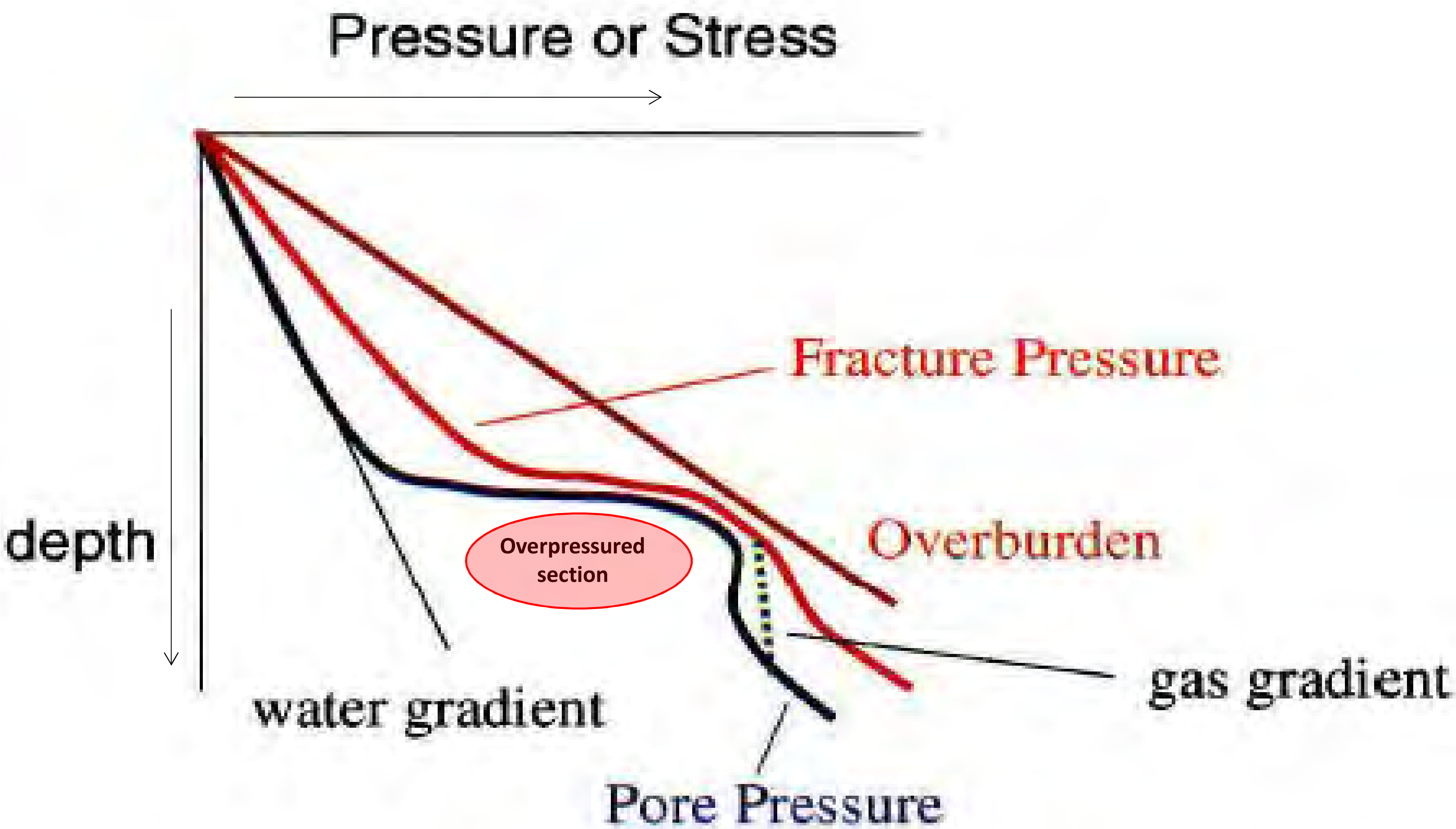
Paleo Overpressure in the Delaware Basin Determined From DST, Resistivity Logs and Mud Logs

May 21, 2019

Mary Van Der Loop
Sanctuary Oaks Consultants Int'l Inc.
P. O. Box 453
Flatonia, TX 78941
361-865-2901
832-434-3639 cell
sanctuaryoaksgeo@yahoo.com

- Introduction
- Methods used to define overpressure
  - DST, Mudlogs, Resistivity Logs
- Delaware Basin overpressure cell as currently defined
  - where did we have to 'mud up' to drill thru overpressure?
- Overpressure seen on resistivity logs does not match that
- Compare DST data to Resistivity data to Mud Weight data
  - DST derived PG psi/ft, MW derived PG psi/ft, Resistivity N/Resistivity OP derived PG psi/ft
- Conclusions -- OverPressure has been depleted in Western Delaware Basin due to Laramide uplift and erosion


Pressure or Stress
depth
Fracture Pressure
Overburden
Overpressured section
gas gradient
water gradient
Pore Pressure

Methods to Determine Overpressure

- ***Seismic*** *velocity increase in overpressure*
- ***DST/RFT*** *Drill Stem Test/Repeat Formation Test*
- ***Mud Weights*** *Increase in Mud Weight*
- ***Casing Seat*** *In previously drilled area*
- ***Resistivity Logs*** *Drop in Resistivity*
- ***Sonic Logs*** *Increase in Sonic Velocity*
- ***ISIP*** *Initial Shut In Pressure*
- ***DFIT*** *Diagnostic Fracture Injection Test*
- ***BHP*** *Bottom Hole Pressure Test (producing well)*

Methods to Determine Overpressure Used in This Study

- *Seismic*
- ***Drill stem tests*** *RFT*
- ***Mud weights***
- *Casing Seat*
- ***Resistivity logs***
- *Sonic Logs*
- *ISIP*
- *DFIT*

AAPG ACE2019 ANNUAL CONVENTION & EXHIBITION
19-22 May • San Antonio, Texas

"Normal Formation Pressure" is slightly higher in the Permian Basin – NOT .45 psi/ft

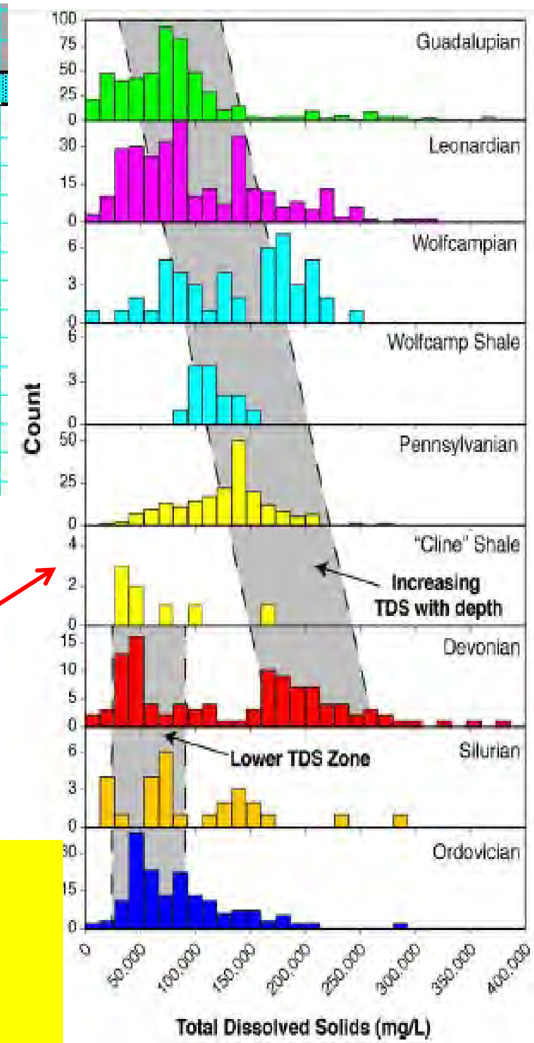
Salinity kppm	Salinity Wt%	Rw B&K @75F ohm-m	COND @75F S/m	Rw ERC @75F ohm-m	COND @75F S/m	Rw DK @75F ohm-m	COND @75F S/m
0.0	0.0	====	0.00	====	0.00	80.739	0.01
10.0	1.0	0.564	1.77	0.575	1.74	0.599	1.67
25.0	2.5	0.242	4.12	0.257	3.89	0.247	4.04
50.0	5.0	0.131	7.63	0.140	7.17	0.130	7.71
75.0	7.5	0.093	10.76	0.098	10.24	0.091	11.01
100.0	10.0	0.074	13.60	0.076	13.19	0.072	13.95
125.0	12.5	0.062	16.19	0.062	16.05	0.061	16.52
150.0	15.0	0.054	18.56	0.053	18.85	0.053	18.72
175.0	17.5	0.048	20.75	0.046	21.58	0.049	20.56
200.0	20.0	0.044	22.79	0.041	24.27	0.045	22.04
225.0	22.5	0.041	24.68	0.037	26.93	0.043	23.14
250.0	25.0	0.038	26.44	0.034	29.54	0.042	23.89

From Craig et al

From Engle et al

From AAPG Wiki

1	Gradient (psi/ft)	Density (g/cc)	TDS (ppm)	TDS (wt %)
2	4.33	1		0
3	0.437	1.01	13,500	13.5
4	0.441	1.02	27,500	27.5
5	0.444	1.029	37,000	37
6	0.445	1.03	41,400	41.4
7	0.451	1.04	55,400	55.4
8	0.454	1.05	69,400	69.4
9	0.459	1.06	83,700	83.7
10	0.463	1.07	98,400	98.4
11	0.465	1.075	100,000	100
12	0.467	1.08	113,200	113.2
13	0.471	1.09	128,300	128.3
14	0.476	1.1	143,500	143.5
15	0.48	1.11	159,500	159.5
16	0.485	1.12	175,800	175.8
17	0.489	1.13	192,400	192.4
18	0.491	1.135	200,000	200
19	0.493	1.137	210,000	210
20	0.5	1.153	230,000	230
21	0.51	1.176	260,000	260



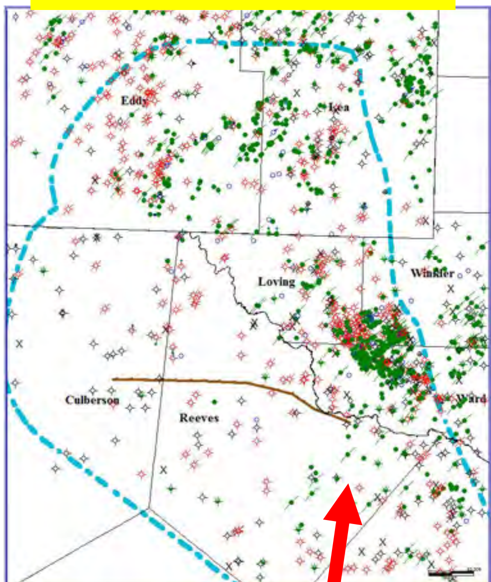
"Normal Formation Pressure" is .48 to .49 psi/ft in the Permian Basin

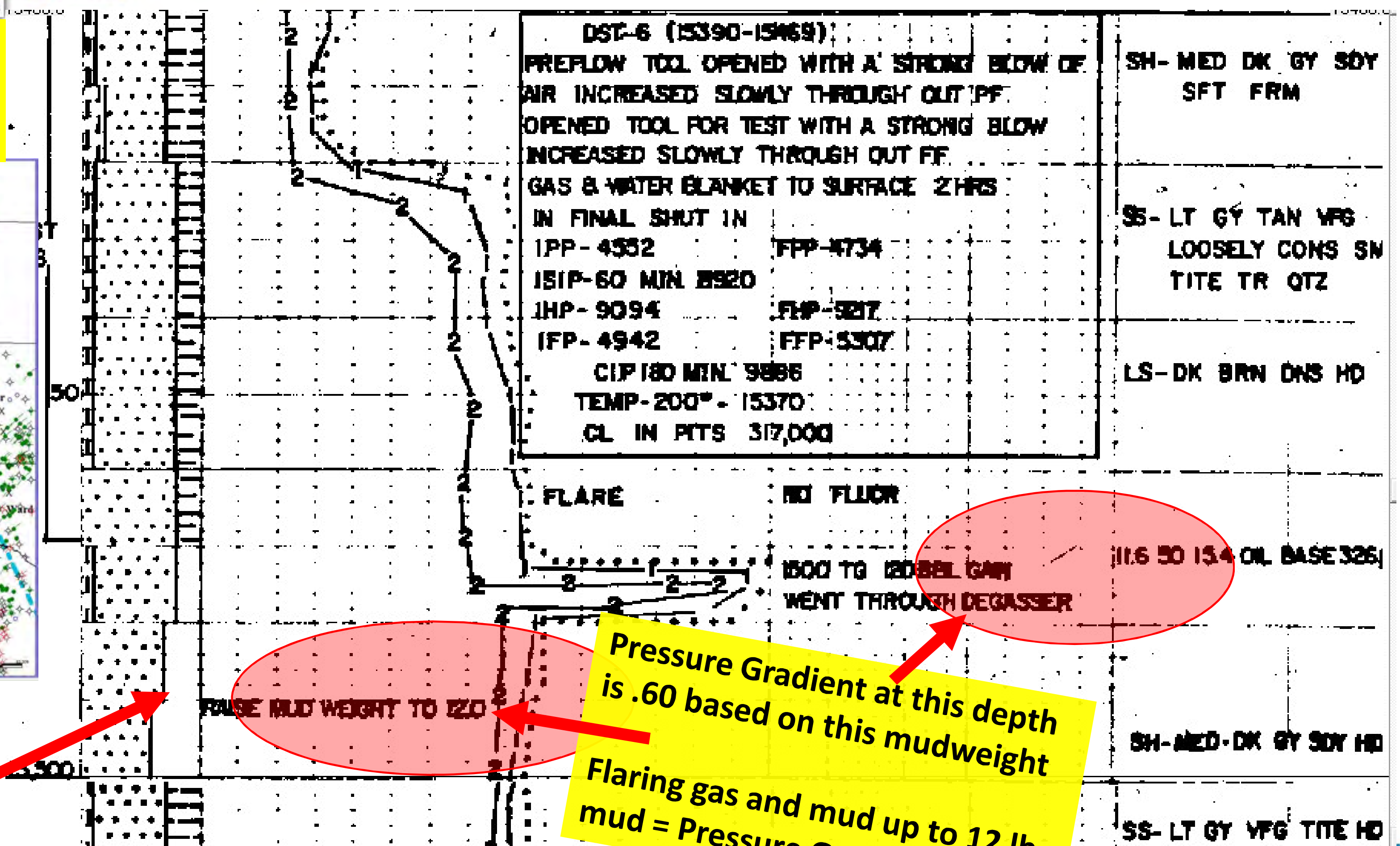
AAPG ACE2019 ANNUAL CONVENTION & EXHIBITION
19-22 May • San Antonio, Texas

Mudweights obtained from **356** Delaware Basin Mudlogs Converted to Pressure Gradient (PG) using the formula

(Depth X Mudwt X .052)/Depth =PG

High Mudweights define overpressure cell in Delaware Basin



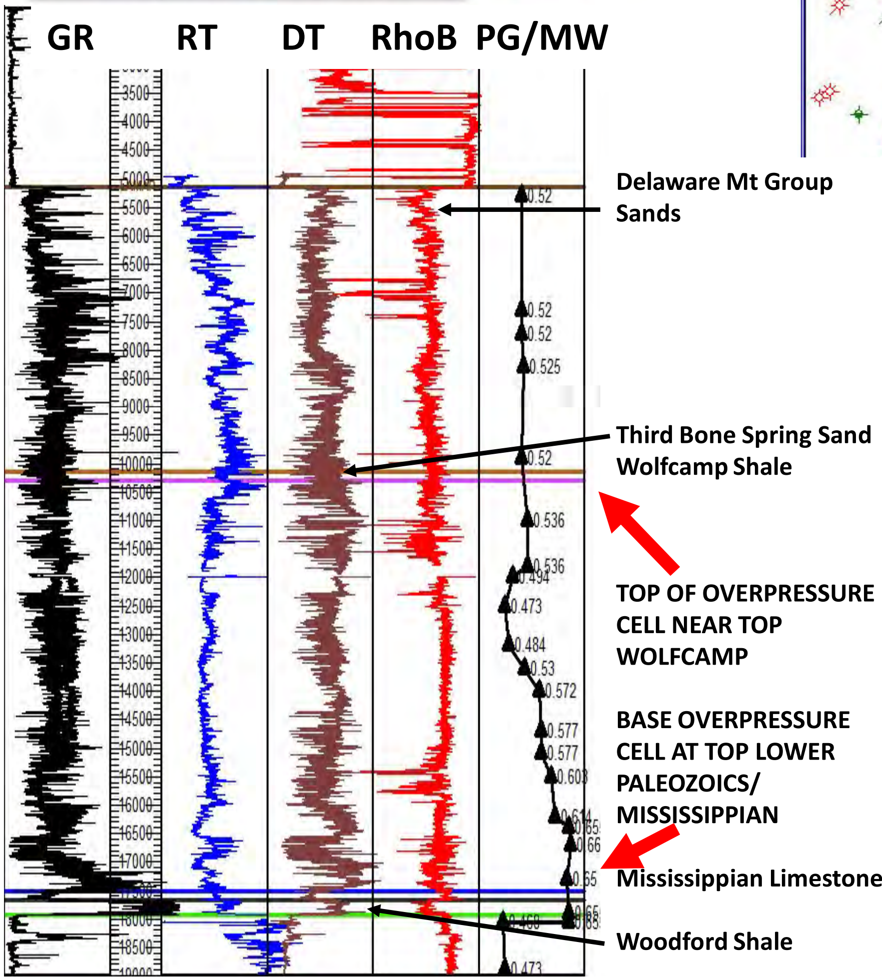


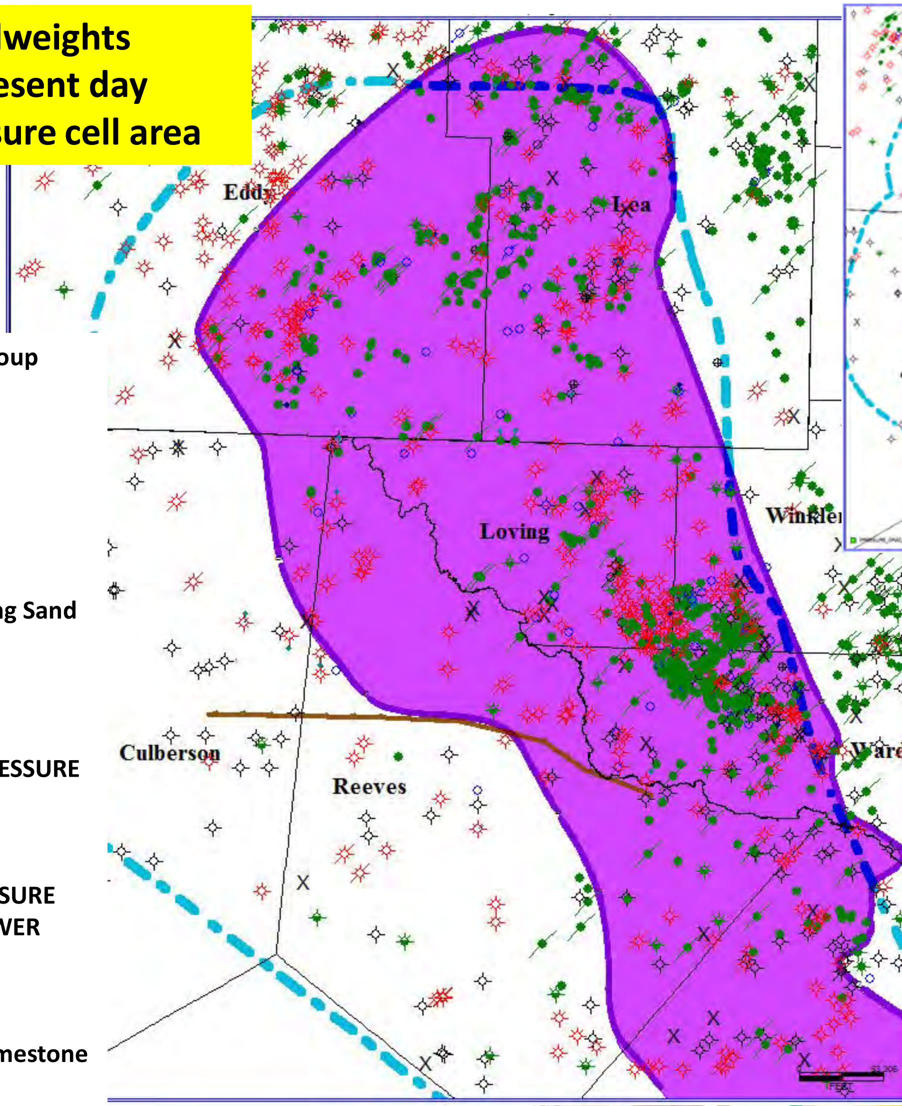
Pressure Gradient at this depth is .60 based on this mudweight

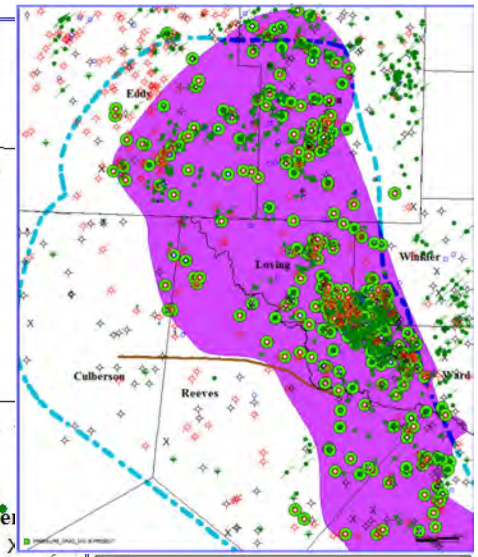
Flaring gas and mud up to 12 lb mud = Pressure Gradient of .624

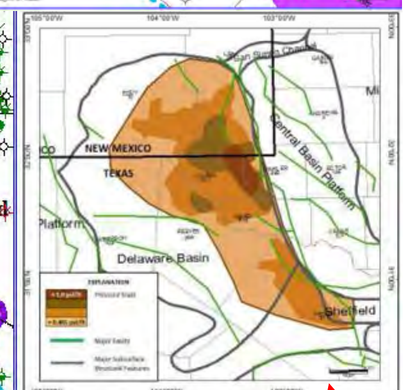
THIS EXAMPLE = Mudlog on Gulf Hamon 42-389-31168

High Mudweights define present day overpressure cell area





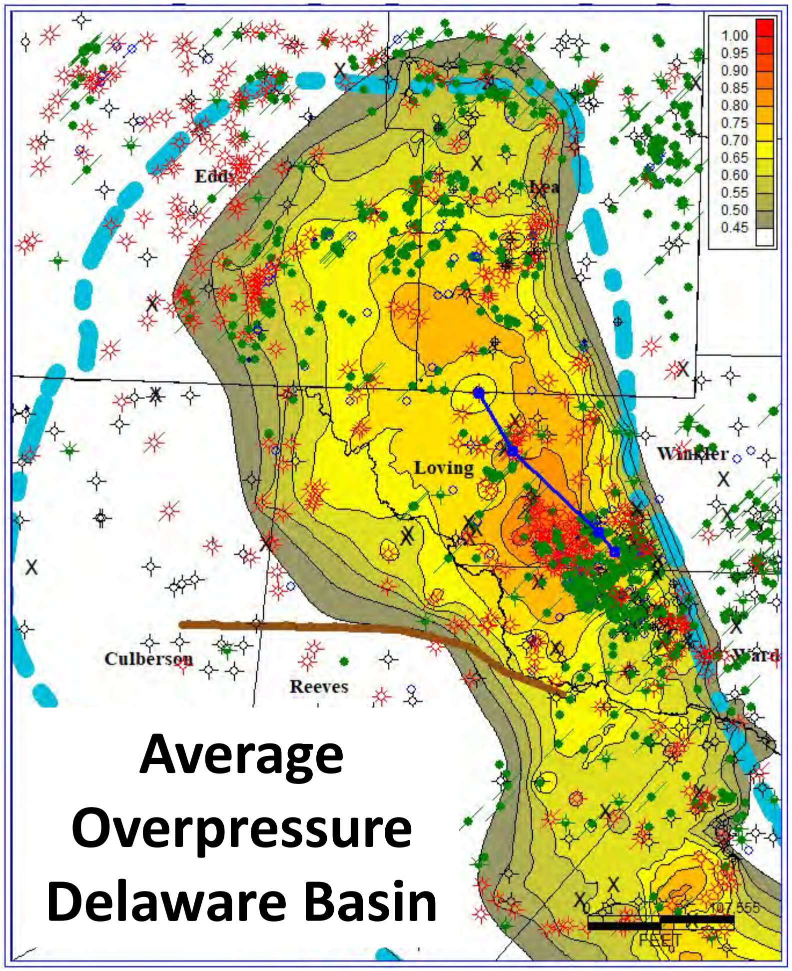




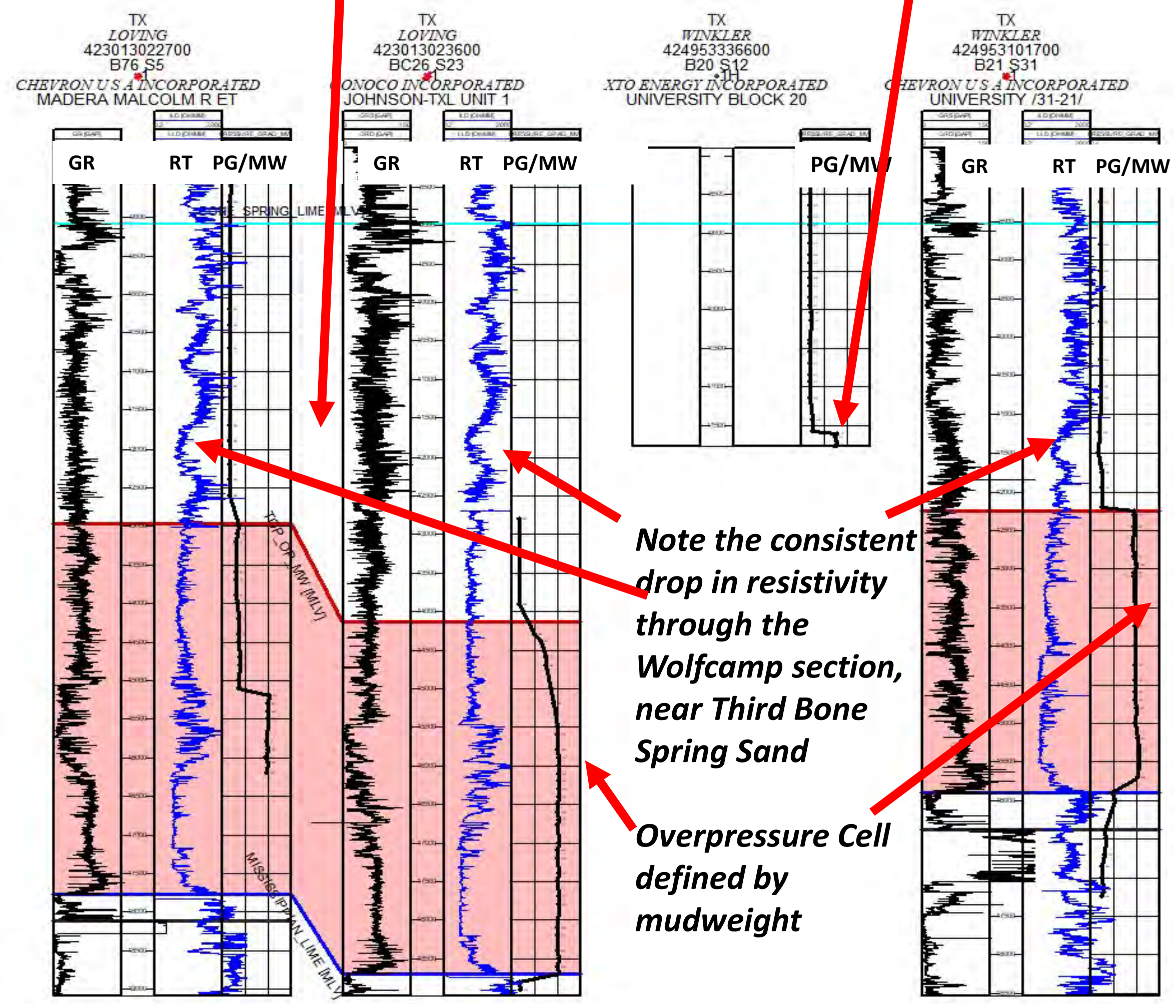
Rittenhouse 2017 (Shell) similar result

ACE 2019 ANNUAL CONVENTION & EXHIBITION
19-22 May • San Antonio, Texas

Top of Overpressure from Mudweight, defined as when Pressure Gradient >.5psi/ft, occurs at variable depths in closely spaced wells. Recent horizontal wells are drilled with heavier mud because they are encountering overpressure at a shallower depth than defined by these mudweights.



Average Overpressure Delaware Basin



From: The Role of Shale Pore Structure on the Sensitivity of Wire Line Logs to Over Pressure, by Bowers, G.L., and Katsube T. J., IN Pressure Regimes in Sedimentary Basins and their Prediction, AAPG Memoir 76 ***Example from Norway***

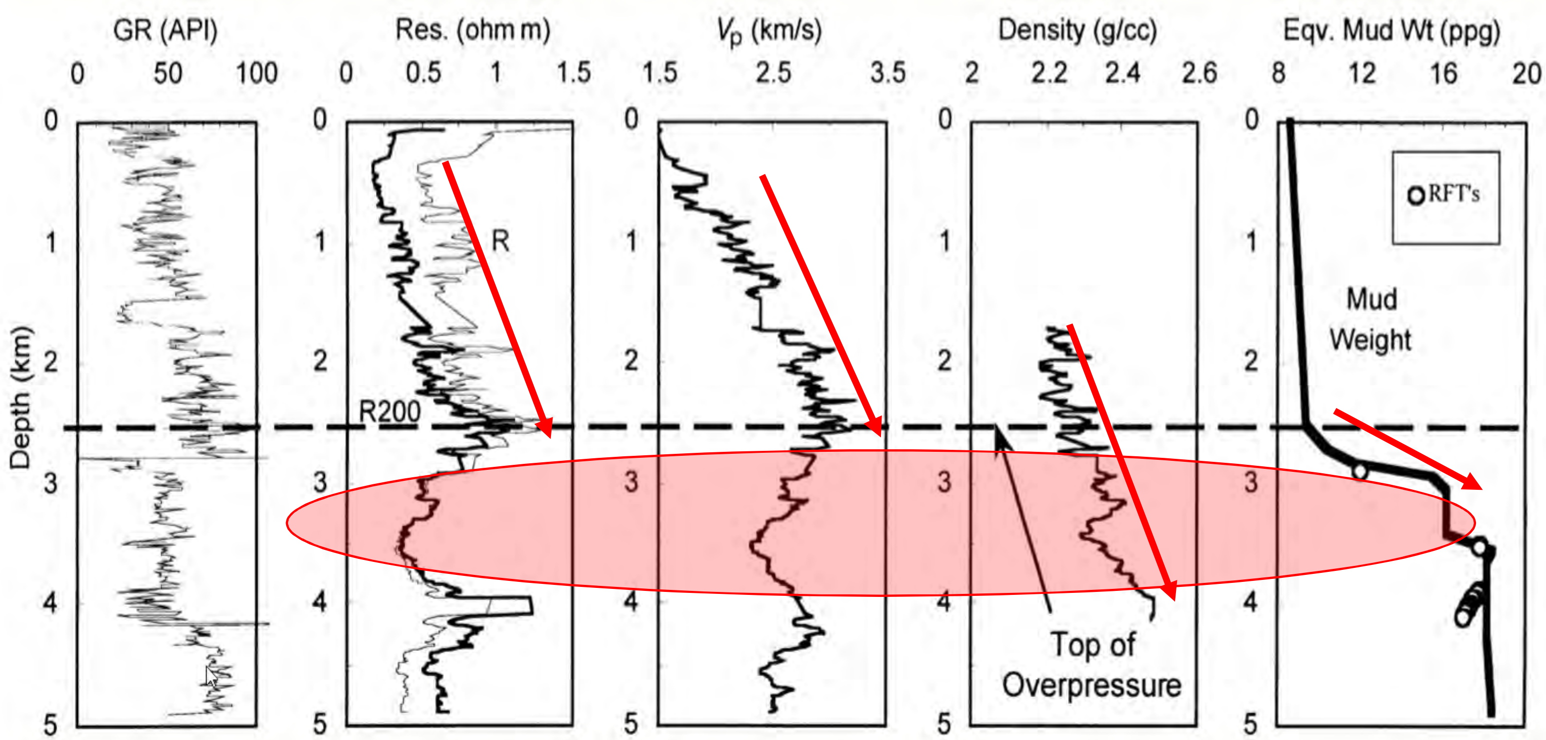


Figure 1. Wire-line data from an overpressured well in which sonic velocity and resistivity show a greater response to the onset of overpressure than bulk density data. The curve labeled "R" is the raw resistivity data; the curve labeled "R200" is the resistivity data normalized to a common temperature of 200°F (93°C).

Resistivity and Sonic Logs both have a distinct response to overpressure --they are responding to changes in the fluid transport properties of the rock, altered by overpressure.

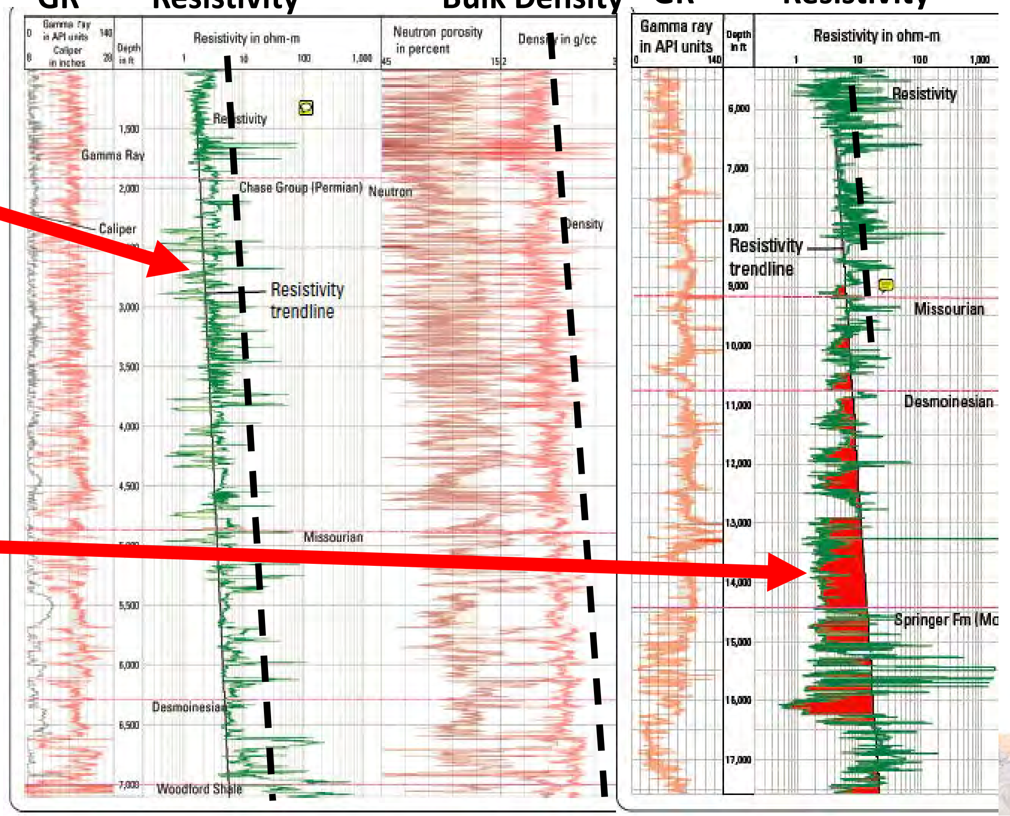
Overpressured rocks are more conductive (a microfracture network has been introduced or enhanced) and porosity can be preserved.

ACE2019 AAPG ANNUAL CONVENTION & EXHIBITION
19-22 May • San Antonio, Texas

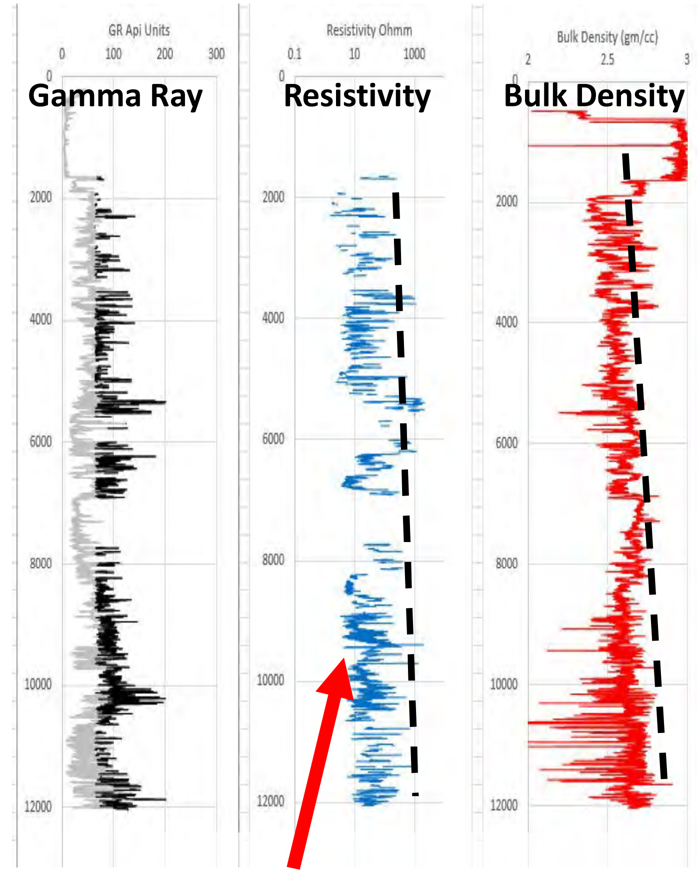
Anadarko Basin Example
Normal Pressure vs Overpressure

In normally pressured area of Anadarko Basin – Northwest Shelf, Resistivity (green line) increases with depth in shales.

However, in Overpressured area of Anadarko Basin, Resistivity (green line) decreases in overpressured section (highlighted in red)



Delaware Basin (Northwest Shelf example)
Normal pressure gradient

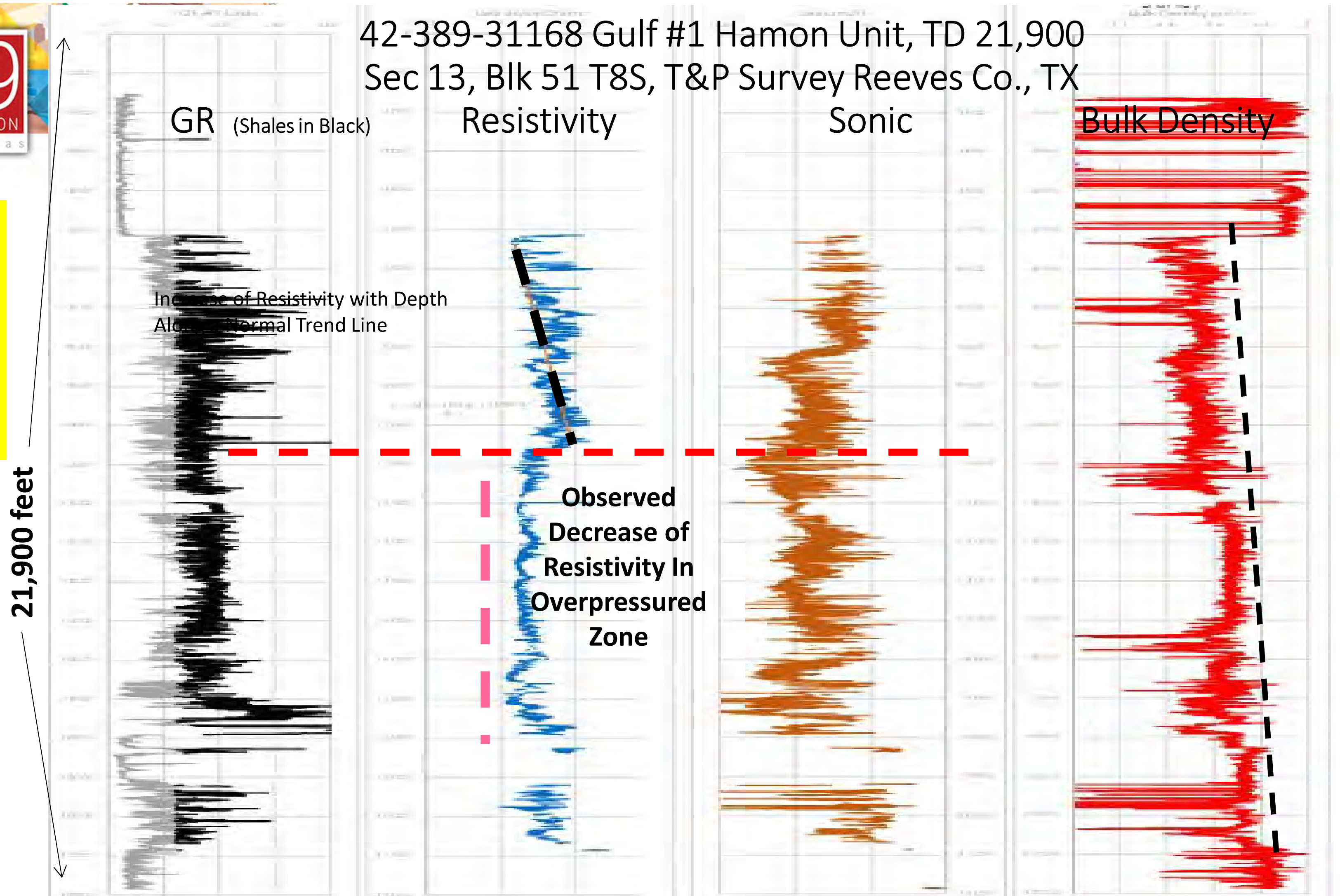


Resistivity (blue line) increases with depth in shales.
Nearby wells were drilled with 9.0 to 9.5 lb mud, no overpressure.

AAPG ACE 2019 ANNUAL CONVENTION & EXHIBITION
19-22 May • San Antonio, Texas

Is there a way to Calculate Pressure Gradient using Observed Log Resistivity Trend in Overpressure compared to Normally Pressured Log Resistivity Trend?

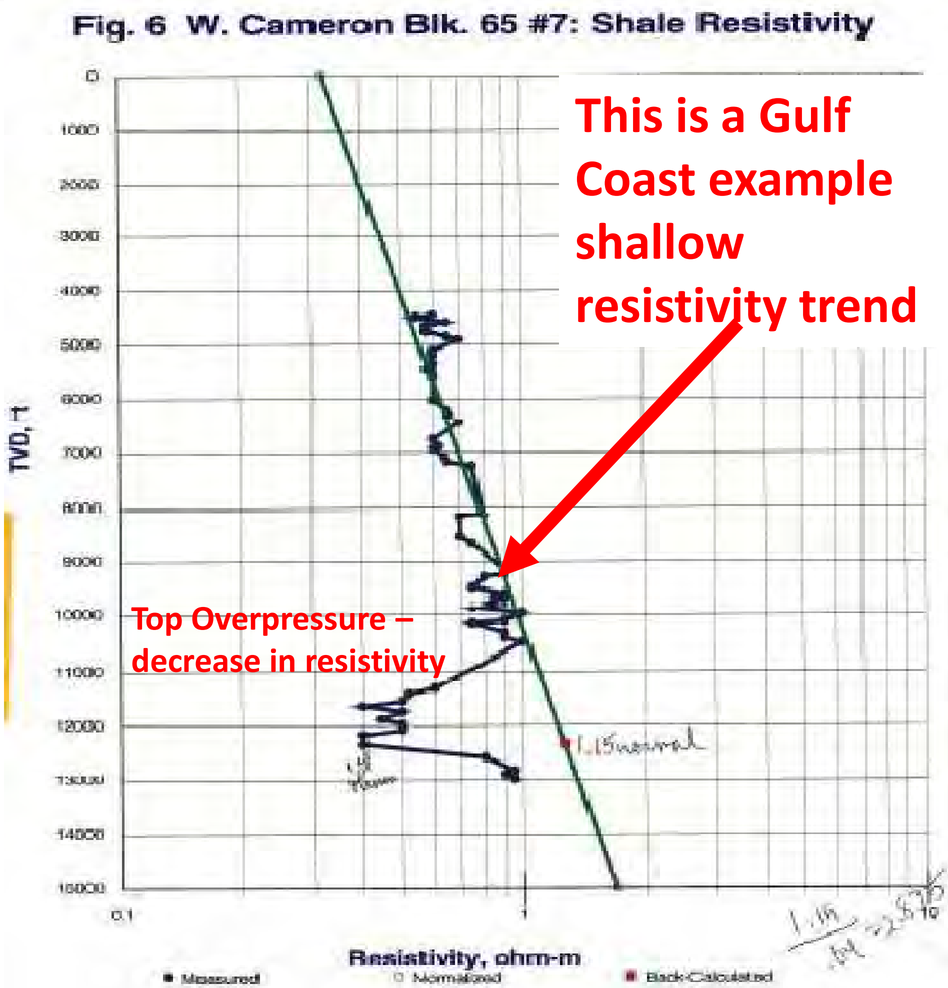
Top Overpressure 10550 in Wolfcamp A

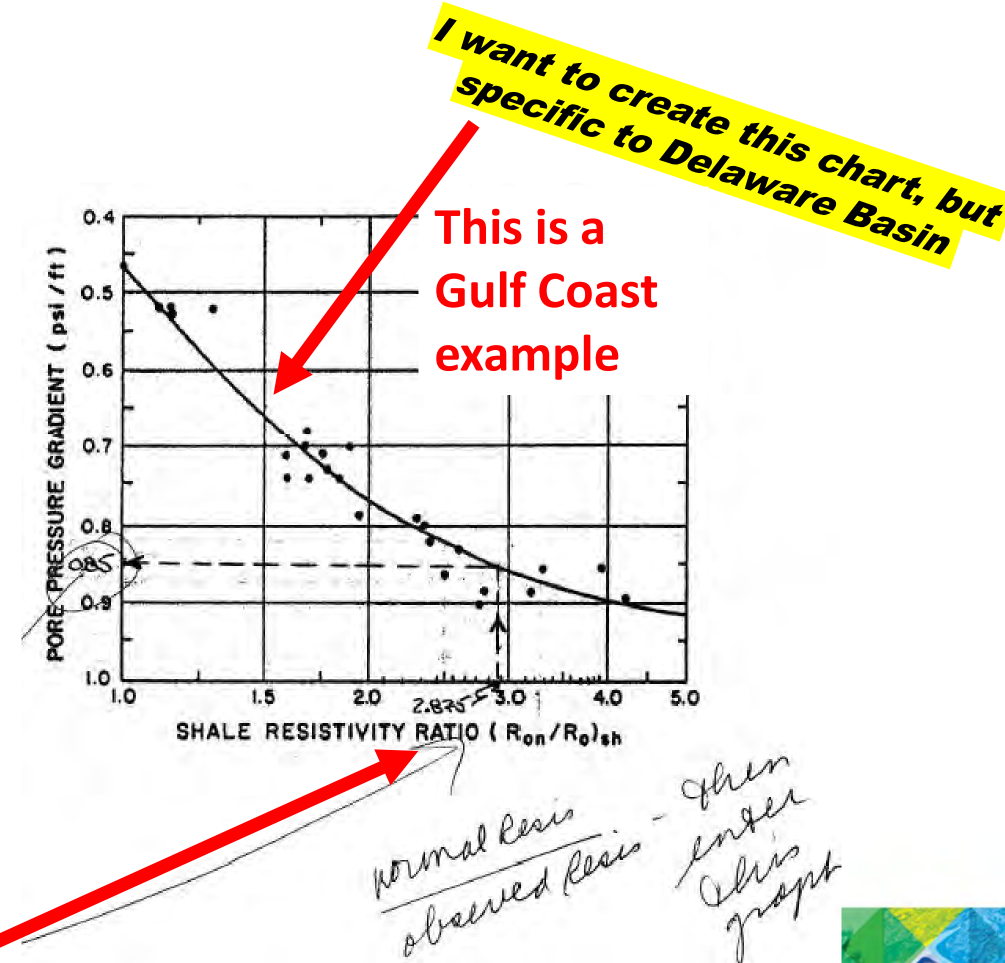


Available database: 55 wells have both Mud logs and Resistivity logs

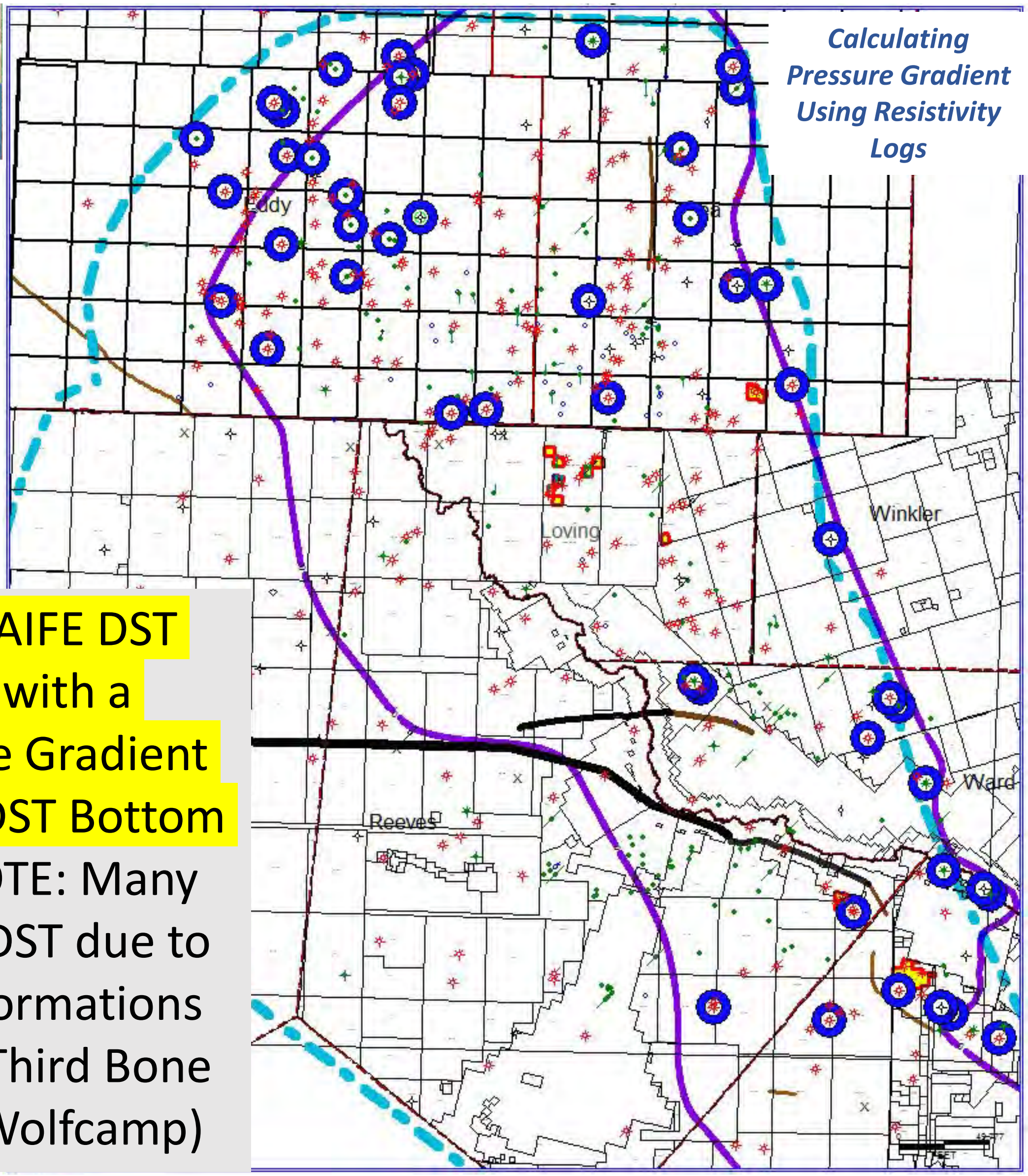
AAPG ACE 2019 ANNUAL CONVENTION & EXHIBITION
19-22 May • San Antonio, Texas

Calculating Pressure Gradient Using Resistivity Logs





Permian Basin Wells in AIFE database which have Pressure Gradient extrapolated from DST data



Wells in Blue are AIFE DST Database wells with a Calculated Pressure Gradient from Extrapolated DST Bottom Hole Pressure. NOTE: Many are Lower Quality DST due to low permeability formations (First, Second and Third Bone Spring Sands and Wolfcamp)

48 wells contain Wolfcamp or Bone Spring DST data and have AIFE calculated Bottom Hole Pressure Projection (on low quality DST results due to low permeability rocks) and a resulting Pressure Gradient calculated; of these wells, only 18 are located in the overpressured area of highest interest in the Delaware Basin

These Pressure Gradients can be compared to Permian Basin Log Resistivity Data

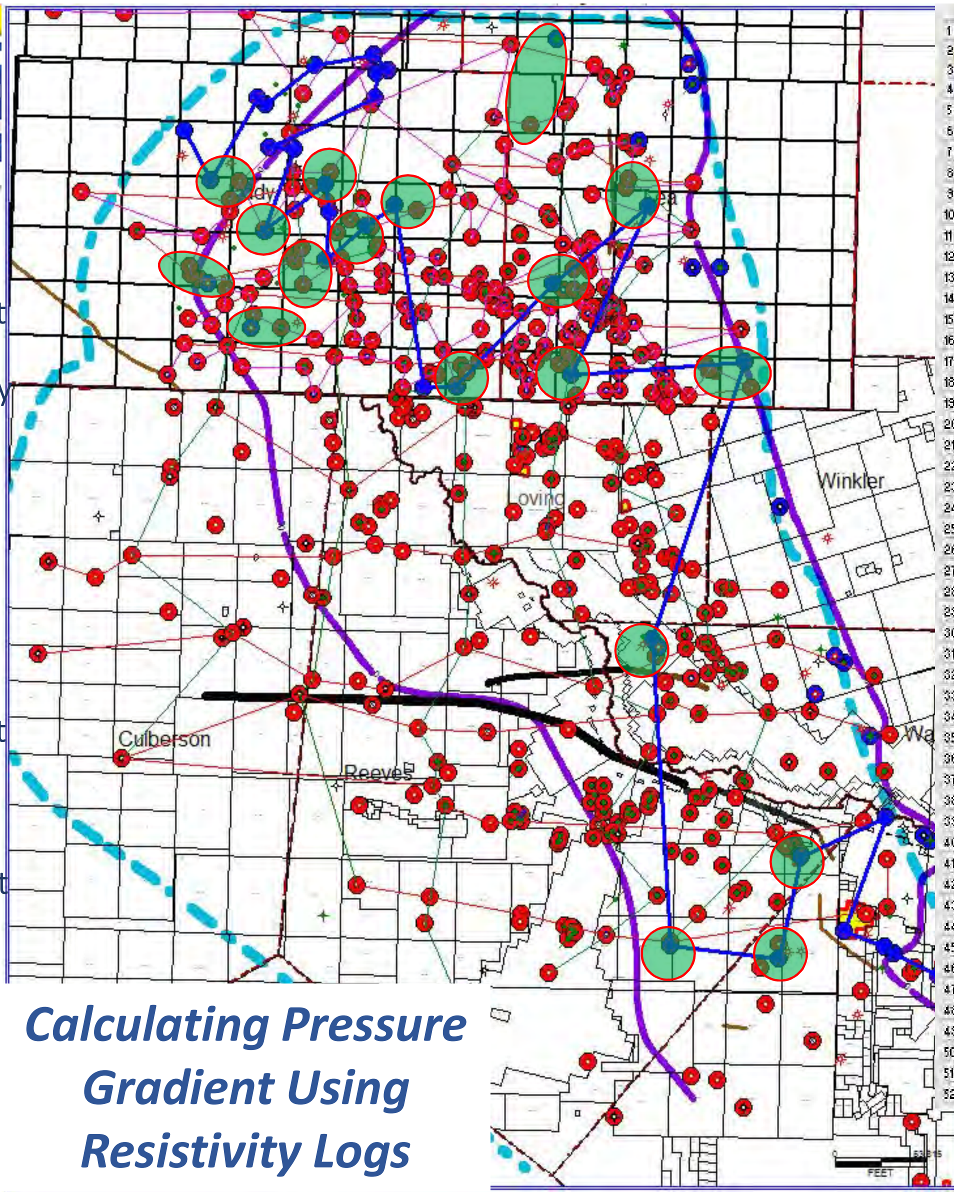
AAPG ACE2019 ANNUAL CONVENTION & EXHIBITION 19-22 May • San Antonio, Texas

AAPG ACE ANNUAL CONVEN
19 - 22 May · San

Data Sources for Chart : Pressure Gradient vs Resistivity Normal/Resistivity Observed

Green Circles = Paired Resistivity Log and DST Pressure Gradient Data

Creates X and Y axes for chart, but specific to Permian Basin

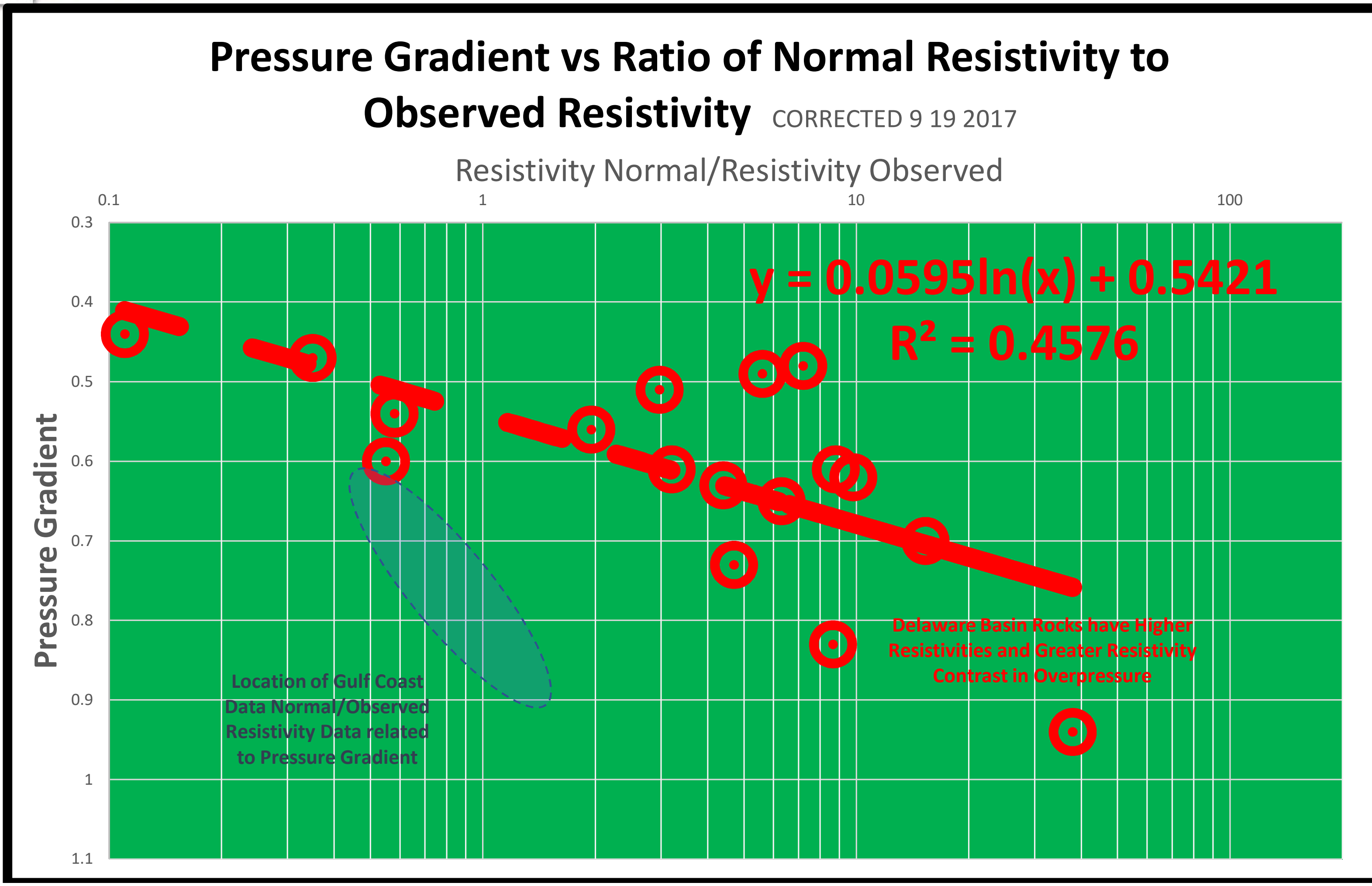


Calculating Pressure Gradient Using Resistivity Logs

	A	B	C	D	E	F
1	Data Source	Pressure Gradient	Observed Resis	Normal Resis	Trend	Normal/Observed
2	Proofread Complete	From AIFE DST	Ohmm	Ohmm		Resistivity
3		Interpretation	at DST depth	Projected from shallow trend		
4			Avg over DST In	Resistivity log to DST Depth		
5	Resis Log Gulf 1 Hamon 4238931168		40	128		3.20
6	DST in Gulf 2 NW Hamon 4238931245 @ 10138, 3BSpg	0.61				
7						
8	Resis Log Mobil 3 Schlosser 4237133589		5.57	211.2		37.92
9	DST in Mobil #1 Schlosser 4237105411 @15126 WFMP G	0.94				
10						
11	Resis log Shell (Oxy) 1-13 Rape 4238910426		72.6	42.4		0.58
12	DST from Shell #1 11 Becken 4238910251 @ 9231, 2BSpg	0.54				
13						
14	Resis log Atapco #1 Talco Unit Log 3002526747		22.5	199		8.84
15	DST in Sinclair SW Jal Federal 3002520843 @11948, WFMP E	0.61				
16						
17	Resis log Cimarex Matador #4 Red Hills unit 3002534626		25	382		15.28
18	DST in Amoco State GR 3002526785 @12903, WFMP E	0.7				
19						
20	Resis Log Kaiser Francis #21 Bell Lake Unit 3002535118		62.9	187		2.97
21	DST in Estoril #1 Triple A Federal 3002527521, @10780, 3 BSPG	0.51				
22						
23	Resis Log Yates #1 Caravan State 3002539609		79.25	375		4.73
24	DST in Devon #1 Federal BM 3002527003 @12963 WFMP E	0.73				
25						
26	Resis Log, DST TX Pacific 1 Phantom Draw 3001521346 @7985	0.47	114.16	71.8		0.63
27						
28	Resis Log Mewbourne 101 49R Ridge 3001534331		32.9	284.9		8.66
29	DST in Mesa 1 Nash Unit 3001521277 @11439 WFMP F	0.83				
30						
31	Resis Log Exxon 2 Laguna Grande 3001522157		21.4	210.8		9.85
32	DST Exxon #1 Laguna Federal 3001521636 @11321 WFMP G (est	0.62				
33						
34	Resis log Marbob #1 Spanky Federal 3001536895		31	137.8		4.45
35	DST in Oxy USA 1 Lightfoot 3001524452 @11510 WFMPH	0.63				
36						
37	Resis Log Marbob 1 Red Ryder State 3001535150		13.6	98.2		7.22
38	DST Yates # 1 Federal K Gas Com 3001522763 @11021 WFMPH	0.48				
39						
40	Resis Log Gruy Petroleum #3 White City 3001533525		24.7	138		5.59
41	DST in Murchison 1 Strong Federal 3001522153 @ 10210 WFMP(	0.49				
42						
43	Resis Log RKI Santa Federal Deep 3001537917		88.1	48.7		0.55
44	DST in Amoco State GO Federal Com 3001522754 @7683, 2BS	0.6				
45						
46	DST AND Log on Amoco #1 State DS.com 3001524119 @10202	0.65	30.2	190		6.29
47						
48	Resis Log on Devon 6-2 Joell 3001533292		161.9	316.1		1.95
49	DST in Oxy #1 New Mexico State V 3001520682 @10143 WFMP(	0.56				
50						
51	Resis Log on Texaco #1-33 Bilbrey Federal 3002530781 (Resis First Bone Spring- wells		173.2	18.8		0.11
52	DST on Sinclair Mahaffee Federal 3002501735 @9452 First BSI	0.44				

DELAWARE BASIN SPECIFIC Relationship of Pressure Gradient to Ratio of Normal Resistivity Trend to Observed Resistivity Trend in Overpressure

Why are there so few data points --so few DST's in Delaware Basin Wolfcamp? It is overpressured and difficult to test with the high likelihood of blowout. "There's gas, sure, but there is nothing in the Wolfcamp, the reservoirs are only as big as this room, it's so impermeable there is no point in running a DST."



ACE 2019 AAPG ANNUAL CONVENTION & EXHIBITION
19-22 May • San Antonio, Texas

Method

Using Resistivity Logs to Calculate Pressure Gradient on 55 wells in Permian Basin

- Select LAS file based on depth, location in basin, complete suite (GR, Resistivity, Sonic, Bulk Density)
- Convert LAS file from Text to Excel
- Delete unneeded curves, merge various GR and Resis Curves to get complete curve over entire well
- Decimate depth from .5 feet to one value every 2 ft because Excel graphs cannot use more than 32,000 pts,
- Histogram on GR to determine what shale breakover is (anything >median API units = Shaley) Median API units per well vary from 40 units to almost 70 units)
- Graph GR for entire well depth in light gray
- Decimate GR values to only shale values per depth
- Graph GR Shale values in Black to highlight shale values
- Use Consistent Depth and GR API Unit scales per graph 0-200 API Units
- Decimate Resistivity curve to use only shale values (GR > median)
- Graph Resistivity shale values
- Use Consistent Depth and Resistivity Ohmm scales per graph .2 to 2000 Ohmm
- Note Resistivity drop at top overpressure – map that value = Structure Top Overpressure by Resistivity log.
- Note Resistivity trend at shallow depths on plotted resistivity log – pick two or more points manually to define shallow resistivity trend, post trendline equation
- Take trendline equation of shallow resistivity trend to define what deeper resistivities would be if no overpressure – this gives Normal Resistivity Trend
- Resistivity curve in overpressure = Observed Resistivity
- Use Pressure Gradient **defined by AIFE DST database** vs Ratio (Normal/Observed) Resistivity graph and trendline equation Data points to define this graph are 18 wells with both DST and Resistivity LAS data, or well pairs of DST well and nearby Resistivity LAS data.
- **Using those two equations compute Pressure Gradient from Observed Resistivity in Excel**
- Load Pressure Gradient Curve as an LAS file to Petra Project.
- **Resulting database of 55 wells with Pressure Gradient derived from Resistivity Log and Pressure Gradient derived from Mudweight**

EXAMPLE From Delaware Basin Drill Stem Tests, Pressure Gradient vs Normal/Observed Resistivity graph

Delaware Basin Pressure Gradient= y = 0.0595ln(x) + 0.5421

Shallow Resistivity Trend Line Equation for Gulf Hamon well = y = 2225.8ln(x) + 746.66***

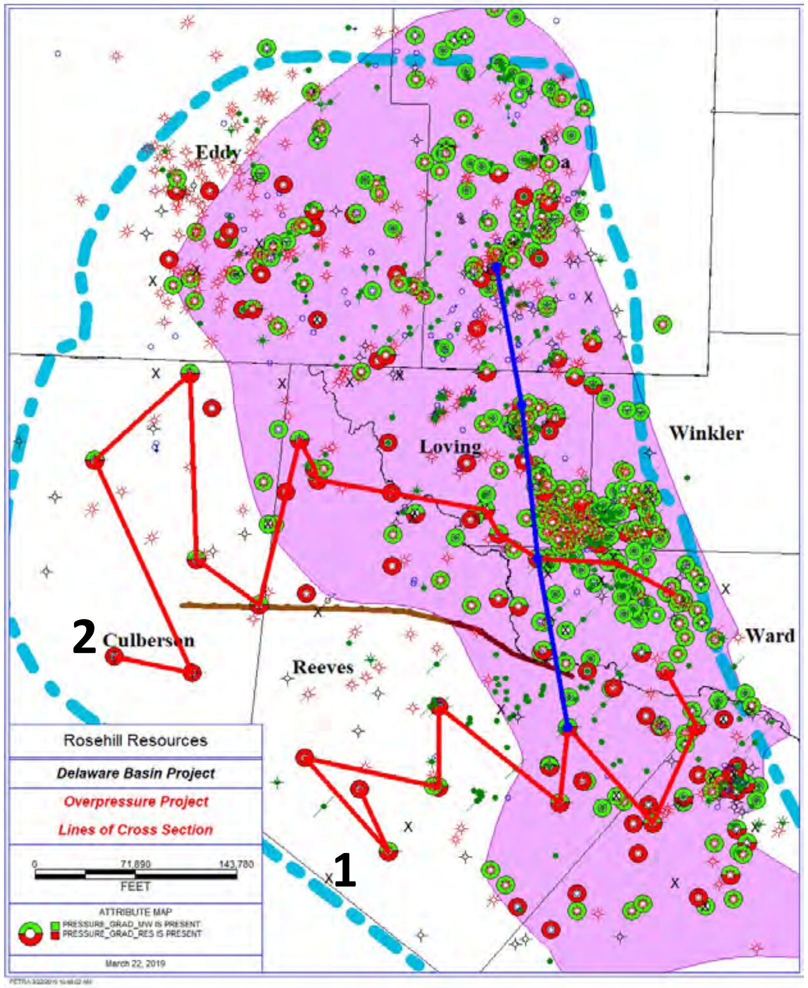
Depth	Observed Resistivity	ln x	x (normal trend resis)	normal/observed	ln Normal/Observed Resis		Depth
	Ohmm, From Logs	(A22-746.66)/2225.8	EXP(C22)	D22/B22	LN(E22)	(F22*0.0595)+0.5421	
		y = 2225.8ln(x) + 746.66				Pressure Gradient	
7000	15.8148	2.81	16.60	1.05	0.05	0.54	7000
7002	27.071	2.81	16.62	0.61	-0.49	0.51	7002
7004	38.9433	2.81	16.63	0.43	-0.85	0.49	7004
7006	30.7784	2.81	16.65	0.54	-0.61	0.51	7006
7008	21.9514	2.81	16.66	0.76	-0.28	0.53	7008
7010	17.8265	2.81	16.68	0.94	-0.07	0.54	7010

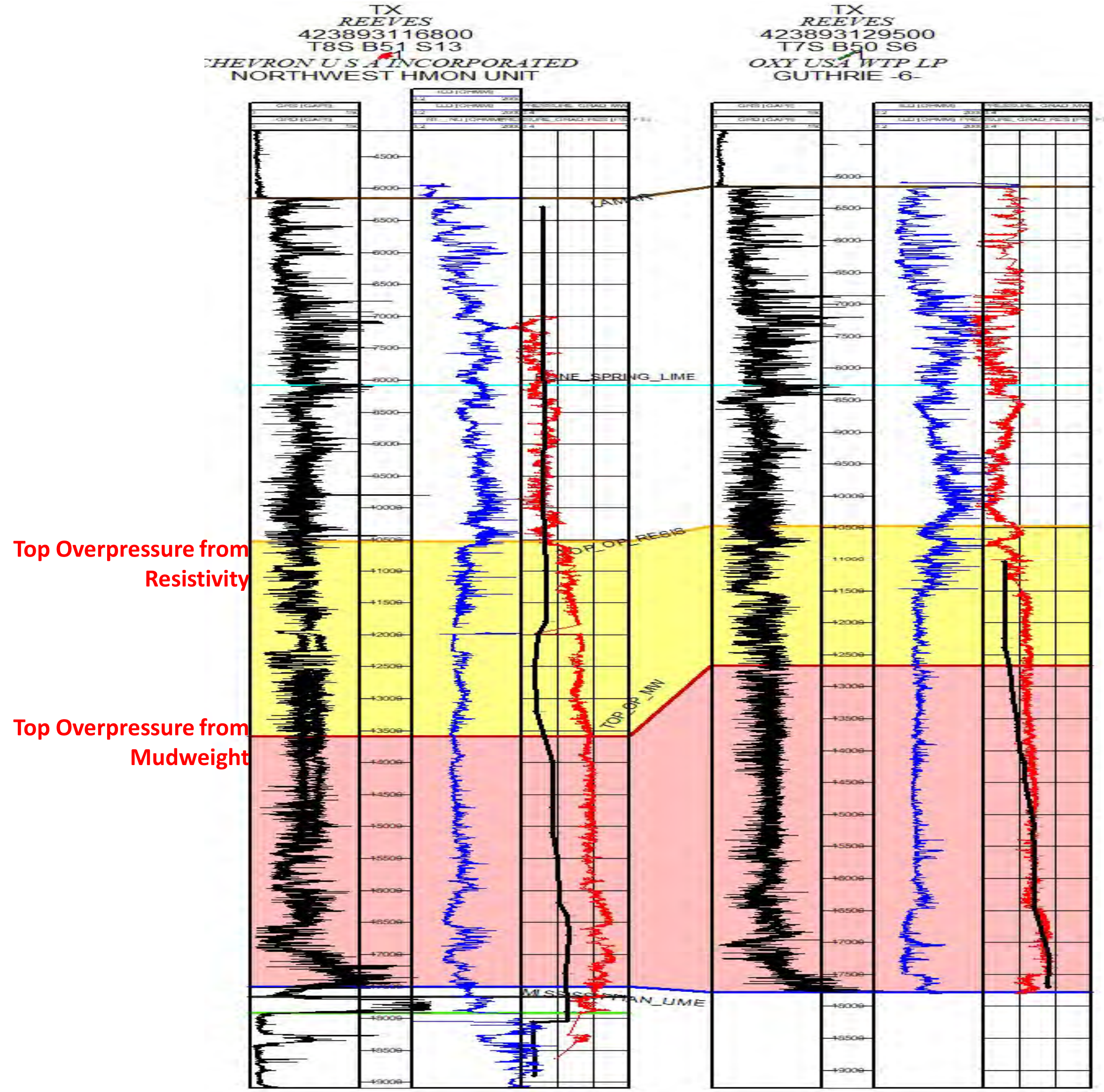
.... Continue to compute Pressure Gradient from Observed Resistivity Values for entire log depth, then graph it

(***different for each well - HAND PICK shallow resistivity trend line for each well)

AAPG ACE 2019 ANNUAL CONVENTION & EXHIBITION

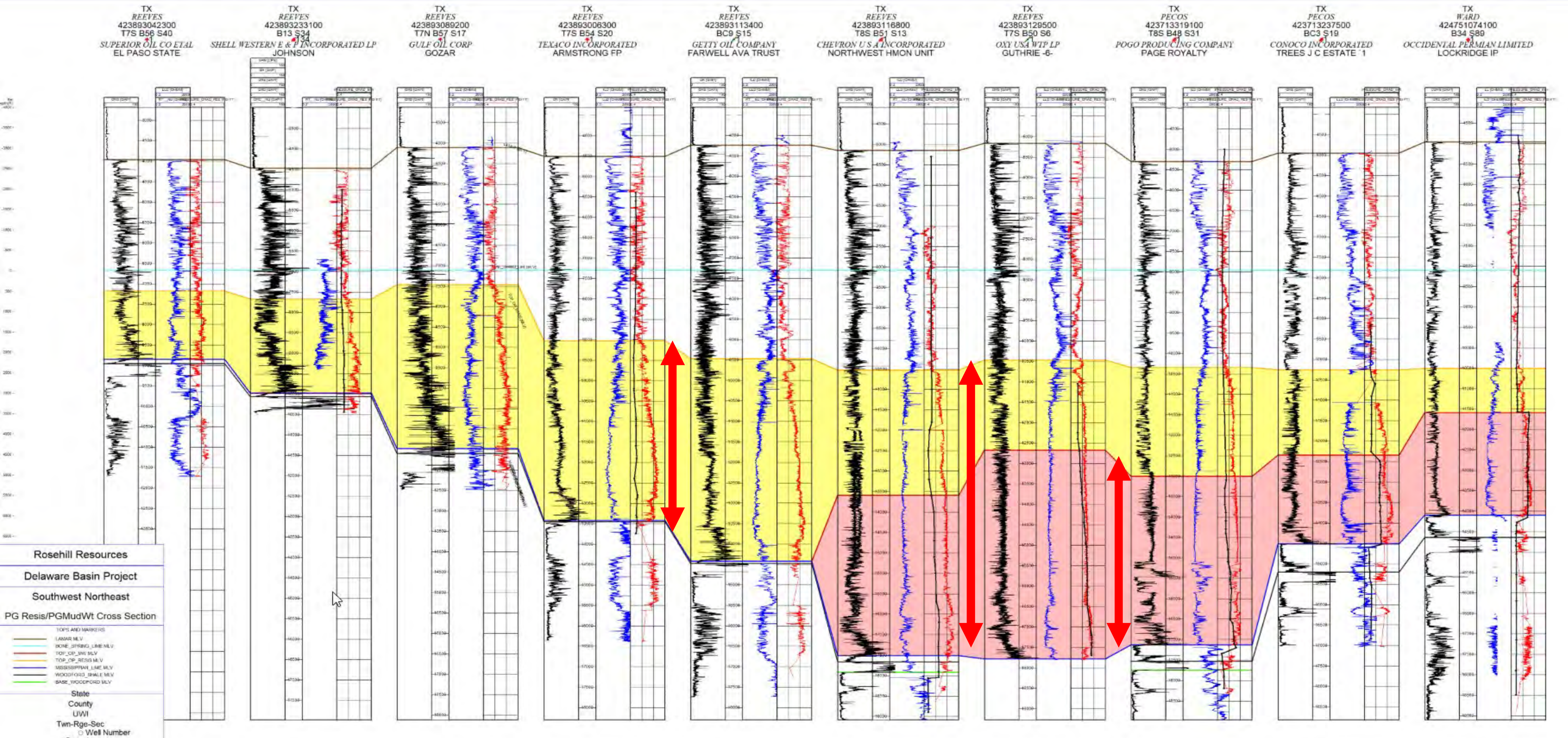
19-22 May • San Antonio, Texas





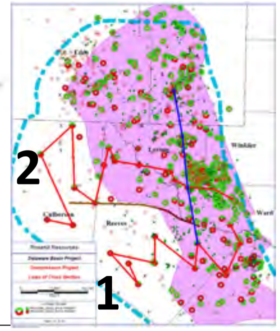
West East Cross Section 1

Datum Top Bone Spring Lime



AAPG ACE 2019 ANNUAL CONVENTION & EXHIBITION

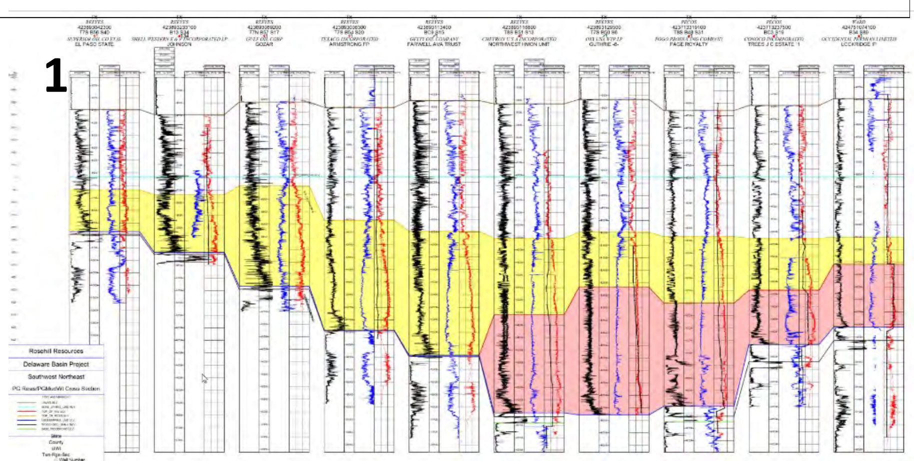
19-22 May • San Antonio, Texas

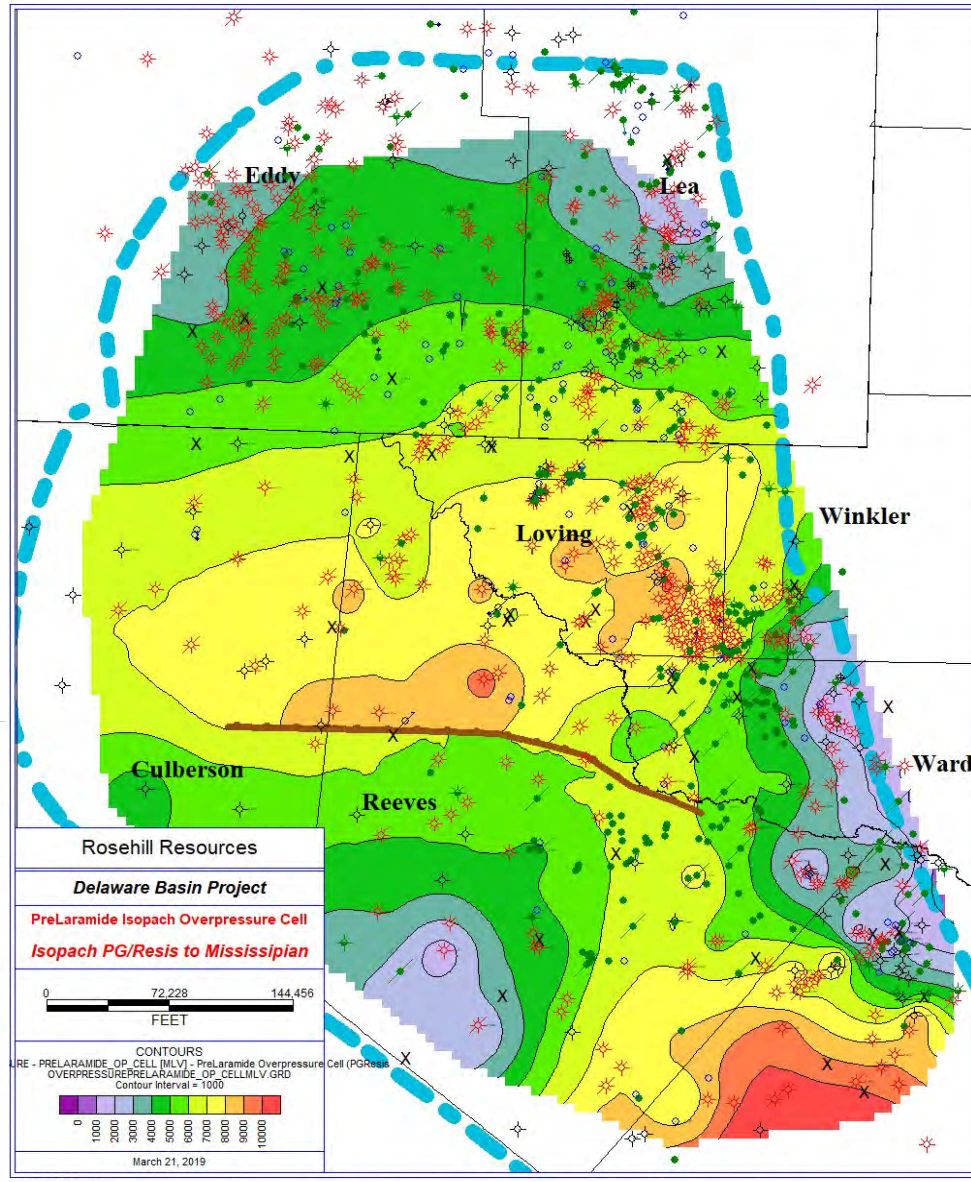


2

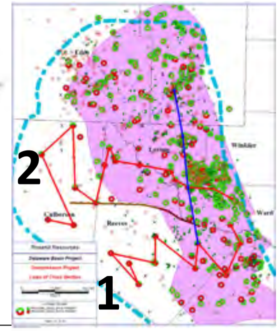
The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

1





AAPG ACE 2019 ANNUAL CONVENTION & EXHIBITION
19-22 May • San Antonio, Texas



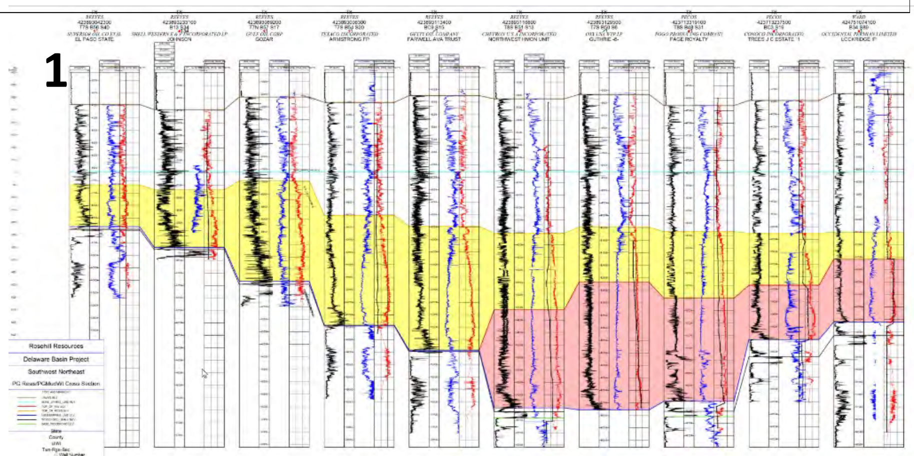
2

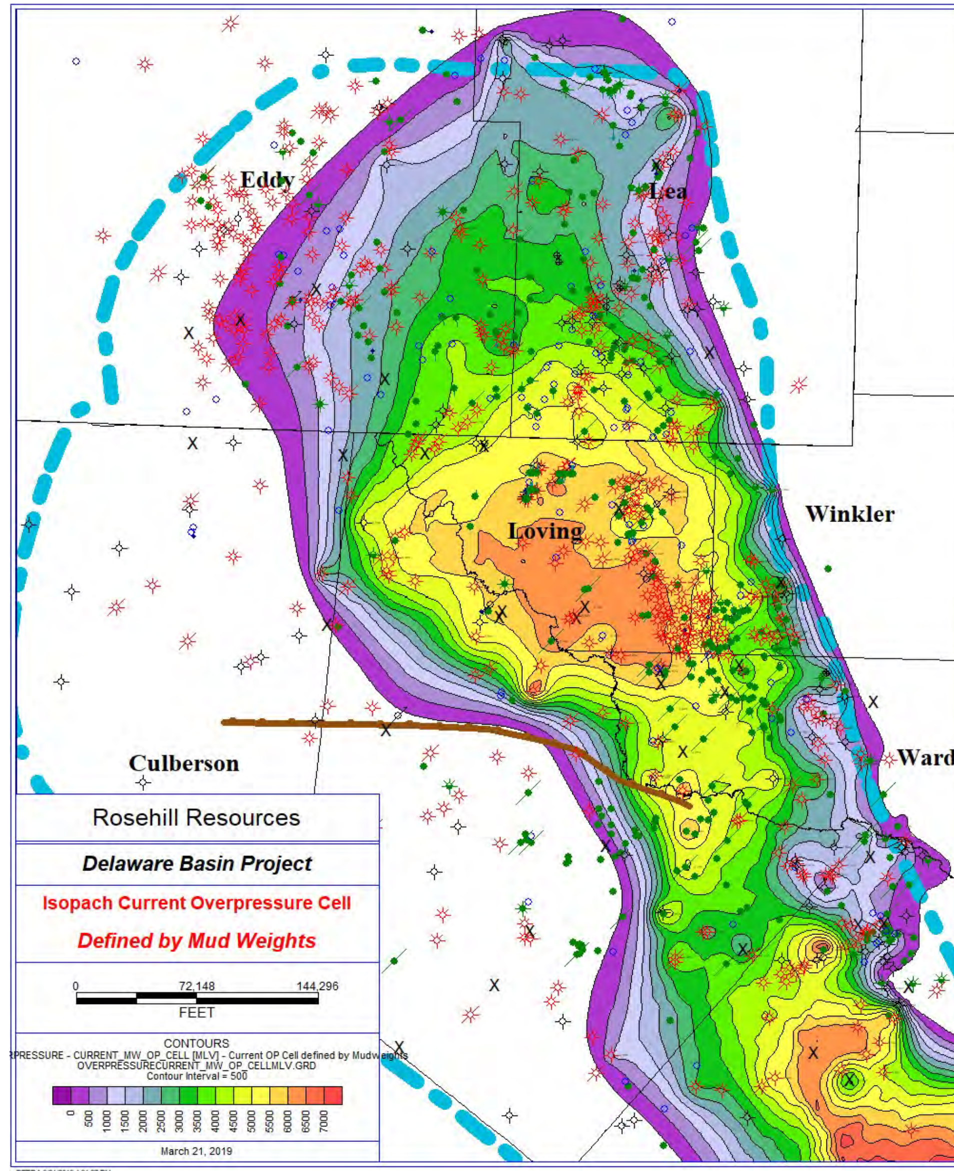
1

2

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

1

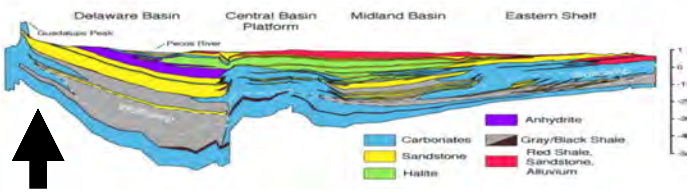


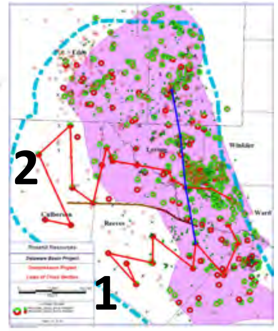


PETRA 3/21/2019 4:21:27 PM

AAPG ACE 2019 ANNUAL CONVENTION & EXHIBITION

19-22 May • San Antonio, Texas



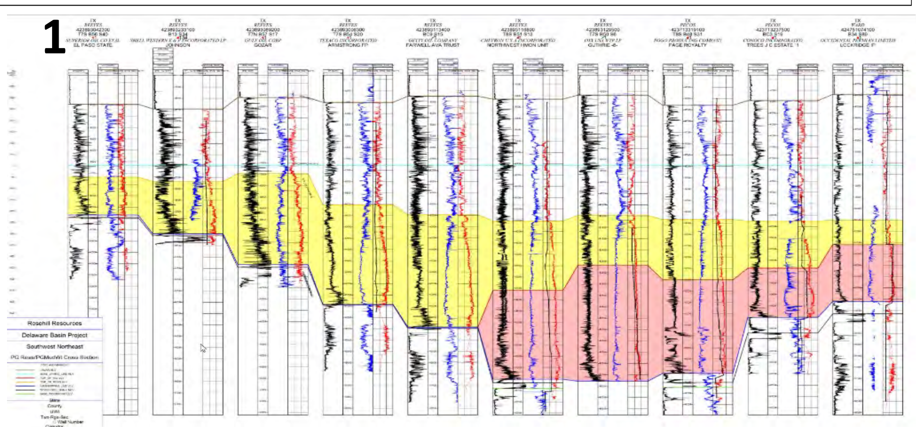


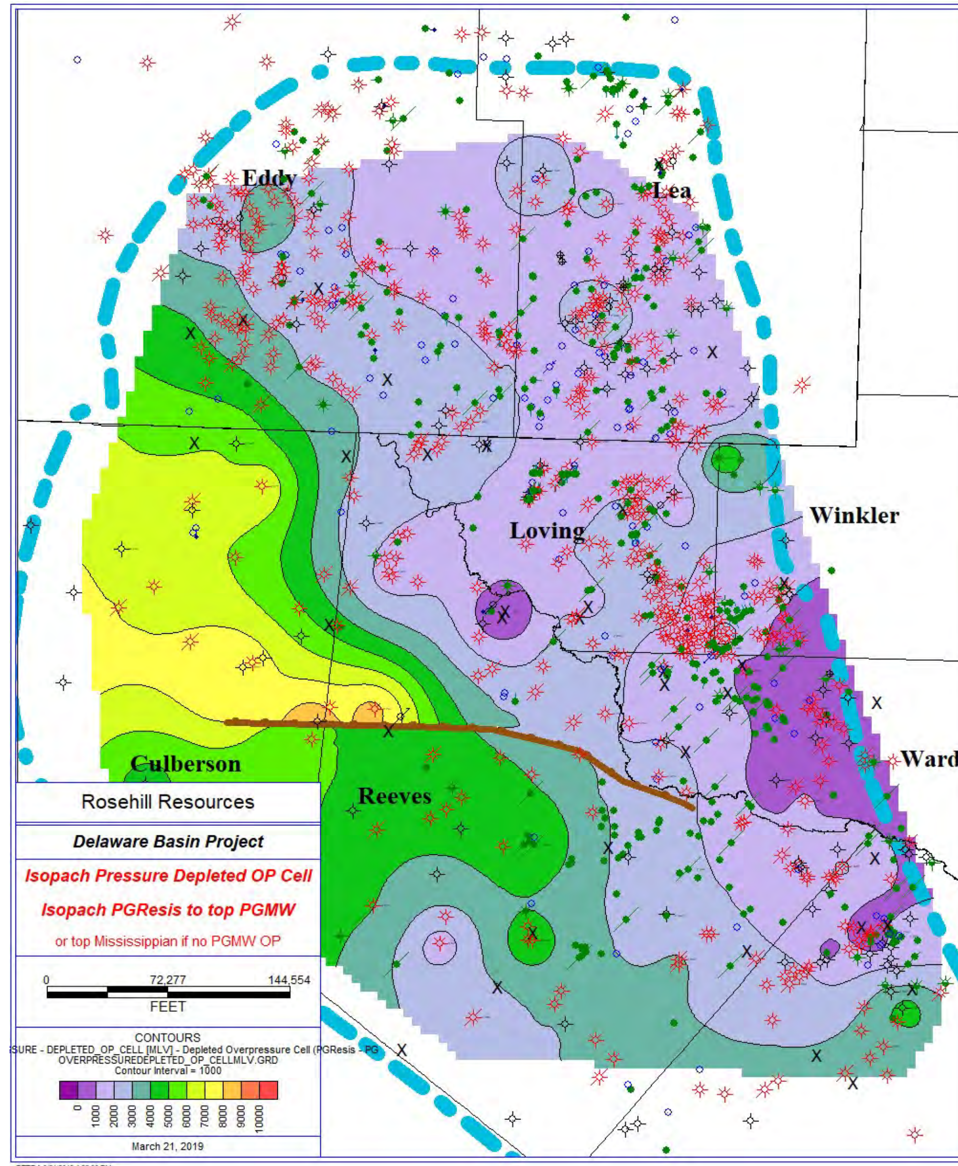
2

1

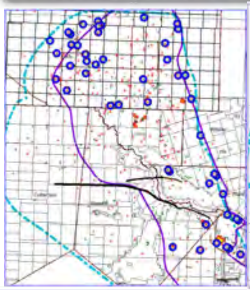
2

1





Anadarko Basin



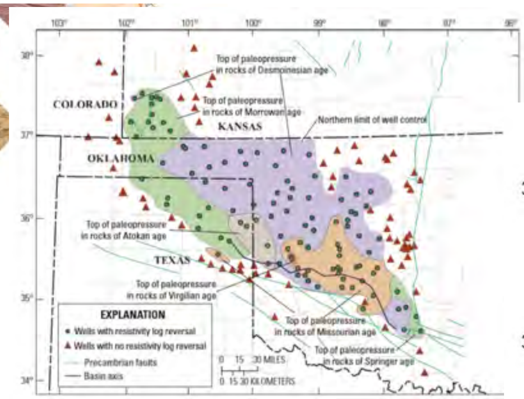


Figure 14. Map of age of rock unit containing top of paleopressure, based on the depth where the resistivity log changes from increasing downwards to decreasing downwards. T green area includes rocks of either Morrowan or Springer age, or both.

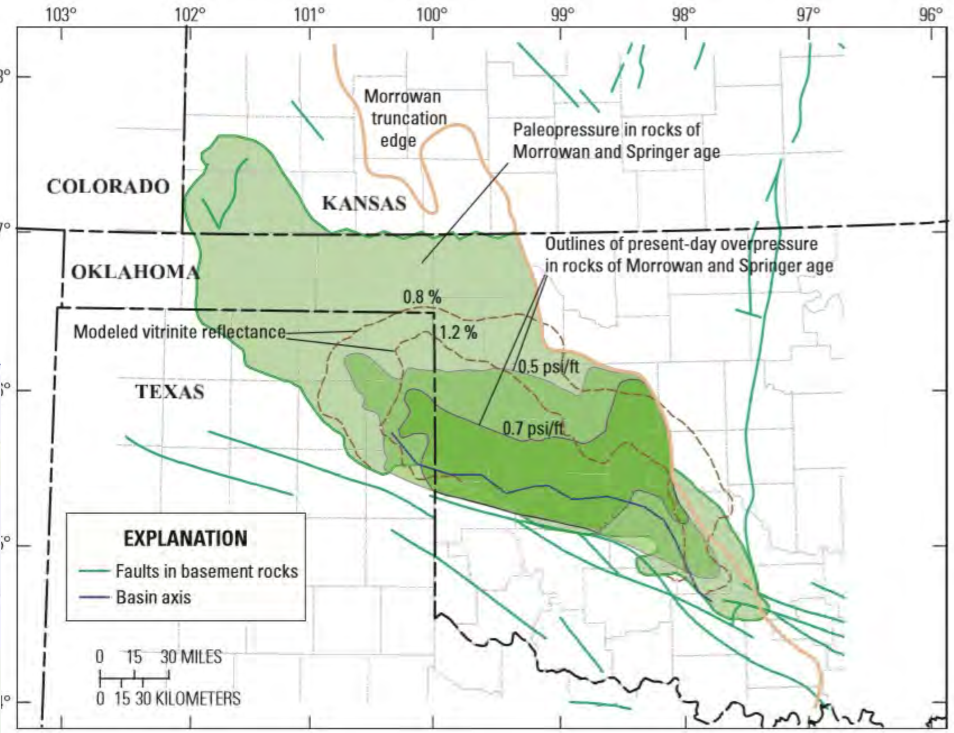
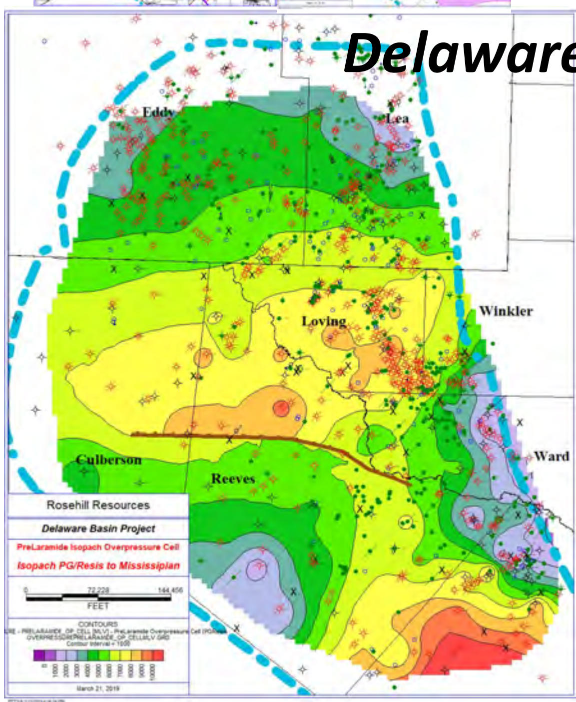
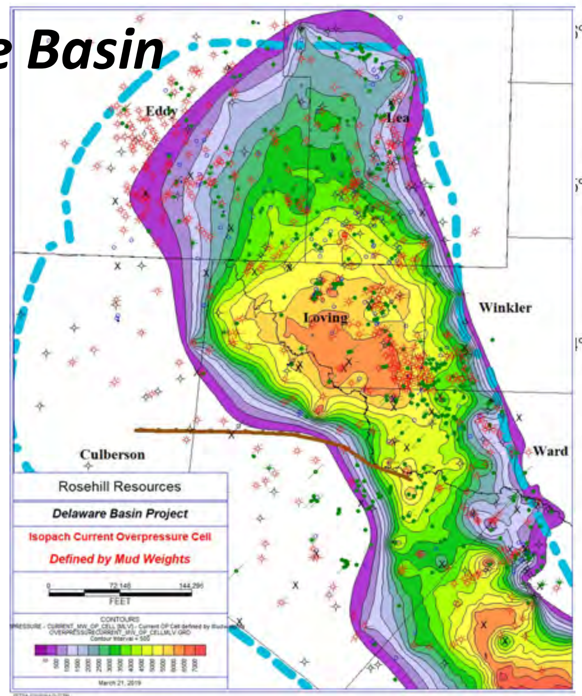


Figure 15. Map showing extents of paleopressure and overpressure in rocks of Morrowan and Springer age. The extent of the paleopressure indicator from resistivity logs is derived from figure 14 and the extent of present-day overpressure from pressure data is taken from figure 7. Modeled vitrinite reflectance contours of 0.8 and 1.2 percent for source rocks of Thirteen Finger lime of Atokan age taken from Higley (chapter 7 of this report).

Delaware Basin





- **Compared DST Pressure data to Resistivity data to Mud Weight data**
  - **DST derived PG psi/ft, MW derived PG psi/ft, Resistivity Normal/Resistivity Overpressured derived PG psi/ft**
- **Conclusions -- Overpressure has been depleted in Western Delaware Basin due to Laramide uplift and erosion, similar to the Anadarko Basin**

AAPG ACE2019 ANNUAL CONVENTION & EXHIBITION
19-22 May • San Antonio, Texas

Thank You!
Any Questions?

ROSEHILL OPERATING

Thanks to Brian Ayers,
VP Geology/ VP Business Development
Rosehill Operating, Houston TX