Production Focused Seismic – Applying Seismic for Well Productivity Analysis and Completion Optimization*

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Search and Discovery Article #41212 (2013)**
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Discussion

Modeling of productivity bypasses prediction of porosity, water saturation, and other variables that are more directly related to reservoir productivity

Well Productivity and Prospectivity Analysis (WPPA) Workflow

- There is a heavy reliance on statistics
  - Need to ensure that you have enough data to have robust correlations and models
  - Stationarity Assumption
- Just because you get a good correlation coefficient doesn't mean that you have a good model!
  - Outliers
  - Over-fitting of the data
    - Too many variables in the model
    - Be sparse with the number of variables versus the number of independent observations
  - Extracting attributes and building models using multiple observations along the wellbore (3D attribute and production values) produces consistently more reproducible models than averaging the attributes for each well (2D attribute and production values).

Accurate velocity models for depth conversion are critical to correlate seismic attributes to production intervals at the right depth

Studies we have done show the importance not only of having the right (X, Y) location for a well, but the correct layer and stratigraphic depth

- There are variations in productivity in 3D
- Not all stages along the reservoir path will be productive
  - Have a tool to predict productivity

Weigh the cost of fracing the stage versus the revenue from the expected production
Design the completion to optimize the profitability of the well

Selected References

Lock, B.E., and L. Peschier, 2006, Boquillas (Eagle Ford) upper slope sediments, West Texas: Outcrop analogs for potential shale reservoirs: GCAGS Transactions, p. 491-508.

Martin., R., J. Baihly, R. Malpani, G. Lindsay, and W.K. Atwood, 2011, Understandin production from Eagle Ford – Austin chalk system: SPE 145117.

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Callarotti, G.F., and S.F. Millican, 2012, Openhole multistage hydraulic fracturing systems expand the potential of the Austin Chalk: SPE 152402.

Laubach, S.E., J.E. Olson, and M.R. Gross, 2009, Mechanical and fracture stratigraphy: AAPG Bulletin, v. 93/11, 1413-1426.

Corbett, K., M. Friedman, and J. Spang, 1987, Fracture development and mechanical stratigraphy of Austin Chalk, Texas: AAPG Bulletin, v. 71/1, p. 17-28.

Production-focused Seismic - Applying Seismic for Well Productivity Analysis and Completion Optimization

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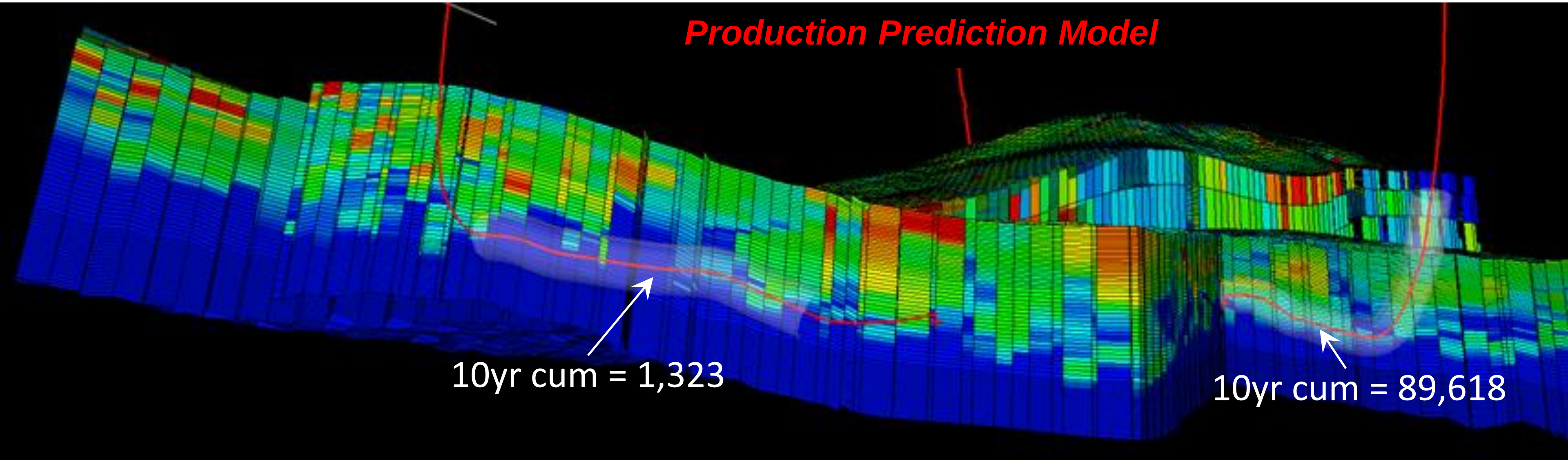
AAPG Workshop
August 6-7, 2013

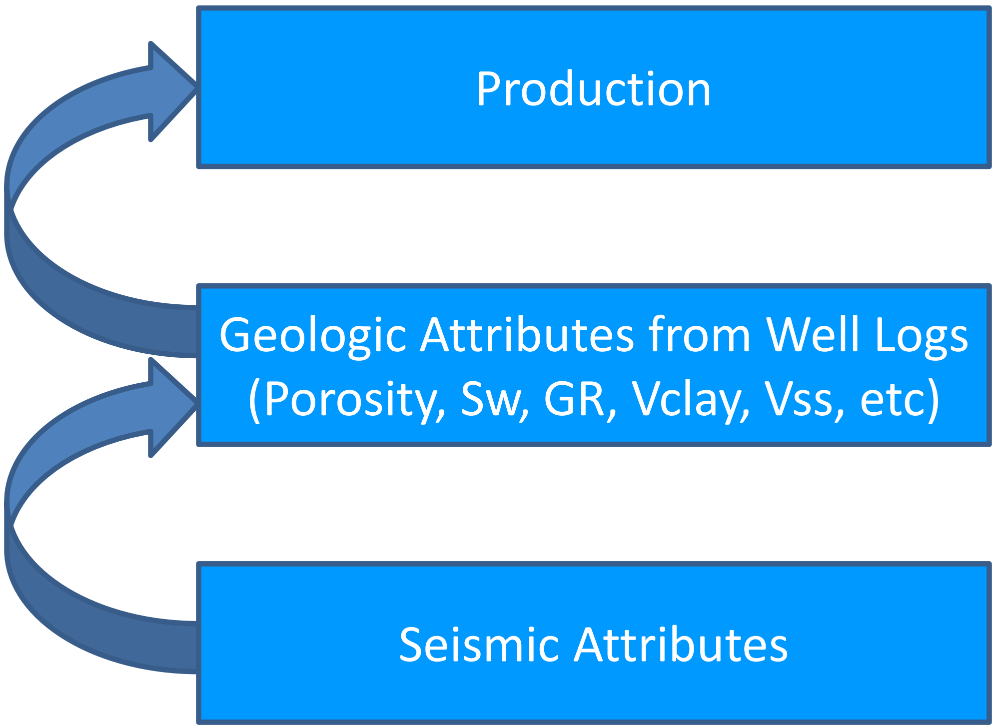


Outline

- Goals
- Assumptions
- Workflow
  - Seismic Attributes
  - Pre-Stack Inversion
  - Velocity Model for Depth Conversion
  - Multi-Attribute Analysis
  - Well Placement
- Example
- Discussion

Goals in the Workflow

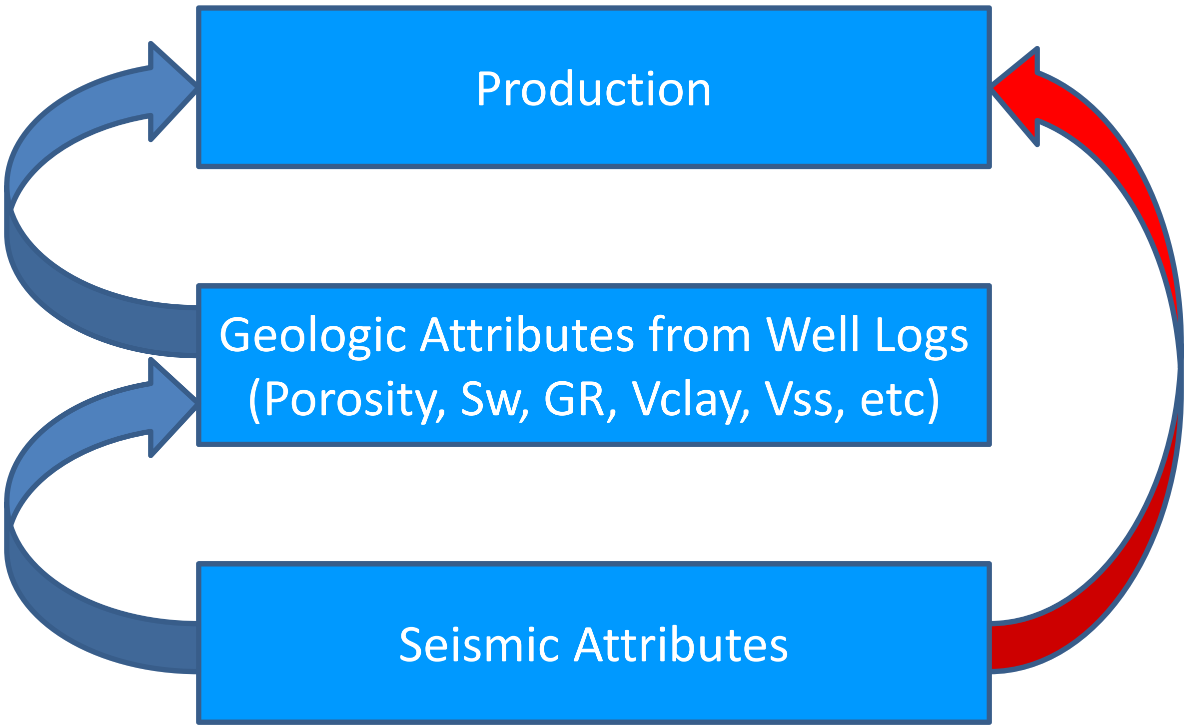
A ***VERY*** simplified overview of the process…



Goal is to understand production ($$$)

Goals in the Workflow

A ***VERY*** simplified overview of the process…



We look for direct seismic attribute correlation to production (i.e., **Proxies for Producibility**)

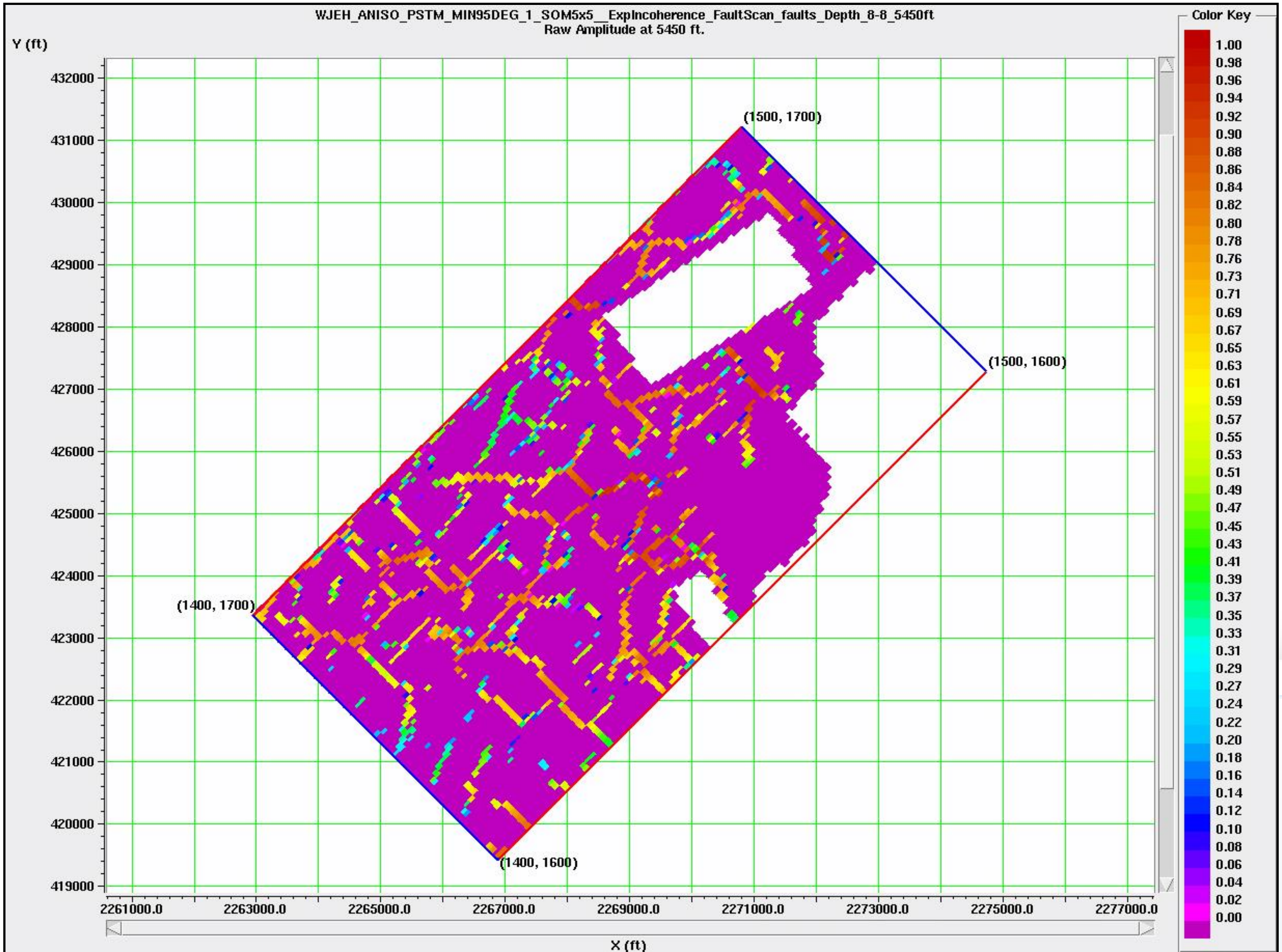
Assumptions

- You have enough independent observations from well data to build robust statistical models
  - Possibility of false correlations when using
    - Too little data
    - Too many attributes
- Stationarity assumption
  - Statistics are the same at all points in space and time

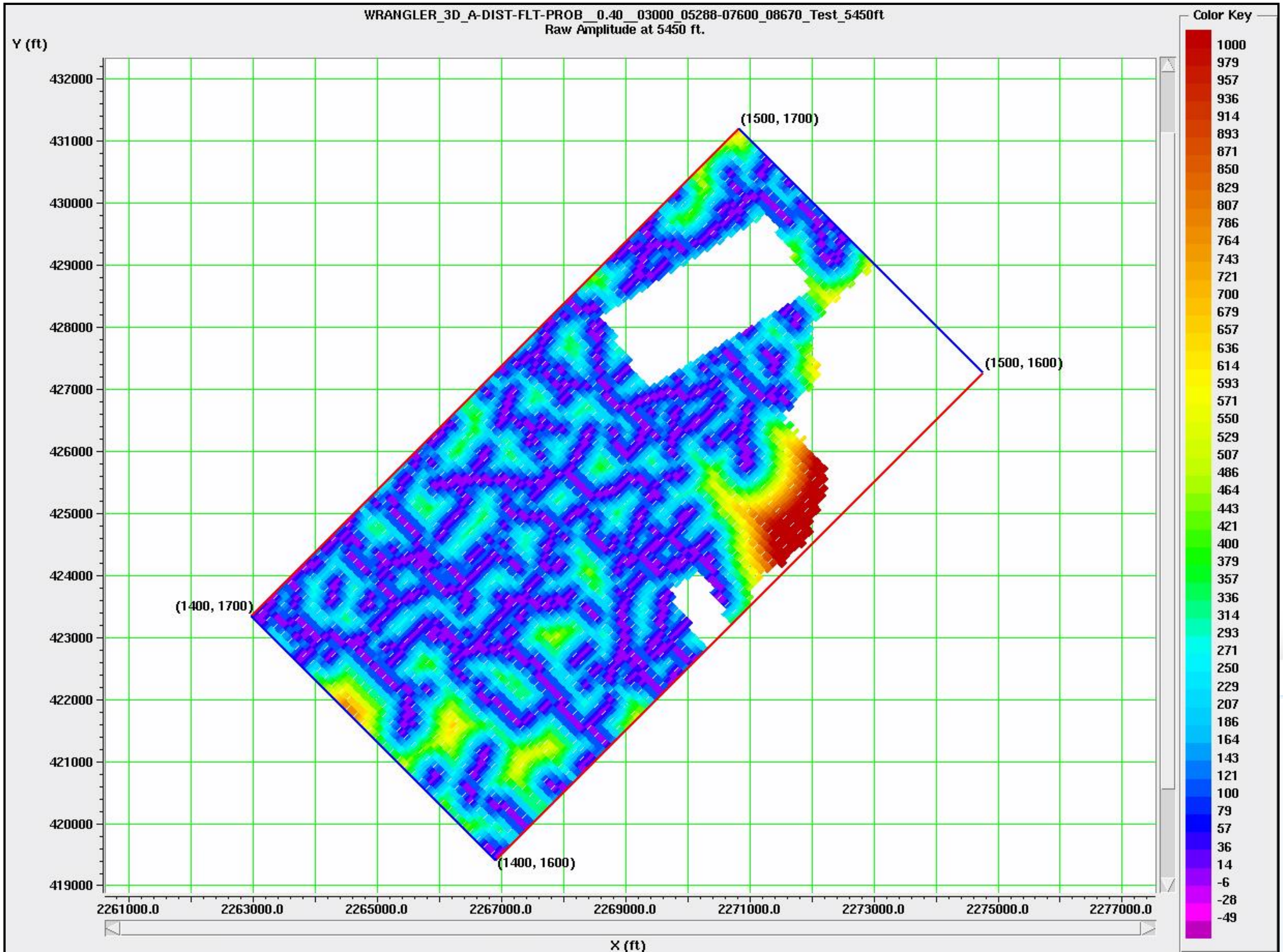
Seismic Attributes

- Attributes calculated on the seismic stack
- Curvature & Incoherence highlight discontinuities in the seismic volume
- Fault Scan uses incoherence as input
- Distance from faults uses the fault scan attribute as input
- Spectral Decomposition attributes appear to be related to zone thicknesses

Depth Slice from the Fault Probability Volume



Depth Slice from the Distance to Fault Volume (Threshold = 0.4)



Pre-Stack Inversion

- Gather Conditioning of offset gathers
- Conversion to angle gathers
- Angle dependent wavelet extraction
- Background Model Building with both wells-only and seismic velocity background models
- Pre-stack Inversion
  - Acoustic Impedance
  - Shear Impedance
  - Density
- Post-Inversion processing
  - Young's Modulus
  - Shear Modulus (Rigidity)
  - Bulk Modulus
  - Lambda, Lambda-Rho, Mu, Mu-Rho
  - Poisson's Ratio
  - Vp/Vs Ratio
  - Relative attributes of all of the above

Velocity Model for Depth Conversion

- Seismic attributes are frequently in the time domain, and wells are in depth
- Need accurate depth models for Well Productivity and Production (WPPA) analysis
  - Correlate seismic attributes with production
  - Use seismic attributes over completed well intervals
  - Completed well intervals must correlate with the seismic volumes to be valid
- Build velocity model that incorporates:
  - The well to seismic ties
  - The seismic velocity field
  - ***Tops at wells that aren't tied to the seismic***

Frequently have only a few wells that you have tied to the seismic, but there can be many wells with logs and tops in depth

Multi-Attribute Analysis

- Goal is to predict production attributes using seismic and other volume-based attributes over the completed intervals
- Works with depth volumes
  - All inversion attribute volumes
  - All structural attribute volumes

Can have 60 to 100+ seismic attribute volumes from various sources

- Remove independent variables that are correlated with each other
- Extract attributes along the wellbore and use these log-scale values to build the statistical model (3D Data (X, Y, Z))
- Produce ***multiple*** productivity models (3D volumes) using different combinations of attributes
  - ***Extract the productivity model values at the well locations to verify the model!***
  - Average the models to derive a most likely model
- Need a way to sort through all of the independent variables to quickly find a combination that produces a robust model
  - Step-wise regression with blind well testing

Stepwise Regression with Blind Well Testing

- A tool to quickly sort through many combinations of attributes to find those that best predict productivity
  - Stepwise Regression
  - Incorporates Blind well testing
    - Produces statistics to limit the number of variables that are input into the model
    - Ensures a more robust model that has predicted wells that weren't used to build the model
- Can be used to identify outliers to be eliminated
- Converts the independent variables (seismic attributes) using various parametric, non-linear transforms

Stepwise Regression with Blind Well Testing

Advantages of the tool

- Can quickly sort through hundreds to thousands of variables to find the ones that are most relevant to the production indicator that you are trying to predict
- Actually gets the formula for the transform between the independent and dependent variables
  - Can use resulting formula in any software that has an attribute calculator
- Performs blind well testing
  - For every well, builds a model using (N-1) wells to predict the well that is left out.
    - Training RMS Error - The error between the predicted and actual dependent variable from the model using N-1 wells
    - Testing RMS Error – The error between the predicted and actual dependent variable from the model using the one well that was left out of the model
  - Allows the user to select a minimal set of independent variables to avoid over-fitting the data.

Example #1: Austin Chalk

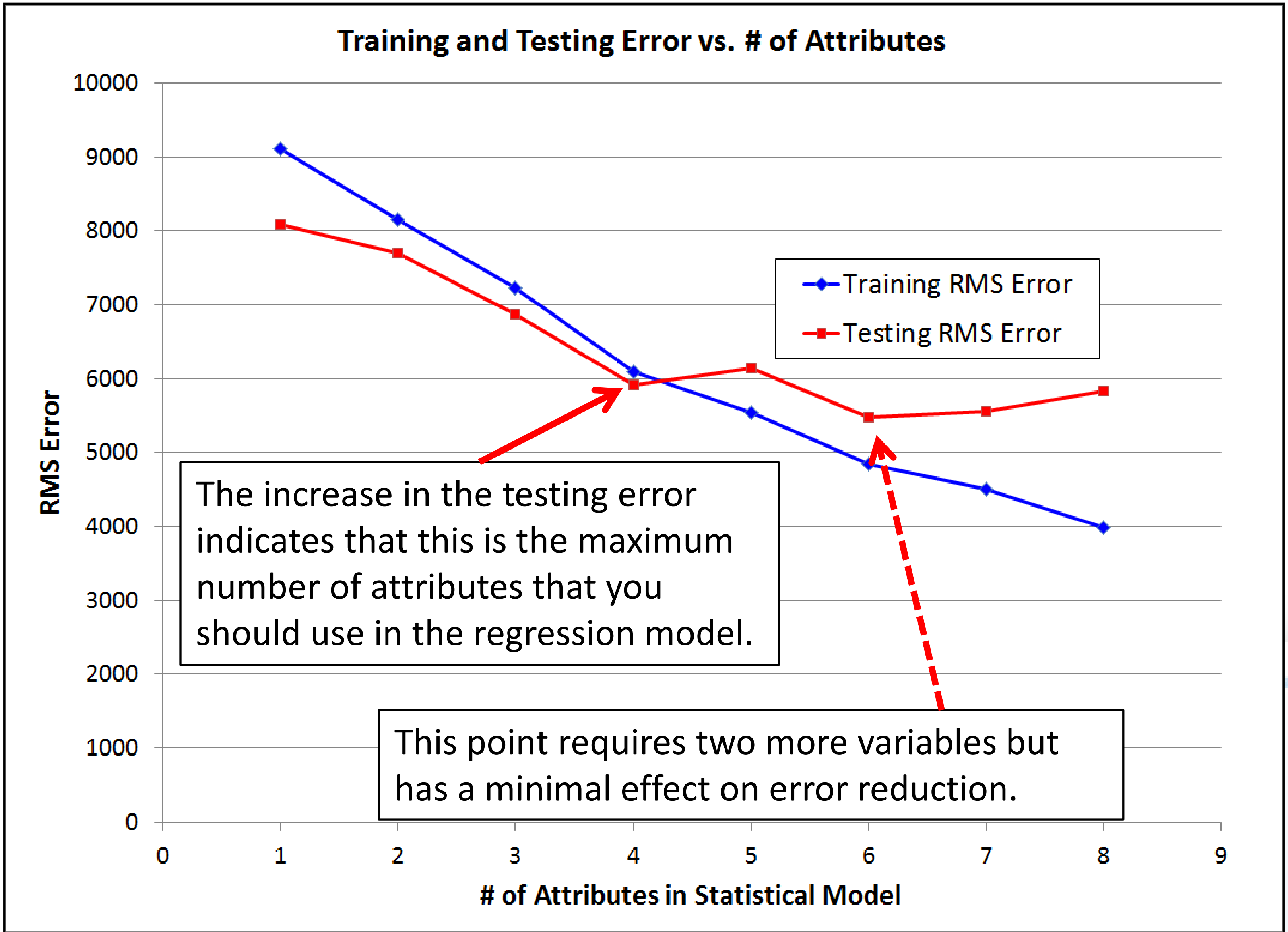
- 27 Wells
- Dependent Variable to predict
  - Well - Cum Oil 10 Yr Cum
- Independent Variables (58 Attributes):

Index	Variable Name
0	WBI Top MD (ft)
1	WBI Base MD (ft)
2	Angle - DownAngle
3	Angle - NorthAngle
4	Angle - EastAngle
5	SpecD - SpecD_22(Hz)
6	SpecD - SpecD_18(Hz)
7	SpecD - SpecD_10(Hz)
8	SpecD - SpecD_42(Hz)
9	SpecD - SpecD_66(Hz)
10	SpecD - SpecD_14(Hz)
11	SpecD - SpecD_34(Hz)
12	SpecD - SpecD_50(Hz)
13	SpecD - SpecD_26(Hz)
14	SpecD - SpecD_30(Hz)
15	SpecD - SpecD_38(Hz)
16	SpecD - SpecD_58(Hz)
17	SpecD - SpecD_62(Hz)
18	SpecD - SpecD_54(Hz)
19	SpecD - SpecD_46(Hz)

Index	Variable Name
20	Bulk Modulus
21	Mu
22	Acoustic Impedance
23	Vp/Vs
24	Mu Rho
25	Time Dip -dip
26	FracFactor
27	Dip
28	Density
29	Poisson's ratio
30	Time-domain Curvature - Krms
31	Time-domain Curvature - Kmin
32	Time-domain Curvature - Kpos
33	Time-domain Curvature - Kmean
34	Time-domain Curvature - Kneg
35	Time-domain Curvature - Kmax
36	Time-domain Curvature - Kmaxmag
37	Azimuth - HorzAng
38	Azimuth - Kmaxmag_azimuth
39	Azimuth - dip_azimuth

Index	Variable Name
40	Azimuth - Kmax_azimuth
41	Azimuth - Kmin_azimuth
42	Azimuth - PlungeAz
43	Azimuth - vfast_azimuth
44	Young's Modulus
45	Fault Probability
46	Amplitude - ANISO_PSTM_MIN95DEG
47	Amplitude - ANISO_PSTM_MIN95DEG)
48	Amplitude – ANISO_PSTM_MIN95DEG_1_SOM5x5
49	Elastic Impedance
50	Lambda Rho
51	Incoherence Probability
52	VelocityP(Interval)
53	Lambda
54	Dimensionless - Kshape
55	Dimensionless - planarity
56	Dimensionless - linearity
57	VelocityS(Interval)

Example #1: Austin Chalk



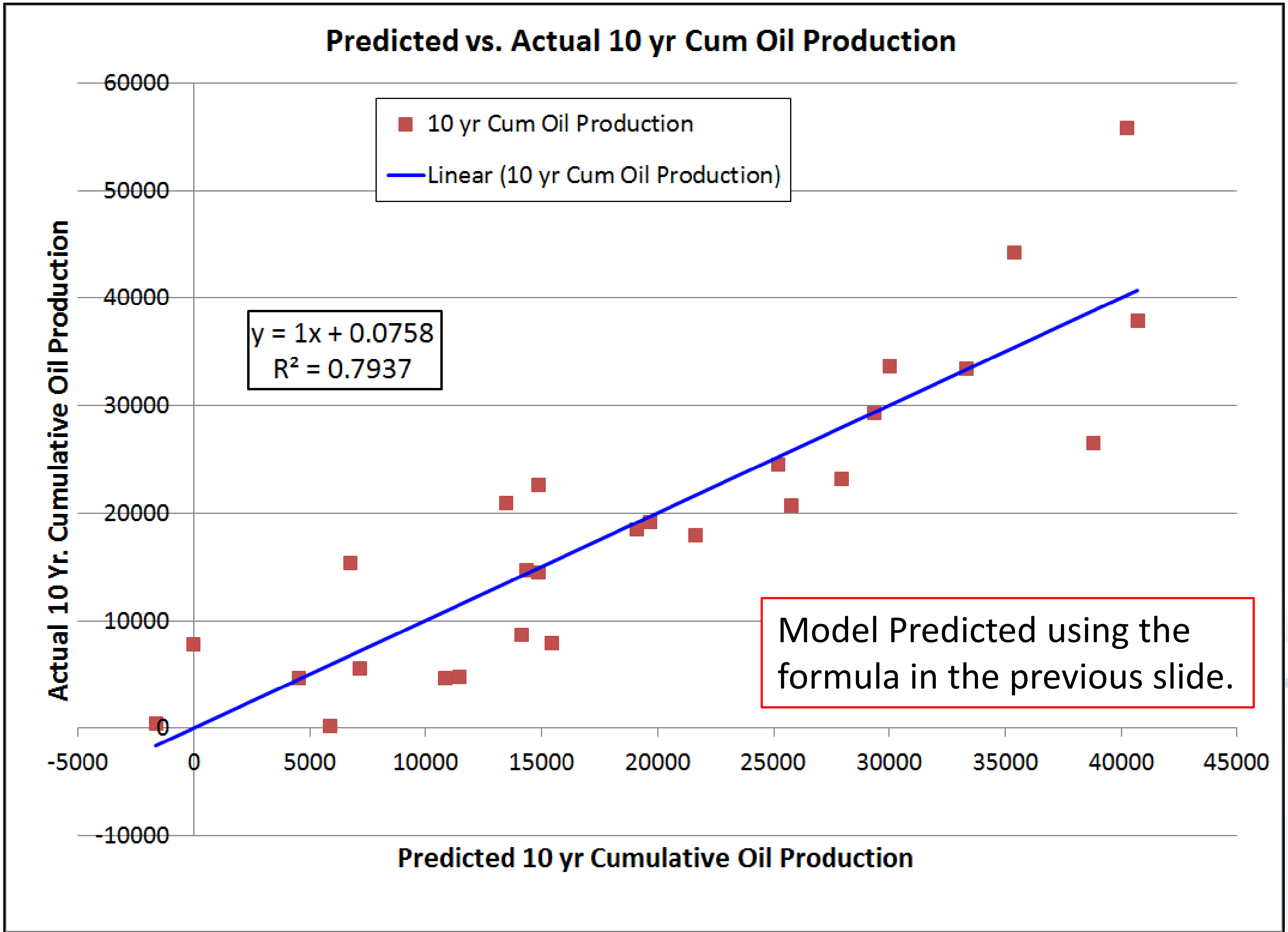
Example #1: Austin Chalk

- Model with **four** independent variables

Well - Cum Oil 10 Yr Cum =
(-3229.41 * Mu) +
(9502.65 * Ln (Fault Probability)) +
(13.2209 * (Azimuth - Kmax_azimuth)^2) +
(-27.5884 * (Azimuth - Kmaxmag_azimuth)^2) +
81012

Minimum Error = 6122.9
Correlation Coefficient (R) between the dependent and predicted Y variable = **0.891**

Example #1: Austin Chalk

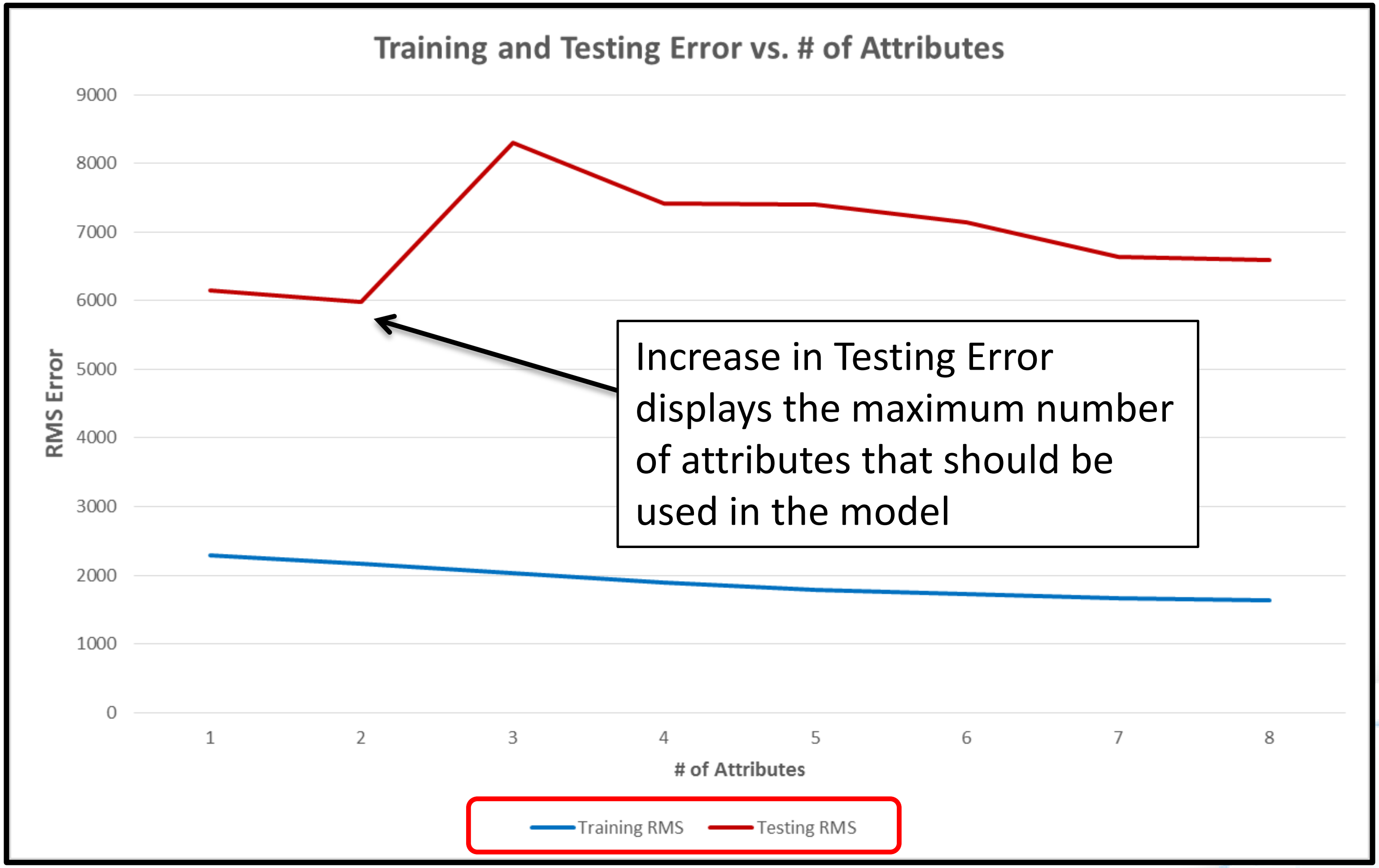


Example #2:
Stepwise Regression #1

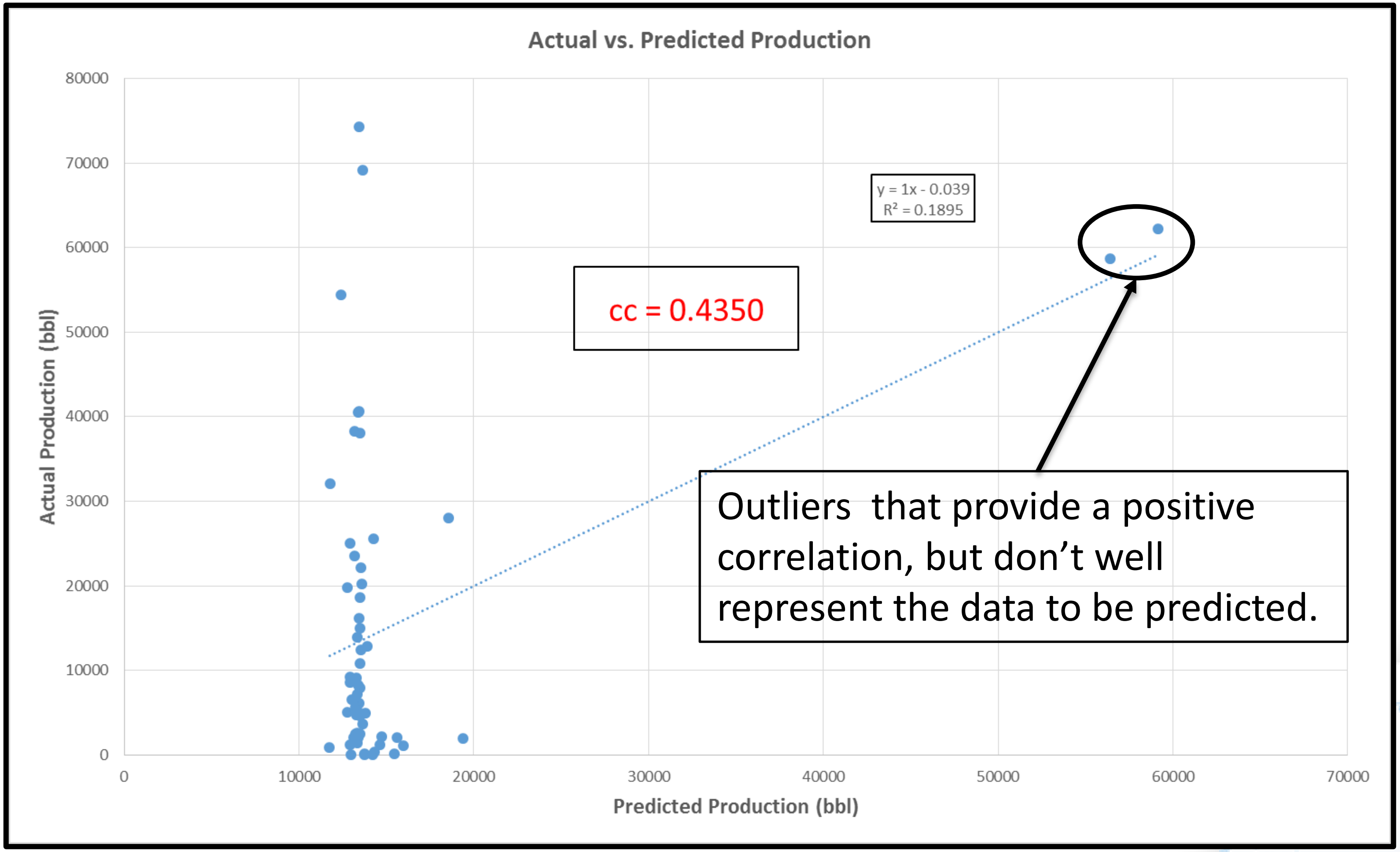
- 59 Vertical Wells
- Dependent Variable
  - Well – Cum Oil - 12-Month Cum Oil (bbl)
- Independent Variables (64 Attributes):

Acoustic Impedance	Fault Probability (Euc)	SpecD - SpecD_38(Hz) (Euc)
Amplitude -ANISO_PSTM_MIN95DEG (Euc)	Relative Shear Impedance (Pa.s/m3)	SpecD - SpecD_42(Hz) (Euc)
Amplitude - ANISO_PSTM_MIN95DEG_SOM5x5 (Euc)	Shear Impedance (Pa.s/m3)	SpecD - SpecD_46(Hz) (Euc)
Angle – Down Angle (dega)	Incoherence Probability (Euc)	SpecD - SpecD_50(Hz) (Euc)
Angle – East Angle (dega)	Lambda (GPa)	SpecD - SpecD_54(Hz) (Euc)
Angle – North Angle (dega)	Relative Lambda (GPa)	SpecD - SpecD_58(Hz) (Euc)
Anisotropy - vfast_mag (Euc)	Lambda Rho (GPa.g/cm3)	SpecD - SpecD_62(Hz) (Euc)
Azimuth - dip_azimuth (dega)	Relative Lambda Rho (GPa.g/cm3)	SpecD - SpecD_66(Hz) (Euc)
Azimuth - Kmax_azimuth (dega)	Mu (GPa)	Time Dip - dip (us/ft)
Azimuth - Kmaxmag_azimuth (dega)	Relative Mu (GPa)	Time-domain Curvature - Kdip (s/ft2)
Azimuth - Kmin_azimuth (dega)	Mu Rho (GPa.g/cm3)	Time-domain Curvature - Kmax (s/ft2)
Azimuth - vfast_azim (dega)	Relative Mu Rho (GPa.g/cm3)	Time-domain Curvature - Kmaxmag (s/ft2)
Azimuth - Horizontal Angle (dega)	Poisson's ratio (Euc)	Time-domain Curvature - Kmean (s/ft2)
Azimuth - Plunge_Azimuth (dega)	Relative Poisson's ratio (Euc)	Time-domain Curvature - Kmin (s/ft2)
Azimuth - dip_azimuth (dega)	Relative Acoustic Impedance (g.ft/cm3.s)	Time-domain Curvature - Kneg (s/ft2)
Bulk Modulus (psi)	SpecD - SpecD_10(Hz) (Euc)	Time-domain Curvature - Kpos (s/ft2)
Relative Bulk Modulus (psi)	SpecD - SpecD_14(Hz) (Euc)	Time-domain Curvature - Krms (s/ft2)
Relative Density (g/cm3)	SpecD - SpecD_22(Hz) (Euc)	Time-domain Curvature - Kstrike (s/ft2)
Density (g/cm3)	SpecD - SpecD_26(Hz) (Euc)	Time-domain Curvature Squared - Kgauss (s2/ft4)
Dimensionless - Kshape (Euc)	SpecD - SpecD_30(Hz) (Euc)	Young's Modulus (GPa)
Dimensionless - planarity (Euc)	SpecD - SpecD_34(Hz) (Euc)	Relative Young's Modulus (GPa)
Dip_SOM5x5 (dega)		

Example #2:
Training and Testing RMS Error



Example #2:
Actual vs. Predicted 12-Month Oil

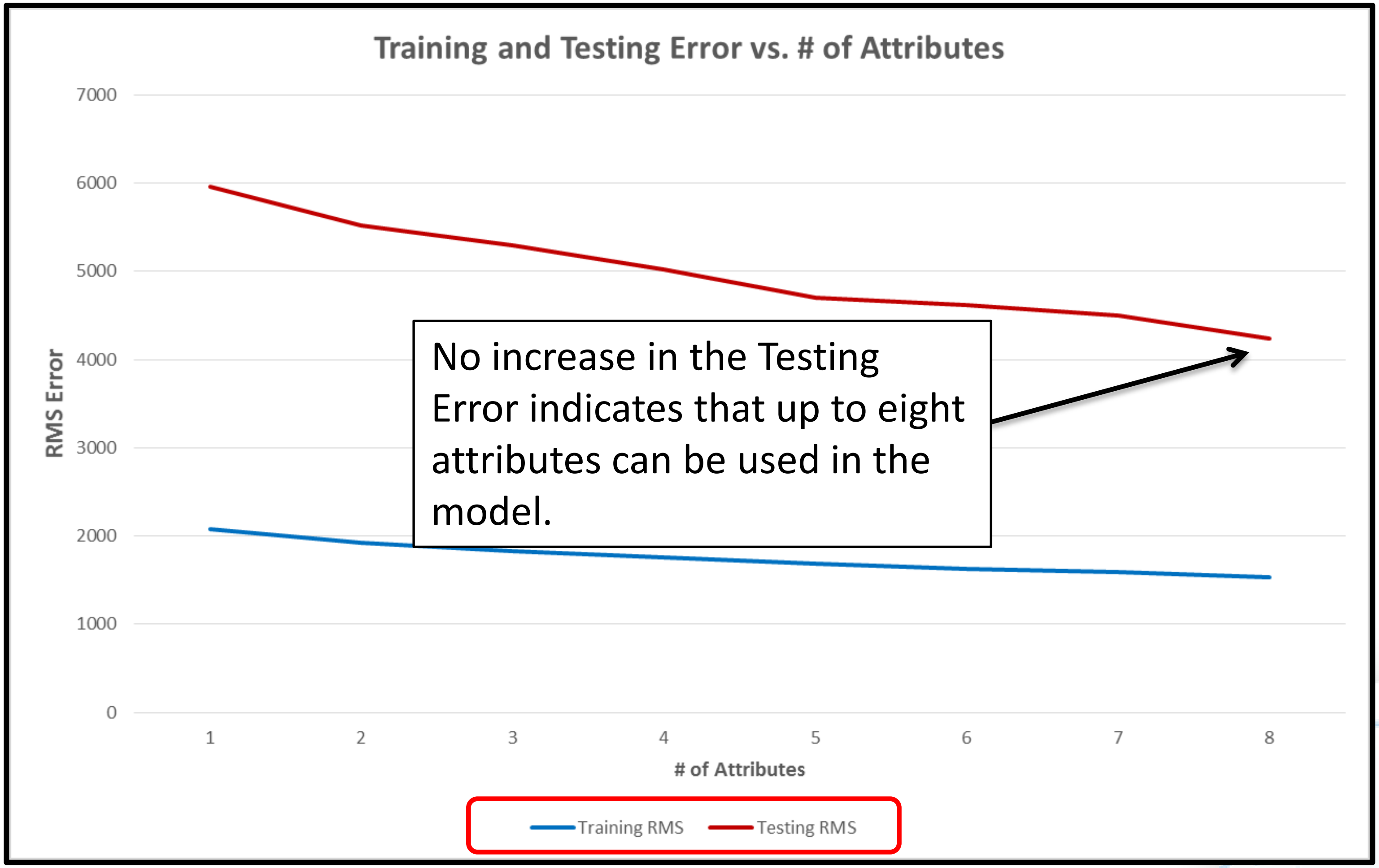


Example #2:
Stepwise Regression #2

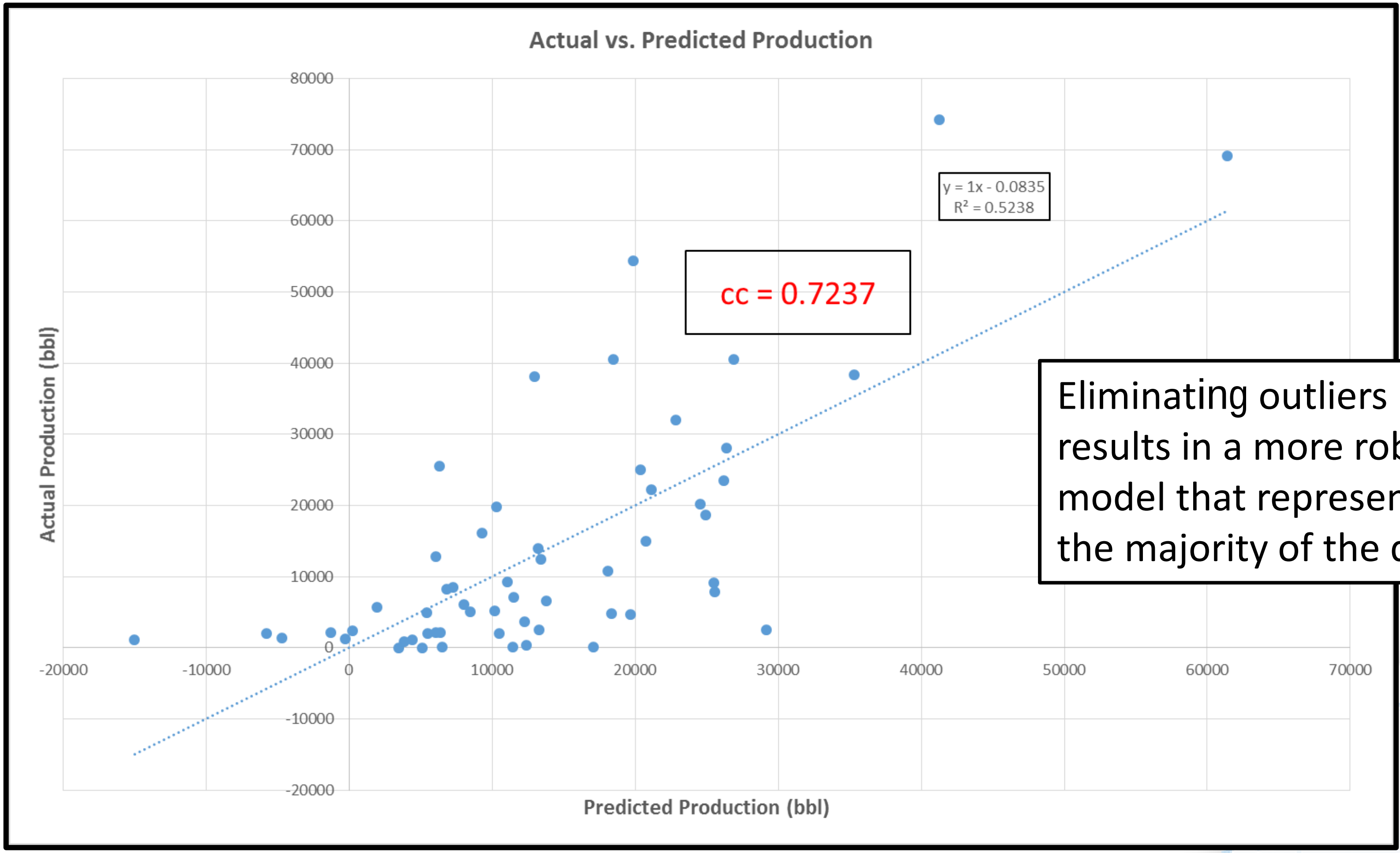
- 57 Vertical Wells
- Dependent Variable
  - Well – Cum Oil - 12-Month Cum Oil (bbl)
- Independent Variables (64 Attributes):

Acoustic Impedance	Fault Probability (Euc)	SpecD - SpecD_38(Hz) (Euc)
Amplitude -ANISO_PSTM_MIN95DEG (Euc)	Relative Shear Impedance (Pa.s/m3)	SpecD - SpecD_42(Hz) (Euc)
Amplitude - ANISO_PSTM_MIN95DEG_SOM5x5 (Euc)	Shear Impedance (Pa.s/m3)	SpecD - SpecD_46(Hz) (Euc)
Angle – Down Angle (dega)	Incoherence Probability (Euc)	SpecD - SpecD_50(Hz) (Euc)
Angle – East Angle (dega)	Lambda (GPa)	SpecD - SpecD_54(Hz) (Euc)
Angle – North Angle (dega)	Relative Lambda (GPa)	SpecD - SpecD_58(Hz) (Euc)
Anisotropy - vfast_mag (Euc)	Lambda Rho (GPa.g/cm3)	SpecD - SpecD_62(Hz) (Euc)
Azimuth - dip_azimuth (dega)	Relative Lambda Rho (GPa.g/cm3)	SpecD - SpecD_66(Hz) (Euc)
Azimuth - Kmax_azimuth (dega)	Mu (GPa)	Time Dip - dip (us/ft)
Azimuth - Kmaxmag_azimuth (dega)	Relative Mu (GPa)	Time-domain Curvature - Kdip (s/ft2)
Azimuth - Kmin_azimuth (dega)	Mu Rho (GPa.g/cm3)	Time-domain Curvature - Kmax (s/ft2)
Azimuth - vfast_azim (dega)	Relative Mu Rho (GPa.g/cm3)	Time-domain Curvature - Kmaxmag (s/ft2)
Azimuth - Horizontal Angle (dega)	Poisson's ratio (Euc)	Time-domain Curvature - Kmean (s/ft2)
Azimuth - Plunge_Azimuth (dega)	Relative Poisson's ratio (Euc)	Time-domain Curvature - Kmin (s/ft2)
Azimuth - dip_azimuth (dega)	Relative Acoustic Impedance (g.ft/cm3.s)	Time-domain Curvature - Kneg (s/ft2)
Bulk Modulus (psi)	SpecD - SpecD_10(Hz) (Euc)	Time-domain Curvature - Kpos (s/ft2)
Relative Bulk Modulus (psi)	SpecD - SpecD_14(Hz) (Euc)	Time-domain Curvature - Krms (s/ft2)
Relative Density (g/cm3)	SpecD - SpecD_22(Hz) (Euc)	Time-domain Curvature - Kstrike (s/ft2)
Density (g/cm3)	SpecD - SpecD_26(Hz) (Euc)	Time-domain Curvature Squared - Kgauss (s2/ft4)
Dimensionless - Kshape (Euc)	SpecD - SpecD_30(Hz) (Euc)	Young's Modulus (GPa)
Dimensionless - planarity (Euc)	SpecD - SpecD_34(Hz) (Euc)	Relative Young's Modulus (GPa)
Dip_SOM5x5 (dega)		

Example #2:
Training and Testing RMS Error



Example #2:
Actual vs. Predicted 12-Month Oil



Eliminating outliers results in a more robust model that represents the majority of the data

Modeling Production and Prospectivity in the Austin Chalk to Optimize Well Placement, Productivity and Completion Design

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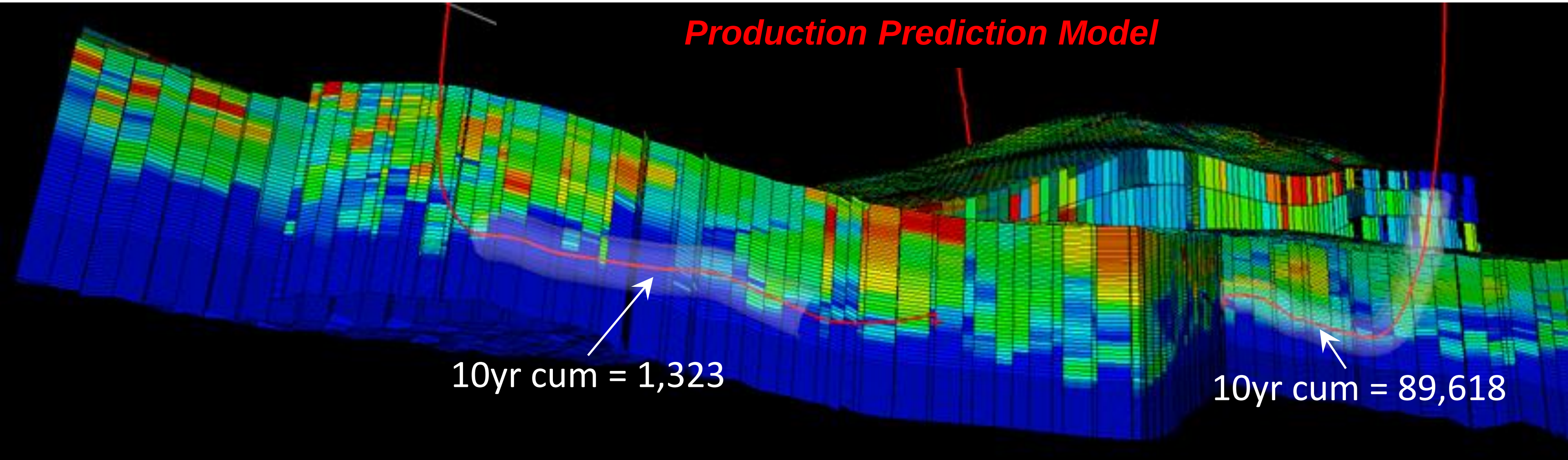
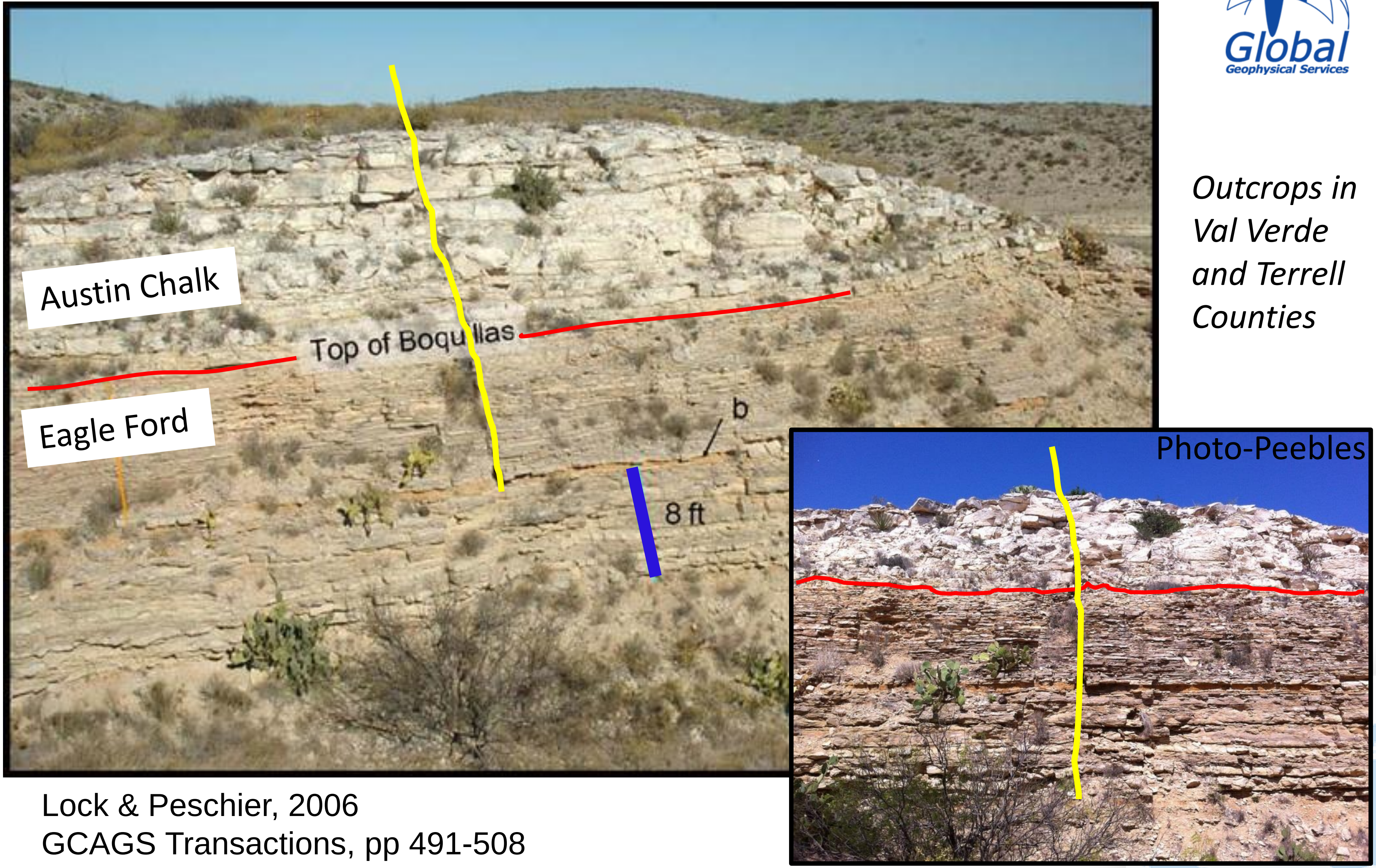
Sean Boerner & Rohit Singh
Global Geophysical



Austin Chalk - Eagle Ford Outcrop

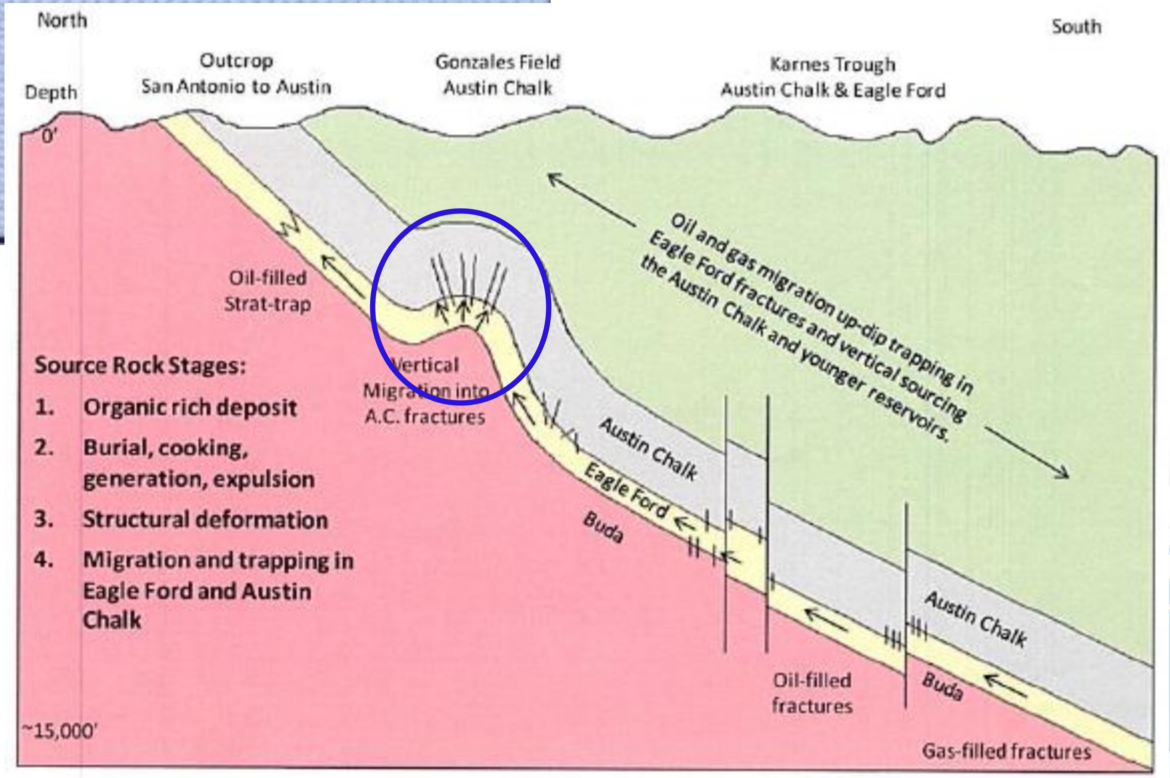


Outcrops in Val Verde and Terrell Counties

Lock & Peschier, 2006
GCAGS Transactions, pp 491-508

Austin Chalk traditional production

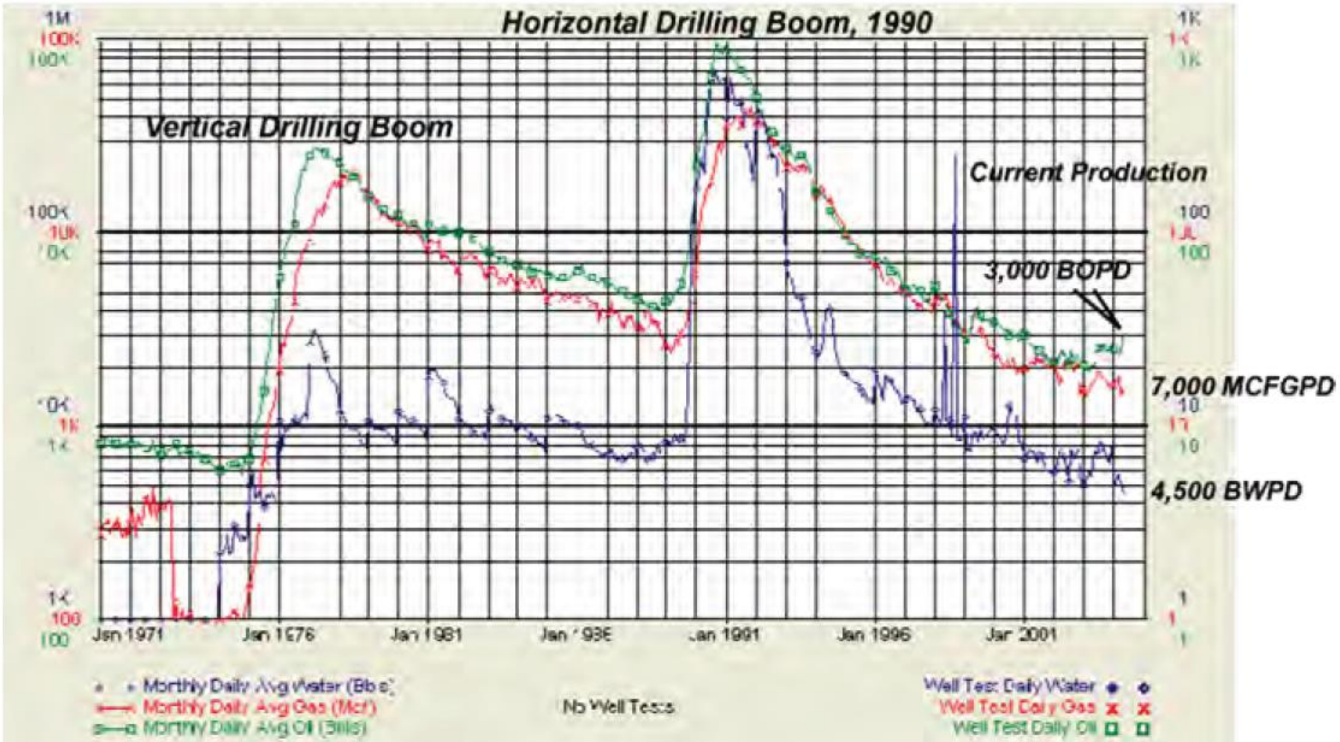
SPE 152402 - 2012



SPE 145117 – 2011; see also Berg & Gangi – 1999, AAPG v83 n5

Pearsall Field's Production History
A Tale of Two "Booms"

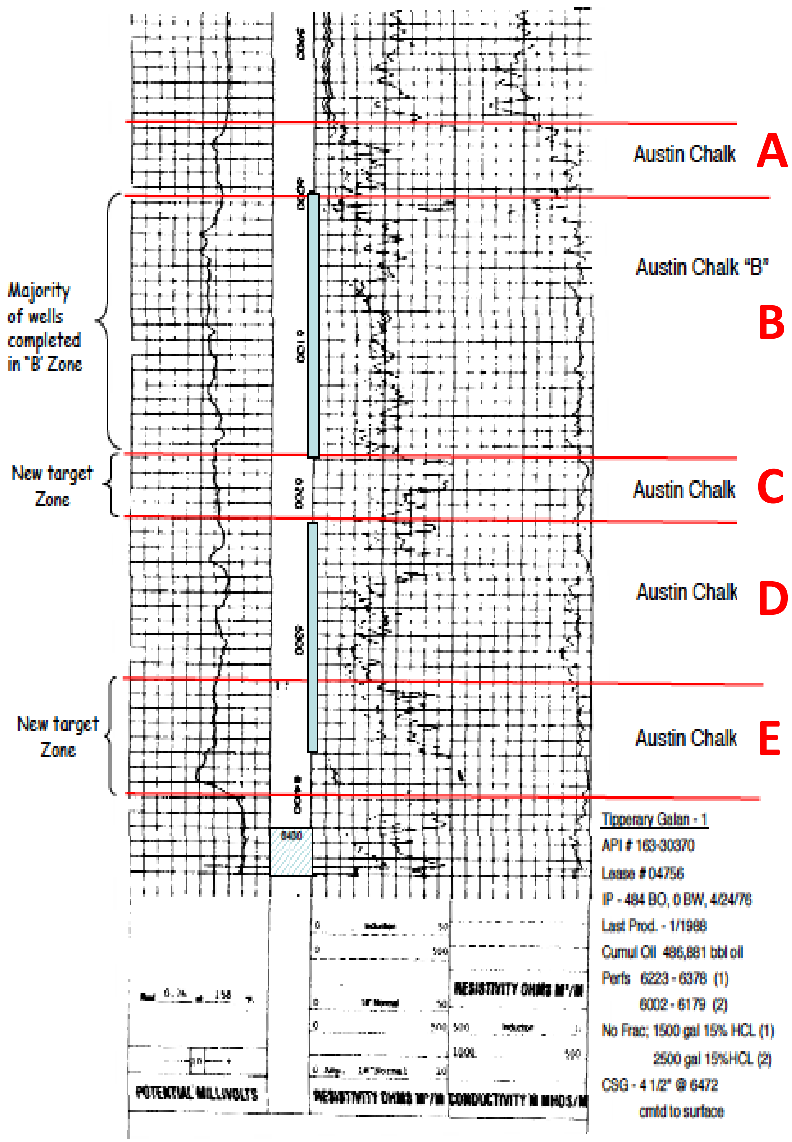
The Production History of Pearsall Field Since 1970
Rate - Time Plot (BOPD, MCFGPD, BWPD)



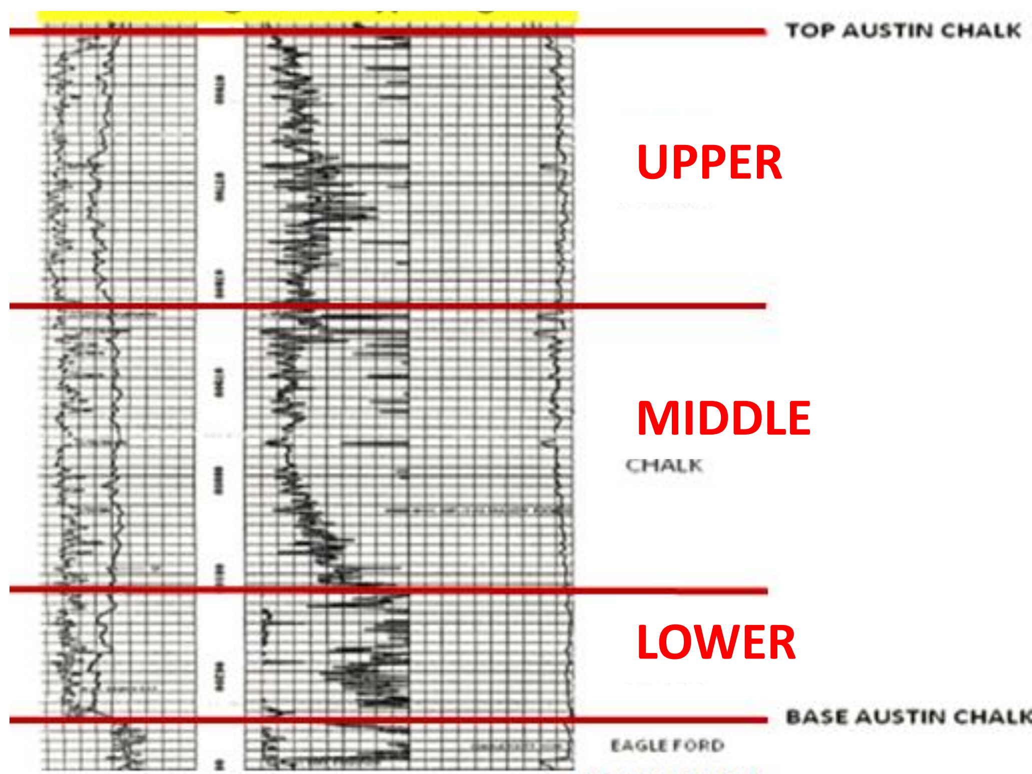
Pearsall Field
Frio County TX

Austin Chalk Stratigraphy

Tipperary #1 Enrique Galan

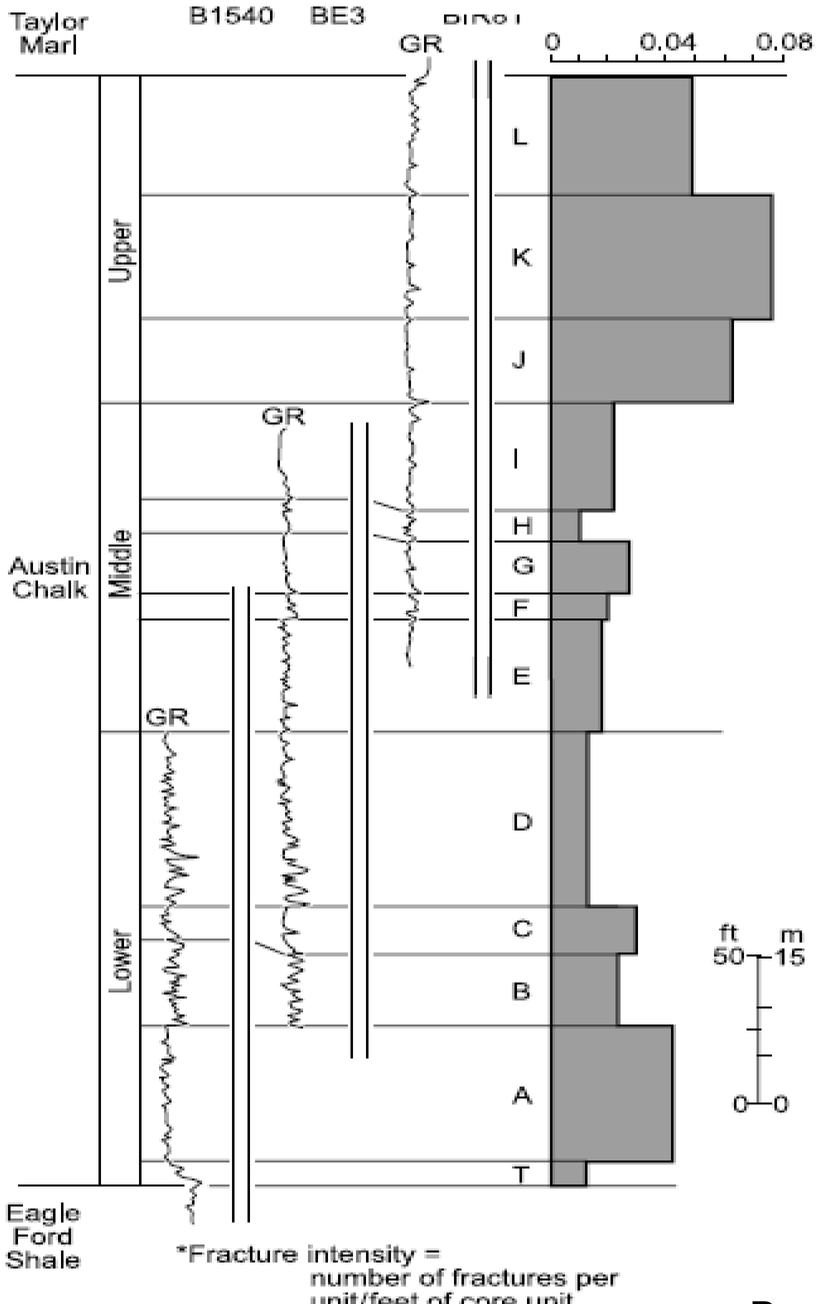


Giddings Field



(SPE 152402)

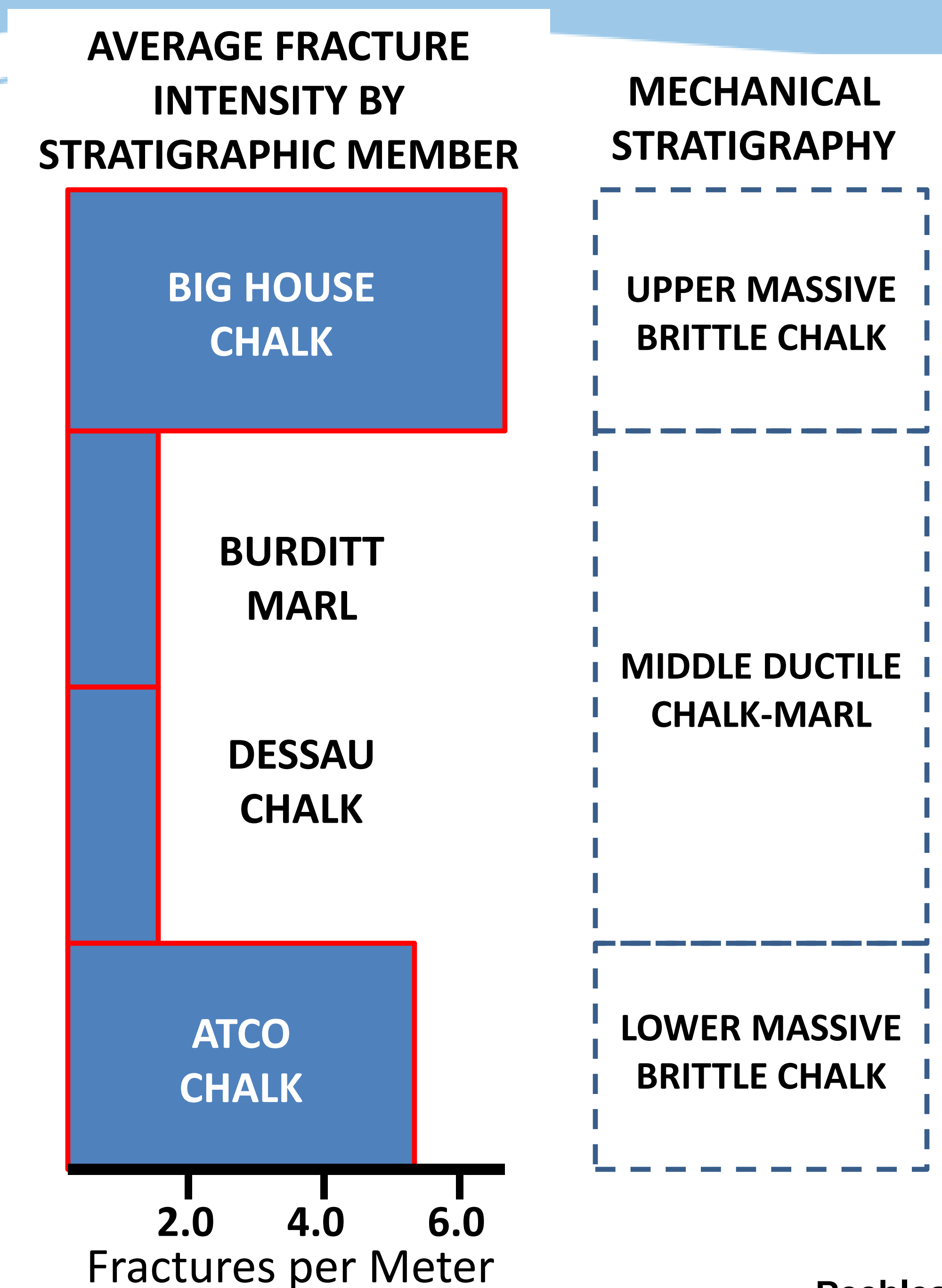
UNIT FRACTURE INTENSITY



Austin Chalk Fracture Stratigraphy

Based on 110 shallow geotechnical cores - SSC

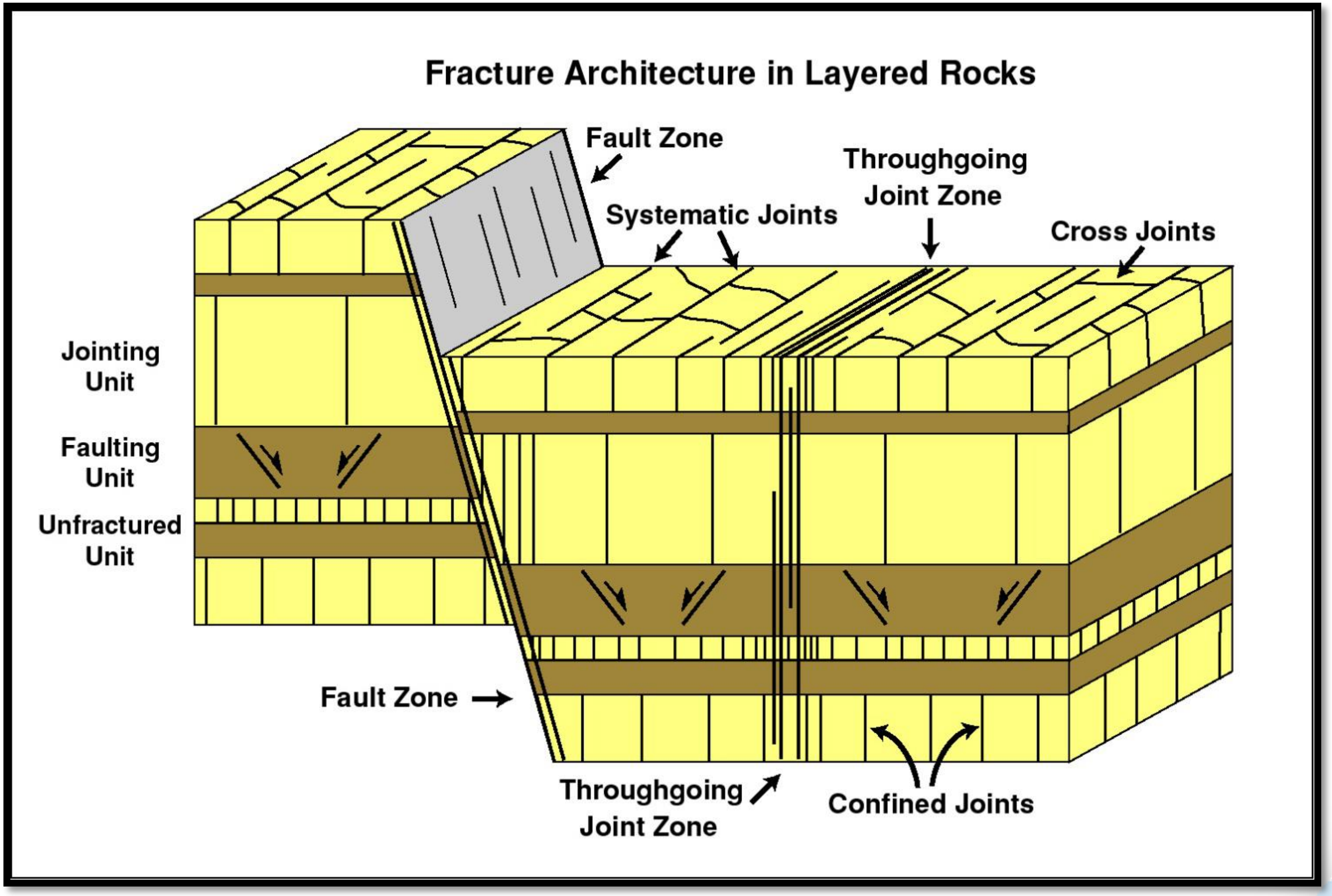
Laubach, Olson & Gross, 2009
AAPG Bulletin, v93, no 11



Austin Chalk Fracture & Mechanical Stratigraphy

Based on outcrop and core studies

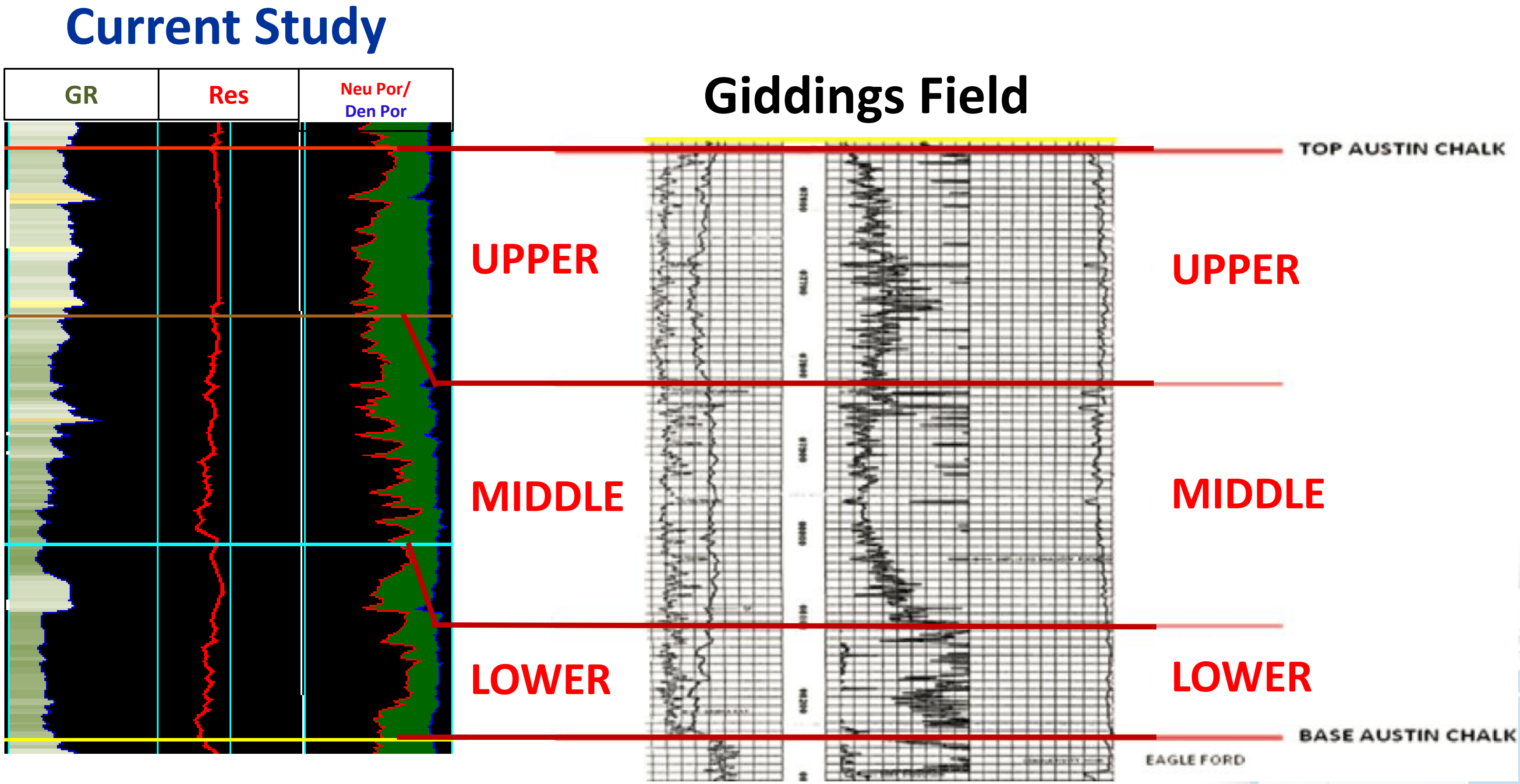
Corbett, Friedman & Spang, 1987
AAPG Bulletin, v71, no 1



Gross, 2013, HGS Mudrocks Conference

Well Log Correlation – 3 Unit Zonation

5 wells with triple combo log suites



(SPE 152402)

Production and Completion Data

114 vertical wells reported producing from the Austin Chalk

- Gathered production intervals and QCed in TX RRC
- Eliminated wells with production intervals outside Austin Chalk
- **51 wells remained for analysis**

Selected only wells with single completion intervals

- ***27 wells in final analysis.***

10 year cumulative oil production was chosen as the production metric.

NOTE: 16 Horizontal Wells in Study Area

Seismic Attributes – 58 in this case

Amplitude & Velocity

(1) Amplitude
(2) Sweetness
(3) HTI Interval Velocities
(4) Depth
(5) Envelope
(6) Phase

Structural Attributes

(7) Incoherence
(8) Incoherence Fault Scan
(9) Kshape
(10) Kmaxmag Azimuth
(11) Dip Azimuth
(12) Time Dip
(13) Kmax Curvature
(14) Kmaxmag Curvature
(15) Kmean Curvature
(16) Kmin Curvature
(17) Kneg Curvature
(18) Kpos Curvature
(19) Krms Curvature
(20) Kgauss Curvature
(21) Planarity
(22) Linearity

Frequency Attributes

(23) Spectral Decomposition 10Hz
(24) Spectral Decomposition 12Hz
(25) Spectral Decomposition 14Hz
(26) Spectral Decomposition 16Hz
(27) Spectral Decomposition 18Hz
(28) Spectral Decomposition 20Hz
(29) Spectral Decomposition 24Hz
(30) Spectral Decomposition 28Hz
(31) Spectral Decomposition 32Hz
(32) Spectral Decomposition 36Hz
(33) Spectral Decomposition 40Hz
(34) Spectral Decomposition 45Hz
(35) Spectral Decomposition 50Hz
(36) Spectral Decomposition 55Hz
(37) Spectral Decomposition 60Hz
(38) Dominant Frequency
(39) Instantaneous Q
(40) Average Frequency

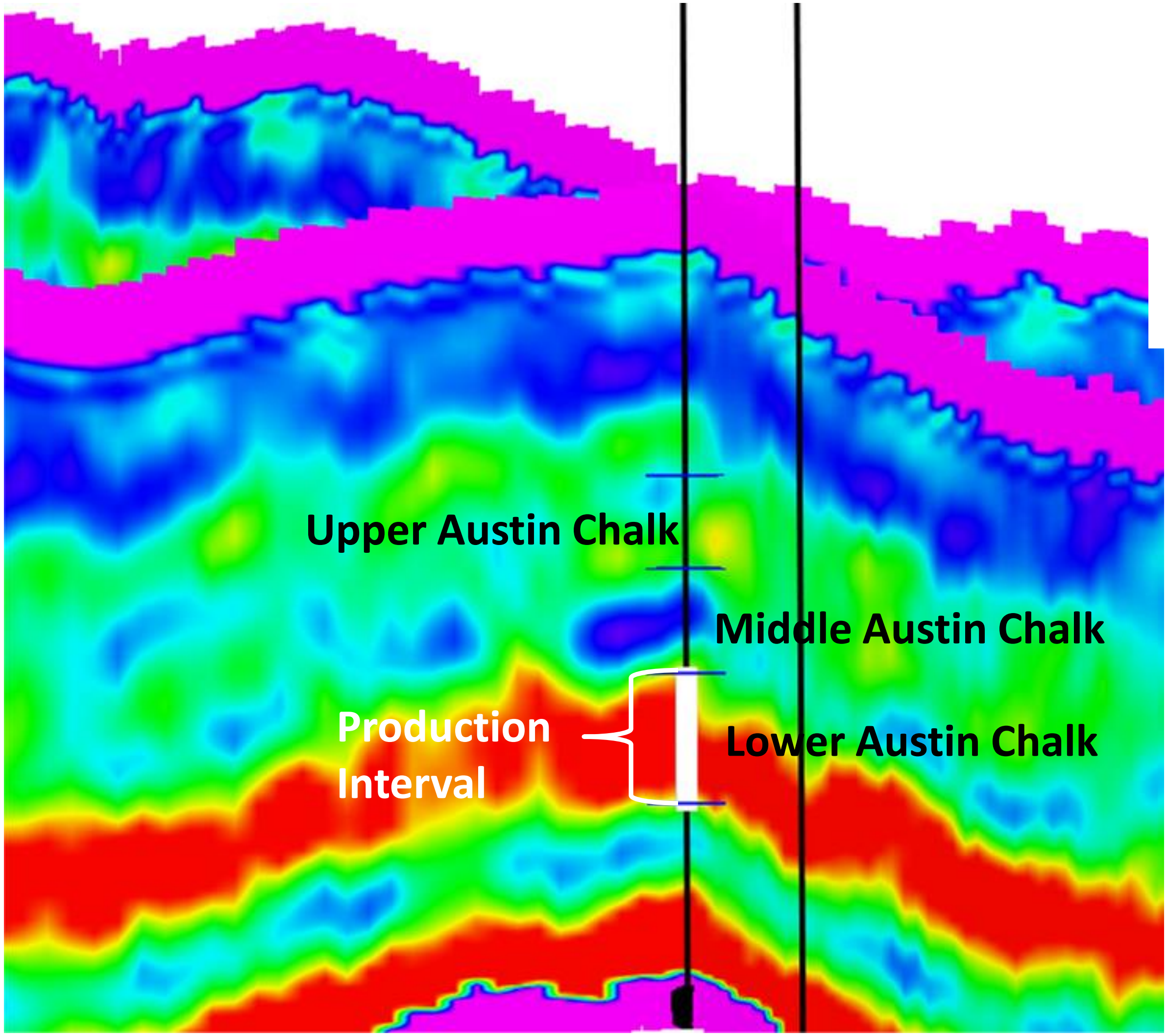
Anisotropy & Other Attributes

(41) HTI Magnitude
(42) HTI Azimuth
(43) VTI ETA Field
(44) Closure Stress Gradient
(45) Thin Bed Indicator

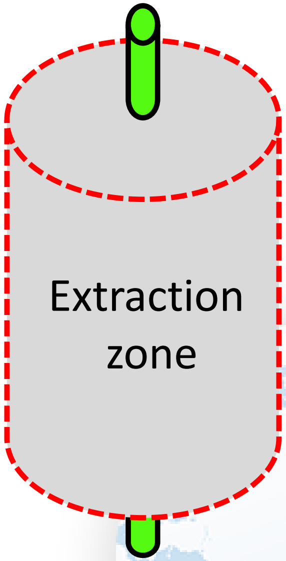
Inversion

(46) Acoustic Impedance
(47) Shear Impedance
(48) Frac Factor™
(49) Bulk Modulus
(50) Density
(51) Poisson's ratio
(52) P-Wave Velocity
(53) Shear Modulus
(54) S-Wave Velocity
(55) Young's Modulus
(56) Lambda Rho
(57) Mu Rho
(58) Brittleness

Austin Chalk Seismic-Production Analytics



58 seismic attributes were extracted around the production interval of each wellbore .



Well Performance Indicators
First Pass – Bivariate Linear Correlations

Attribute	Correlation to Production
Well - Cum Oil - 10 Year Cumulative	1.0
PI - Acoustic Impedance - Acoustic Impedance	-0.713
PI - Amplitude - Amplitude - ANISO_PSTM_MIN95DEG	0.194
PI - Amplitude - Amplitude - ANISO_PSTM_MIN95DEG_1_SOM5x5	0.201
PI - Amplitude - Amplitude - ANISO_PSTM_MIN95DEG)	0.194
PI - Angle - Angle - DownAngle	0.179
PI - Angle - Angle - EastAngle	-0.079
PI - Angle - Angle - NorthAngle	0.411
PI - Azimuth - Azimuth - dip_azimuth	0.205
PI - Azimuth - Azimuth - HorzAng	0.566
PI - Azimuth - Azimuth - Kmax_azimuth	-0.023
PI - Azimuth - Azimuth - Kmaxmag_azimuth	0.221
PI - Azimuth - Azimuth - Kmin_azimuth	0.058
PI - Azimuth - Azimuth - PlungeAz	0.388
PI - Azimuth - Azimuth - vfast_azimuth	-0.077
PI - Bulk Modulus - Bulk Modulus	-0.708
PI - Density - Density	-0.7
PI - Dimensionless - Dimensionless - Kshape	0.059
PI - Dimensionless - Dimensionless - linearity	0.126
PI - Dimensionless - Dimensionless - planarity	-0.151
PI - Dip - Dip	-0.079
PI - Elastic Impedance - Elastic Impedance	-0.673
PI - Fault Probability - Fault Probability	0.56
PI - FracFactor - FracFactor	-0.069
PI - Incoherence Probability - Incoherence Probability	0.297
PI - Lambda - Lambda	-0.687
PI - Lambda Rho - Lambda Rho	-0.672
PI - Mu - Mu	-0.735
PI - Mu Rho - Mu Rho	-0.665

Attribute	Correlation to Production
PI - Poisson's ratio - Poisson's ratio	0.083
PI - SpecD - SpecD - SpecD_10(Hz)	0.251
PI - SpecD - SpecD - SpecD_14(Hz)	-0.236
PI - SpecD - SpecD - SpecD_18(Hz)	-0.152
PI - SpecD - SpecD - SpecD_22(Hz)	-0.478
PI - SpecD - SpecD - SpecD_26(Hz)	-0.559
PI - SpecD - SpecD - SpecD_30(Hz)	-0.567
PI - SpecD - SpecD - SpecD_34(Hz)	-0.417
PI - SpecD - SpecD - SpecD_38(Hz)	-0.155
PI - SpecD - SpecD - SpecD_42(Hz)	-0.002
PI - SpecD - SpecD - SpecD_46(Hz)	0.066
PI - SpecD - SpecD - SpecD_50(Hz)	0.086
PI - SpecD - SpecD - SpecD_54(Hz)	0.079
PI - SpecD - SpecD - SpecD_58(Hz)	0.051
PI - SpecD - SpecD - SpecD_62(Hz)	0.017
PI - SpecD - SpecD - SpecD_66(Hz)	-0.012
PI - Time Dip - Time Dip -dip	-0.141
PI - Time-domain Curvature - Time-domain Curvature - Kdip	0.211
PI - Time-domain Curvature - Time-domain Curvature - Kmax	0.103
PI - Time-domain Curvature - Time-domain Curvature - Kmaxmag	0.188
PI - Time-domain Curvature - Time-domain Curvature - Kmean	0.154
PI - Time-domain Curvature - Time-domain Curvature - Kmin	-0.195
PI - Time-domain Curvature - Time-domain Curvature - Kneg	-0.136
PI - Time-domain Curvature - Time-domain Curvature - Kpos	0.145
PI - Time-domain Curvature - Time-domain Curvature - Krms	0.167
PI - VelocityP(Interval) - VelocityP(Interval)	-0.714
PI - VelocityS(Interval) - VelocityS(Interval)	-0.668
PI - Vp/Vs - Vp/Vs	0.077
PI - Young's Modulus - Young's Modulus	-0.677

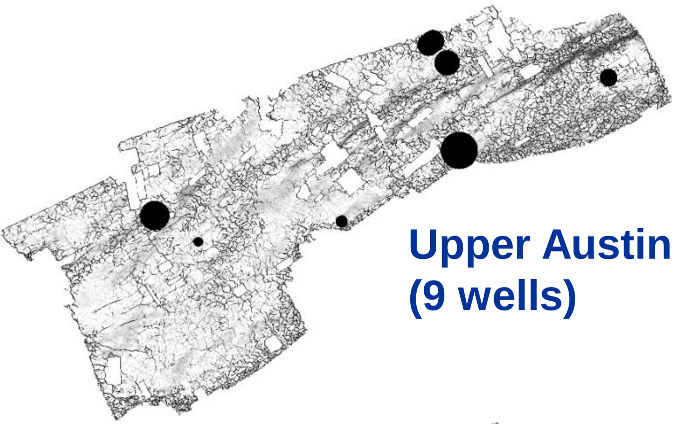
Primary Performance Indicators for 10 Year Cumulative Oil Production

5 primary performance indicators:

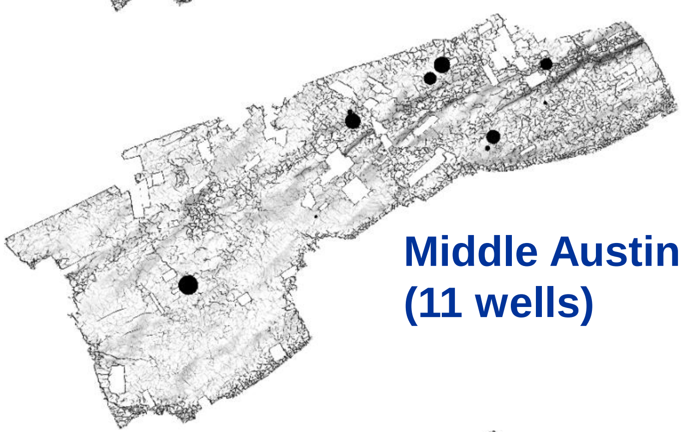
Attribute	Correlation to Production	Indicator of
– Mu:	CC -0.735	Rigidity
– Lambda:	CC -0.687	Incompressibility
– Spec D 30 Hz:	CC -0.567	Related to reservoir thickness
– Fault Probability:	CC 0.560	Faults and Fractures
– Horizontal Angle:	CC 0.566	Bedding dip orientation

- Attributes with high correlations with each other (i.e., Mu and Mu-rho) are considered redundant and are not used in the analysis.

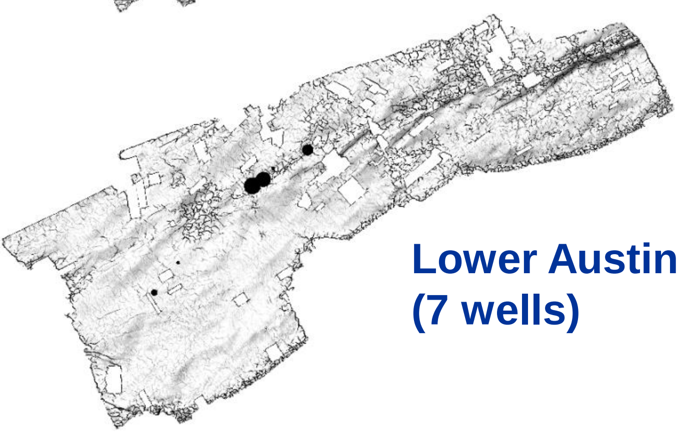
Average Fault Probability over 3 Austin Chalk Zones



Upper Austin Chalk
(9 wells)



Middle Austin Chalk
(11 wells)



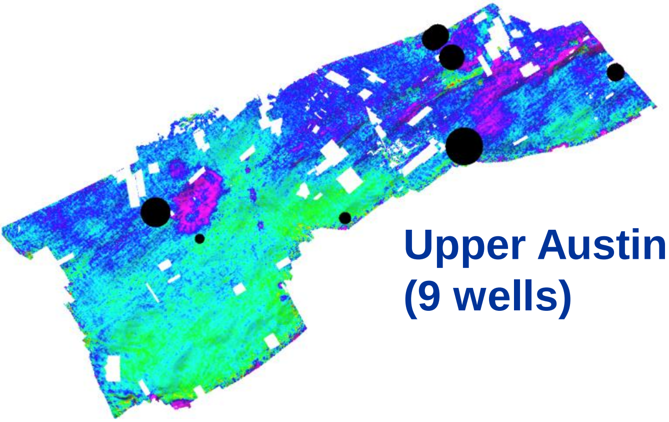
Lower Austin Chalk
(7 wells)

0 .28

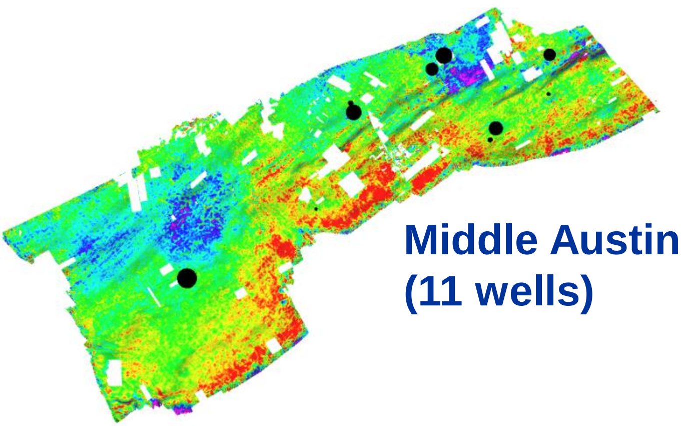
Upper Austin Chalk Faults & Fractures

Peebles et al Global Geophysical Services May 2013

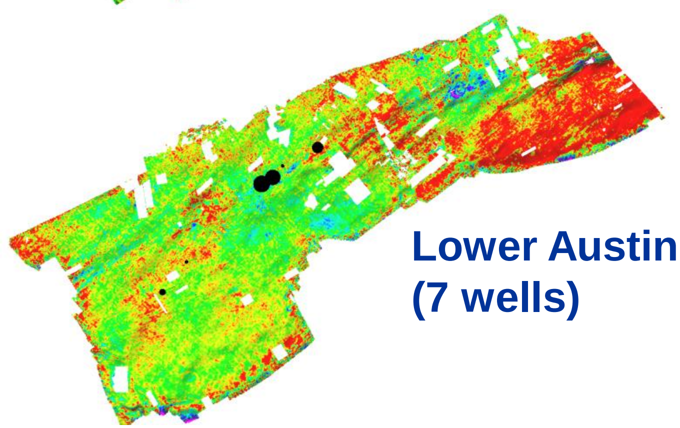
Average Mu Over 3 Austin Chalk Zones



Upper Austin Chalk (9 wells)

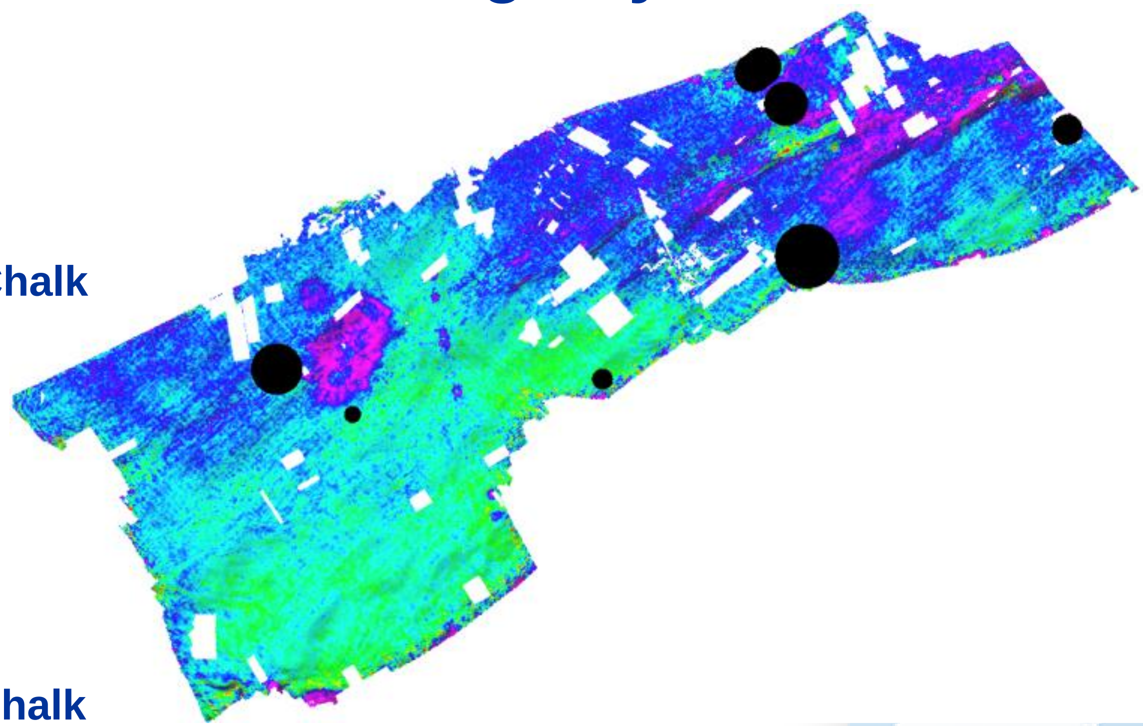


Middle Austin Chalk (11 wells)



Lower Austin Chalk (7 wells)

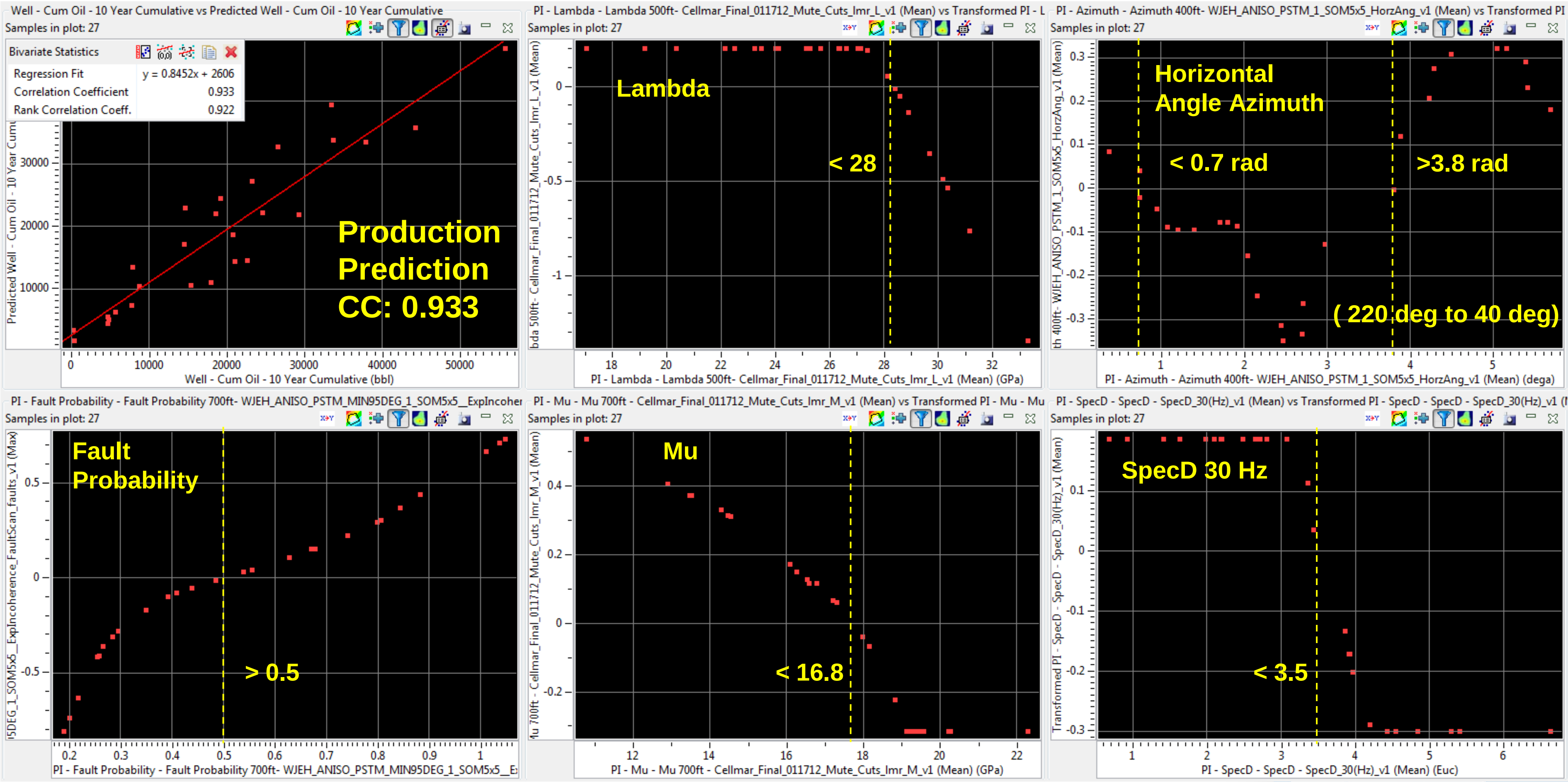
Upper Austin Chalk Mu - rigidity



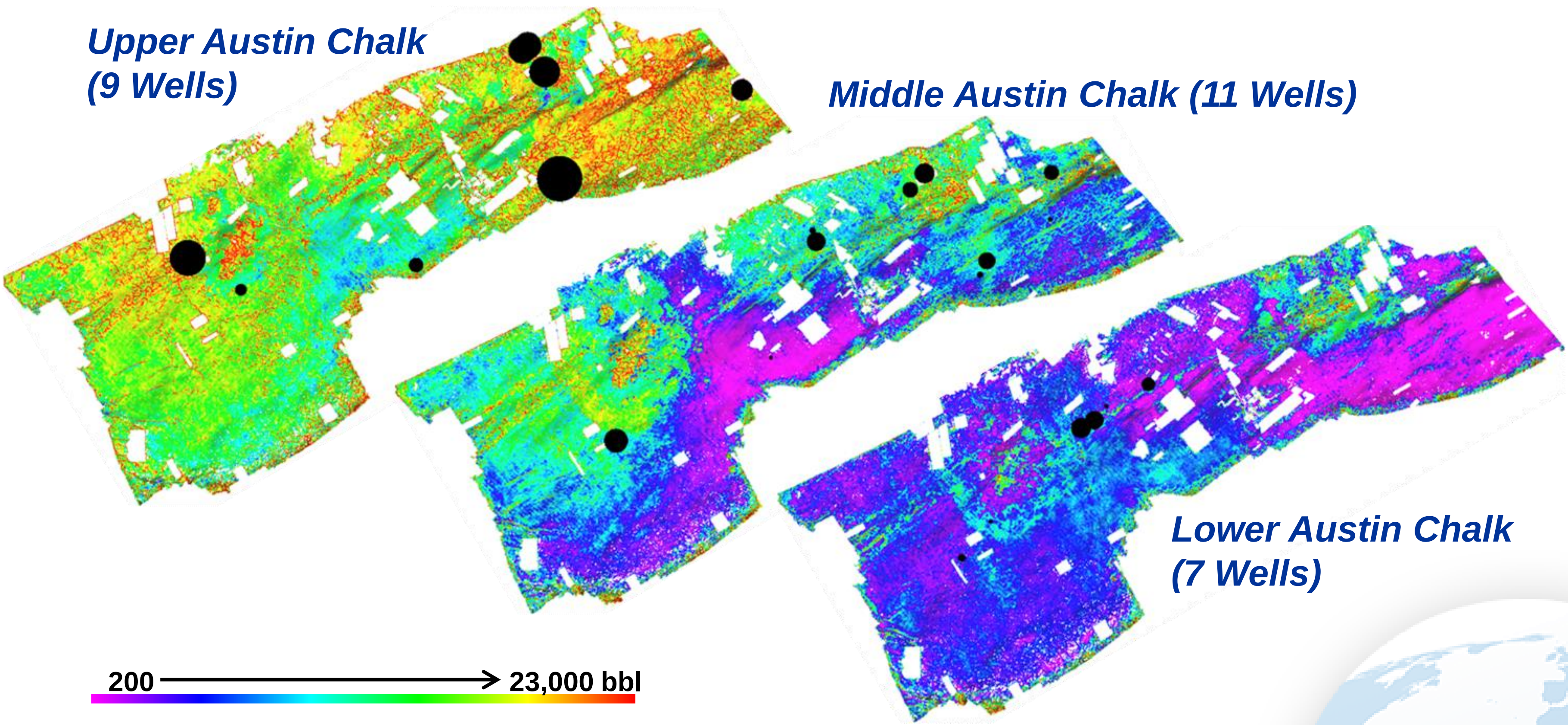
15 → 23 GPa

Multivariate Statistics Non-linear Regression

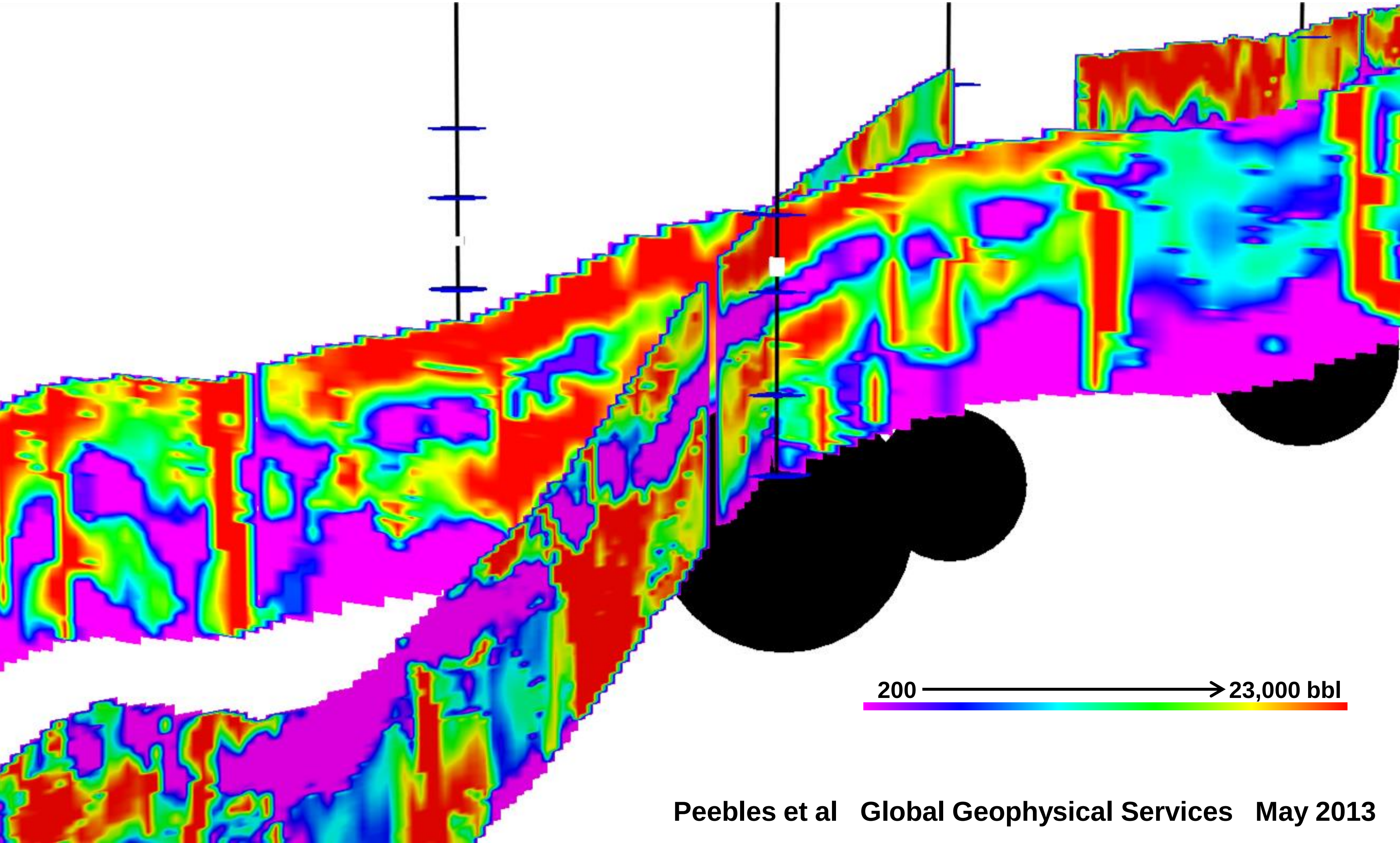
The key attributes are combined into a multivariate non-linear regression to create a seismic-production prediction transform



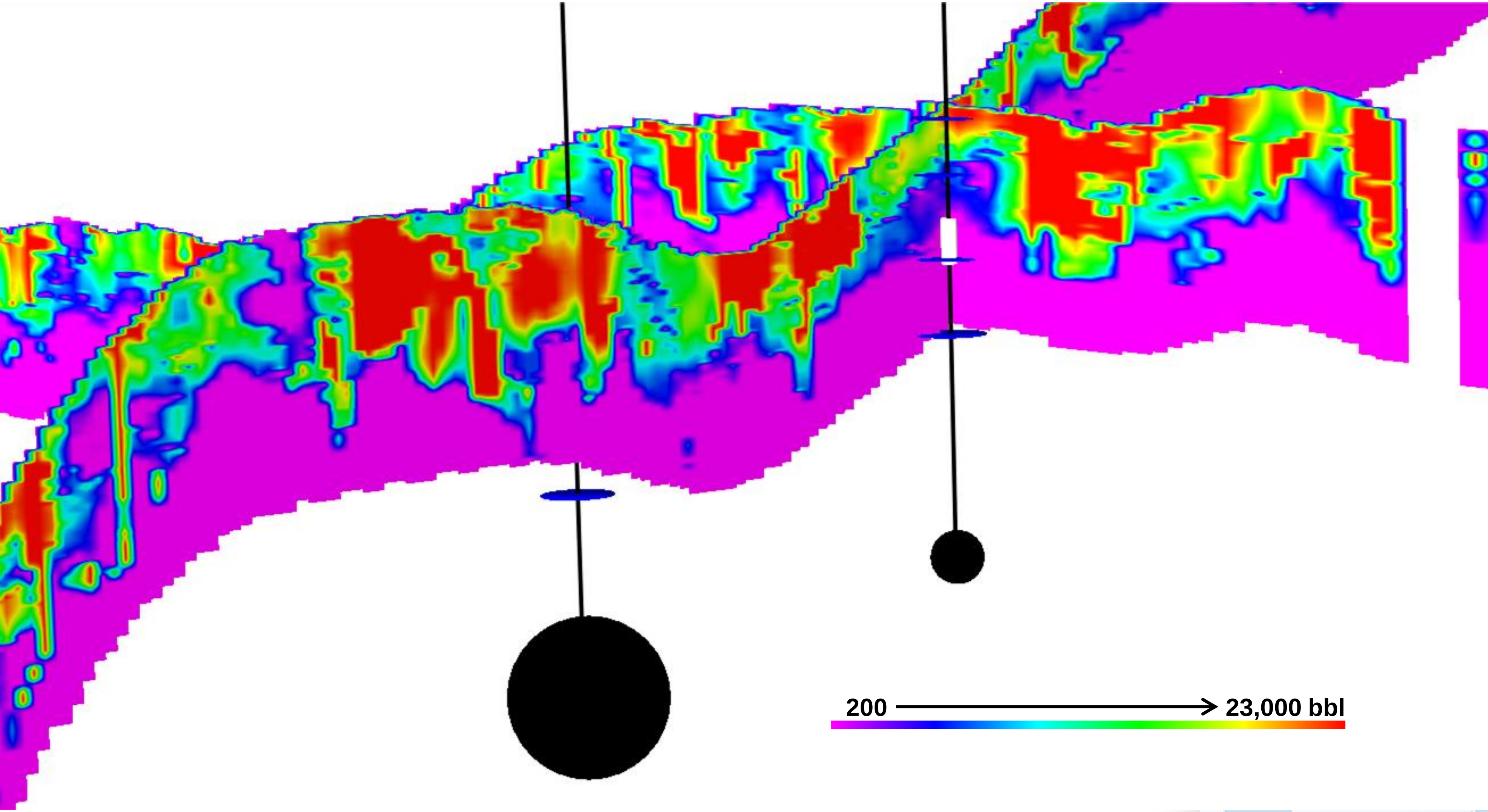
Average 10 Year Cum Production Prediction



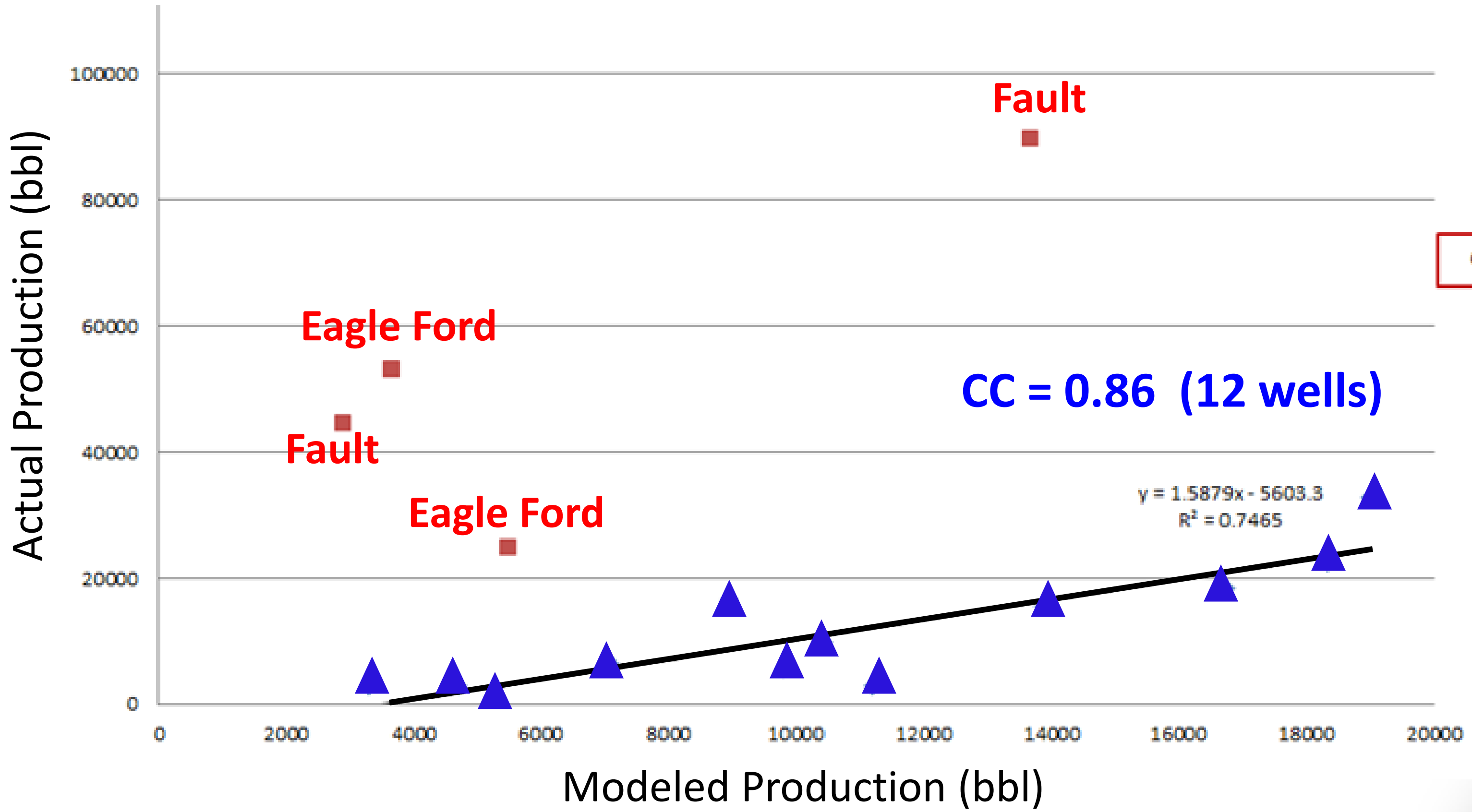
Production Prediction Sectional View
High Producing Well



Production Prediction Sectional View
Low Producing Well

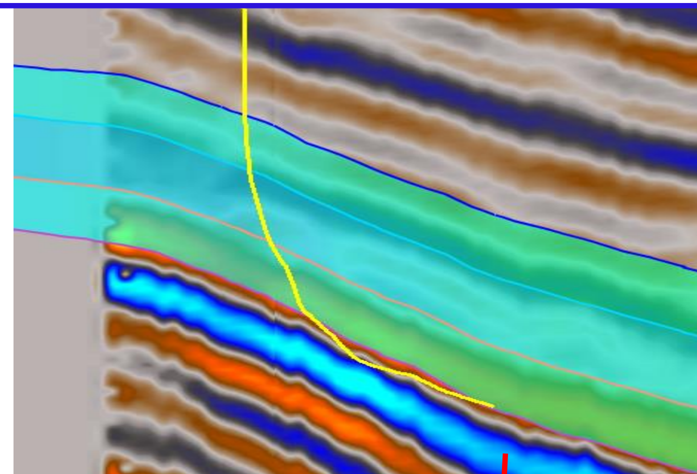


Correlation of 16 Horizontal Wells with Production Model (Blind Test)

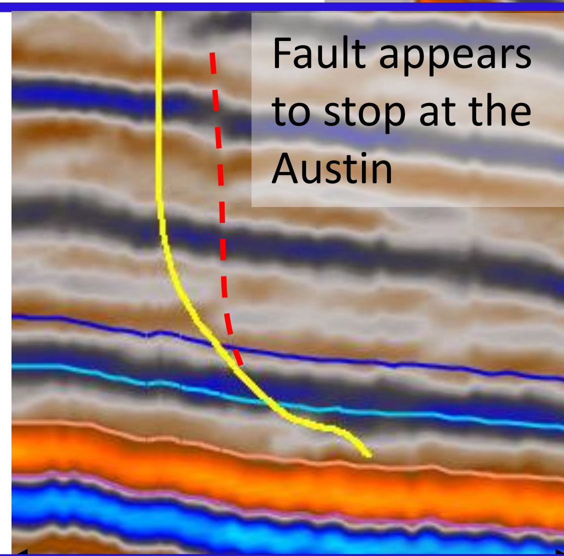


Outlier Analysis

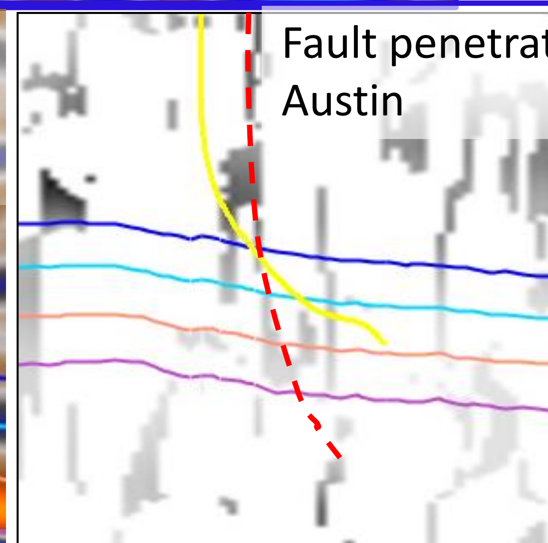
42-493-32239 – Well appears to have been completed in the Upper Eagle Ford .



42-493-30173 - Appears that the well penetrated a small fault that is almost sub-seismic in scale.



Amplitudes

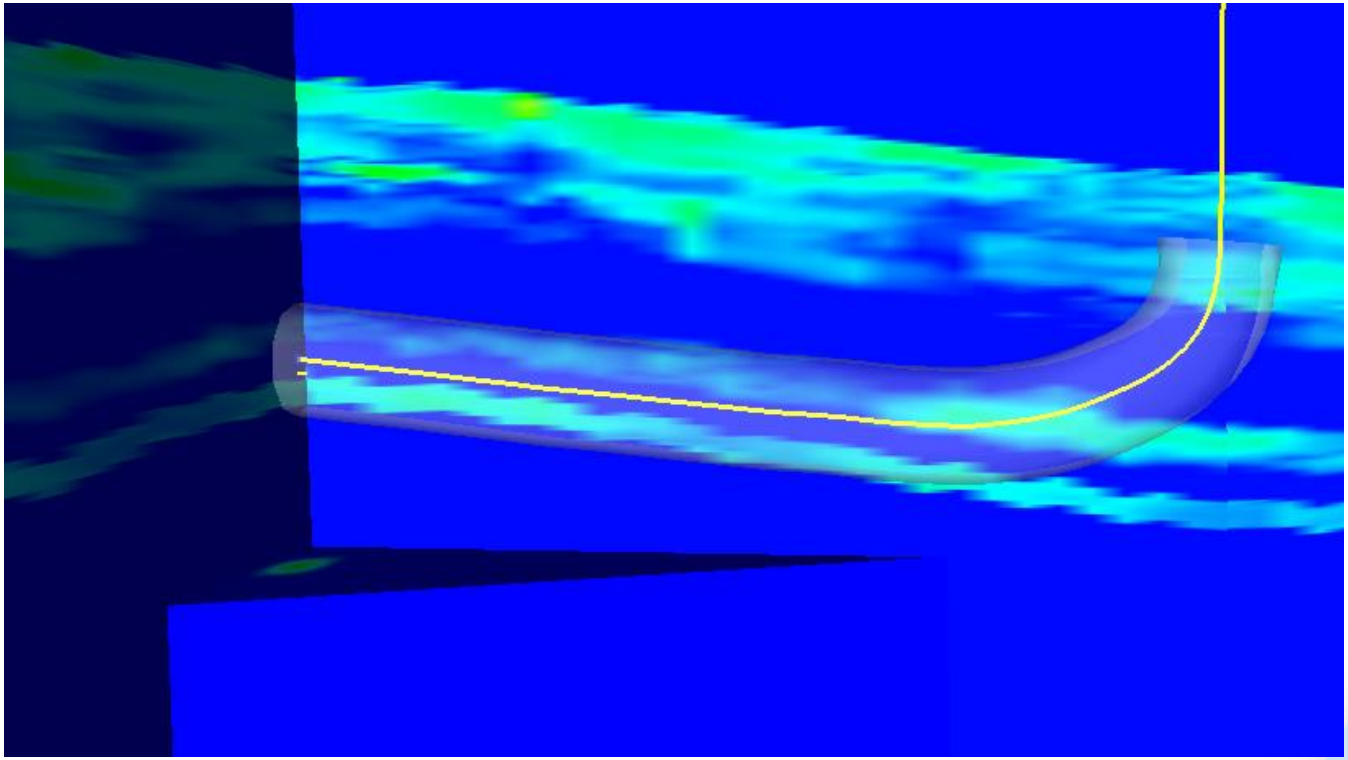


Fault Probability Attribute

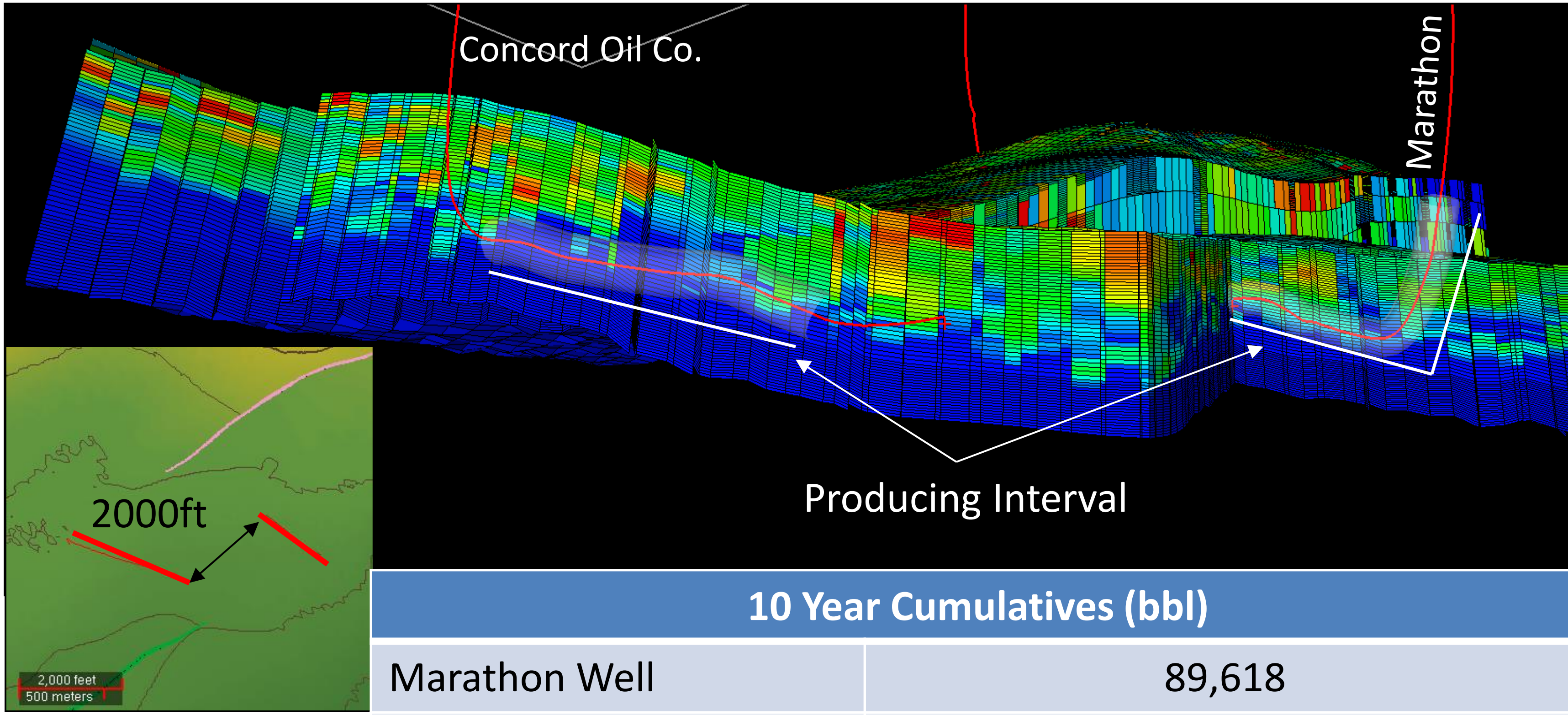
Prediction: Blind Horizontal Well

Actual Production: 2856 bbl

Predicted Production: 3287 bbl



Production Prediction Model and Two Horizontal Wells



10 Year Cumulatives (bbl)	
Marathon Well	89,618
Concord Oil Well	1,323

- 80 – 90 % of Concord's producing interval outside any area of significant production.
- Marathon almost fully in high-producing regions, although could have been even better if they had landed shallower.

Discussion

- Modeling of productivity bypasses prediction of porosity, water saturation, and other variables that are more directly related to reservoir productivity
- Well Productivity and Prospectivity Analysis (WPPA) Workflow
  - There is a heavy reliance on statistics
    - Need to ensure that you have enough data to have robust correlations and models
    - Stationarity Assumption
  - Just because you get a good correlation coefficient doesn't mean that you have a good model!
    - Outliers
    - Over-fitting of the data
      - Too many variables in the model
      - Be sparse with the number of variables versus the number of independent observations

Discussion

- Well Productivity and Prospectivity Analysis Workflow (cont.)
  - Extracting attributes and building models using multiple observations along the wellbore (3D attribute and production values) produces consistently more reproducible models than averaging the attributes for each well (2D attribute and production values).
- Accurate velocity models for depth conversion are critical to correlate seismic attributes to production intervals at the right depth
- Studies we have done show the importance not only of having the right (X, Y) location for a well, but the correct layer and stratigraphic depth
  - There are variations in productivity in 3D
  - Not all stages along the reservoir path will be productive
    - Have a tool to predict productivity
    - Weigh the cost of fracing the stage versus the revenue from the expected production
    - Design the completion to optimize the profitability of the well

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Thank you

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