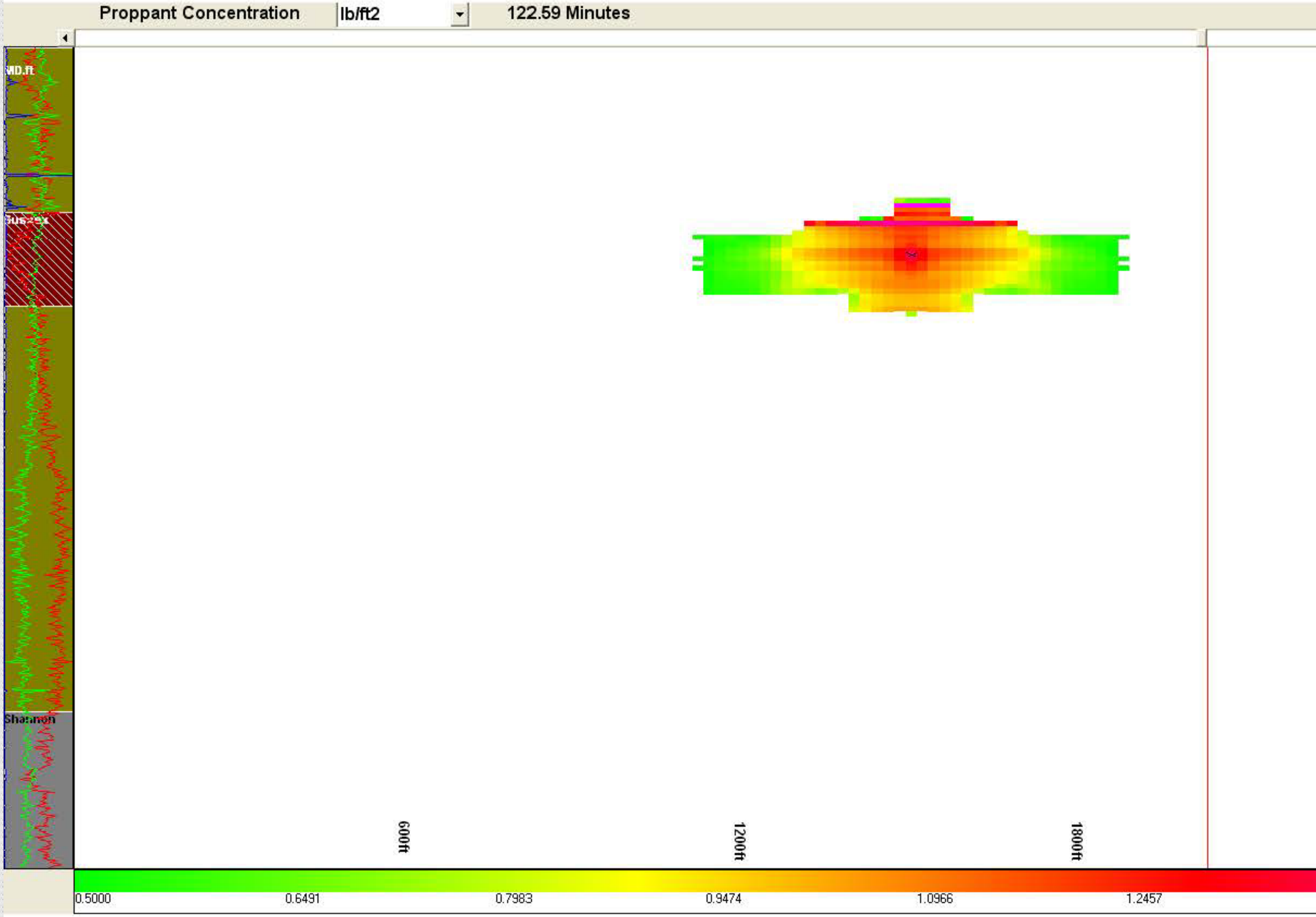




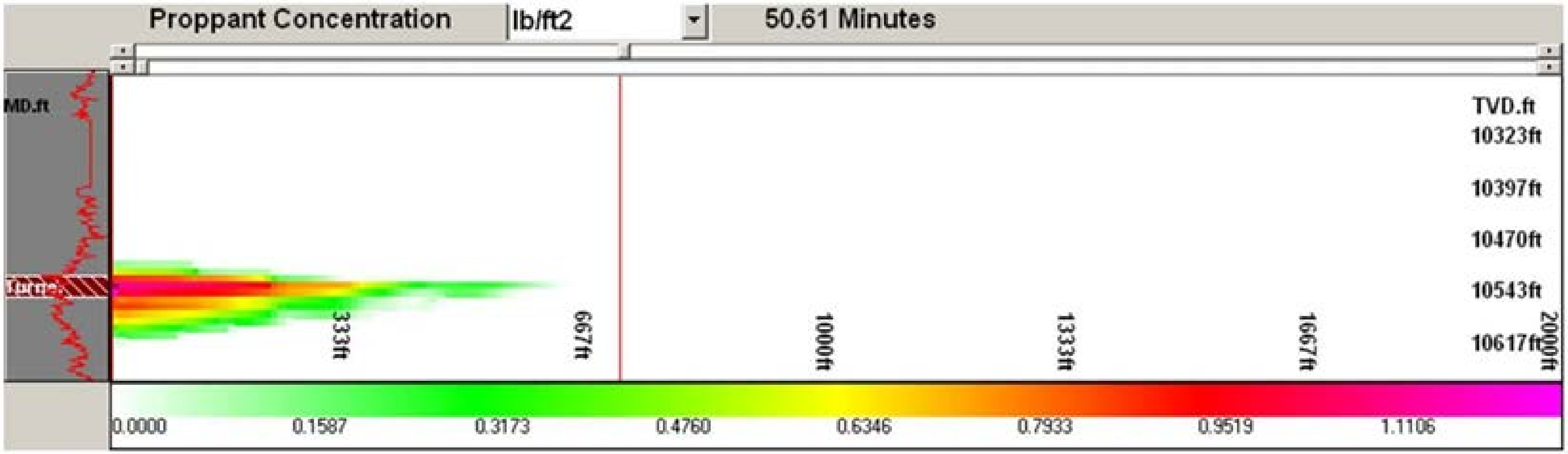
Frame 1 of a modeling sequence shows a hydraulic fracture may contact a depleted reservoir section of multiple parent wells—inducing a frac hit across the pad. A larger fracture network develops around the child well only after the fracturing fluids have filled that depleted area, shown in frames 2 and 3. *Source: Barree & Associates*

Ref: **Oil and Gas Producers Find Frac Hits in Shale Wells a Major Challenge ,** Trent Jacobs, JPT Digital Editor | 01 April 2017

WinGOHFER Proppant Concentration
0.5 lbs/ft^2 Proppant Concentration Cutoff



WinGOHFER Proppant Concentration



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Unstimulated Radius from Stimulated Vertical Wells

Analysis of Hornbuckle Sussex vertical and horizontal well drainage areas indicates a ratio of horizontal to vertical Drainage Radius (Rh / Rv) = 407 / 1150 = 0.35

WOGCC Docket No. 208-2012 and 212-2012 Exhibit E-1
Samson Resources
Application for 640-Acre Drilling and Spacing Unit and Increased Density
Section 36, T43N, R76W, Campbell County, Wyoming

Sussex Well Drainage Area - Analogy to Hornbuckle and Spearhead Ranch

Well	Estimated Ultimate Oil (BO)	PHI-H** (feet)	Bo	Drainage Area (Acres)	Lateral (from Slotted Liner MDs) (Feet)	Fracture Half Length X_f (feet)	Drainage Radius (feet)		Comment
Vertical - 43 well field average	139,000	2.48	1.2	**95**	-	-	**1150**	r_v	Circular drainage area
Horizontal - 20 well normalization	304,773	2.53	1.2	**204**	4087	-	**825**	$r_{h\ (Joshi)}$	Joshi Method
Horizontal - 20 well normalization	304,773	2.53	1.2	**204**	4087	500	**407**	$r_{h\ (Rectangle)}$	Rectangle Method
Horizontal - 20 well normalization	304,773	2.53	1.2	**209**	4200	500	**407**	$r_{h\ (Rectangle)}$	Rectangle Method Adjusted to 4200' Lateral

Ratio of horizontal to vertical Drainage Radius (r_h / r_v) = 407 / 1150 = 0.35

Reservoir constant properties for Drainage Area Calculation Area = (EUR* Bo)/(7758*H*phi*(1-Sw)*RF)

40% Sw - Water Saturation (Samson petrophysical model with mineral corrections)

15.0% RF - Recovery Factor

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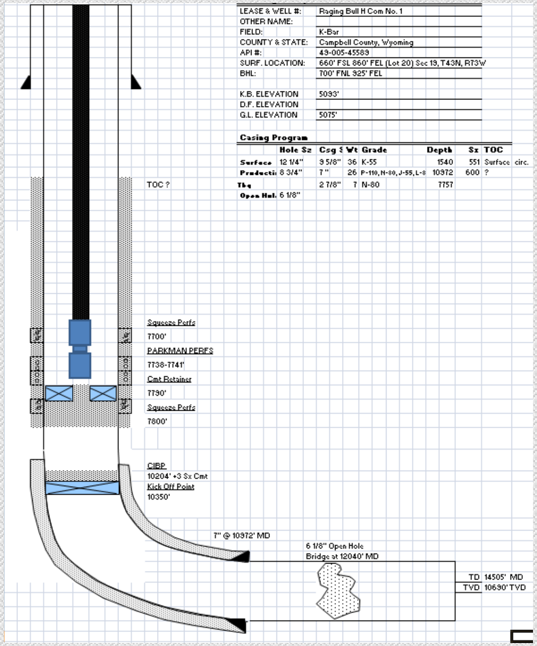
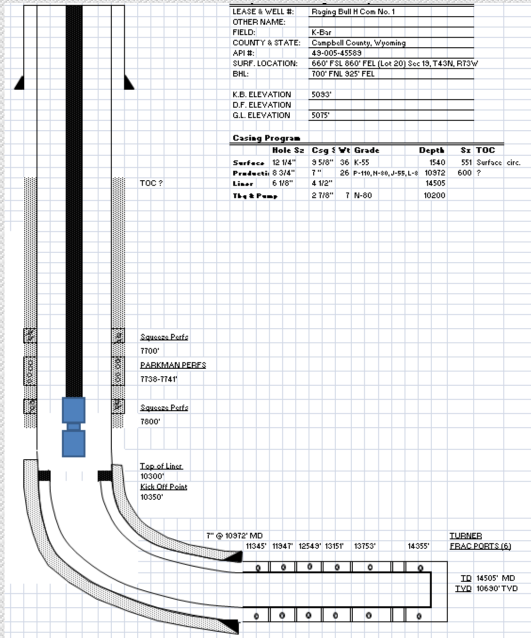
AN ENGINEER

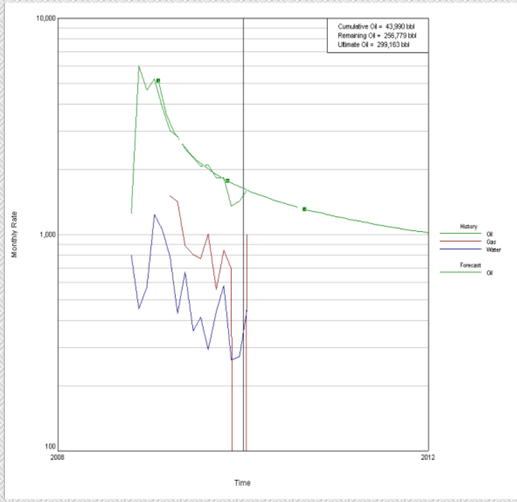
An Engineer Is a Person Who Passes as an exacting expert on the basis of being able to turn out with prolific fortitude infinite strings of incomprehensible formulas calculated with micromatic precision from vague assumptions which are based on debatable figures taken from inconclusive experiments carried out with instruments of problematical accuracy by persons of questionable mentality for the avowed purpose of annoying and confusing a hopelessly chimerical group of esoteric fanatics referred to altogether too frequently as technicians.

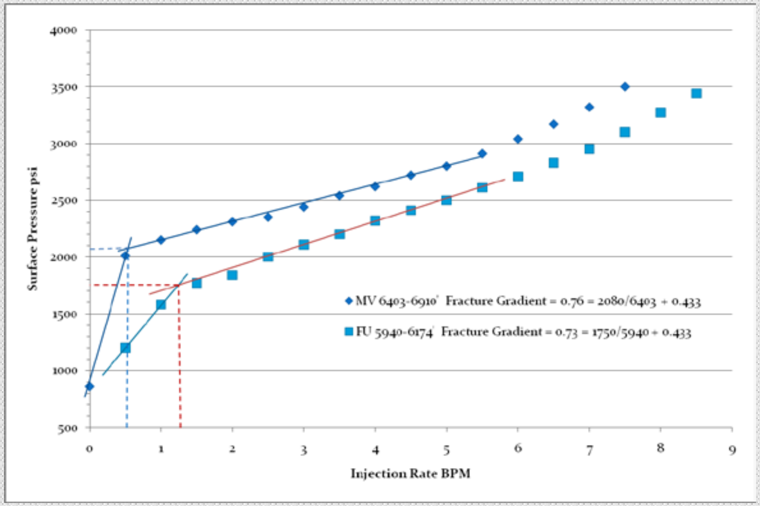
- unknown

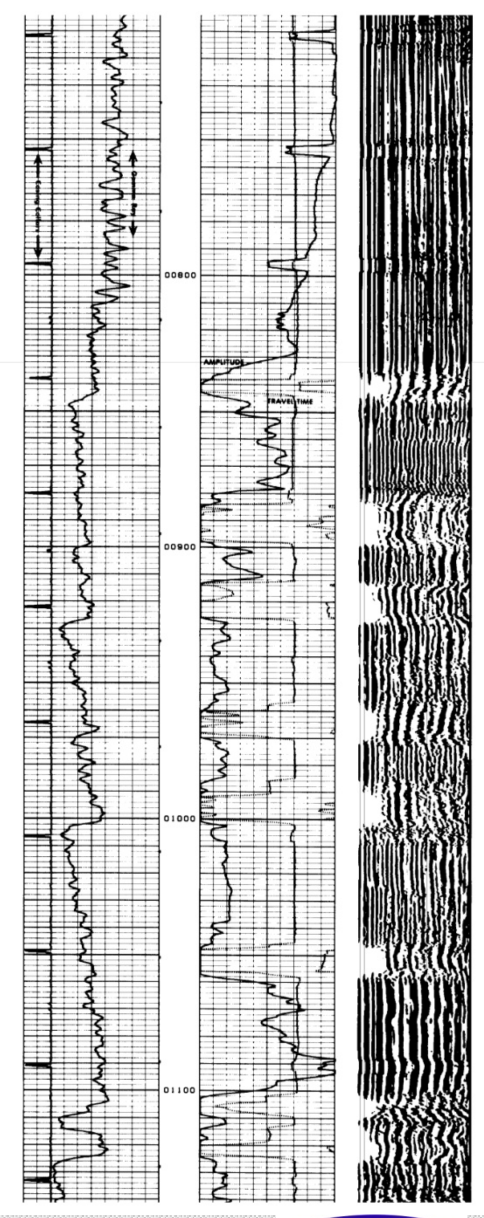




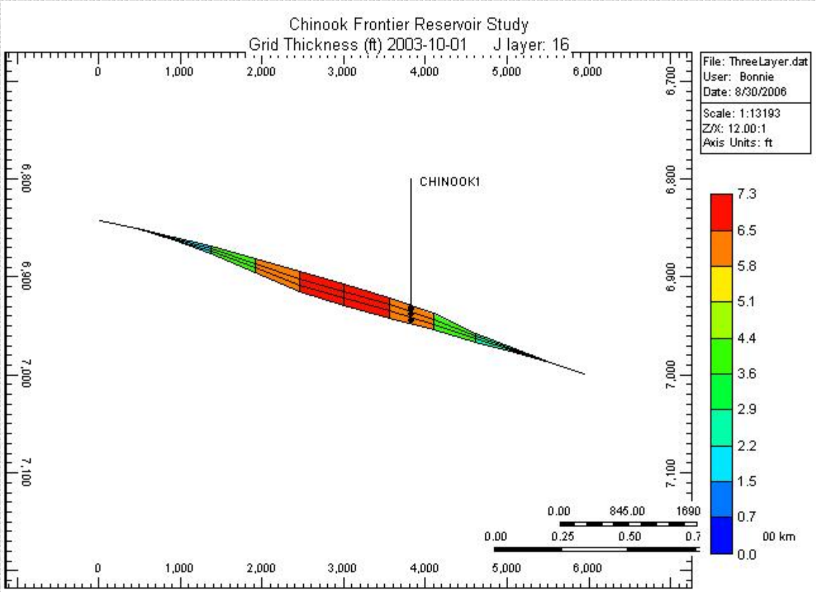
Horizontal Wells and Water Disposal

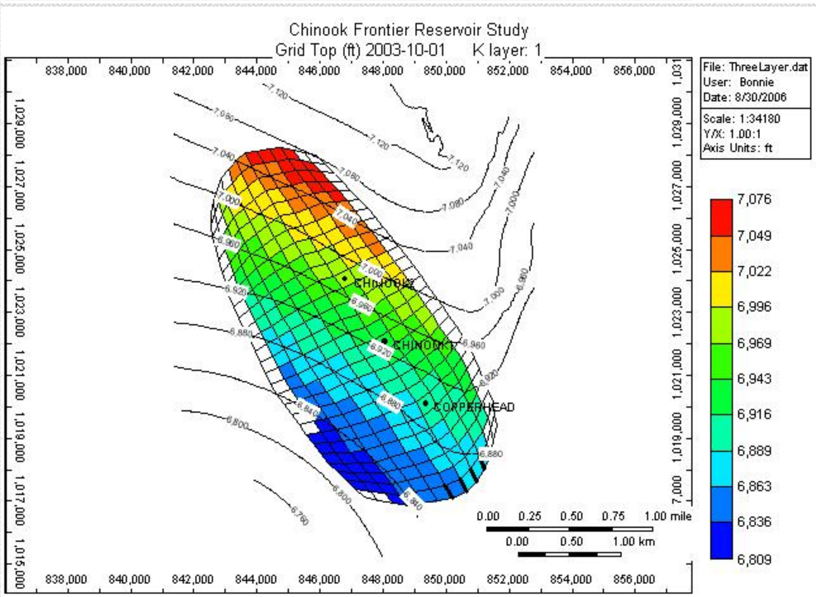




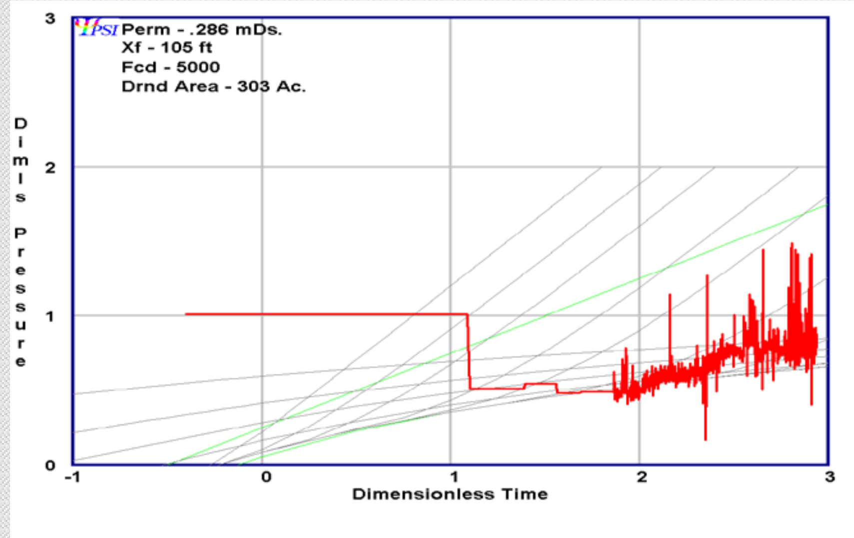


Reservoir Simulation

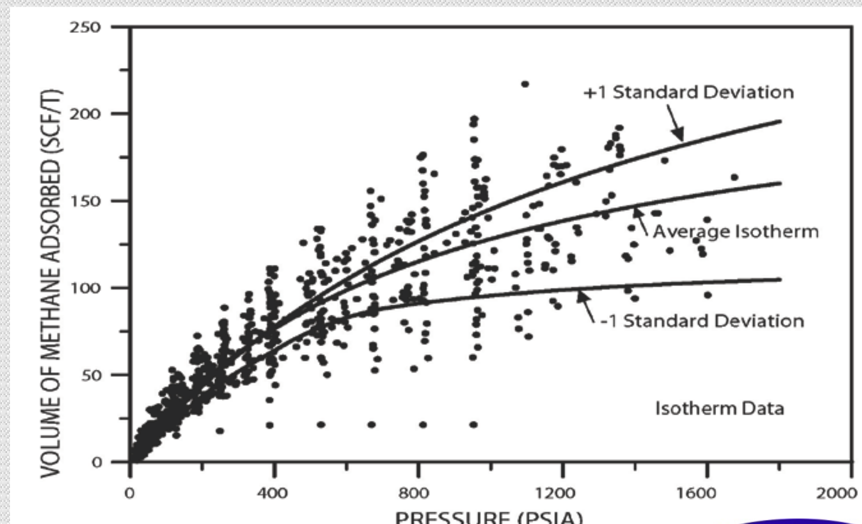




Rate Transient Analysis



Coal Bed Methane



GGA
Gene R. George & Associates, Inc.

Tight Gas Sands

Pressure Data Analysis For Infill Evaluation