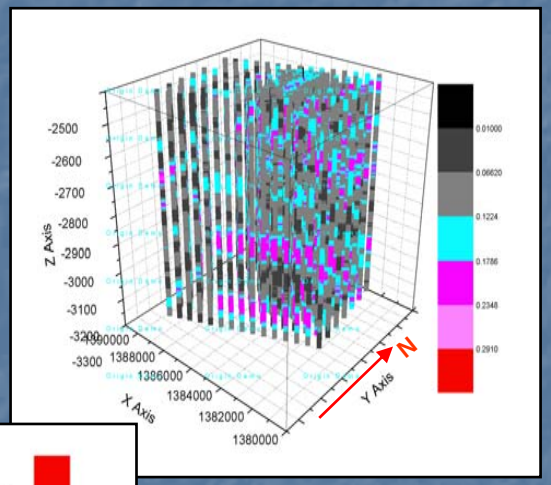
Final Results

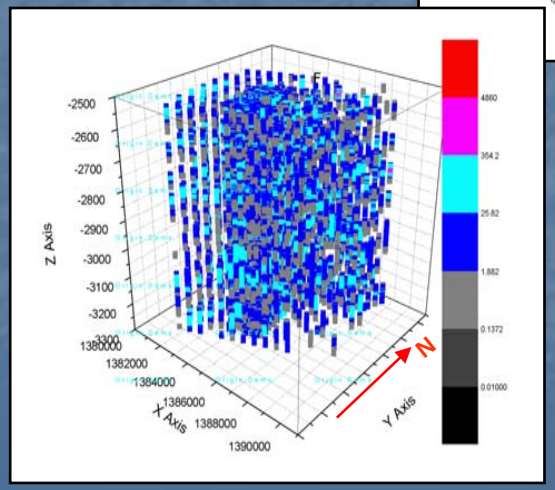
Development of an Advanced Approach for Next-Generation, High-Resolution, Integrated Reservoir Characterization



DOE Award No. DE-FC26-01BC15357

Presented To:

U.S. DOE - NPTO



Presented by:

Advanced Resources International

August 27, 2004

Tulsa, Oklahoma

ChevronTexaco

Presentation Outline

- Background/Objectives
- Test Site Description
- Data Processing
- Predictive Models
- Reservoir Characterization Results
- Conclusions/Final Steps

The Industry Need

- Effective oilfield management requires 3-D, high resolution reservoir characterization to identify reservoir heterogeneity.
  - SOR/IOR
  - EOR
  - CO_2 sequestration
- Surface seismic is the most cost-efficient method to obtain inter-well volumetric reservoir information, but vertical resolution is insufficient (>50 ft) for optimized injection management.

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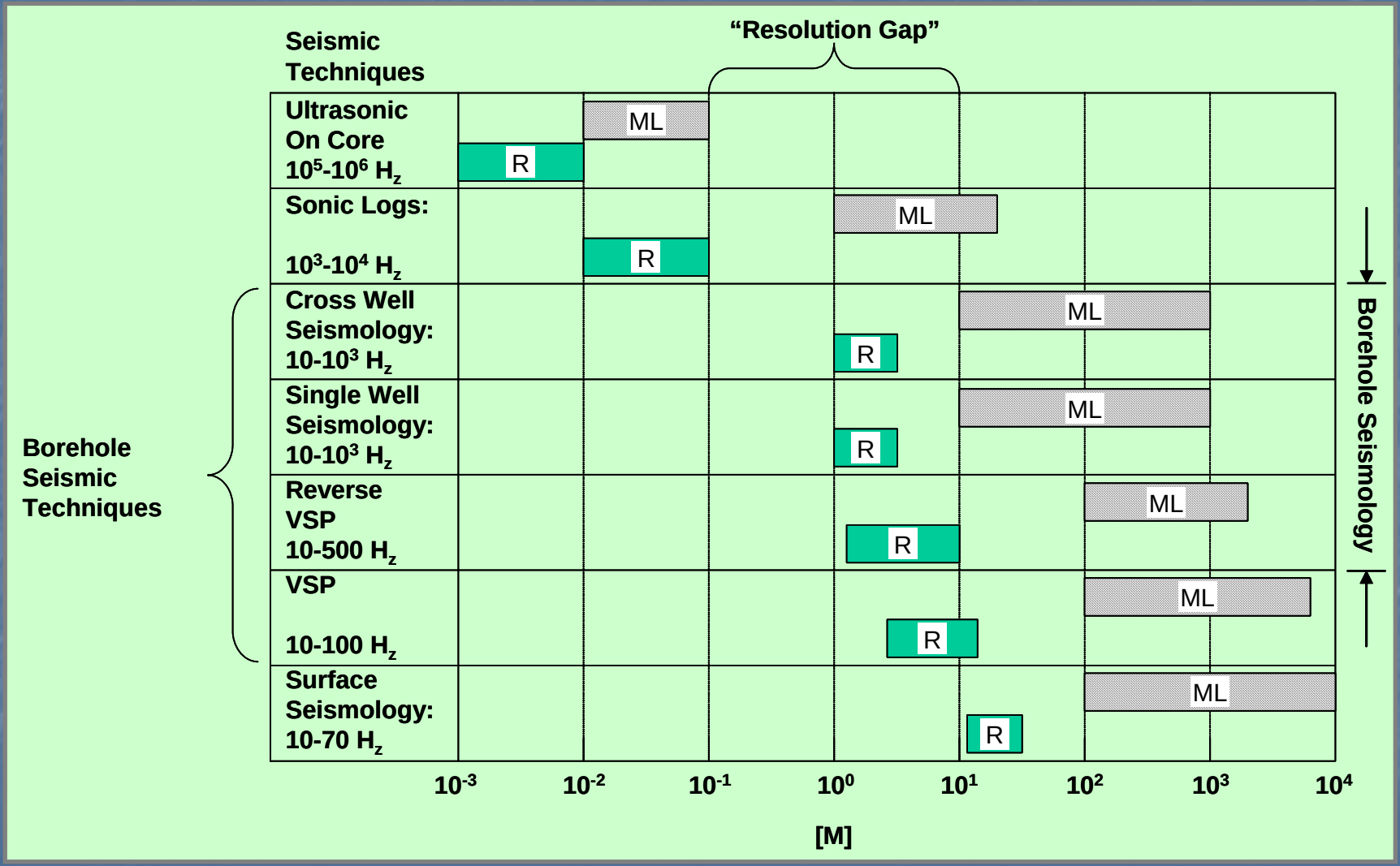
ARI's Technology Development Goals

- Using existing data acquisition capabilities, improve vertical resolution and reduce uncertainty of reservoir characterization.
- Present result in engineering terms required for flow modeling and performance forecasting (ϕ, k).
- Reduce time/cost requirements.
- "Better, faster, cheaper".

Approach

- Apply advanced pattern recognition technologies (artificial neural networks, clustering, etc.) to integrate multi-scale data (cores, logs, seismic).
  - Simple
  - Data-Driven
  - Deterministic
- Generate “high-frequency” reservoir description at each 3-D seismic trace location.
- Incorporate intermediate-scale data (e.g., crosswell seismic or VSP) to bridge resolution gap and reduce uncertainty.

Borehole Seismic Fills "Resolution Gap"



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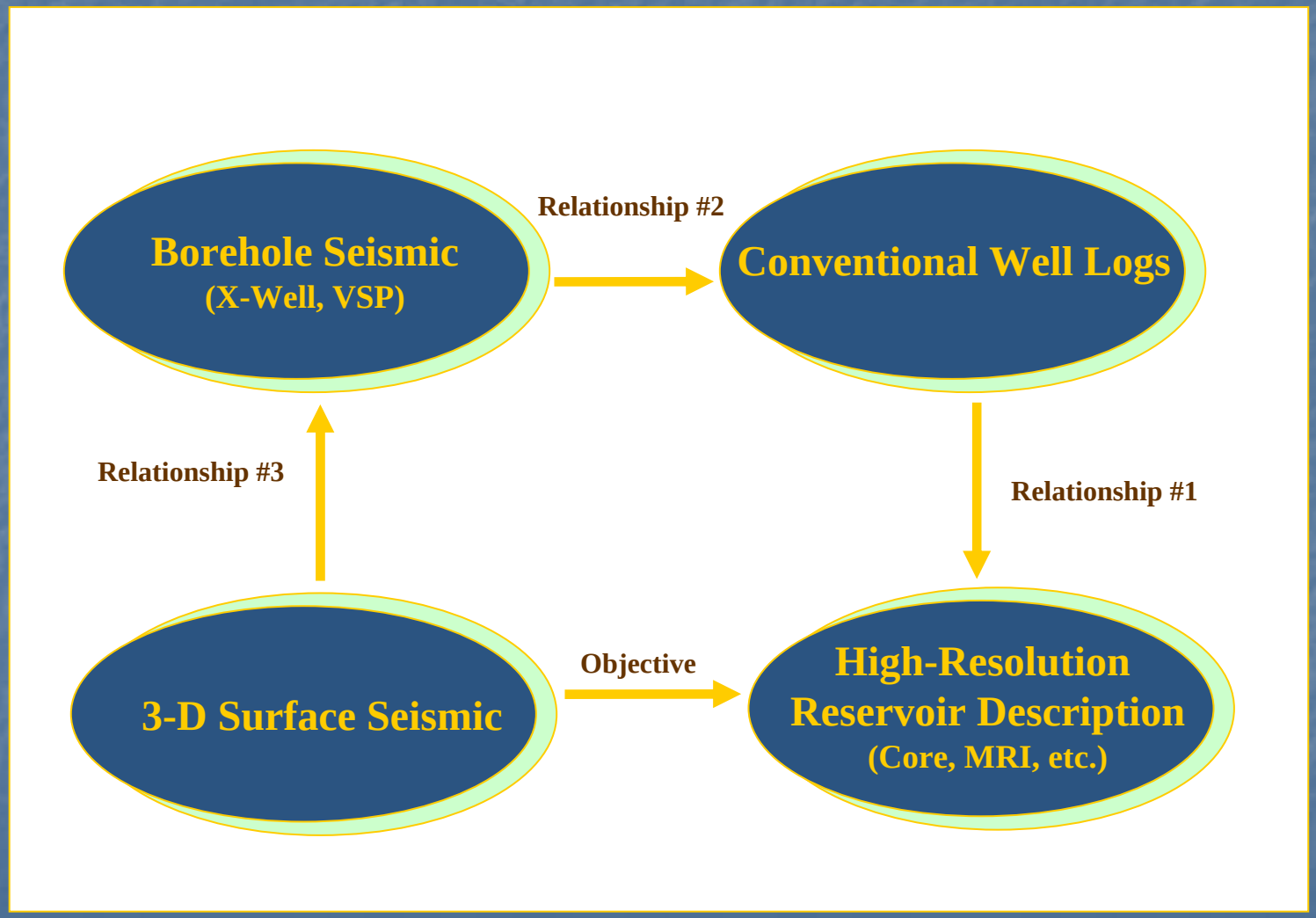
Proposed Pathway to High-Resolution Reservoir Characterization



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Differences with Inversion

- Data-driven modeling, not analytic.
- Handles noisy data.
- Directly predicts permeability in addition to porosity (not via a ϕ/k relationship).
- Deterministic outcome (not series of equi-probable outcomes).
- Simple & fast.

Phase 1: Feasibility Study

- "An Intelligent Systems Approach for High-Resolution, Inter-Well Oil Reservoir Characterization".
- DOE STTR Grant.
- 12-month project.
- Completed 12/31/01.

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Datasets Utilized for Feasibility Study

- Log-MRI Log (proxy for core):
  - Carthage field, East Texas, Cotton Valley Sandstone
  - Mohaghegh, SPE 51075 & SPE 65675
- Xwell-Log:
  - Sulimar field, West Texas, Queen formation
  - Chawathe, SPE 38747
- 3D-Xwell:
  - Steepbank field, Alberta (Canada), McMurray tar sand
  - Reeves, SPE 77759

Conclusions

- The various relationships are feasible using (supervised) ANN approaches.
- A fully integrated demonstration is required to test the approach.
- See SPE 77759.

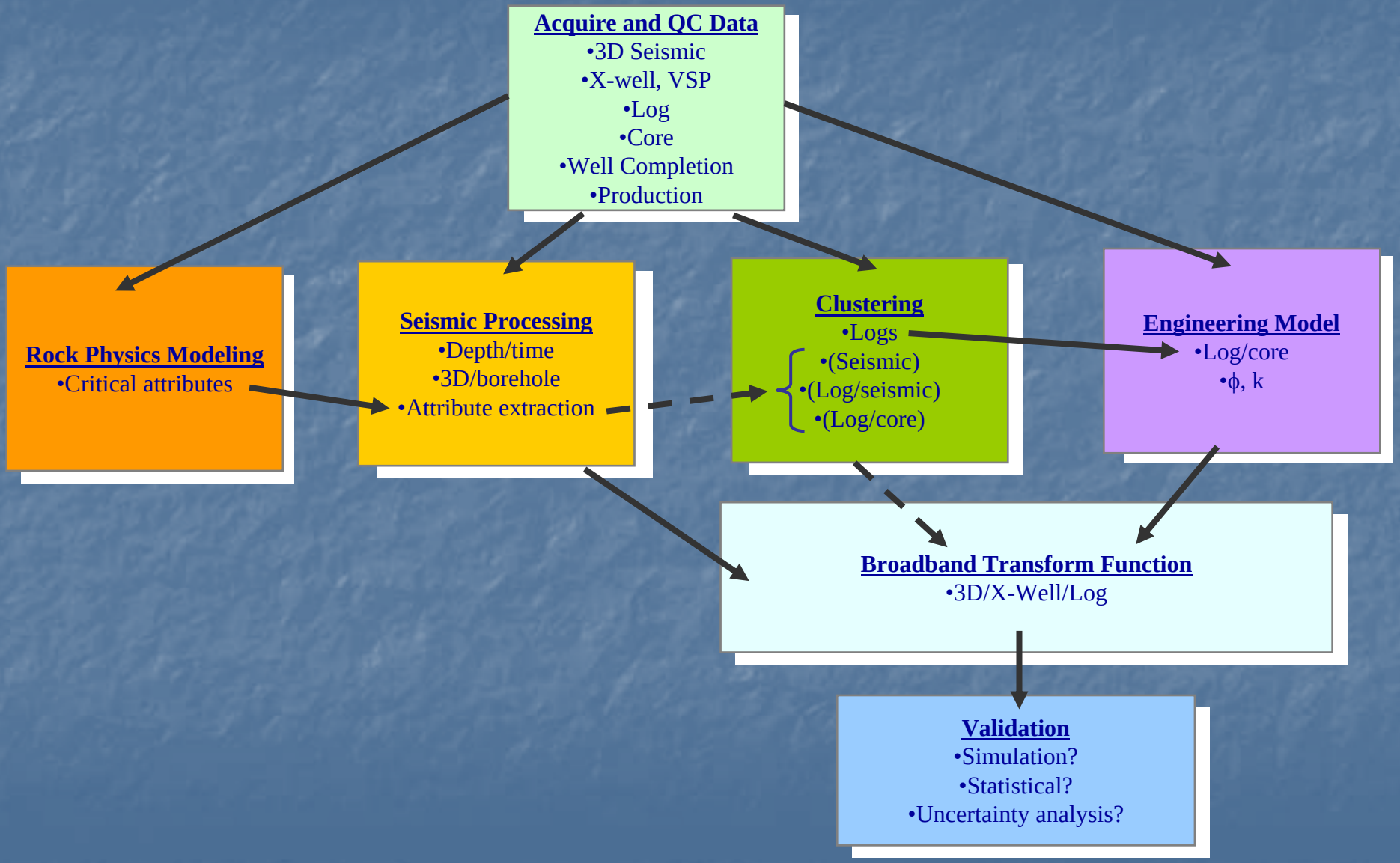
Phase 2: Current Project

- "Development of an Advanced Approach for Next-Generation, High-Resolution, Integrated Reservoir Characterization".
- DOE Cooperative Agreement.
- 36 month project.
- Initiated 10/1/01, completion 9/30/04.

Project Objective

- Demonstrate and validate the integrated (virtual intelligence) procedure at a single field.

Analytic Work Flow



Project Team

- Advanced Resources International
  - Project Management
  - Reservoir Engineering
- WellSeismic Computing Services
  - Seismic Processing
- Advanced Reservoir Technologies
  - Rock Physics
  - Transform Function
- Eric Geoscience
  - Cluster Analysis
- ChevronTexaco/BEG
  - Test Site
  - Data Transfer

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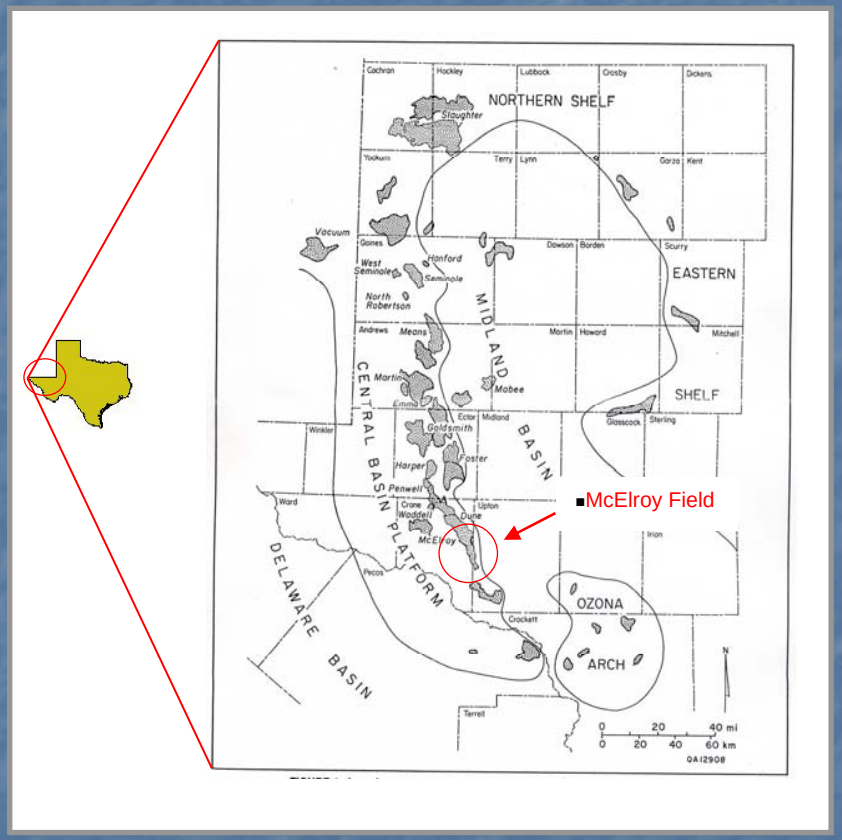
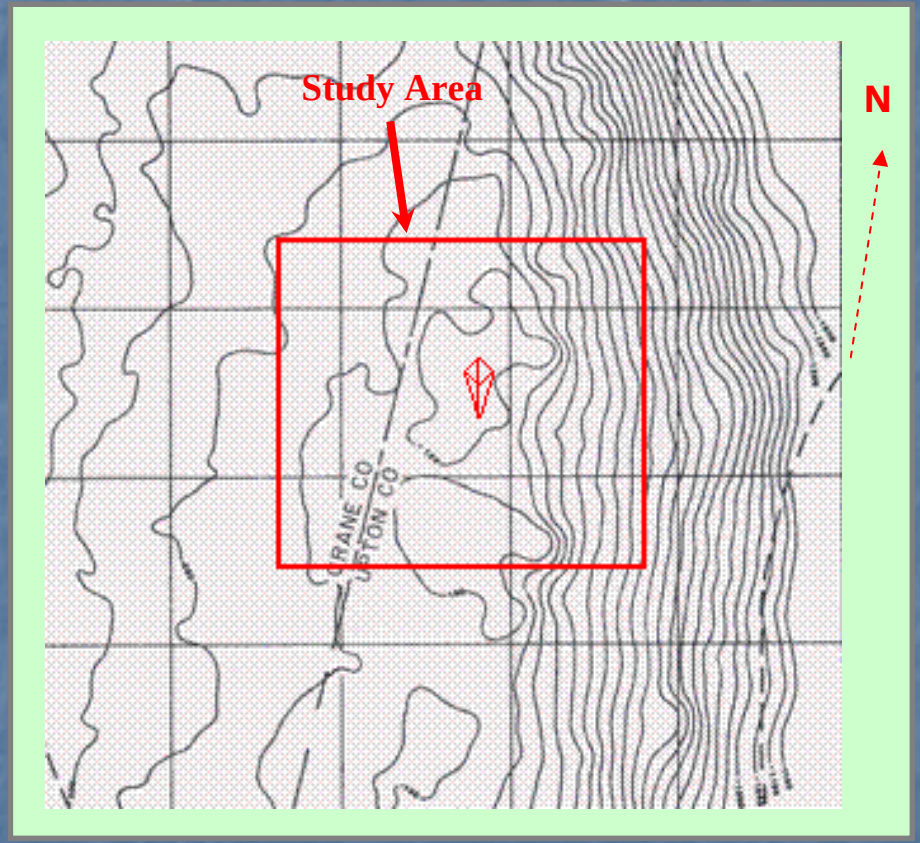
Site Location





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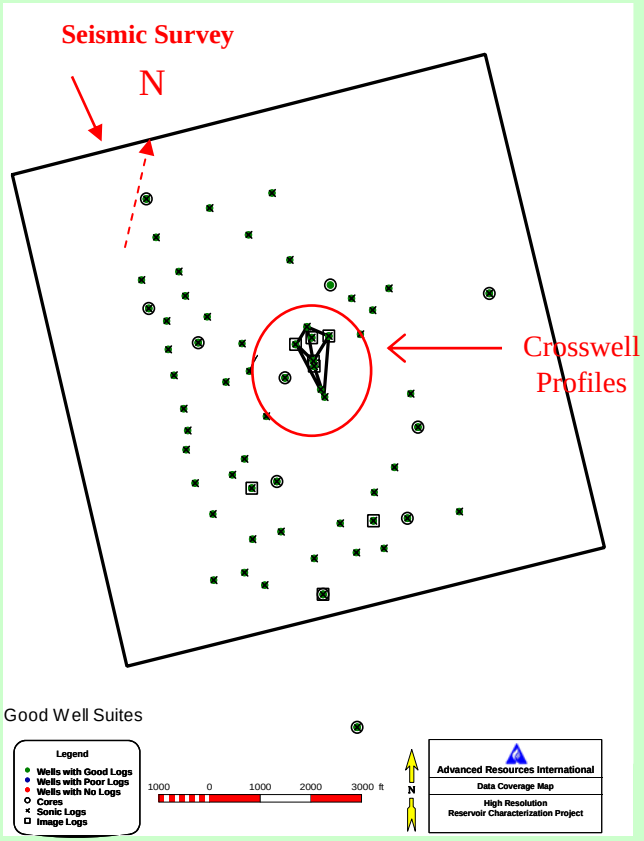
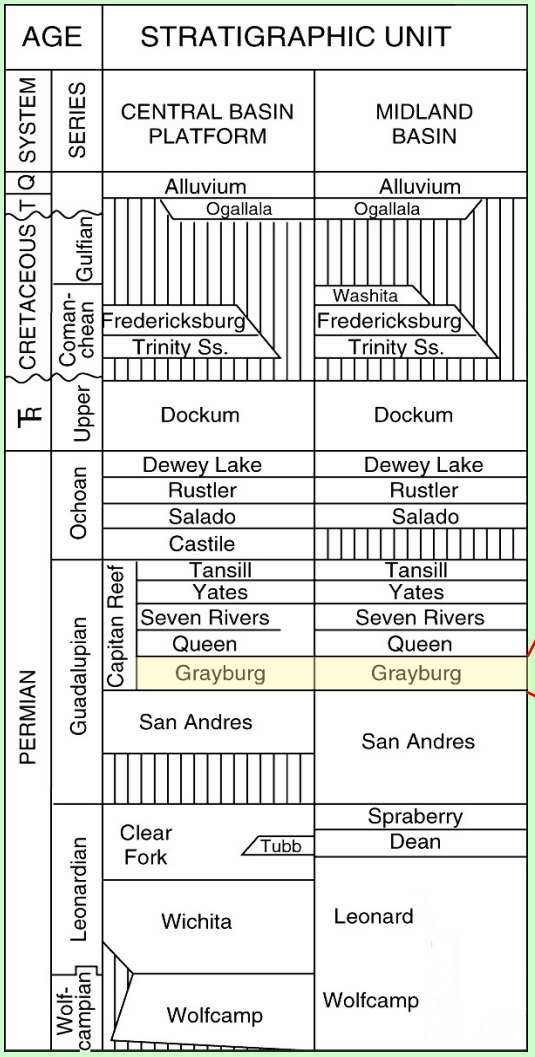
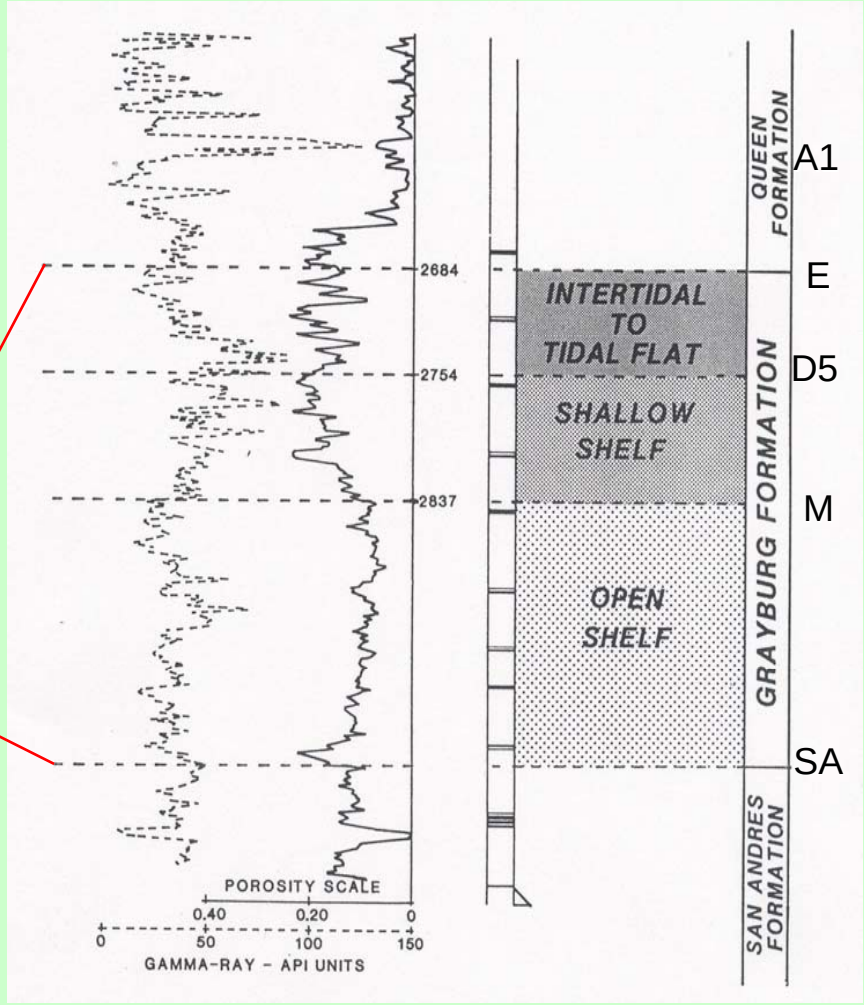
Summary of Data Received



Data Type	Amount Available
Well Locations	192
Seismic Survey, 3D P-P	2.5 sq. mi. (2000, post-steam) migrated stacked time
Crosswell Profiles	8 crosswell profile data files (1997, pre-steam)
Well Logs	Complete modern log suites for 59 wells (1984 – 2001)
Sonic Logs	84 sonic logs over survey area
Formation Tops	Interpreted formation tops (5) in 150 wells
Image Logs	8 image log files within the survey area
Core Logs	Core analysis logs for 13 cored wells in survey: approx. 325 ft. of whole core each with core porosity, saturation, and permeability measurements on ½ foot intervals.

Stratigraphic Column





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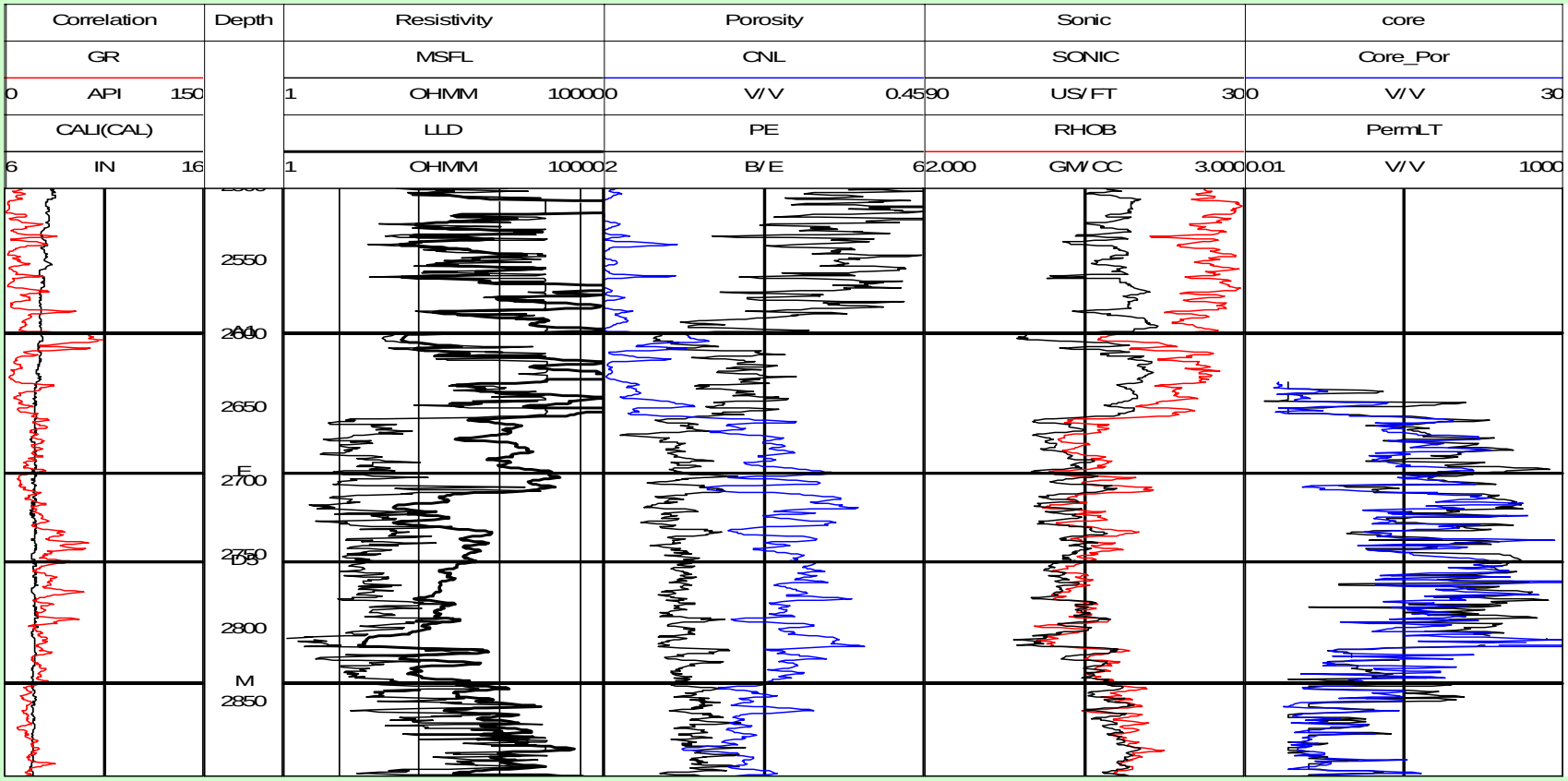
Sample Log/Core Data



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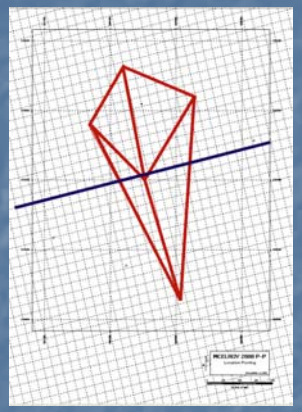
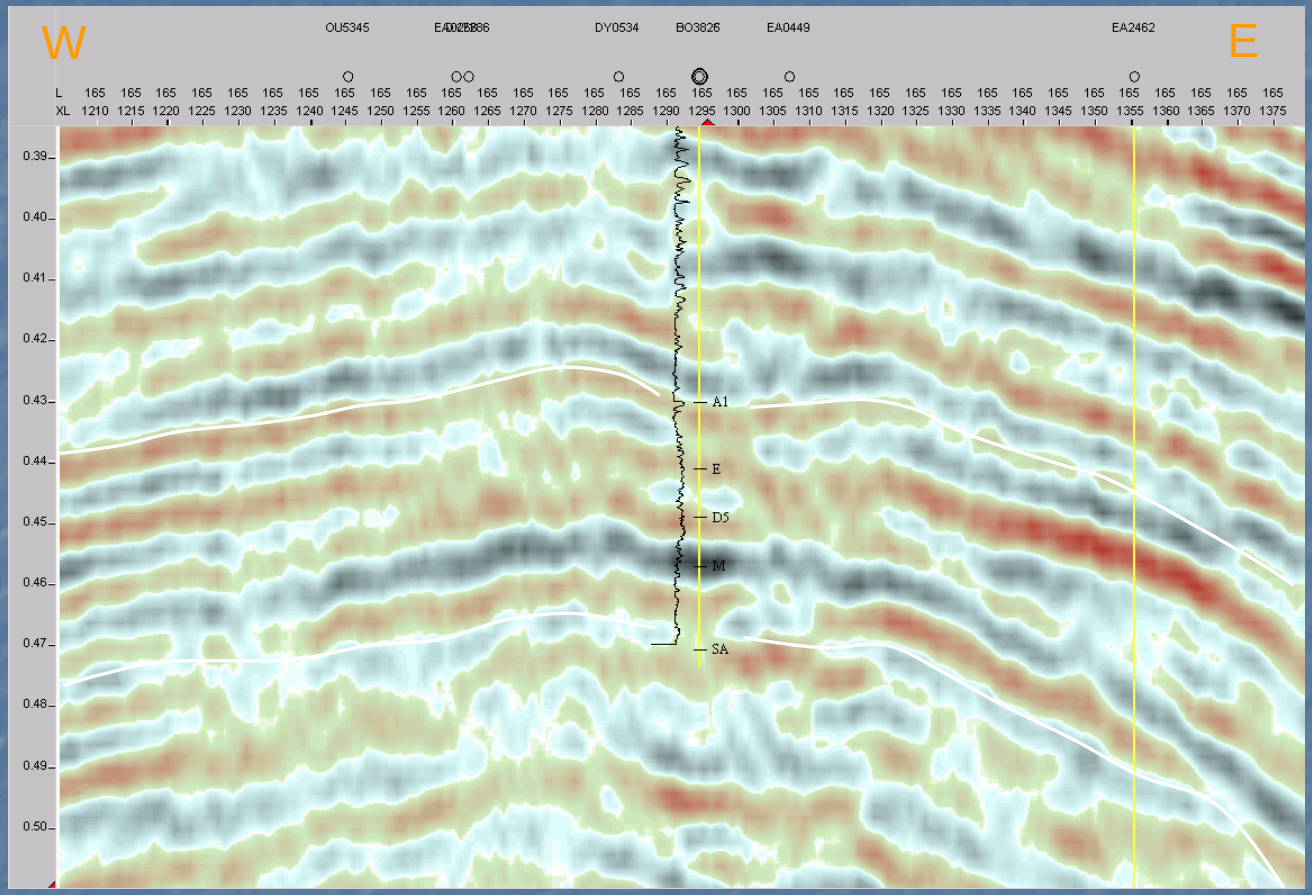
Sample Surface Seismic Inline



Inline 165



~ 2.25 mi.

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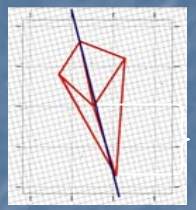
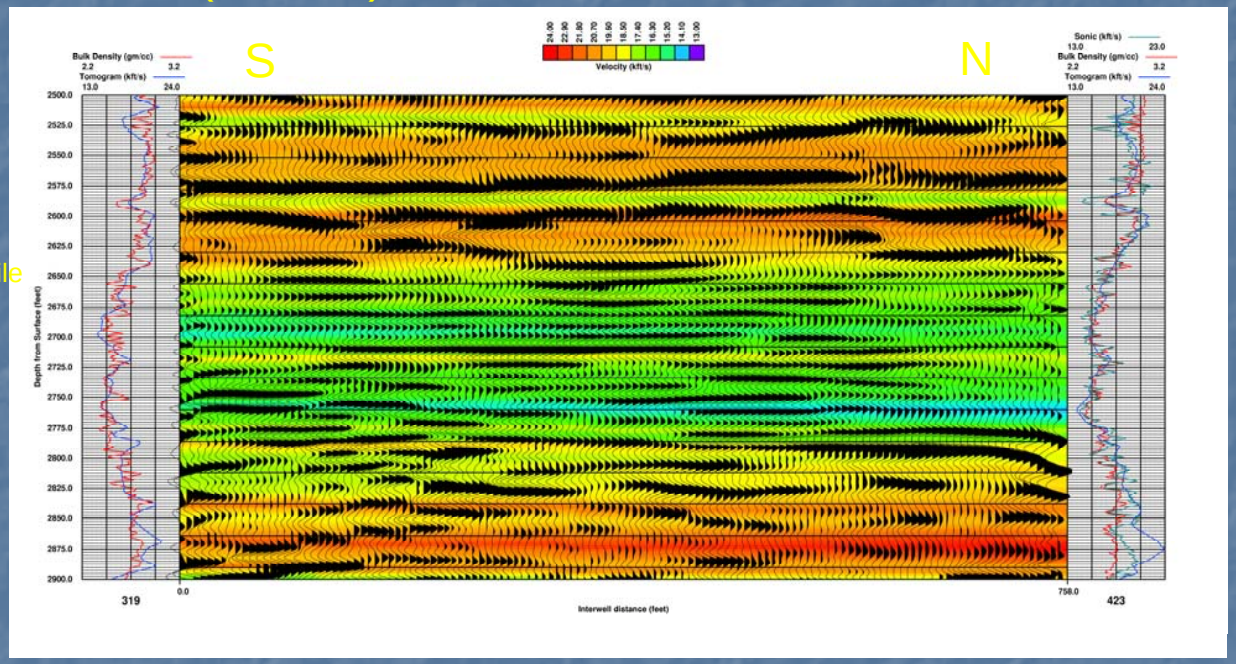
Sample X-well Profile

DY0386 (CM319) BO3826



X-well Profile

X-line 1295



758 ft.

- Tomography (background) shows velocity
  - Orange/Red – High Velocity
  - Green/Blue – Low Velocity
- Reflection Series (wiggle trace) as conventional seismic display

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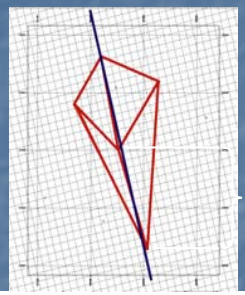
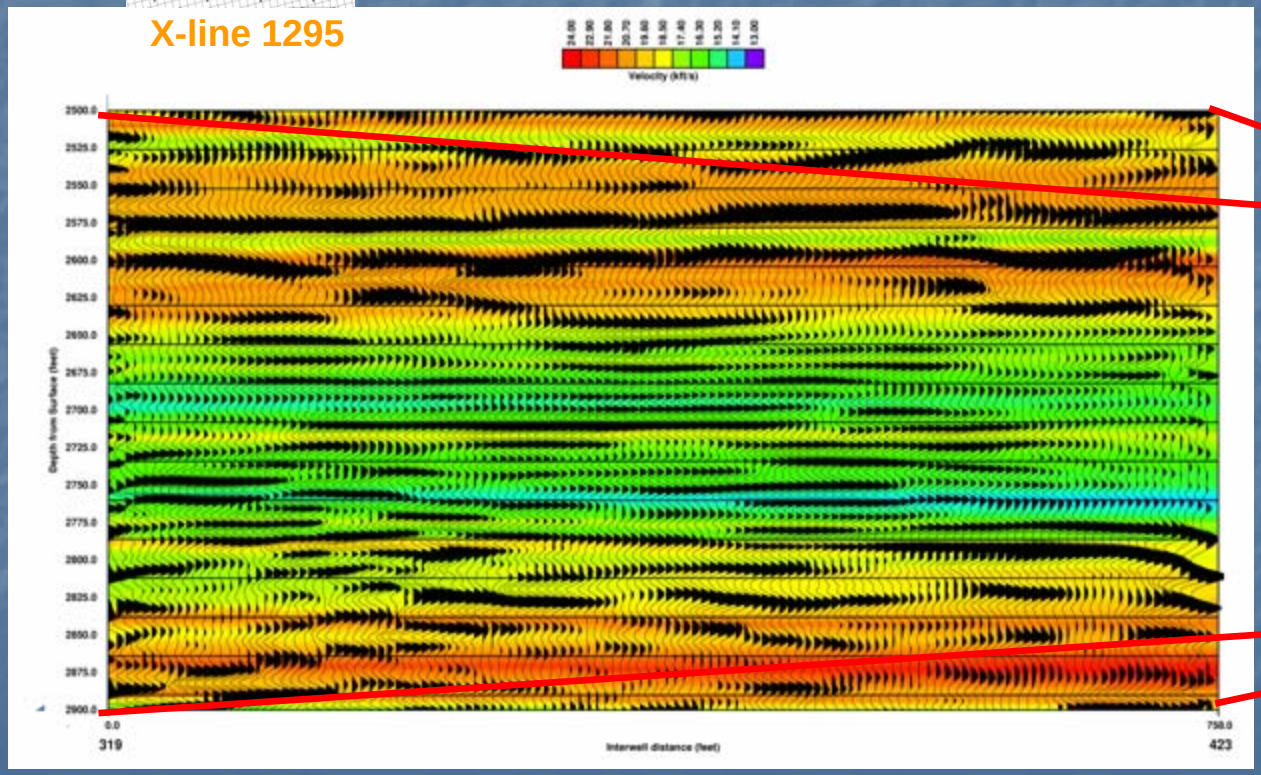
Comparison of Surface & X-well Data

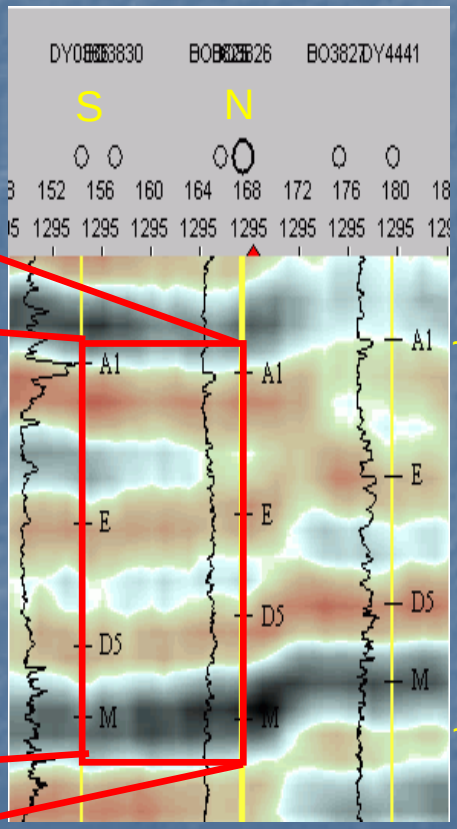


X-well Profile

•Illustrates improved resolution of intermediate-scale crosswell data!

X-line 1295





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Presentation Outline

- Background/Objectives
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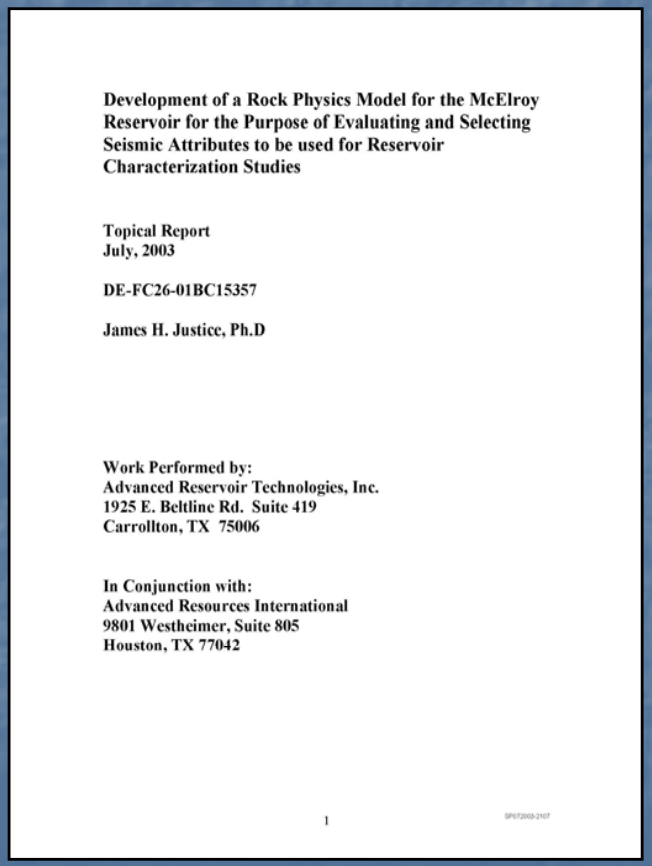
Four Main “Data Processing” Elements

- Rock Physics Modeling
- Seismic Processing & Attribute Extraction
- Log Clustering
- Log-Core Model

Rock Physics Modeling - Objectives

- Identify and prioritize seismic attributes most likely to be influenced by reservoir properties of interest (ϕ).
- Results used to select attributes to include in predictive models.
- See Topical Report.



Development of a Rock Physics Model for the McElroy Reservoir for the Purpose of Evaluating and Selecting Seismic Attributes to be used for Reservoir Characterization Studies

Topical Report
July, 2003

DE-FC26-01BC15357

James H. Justice, Ph.D

Work Performed by:
Advanced Reservoir Technologies, Inc.
1925 E. Beltline Rd. Suite 419
Carrollton, TX 75006

In Conjunction with:
Advanced Resources International
9801 Westheimer, Suite 805
Houston, TX 77042

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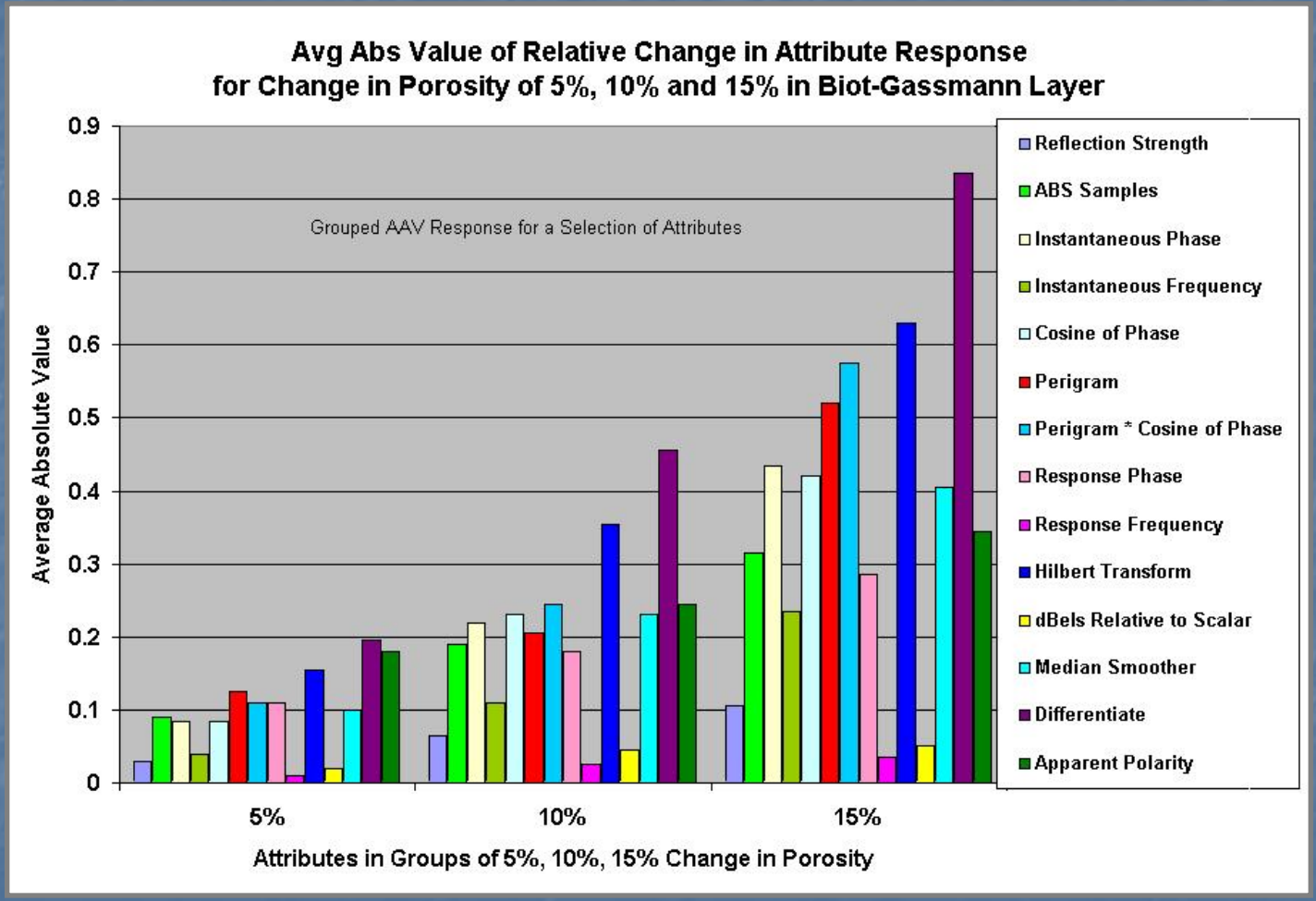
Ranking of Attributes Affected by Porosity



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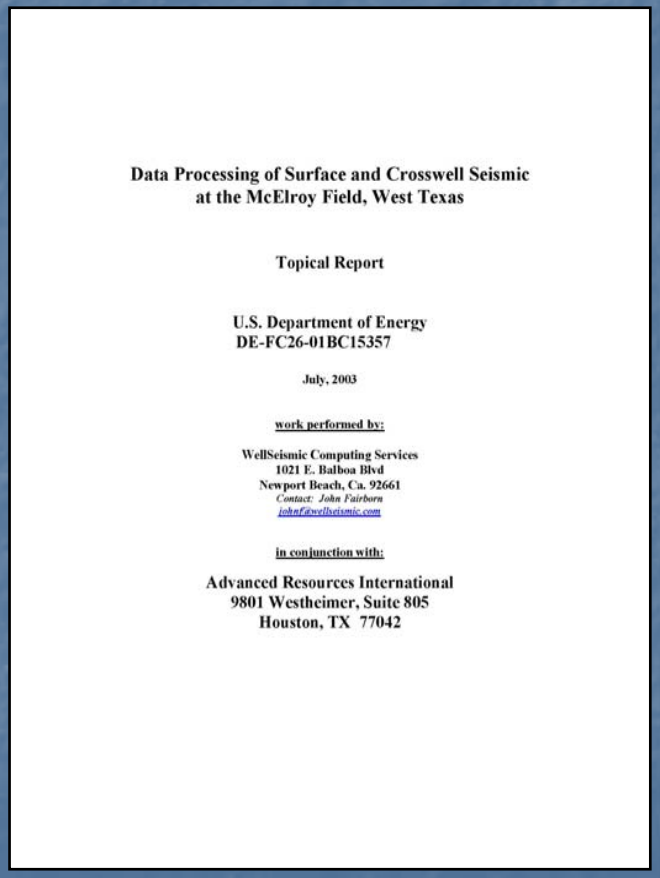
“High-Priority” Attributes

- Trace Differentiation
- Hilbert Transform (complex part of the analytic tract)
- Perigram (zero mean of the complex amplitude of the trace)
- Cosine of Phase (cosine of the instantaneous phase)
- Perigram * Cosine of Phase (product of these two attributes)
- Instantaneous Phase
- Instantaneous Frequency (time derivative of instantaneous phase)
- Median Smoother (3 point)
- Absolute Value of Trace
- Response Phase (instantaneous phase at the trace envelope peaks in degrees)
- Seismic Amplitude

Seismic Processing and Attribute Extraction - Objectives

- Data QC, time/depth conversion, tie (collocate) surface & Xwell traces.
- Calculate and extract “high priority” attributes from depth seismic.
- See Topical Report.



Data Processing of Surface and Crosswell Seismic
at the McElroy Field, West Texas

Topical Report

U.S. Department of Energy
DE-FC26-01BC15357

July, 2003

work performed by:

WellSeismic Computing Services
1021 E. Balboa Blvd
Newport Beach, Ca. 92661
Contact: John Fairborn
johnf@wellseismic.com

in conjunction with:

Advanced Resources International
9801 Westheimer, Suite 805
Houston, TX 77042

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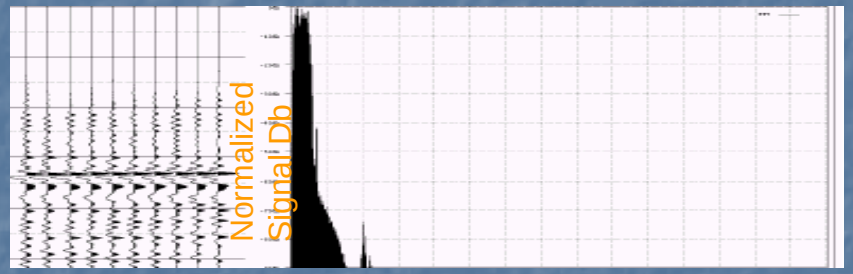
Seismic Data QC

- Two datasets to reprocess
  - 2000 vintage surface P-P seismic cube (post-steam)
    - ~2.5 square mile reflection seismic survey
    - 176 inlines, 176 crosslines
    - 55 ft. bin spacing CMP gathers
    - Central frequency 65 Hz.
    - Zero to 2 sec. data @ 2 ms. Sampling
  - October, 1997 vintage Xwell surveys (pre-steam)
    - 8 Crosswell seismic surveys
    - Lengths from 443 ft. to 758 ft. in six surveys
    - Two surveys approx. 1,250 ft. very poor quality
    - Shot depths approx. 1,700-2,950 ft.
    - Receiver depths 2,200-2,900 ft.
    - Sample interval 0.15 ms.
    - Varying Data Quality
  - Second Crosswell program 3/99
    - Data unavailable

Seismic Frequency Spectra

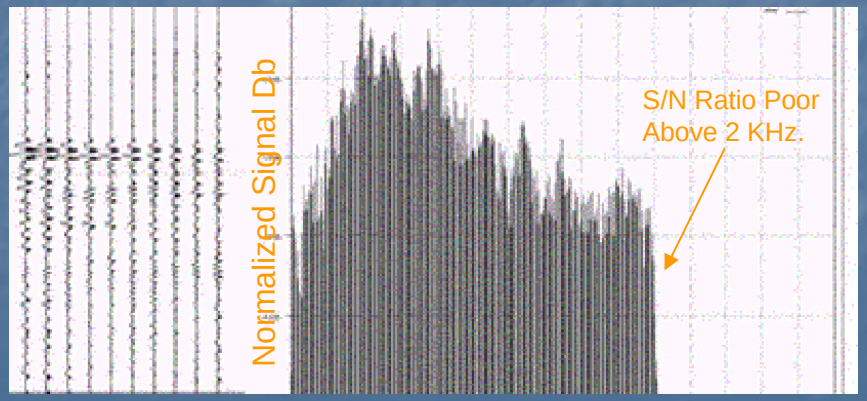
- Overall Good Quality Surface Data
- Signal to Noise Difficult in Crosswell

- Surface Seismic
  - Good S/N 20 to 100 Hz
  - Implied vertical resolution ~40 ft.



Ten Traces 0 Freq. Hz 3000

- Crosswell Seismic
  - Source Sweep 100-2,000 Hz.
  - Signal to Noise as high as 20 db.
  - Falloff above 2000 Hz. – Poor data quality
  - Implied vertical resolution ~ 5 ft.

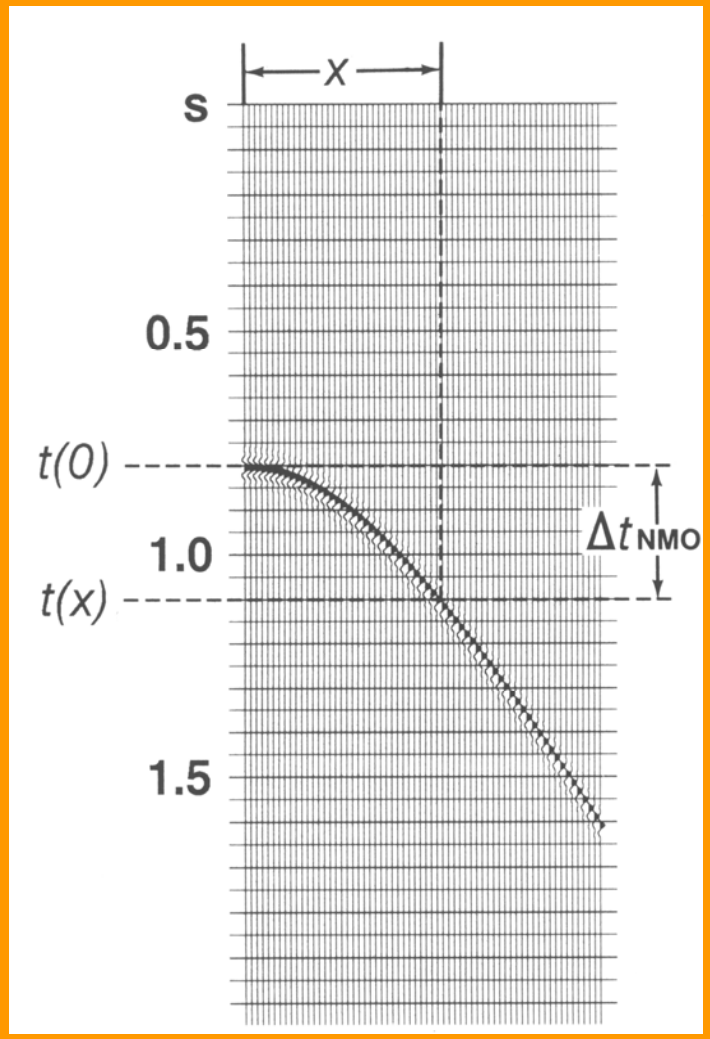


Ten Traces 0 Freq. Hz 3000

Time to Depth Conversion of Surface Seismic

- Did not have checkshot or VSP data
- Sonic logs do not extend to surface
- 1D (synthetic) methods based on well logs were difficult to tie
- Used Stacking Velocity Analysis to improve tie
  - Obtained uni-azmithal gathers
  - Calculated normal moveout velocities
  - Calculated T-d relationship at points throughout survey
- Used NMO T-d relationship to place synthetic seismic against observed data

Velocity Analysis Using NMO Gathers



- Can compute interval velocity using Seismic NMO Gathers
- Use Dx and Dt to calculate v_i
- Determine v_i in several vertical locations
- Determine v_i in several places around survey
- Result is "Stacking Velocities"
- Can be used for t-D conversion
- Very reliable t-D at McElroy due to certain factors
  - Virtually horizontal reflectors
  - Velocity constant laterally

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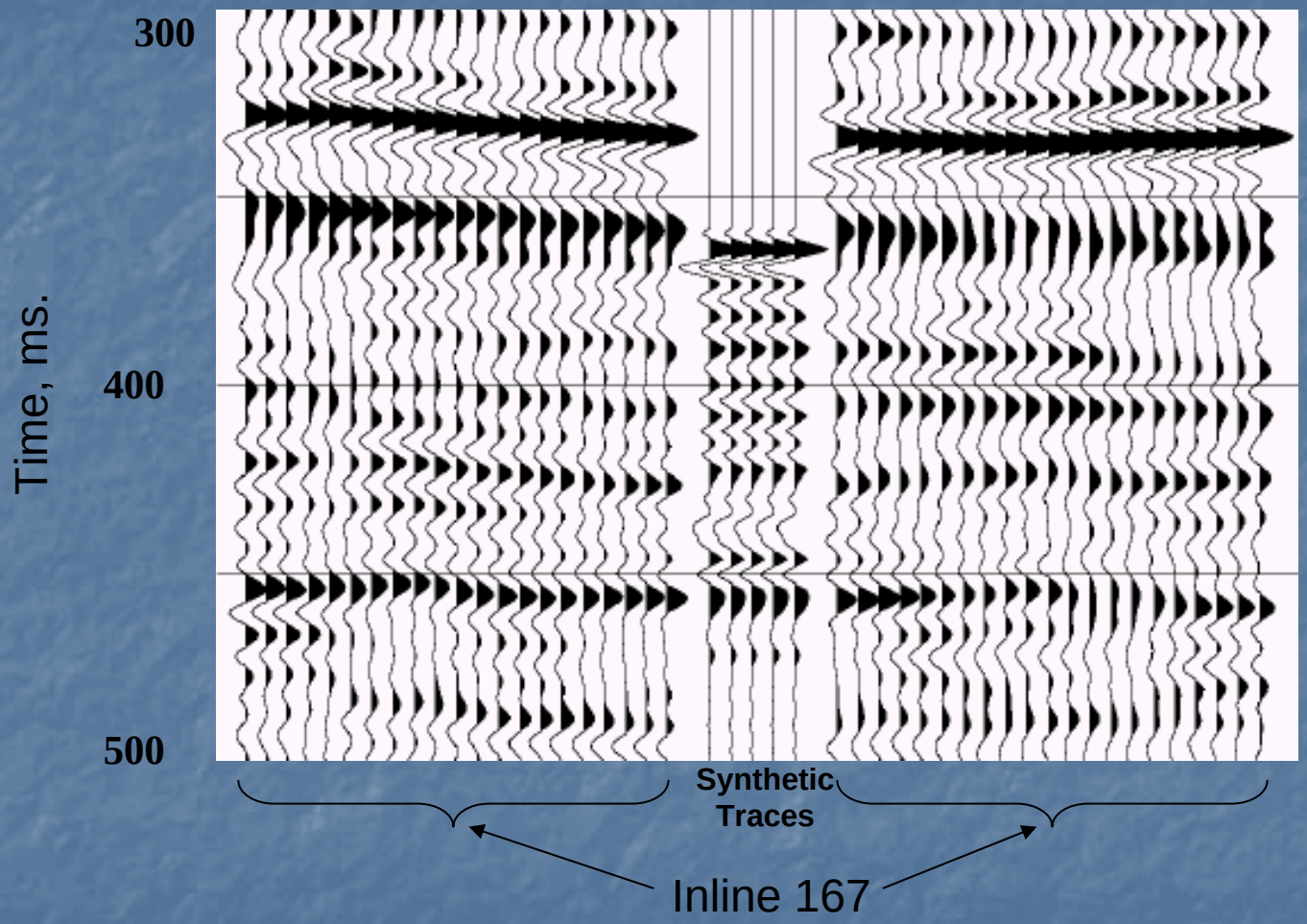
Tie at Well BO3826



- This well is central to the crosswell data, so a good T-d here is essential to a tie between surface and Xwell data.

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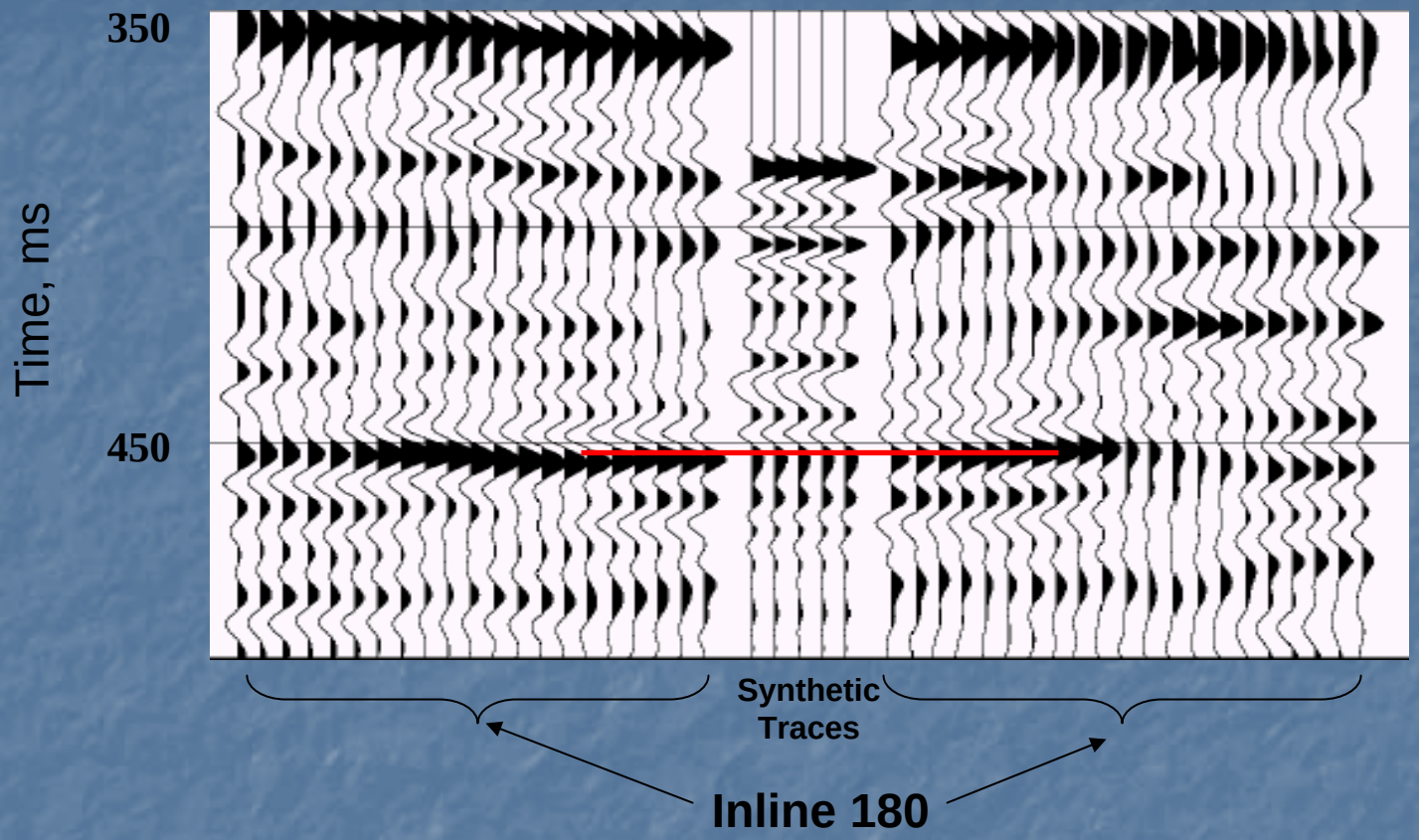
Tie at Well DY4441



- Tie point based on the alignment of reflections at 454 msec.
- Could also have tied at 390 ms
  - Better agreement with t-D computed from NMO velocities.

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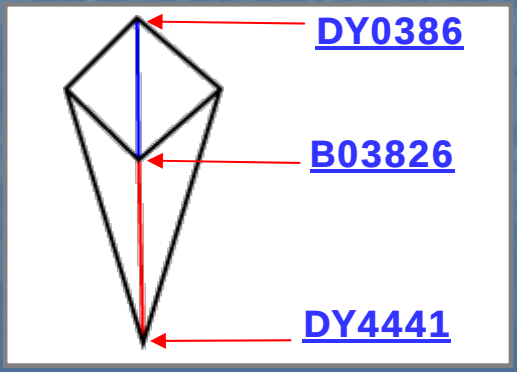
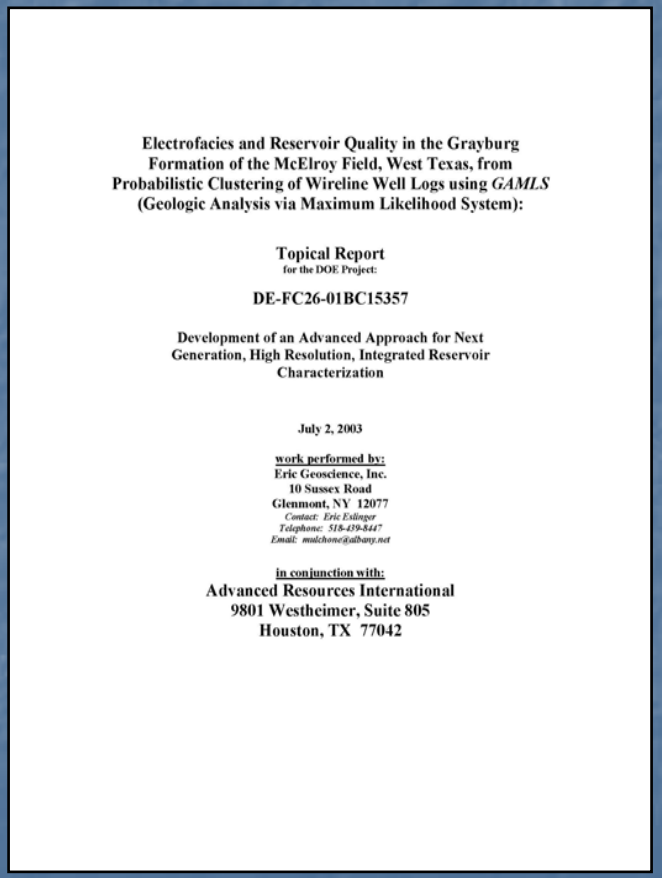
Crosswell Data

- Most data of poor quality.
  - Tube-wave noise
- Two profiles suitable for analysis.
  - Well DY0386 – B03826 (CM319 – CM423)
  - Well B03826 – DY4441 (CM423 – CM314)



Clustering - Objectives

- Facies definition in log data.
- To be used in log-core model.
- See Topical Report.



Electrofacies and Reservoir Quality in the Grayburg Formation of the McElroy Field, West Texas, from Probabilistic Clustering of Wireline Well Logs using *GAMLS* (Geologic Analysis via Maximum Likelihood System):

Topical Report
for the DOE Project:

DE-FC26-01BC15357

Development of an Advanced Approach for Next Generation, High Resolution, Integrated Reservoir Characterization

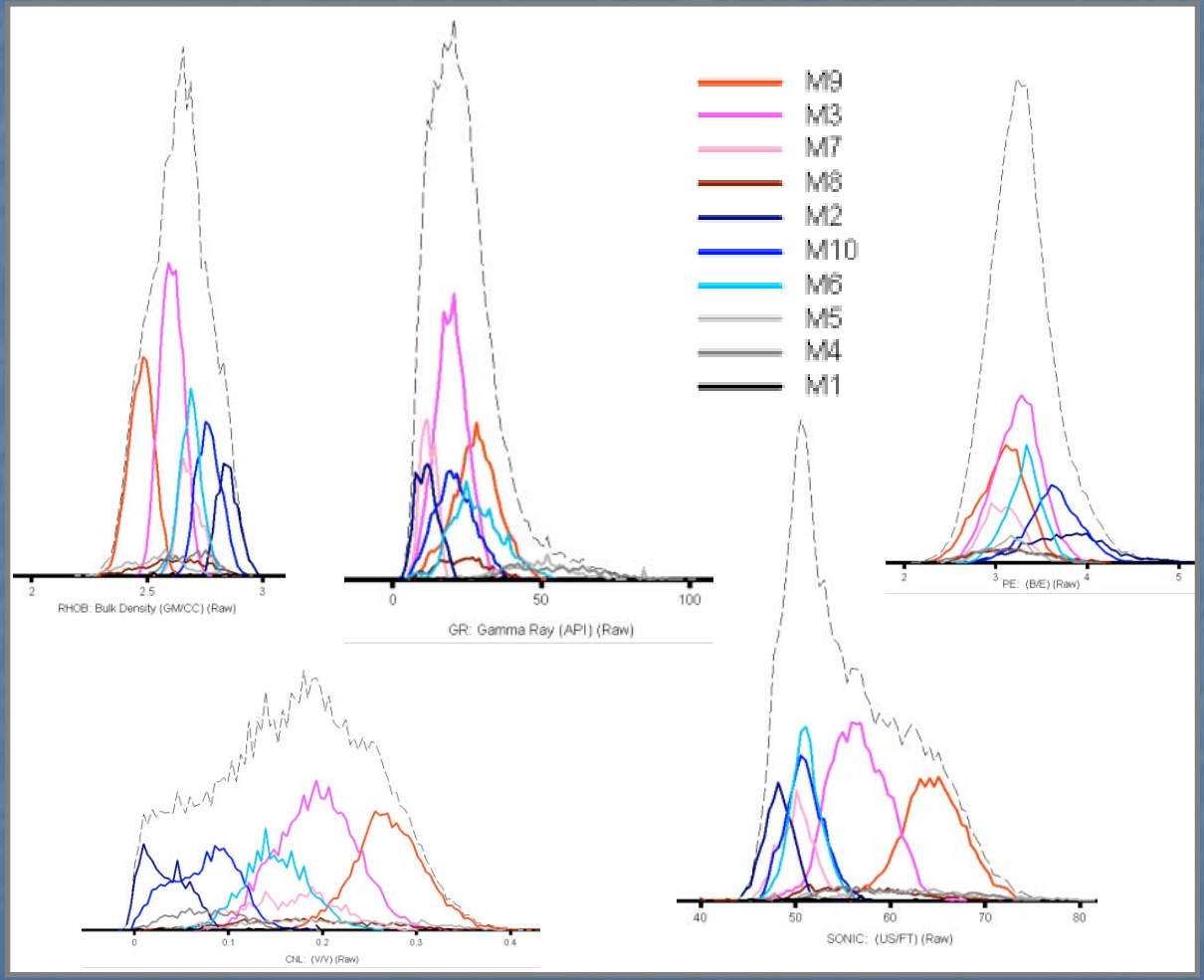
July 2, 2003

work performed by:
Eric Geoscience, Inc.
10 Sussex Road
Glenmont, NY 12077
Contact: Eric Eslinger
Telephone: 518-439-8447
Email: mulchone@albany.net

in conjunction with:
Advanced Resources International
9801 Westheimer, Suite 805
Houston, TX 77042

Advanced Resources International

Frequency Distribution Curves for Logs



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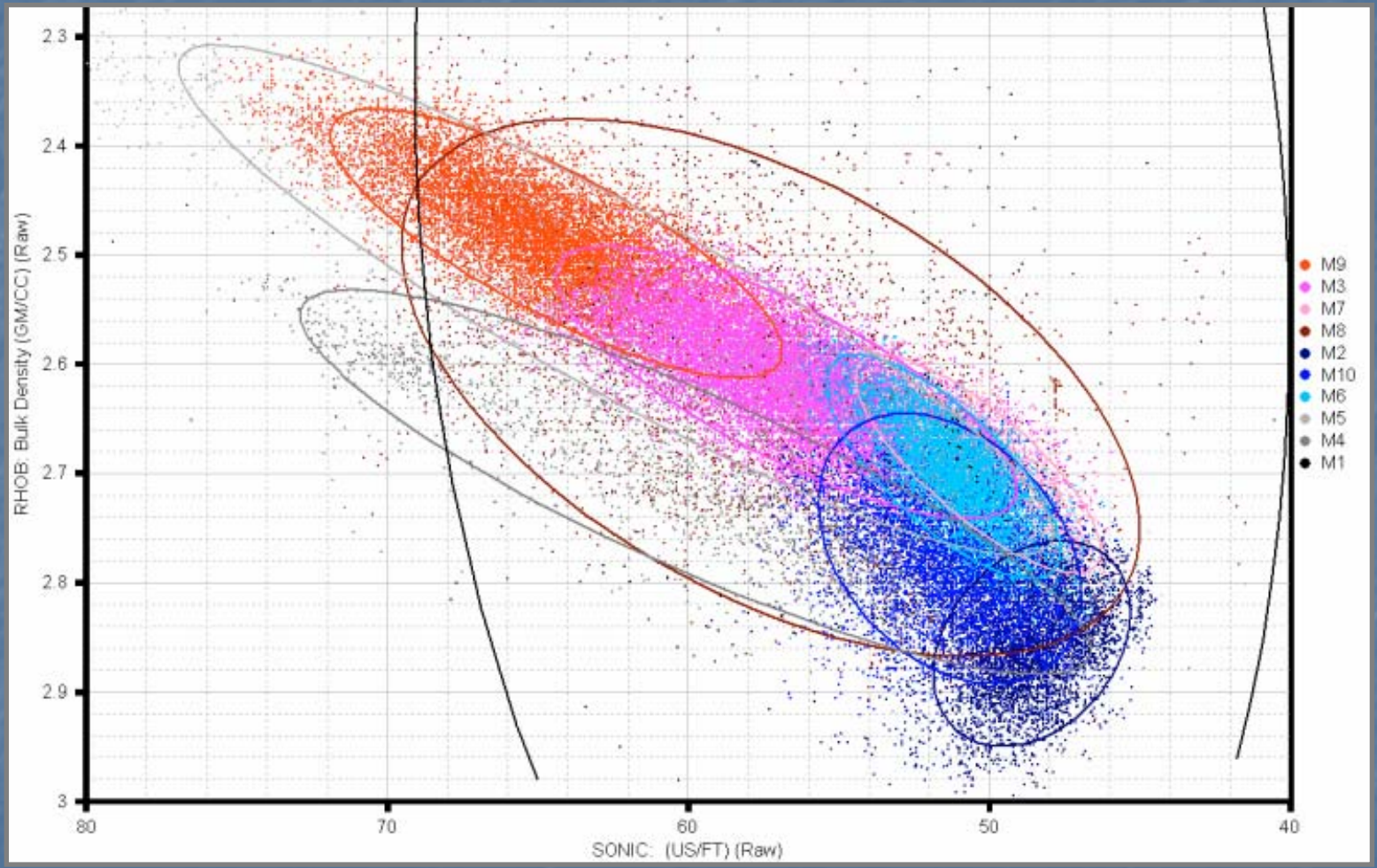
Example Multi-Dimensional Crossplot



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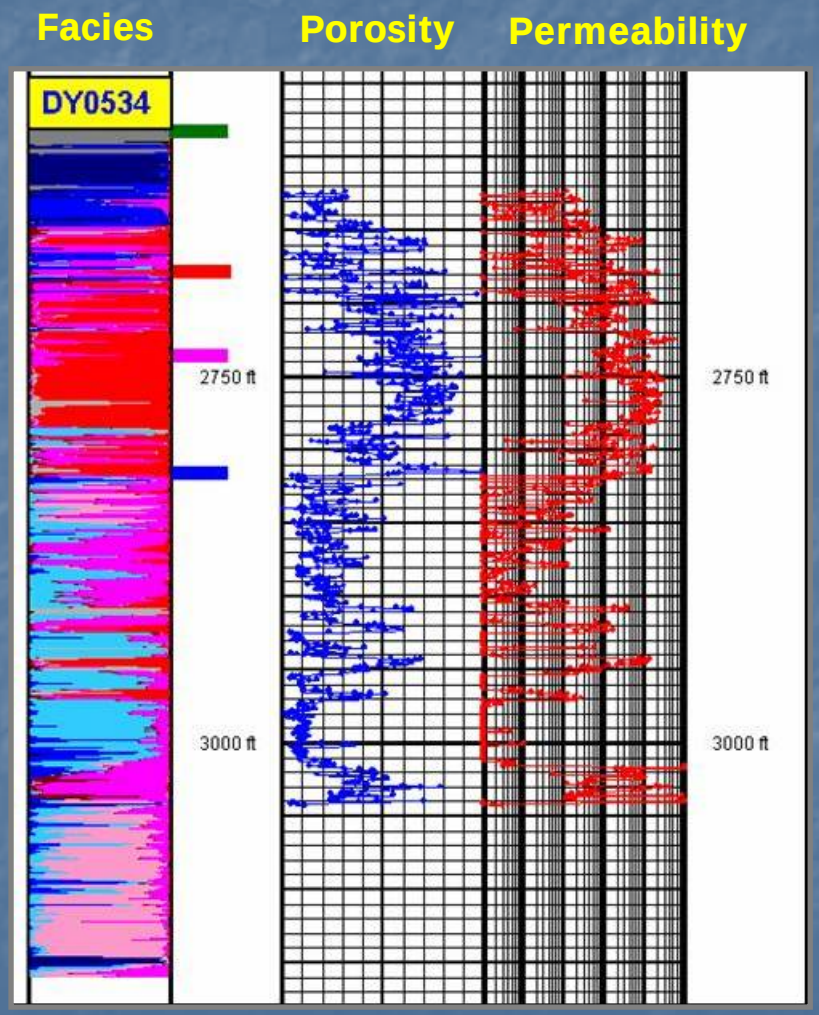
Multi-Well Clustering Results

Mode	6	4	2	5	10	8	1	7	9	3
Color	gold	dk gry	purple	med blue	lt blue	lt gry	dk grn	med grn	red	pink
%	6.1	3.9	10	17.2	2	0.9	5.9	12	8.8	33.1
Grn Den	2.93	2.86	2.87	2.86	2.88	2.87	2.76	2.77	2.82	2.88
DT	50	59	49	53	53	57	57	52	63	61
CNL	0.02	0.07	0.09	0.14	0.15	0.17	0.18	0.18	0.24	0.24
GR (API)	17	51	14	27	28	54	21	15	39	25
Rock Type	Anhydrite	Shaley	Mixed	Mixed	Mixed	Shaley	Mixed	Mixed	Best Res.	Best Res.

- Results left to right in increasing apparent porosity (NPHI)

Cluster Assignments Compared to Core Data



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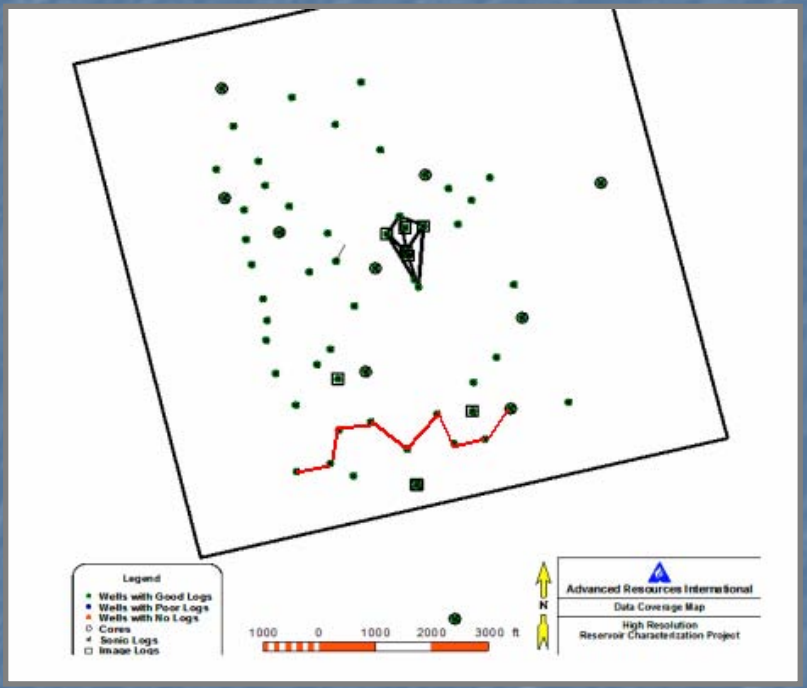
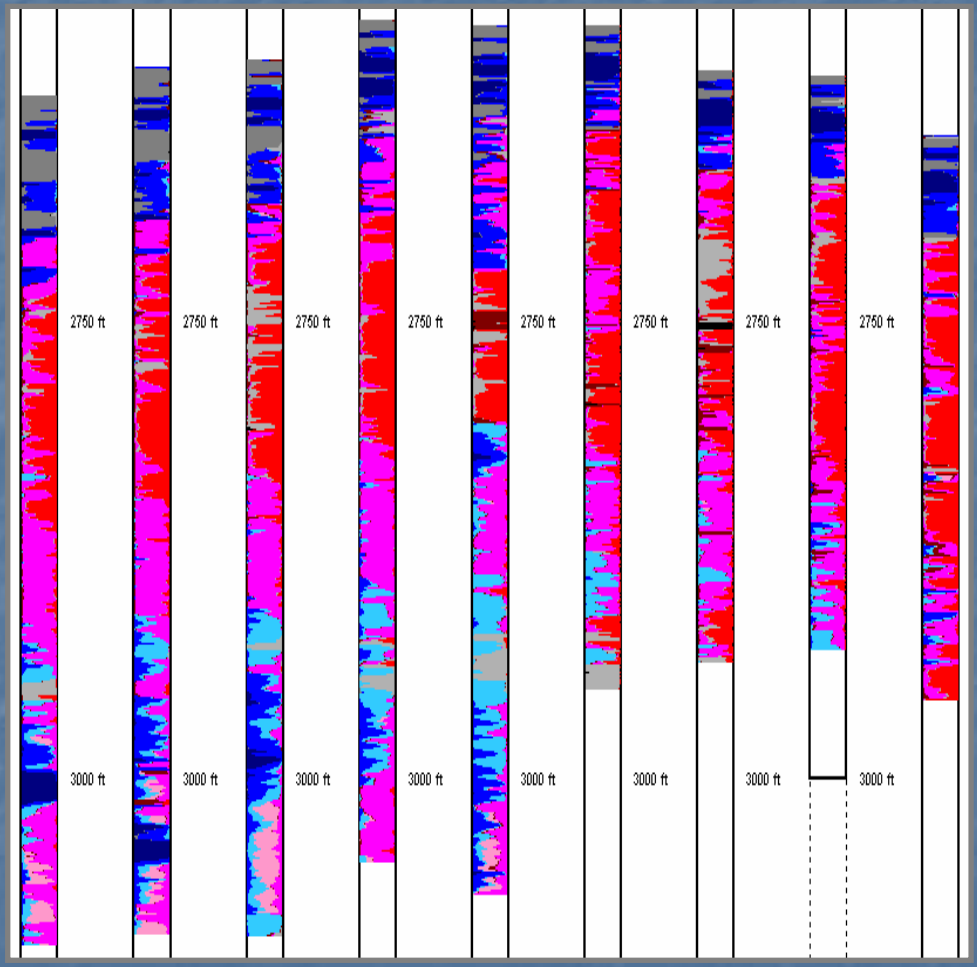
Facies Cross-Section





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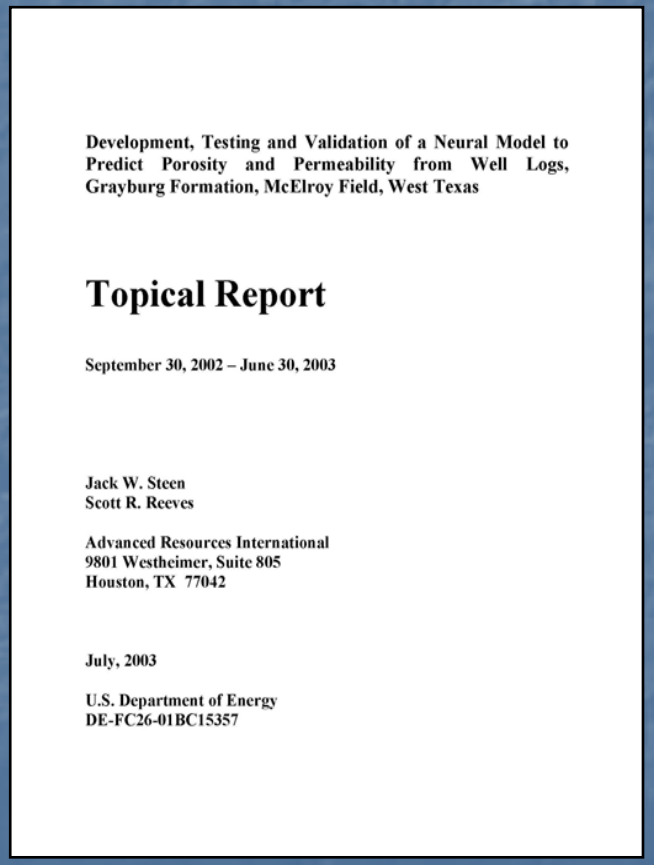
Log-to-Core Model

- +/- 6500 datapoints; (10 wells x 325 ft @ ½ ft increments).
- 6 logs as input; core porosity and permeability as output.
- Use 60% data for training, 20% for testing, 20% for validation.
- See Topical Report.



Development, Testing and Validation of a Neural Model to Predict Porosity and Permeability from Well Logs, Grayburg Formation, McElroy Field, West Texas

Topical Report

September 30, 2002 – June 30, 2003

Jack W. Steen
Scott R. Reeves

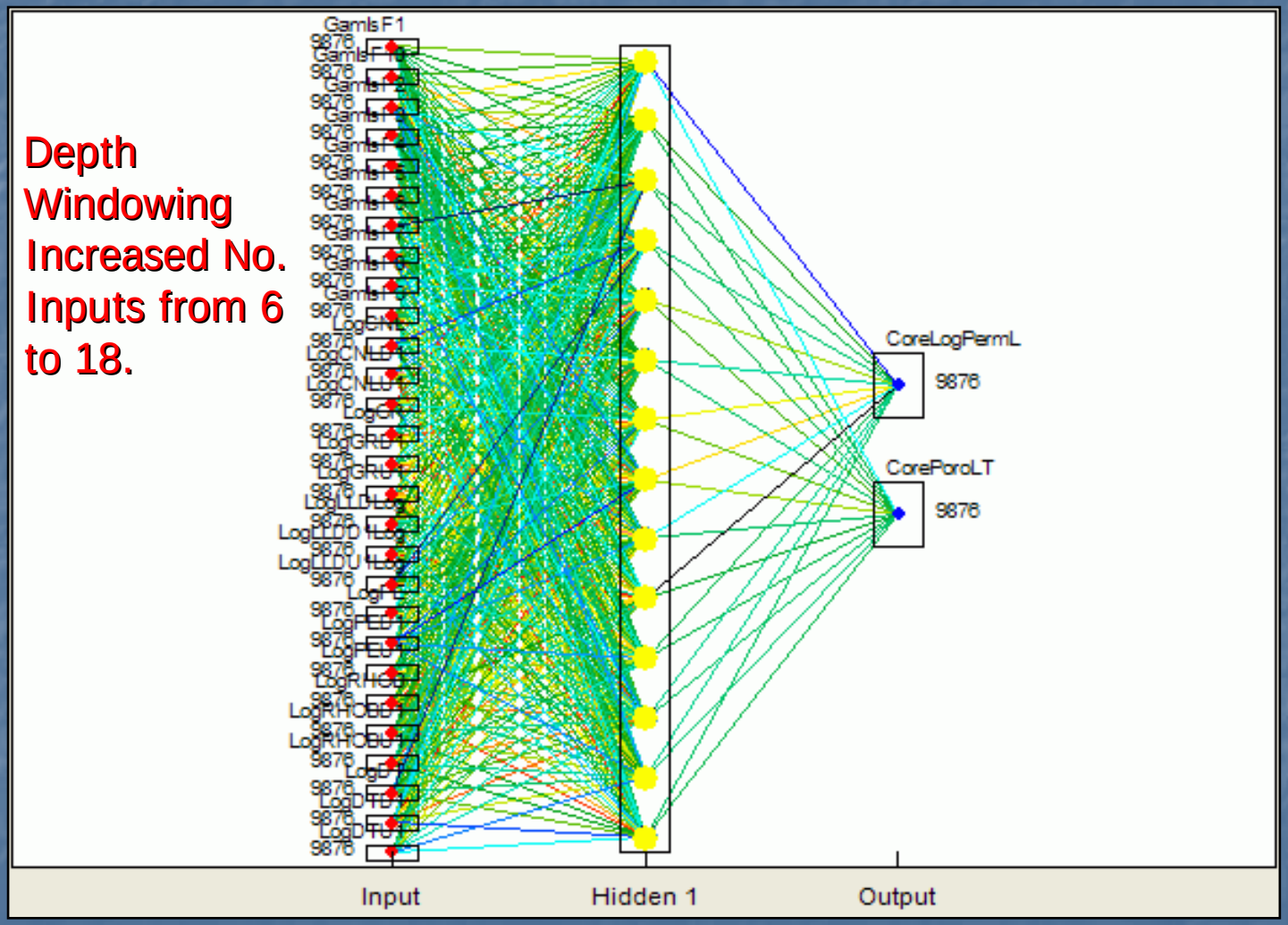
Advanced Resources International
9801 Westheimer, Suite 805
Houston, TX 77042

July, 2003

U.S. Department of Energy
DE-FC26-01BC15357

ANN Model Structure

Depth Windowing Increased No. Inputs from 6 to 18.



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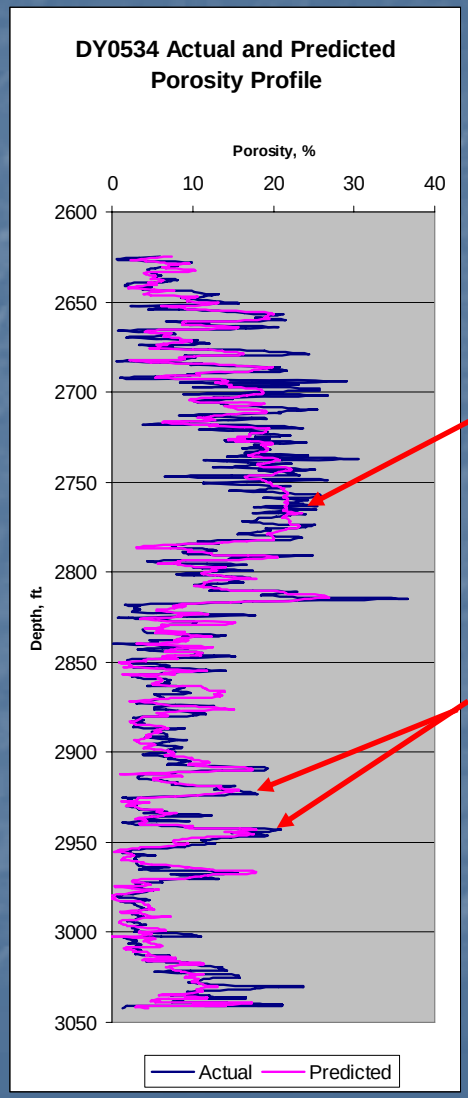
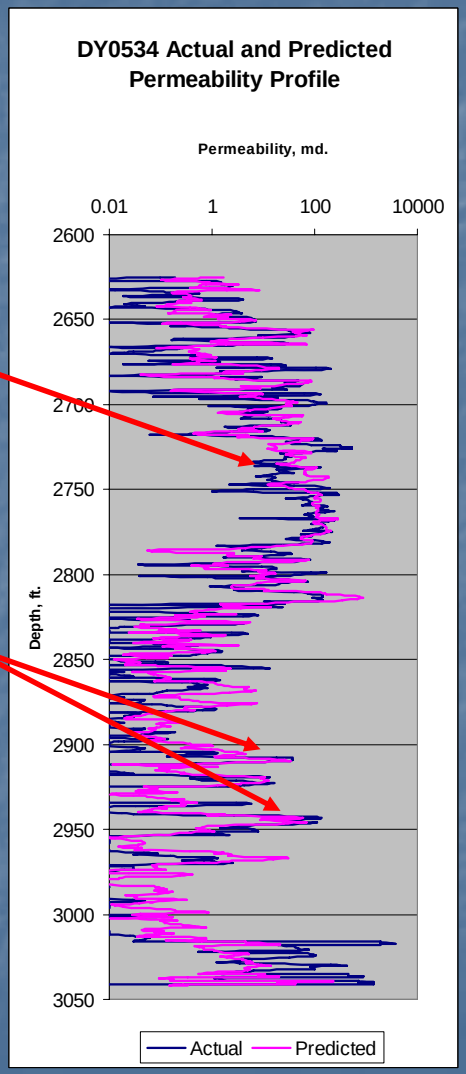
Actual vs. Predicted Porosity & Permeability



"Smoothing"

Porosity/ Permeability "Streaks"



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Benefits of ANN Model

Predictor	Correlation R^2	
	Porosity	Permeability
CNL log	0.54	0.09
GR log	0.02	<0.01
LLD log	0.10	0.01
PE log	0.24	0.02
RHOB log	0.58	0.13
DP log	0.67	0.17
ANN Model	0.74	0.71

Presentation Outline

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Two Models Evaluated

- "Sequential" System (original objective)
  - 3-D to XWell
  - XWell to Log
  - Log to Core

  } Series of Supervised ANN's

- "One-Step" System
  - Clustering

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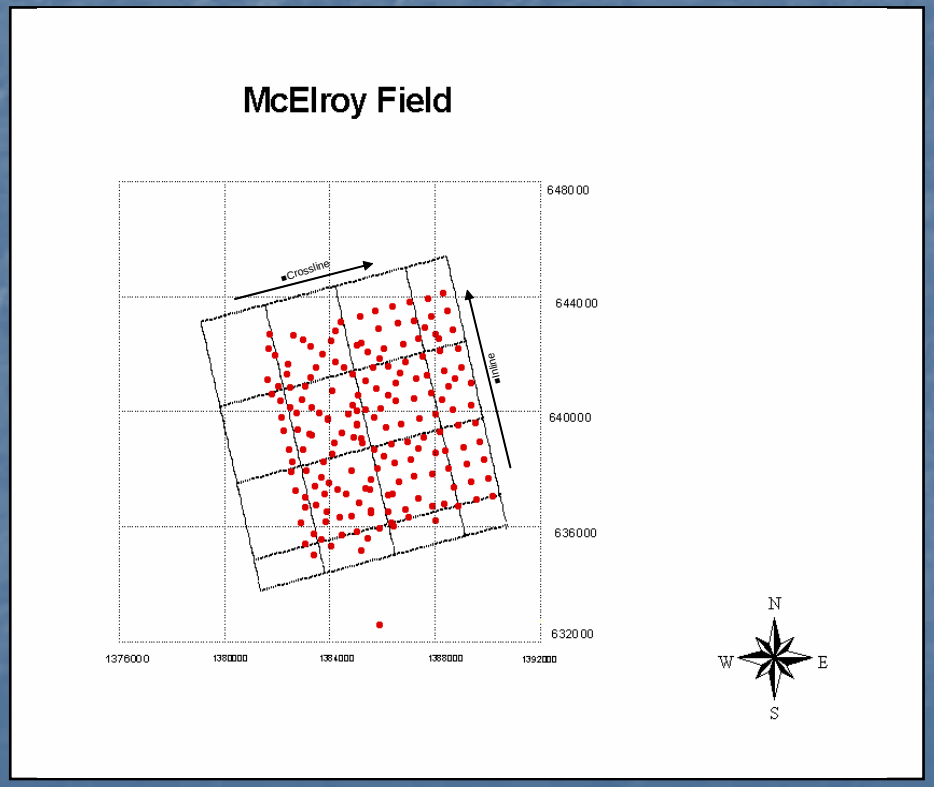
Seismic Data Volume

- 176 inlines and 176 crosslines @ 55 ft bin spacing

  > 30,000 traces

- 300 ft X 0.5 ft sample intervals, 11 attributes

  > 200,000,000 records



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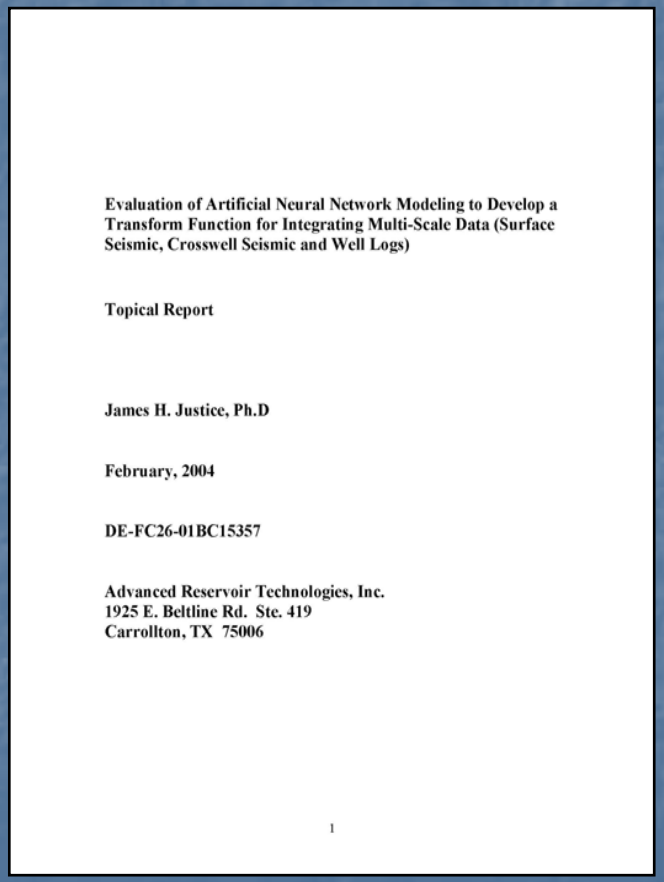
Supervised ANN Modeling

- Constructed two, cascading ANN models
  - 3D-Xwell
  - Xwell-Log
- Data Breakout
  - 60% Training
  - 20% Testing
  - 20% Validation



Evaluation of Artificial Neural Network Modeling to Develop a Transform Function for Integrating Multi-Scale Data (Surface Seismic, Crosswell Seismic and Well Logs)

Topical Report

James H. Justice, Ph.D

February, 2004

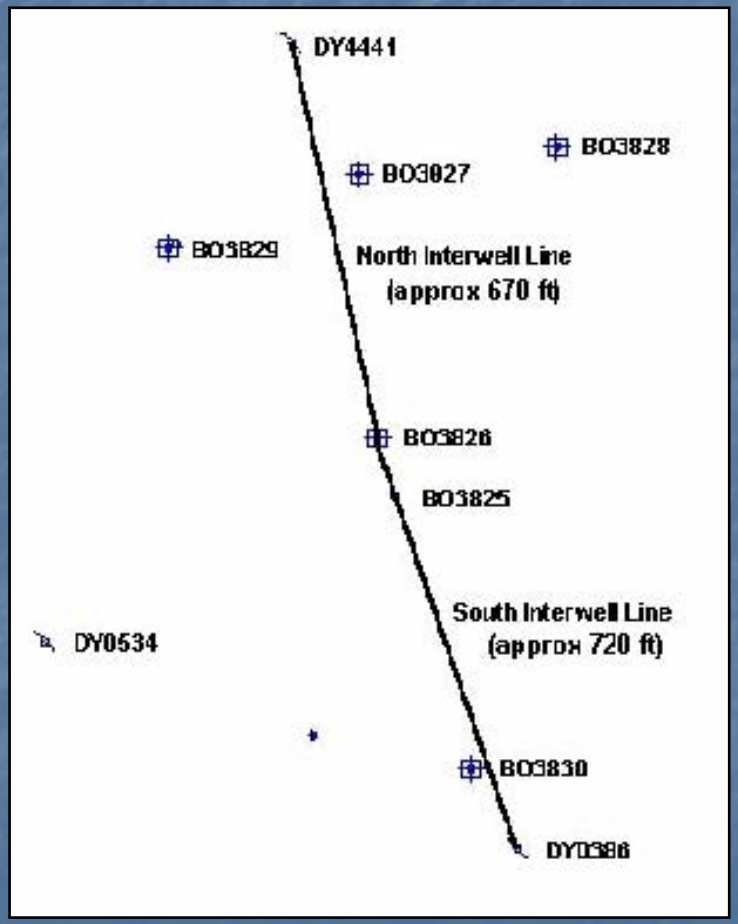
DE-FC26-01BC15357

Advanced Reservoir Technologies, Inc.
1925 E. Beltline Rd. Ste. 419
Carrollton, TX 75006

1

Results From Selected Test Wells

Actual vs. Predicted Logs (R_2)							
	DY4441	BO3826	DY0386	BO3825	BO3828	BO3829	DY0534
Sonic Scatter Plot	0.5940	0.4827	0.3146	0.0125	0.1465	0.0005	0.0366
RHOB Scatter Plot		0.6027			0.1094		0.0287
PE Scatter Plot		0.3616			0.1166		0.0034
LLD Scatter Plot		0.5319			0.0258		0.0009
GR Scatter Plot		0.3882			0.1465		0.0474
CNL Scatter Plot		0.6180			0.0014		0.0245



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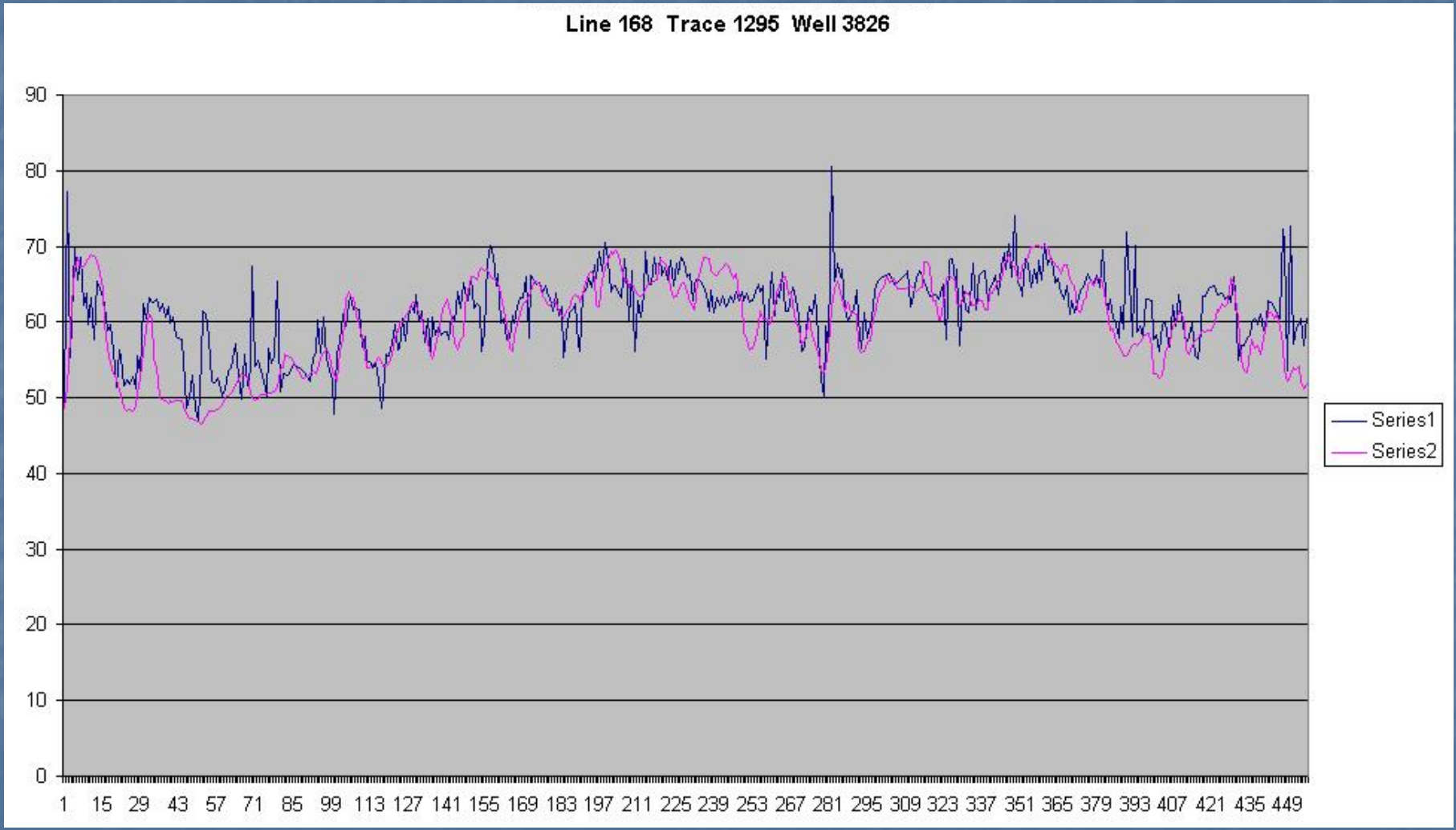
Predicted vs Actual Sonic



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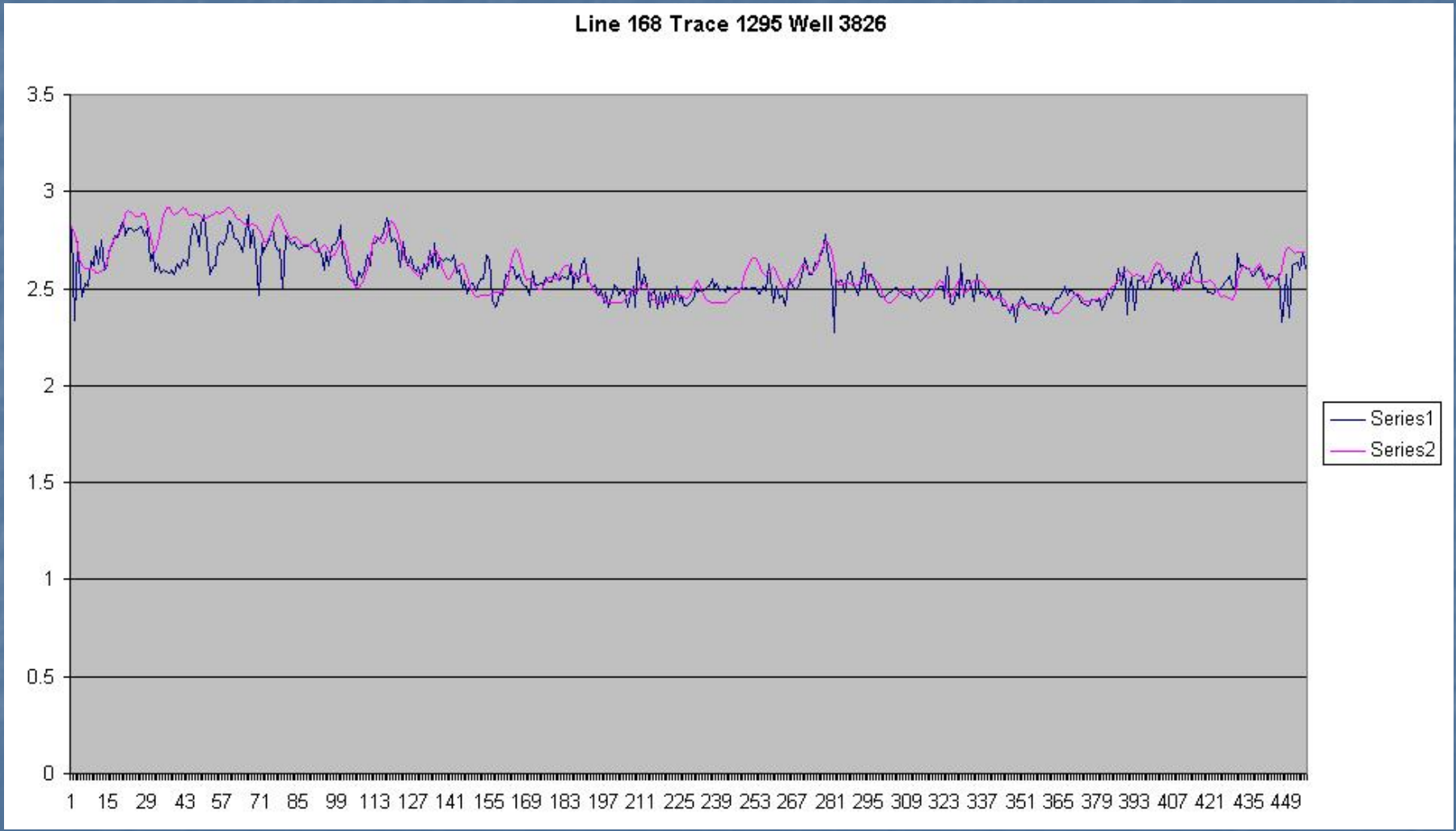
Predicted vs Actual RHOB



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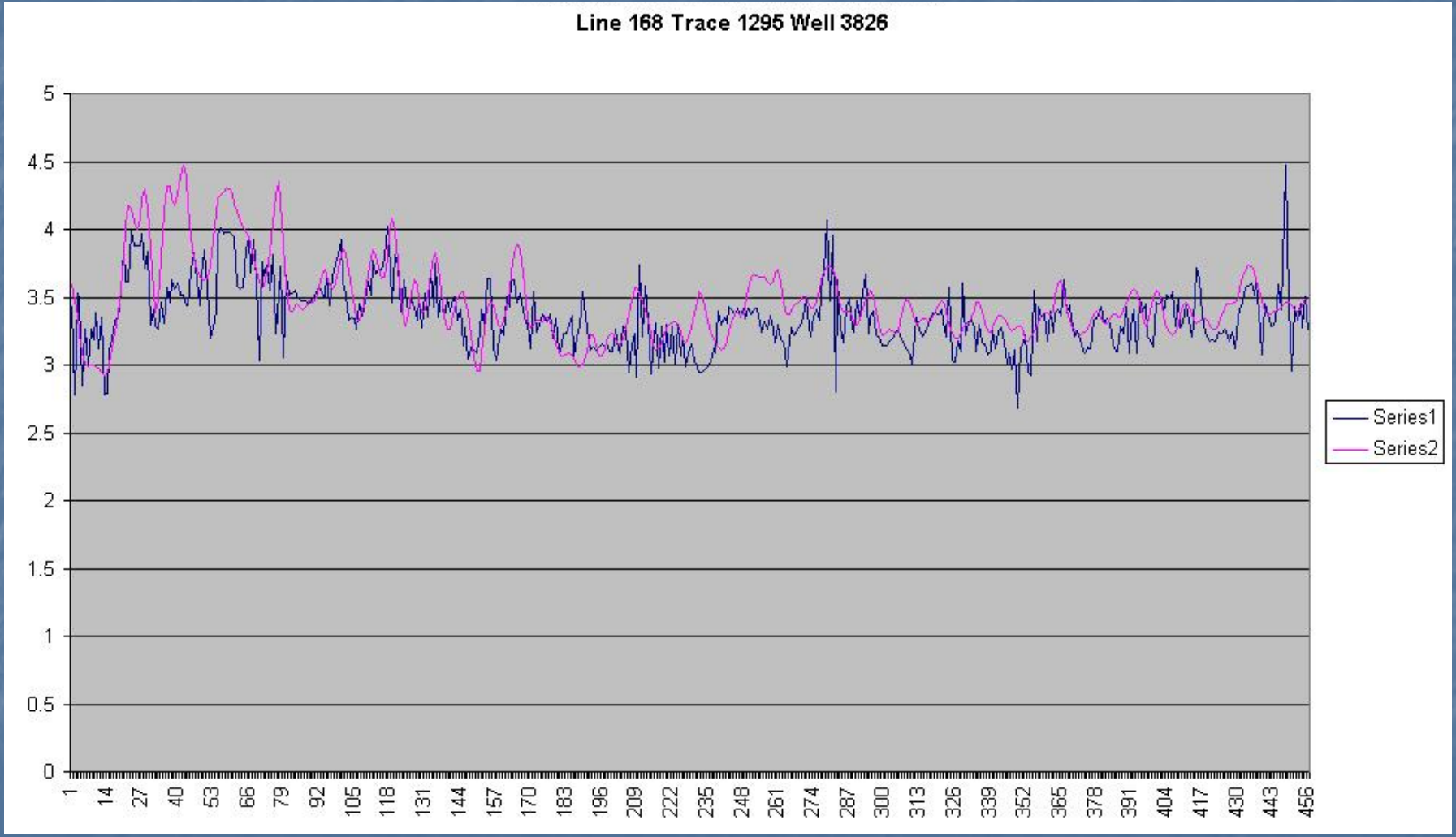
Predicted vs Actual PE



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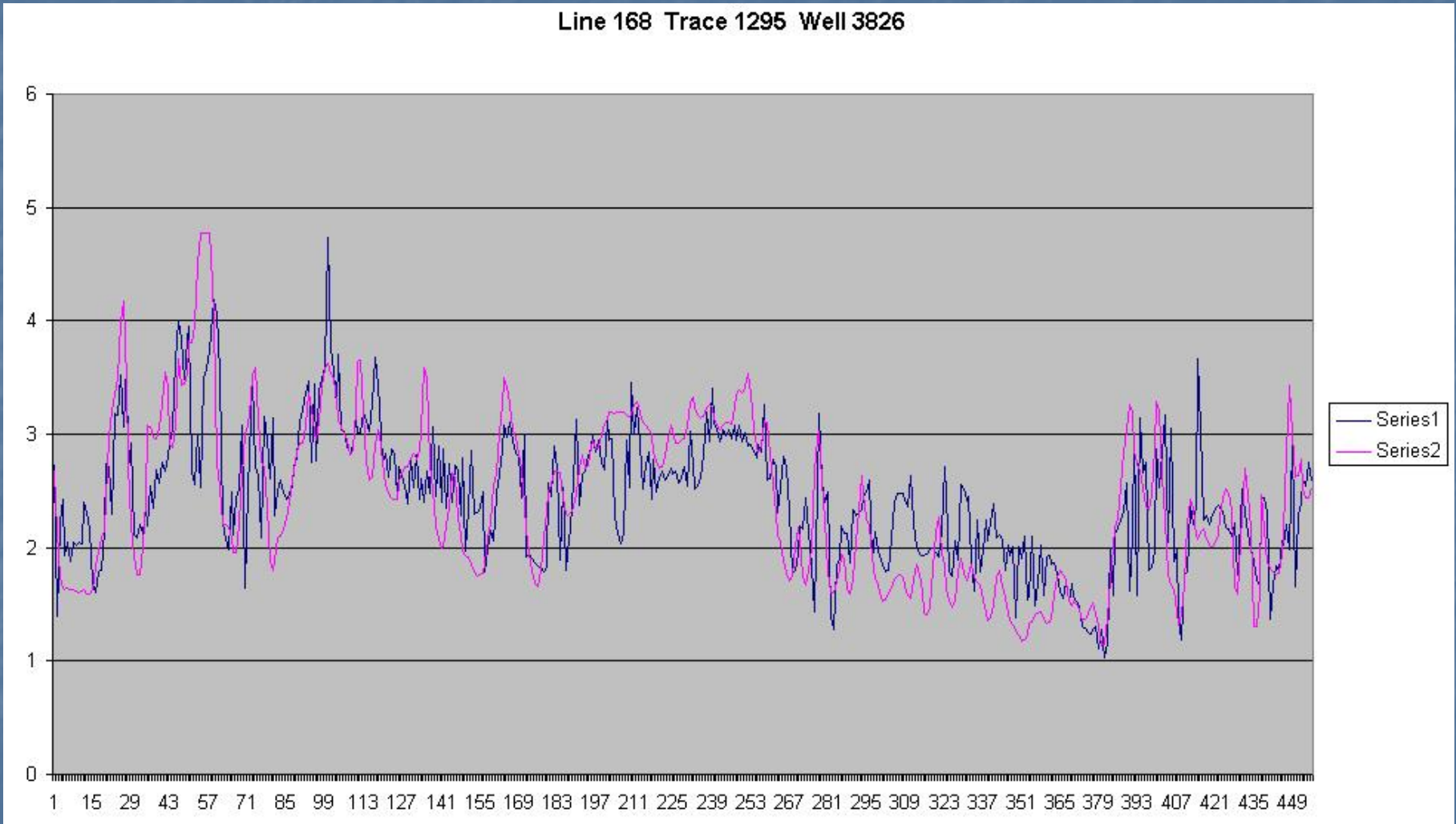
Predicted vs Actual log10 LLD



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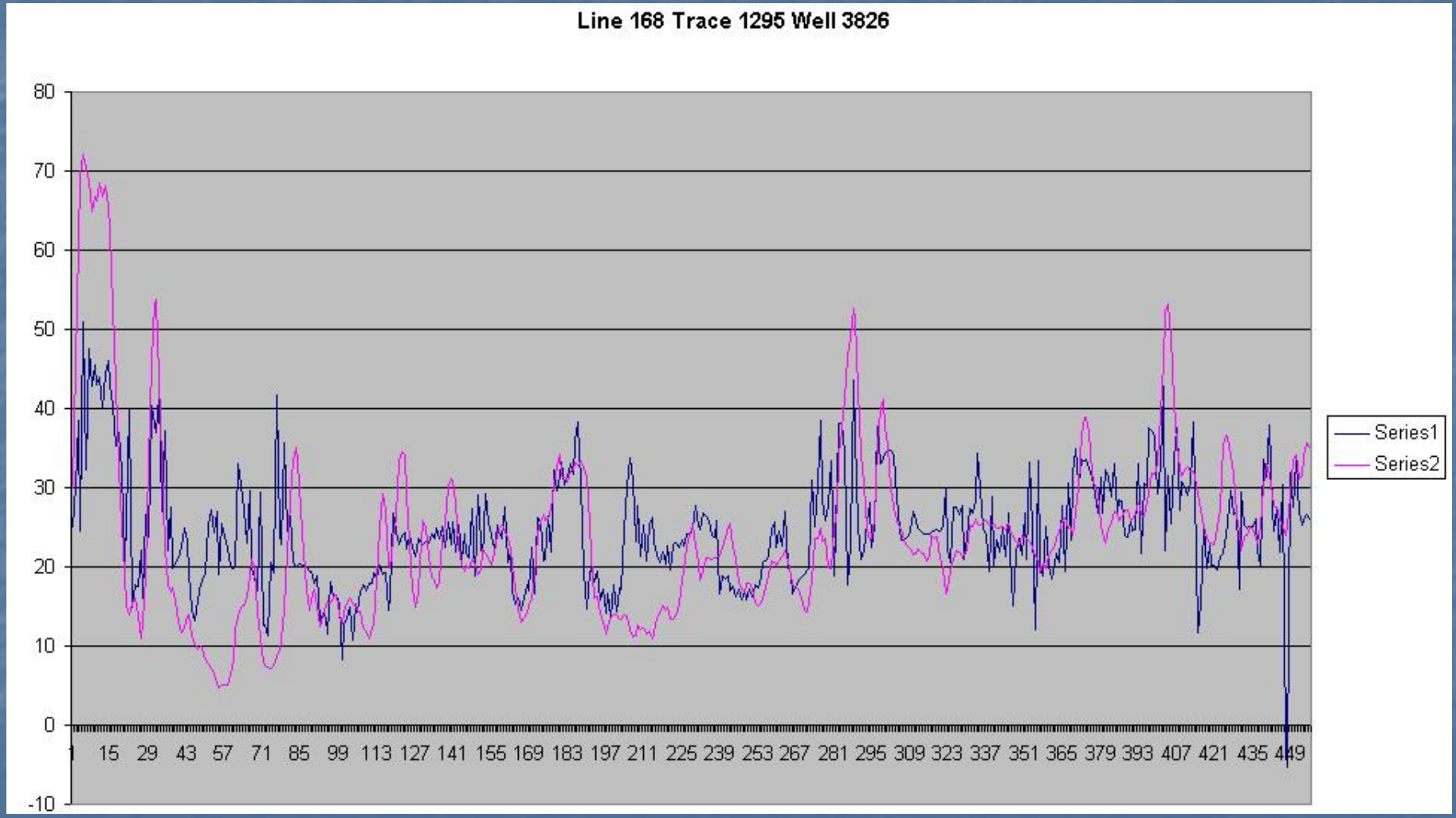
Predicted vs Actual GR



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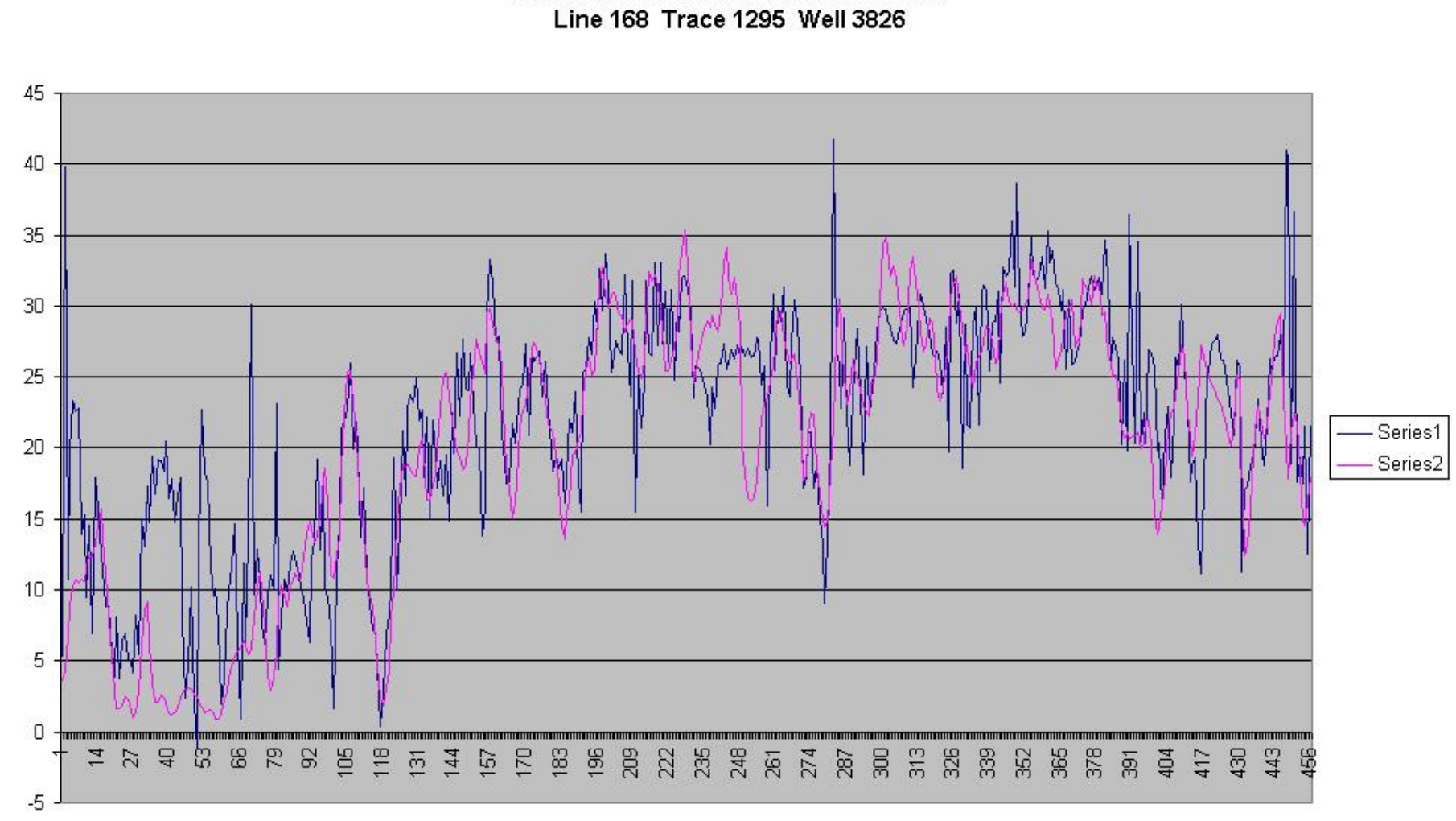
Predicted vs Actual CNL



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Model 1 Conclusions

- Results were reasonable at center well, but not beyond that location.
- Model was deemed unacceptable for widespread application.

Model 2: Clustering

- Data "gap-filling" procedure

Data Matrix					
Data	**# Wells**	**Core**	**Log**	**XWell**	**Surface**
Core	11	✓	✓	✗	✗
XWell	4	✗	✓	✓	✓
Logs (non-cored wells)	~50	✗	✓	✗	✓
Surface Seismic	~30,000	✗	✗	✗	✓

Prediction of Core Data from Well Logs

- Constructed cluster model using 6 wells
  - 5 logs as input
  - P&P as output
- Validated model on 5 wells

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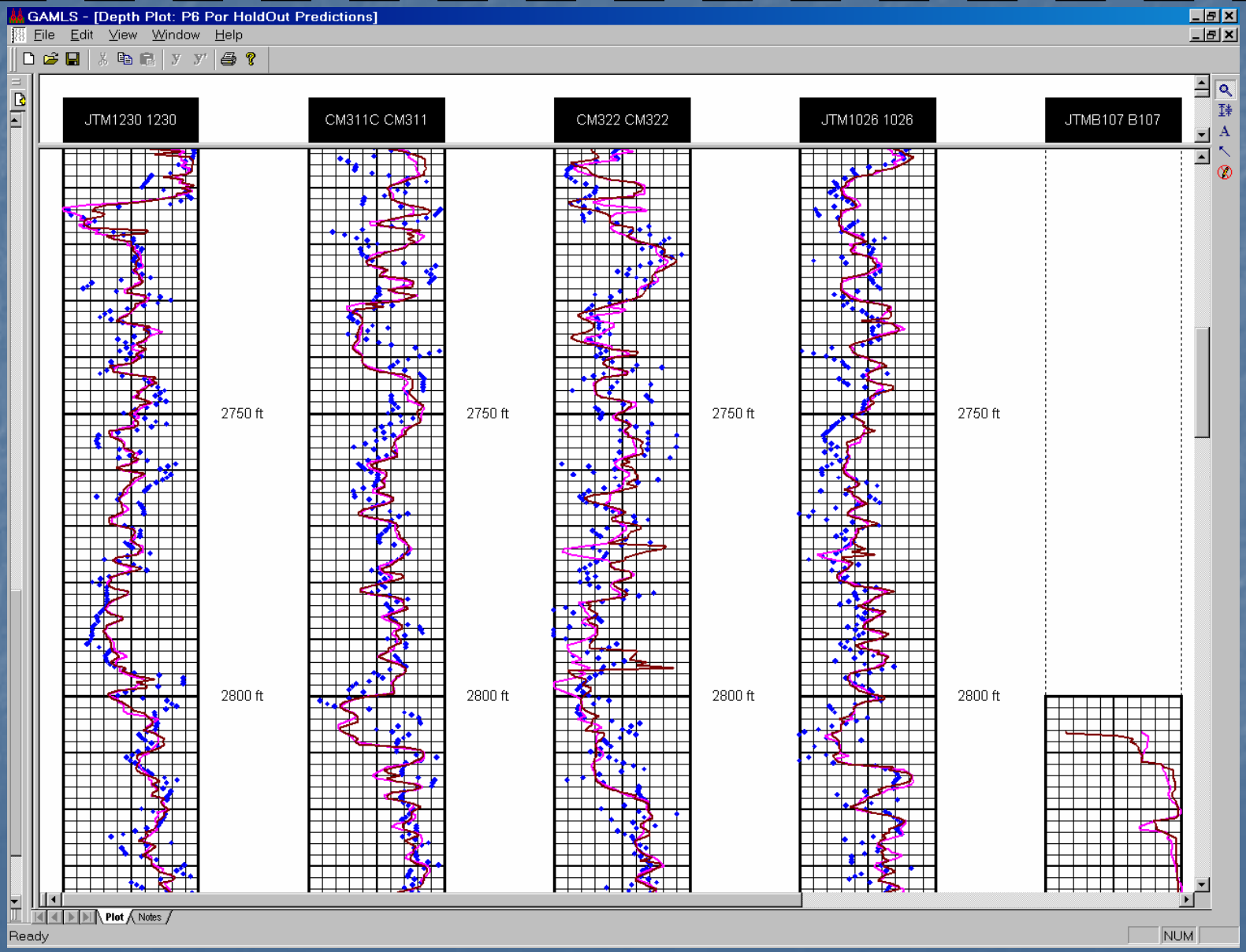
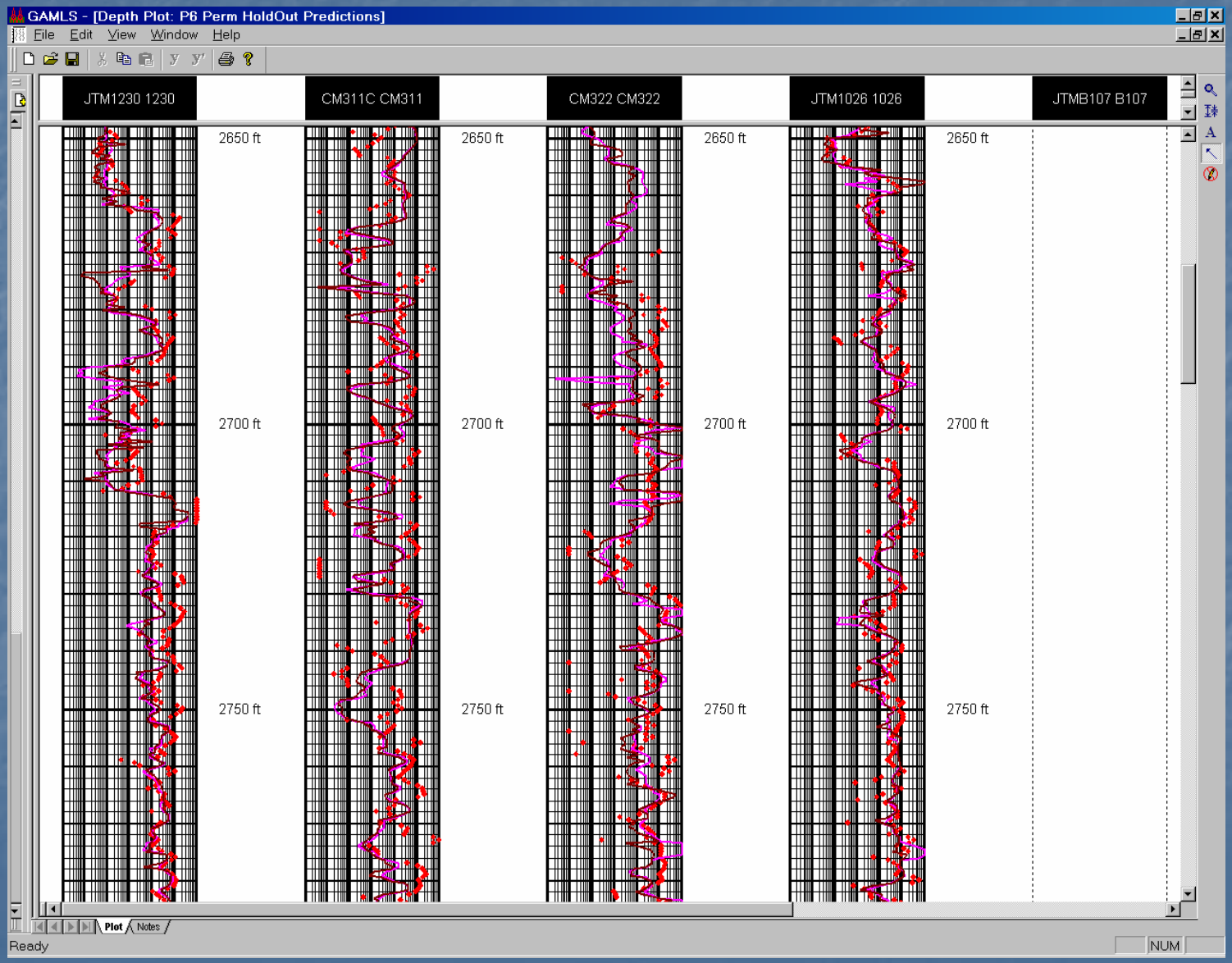
Porosity Predictions for Holdout Wells



Permeability Predictions for Holdout Wells



Predictions Better in HRQ Rock

Permeability Correlations (R Values)

between Core Perm and Predicted Perm P6 (all samples): 0.835
between Core Perm and Predicted Perm P7 (all samples): 0.724

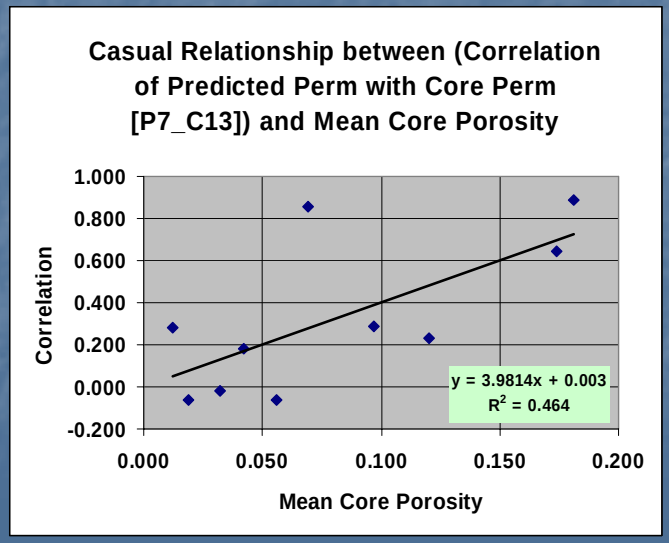
between Predicted Perm P6 and Predicted Perm P7 (all samples): 0.911

between Core Porosity and Predicted Porosity P6 (all samples): 0.775
between Core Porosity and Predicted Porosity P7 (all samples): 0.797

between Predicted Porosity P6 and Predicted Porosity P7 (all samples): 0.953

Correlations by Mode

Mode #	Smpls	R	Mean Core Por	Mean Core Perm (arith)
1	33	0.887	0.181	203.4
2	49	-0.062	0.019	0.6
3	23	-0.020	0.032	0.4
4	68	0.858	0.069	4.3
10	5		0.023	
12	64	0.285	0.097	19.2
14	5		0.079	
17	75	0.184	0.042	0.5
18	20	-0.061	0.056	1.5
19	150	0.231	0.120	29.6
22	27	0.279	0.012	1.7
25	76	0.642	0.174	236.8



Prediction of P&P from Surface Seismic

- 11 total variables
  - P&P
  - Well log (acoustic impedence-computed)
  - 4 Xwell attributes
  - 4 surface seismic attributes

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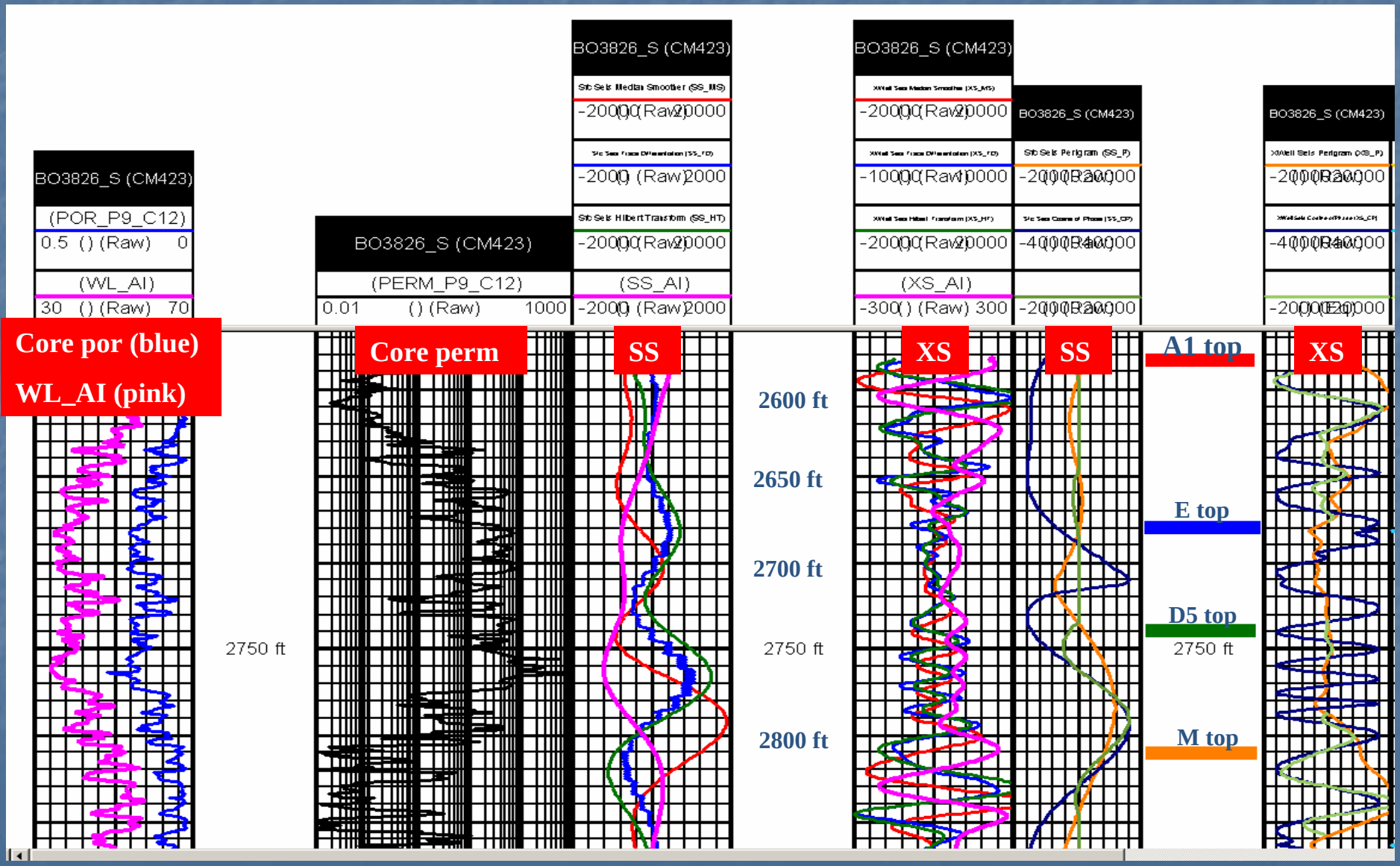
Selected Seismic Attributes

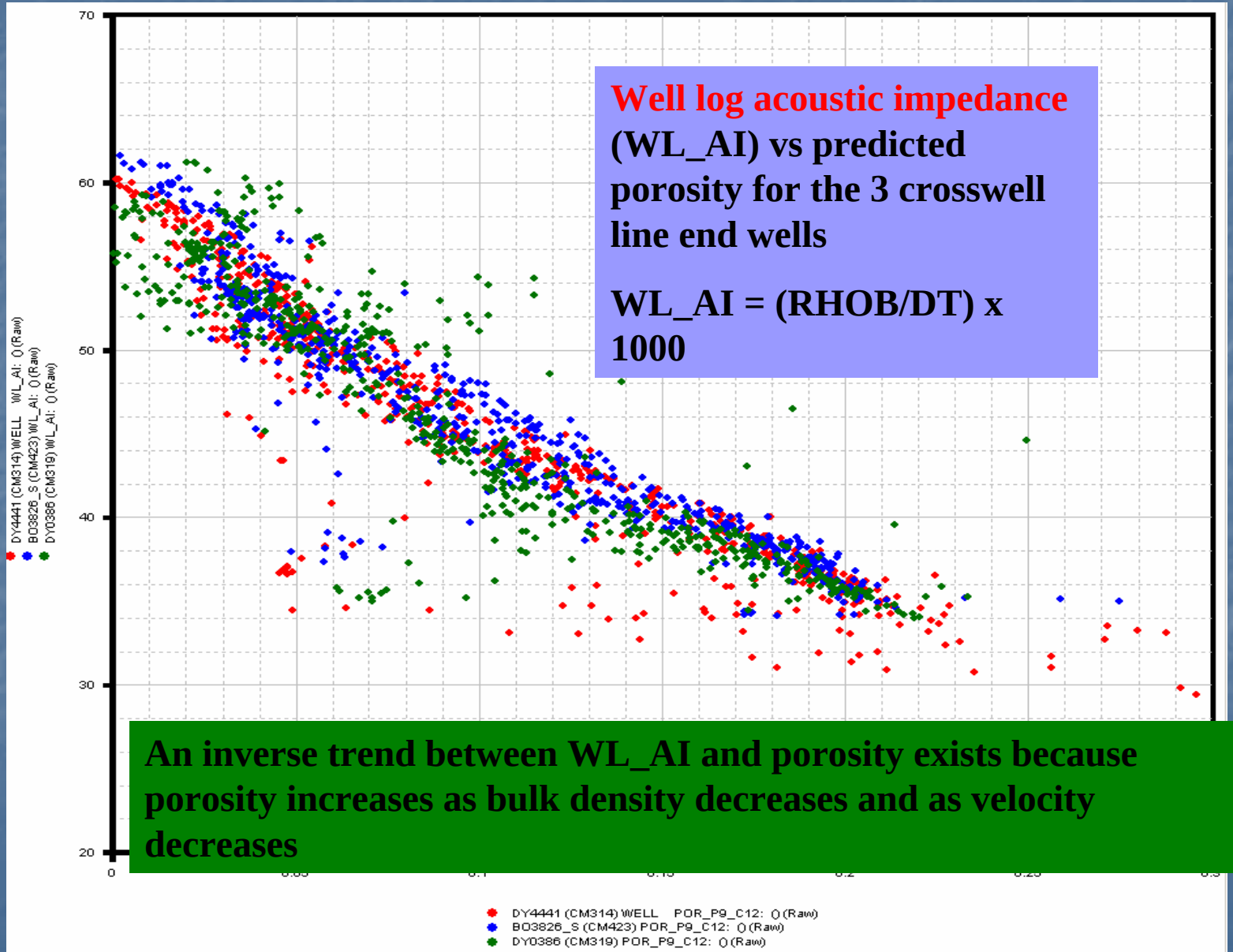
ABS = absolute value (of the amplitude trace)
CP = Cosine of instantaneous Phase
D (TD) = Trace Derivative
HT = Hilbert Transform
IF = Instantaneous Frequency
IP = Instantaneous Phase
P = Perigram
PCP = Perigram * (Cosine of Phase)
RP = Response Phase
Ms = Median Smoother

AI = Acoustic Impedance

Illustration of Different Data Frequencies



Acoustic Impedence Good Predictor of Porosity

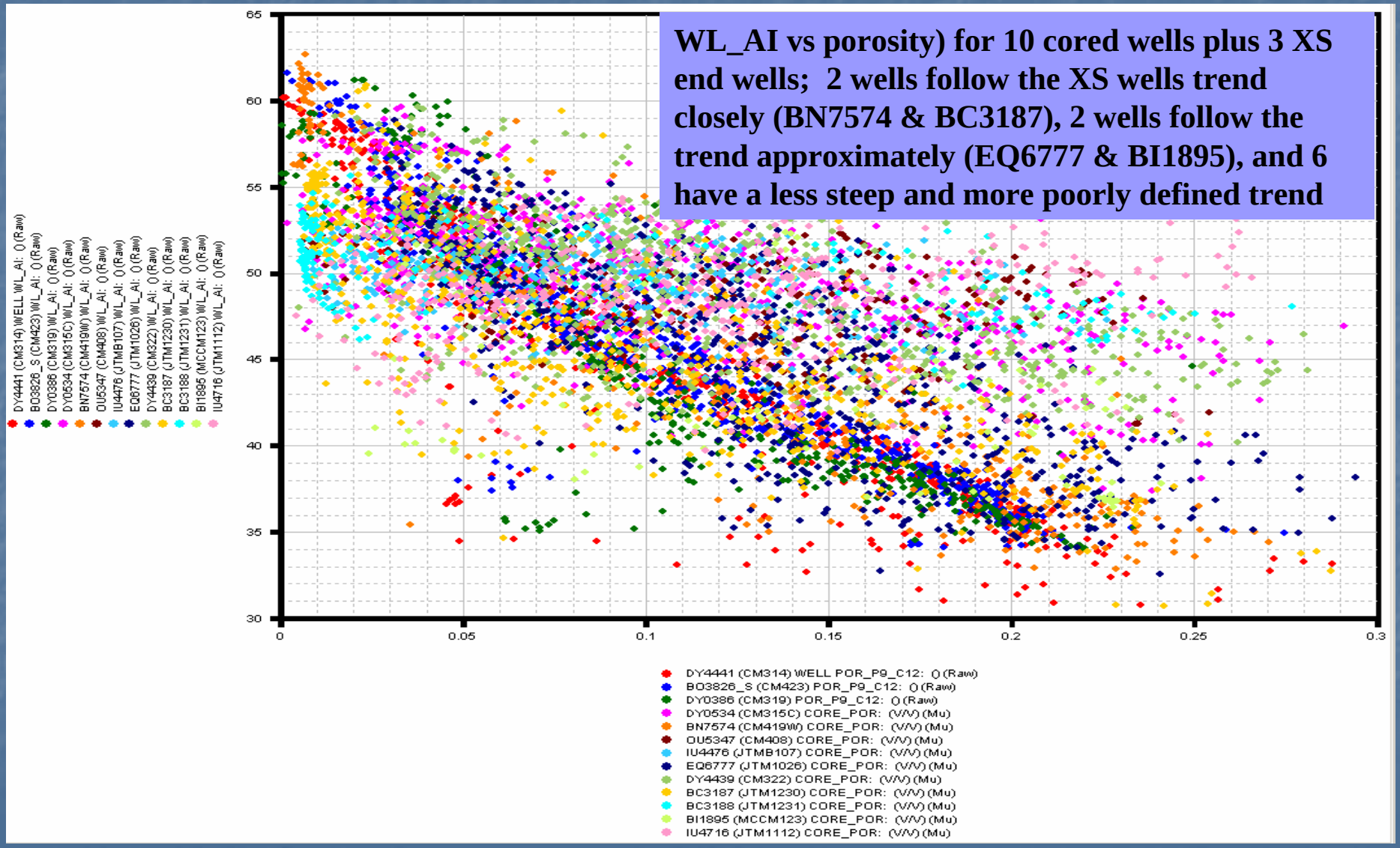


Well log acoustic impedance (WL_AI) vs predicted porosity for the 3 crosswell line end wells

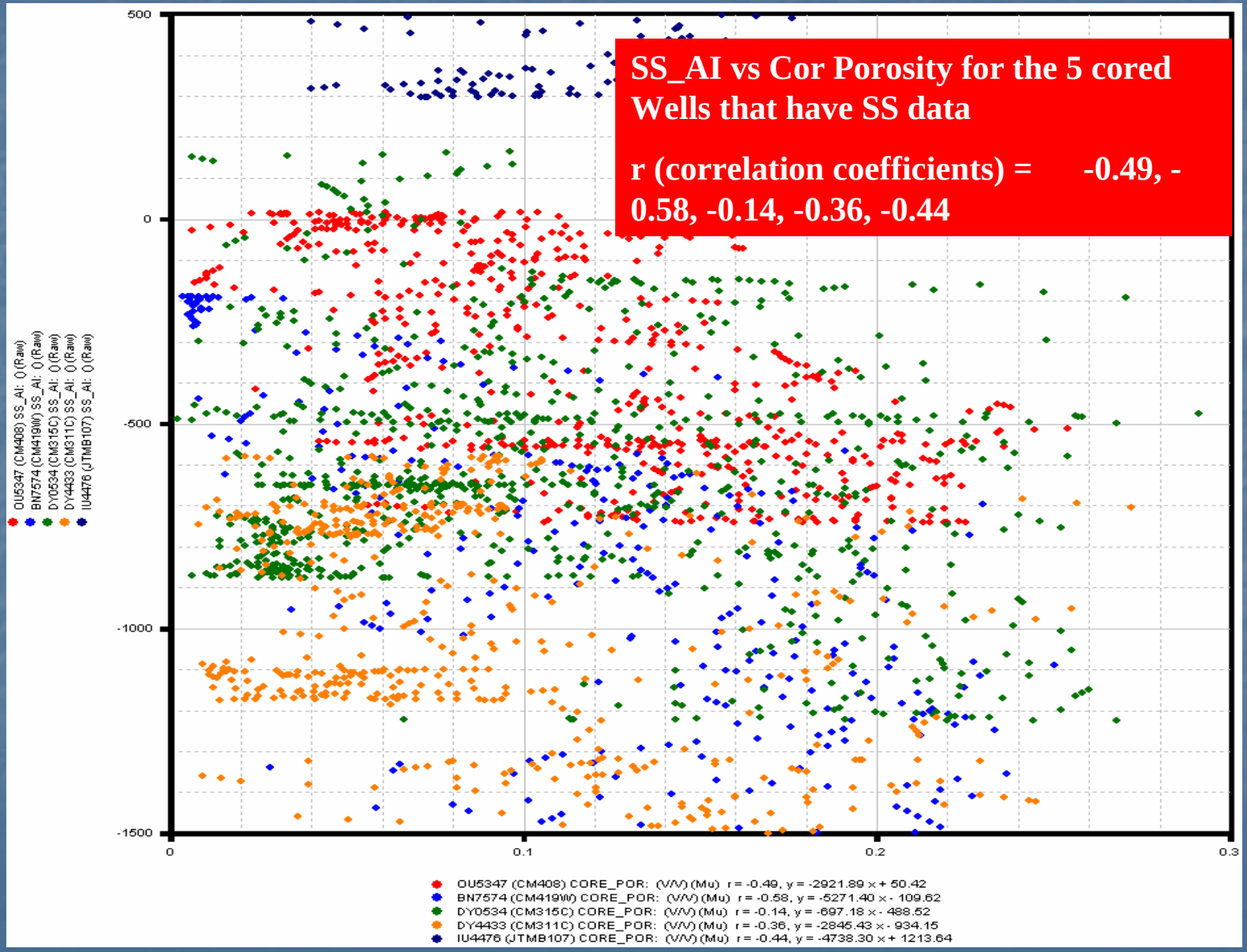
WL_AI = (RHOB/DT) x 1000

An inverse trend between WL_AI and porosity exists because porosity increases as bulk density decreases and as velocity decreases

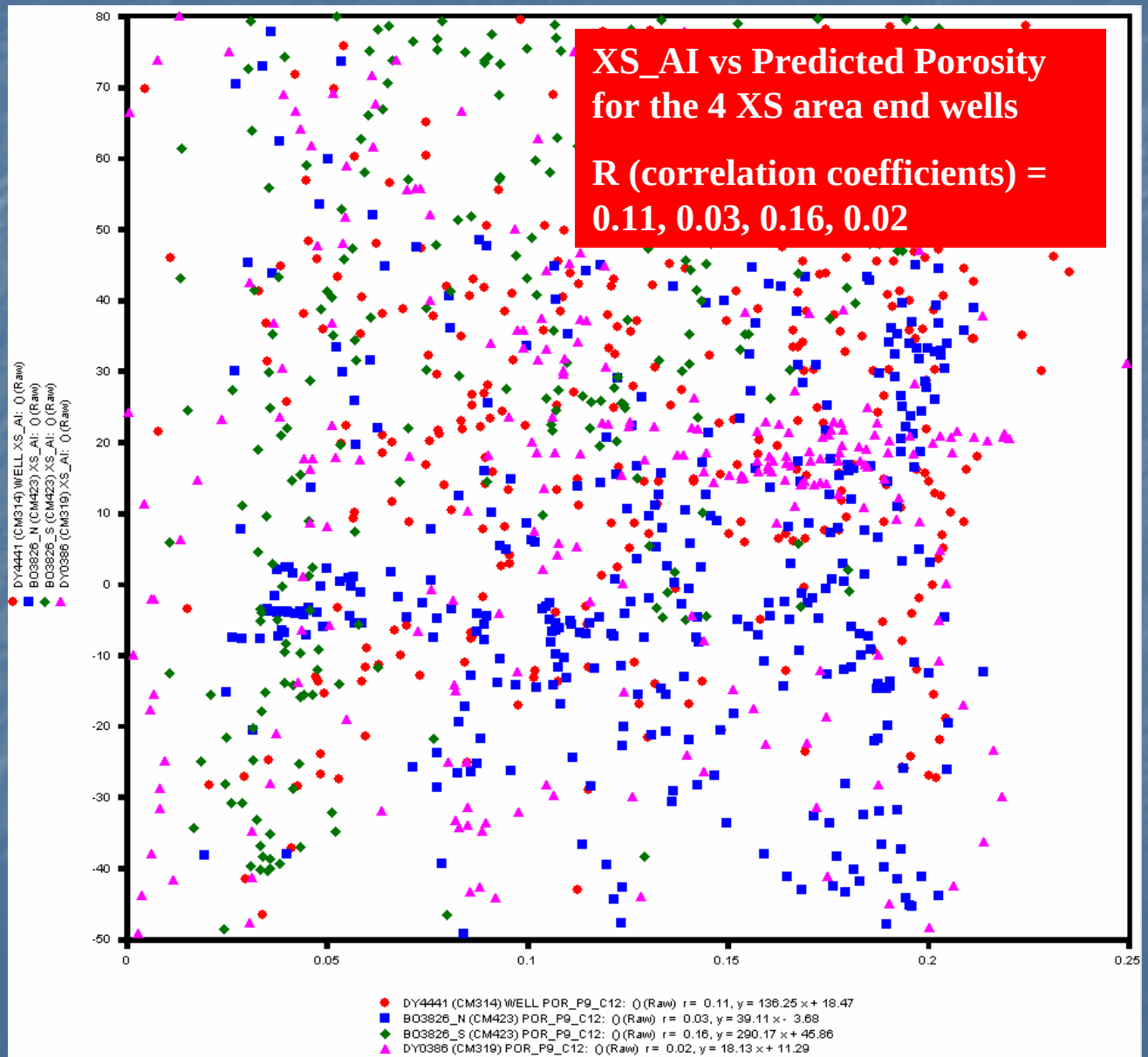
...But Not Always



Relationship Also Holds (Somewhat) for Surface Seismic

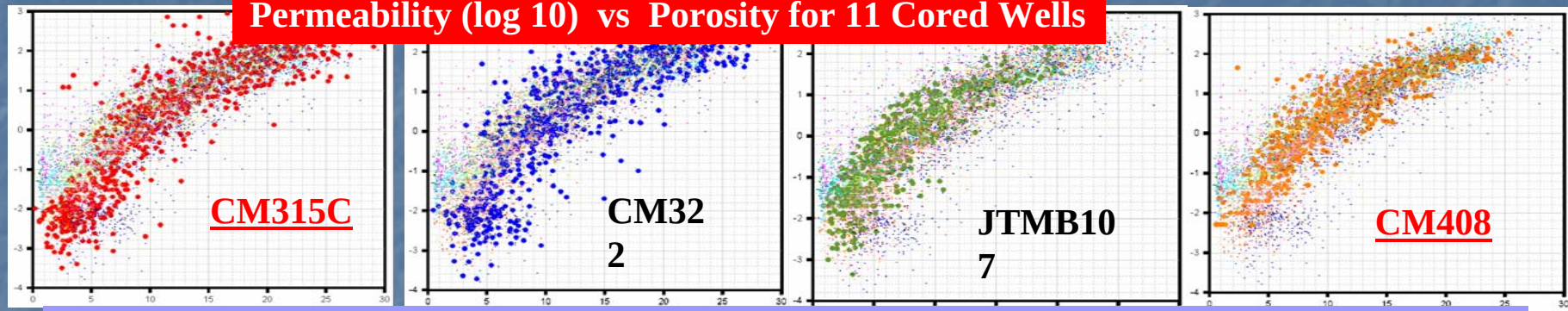


...But Not for Crosswell

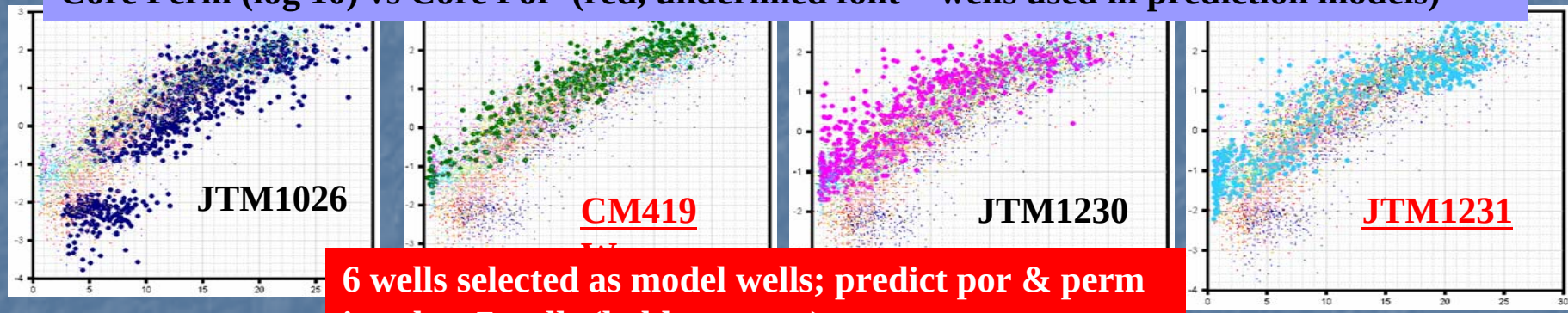


Permeability can be Related to Porosity

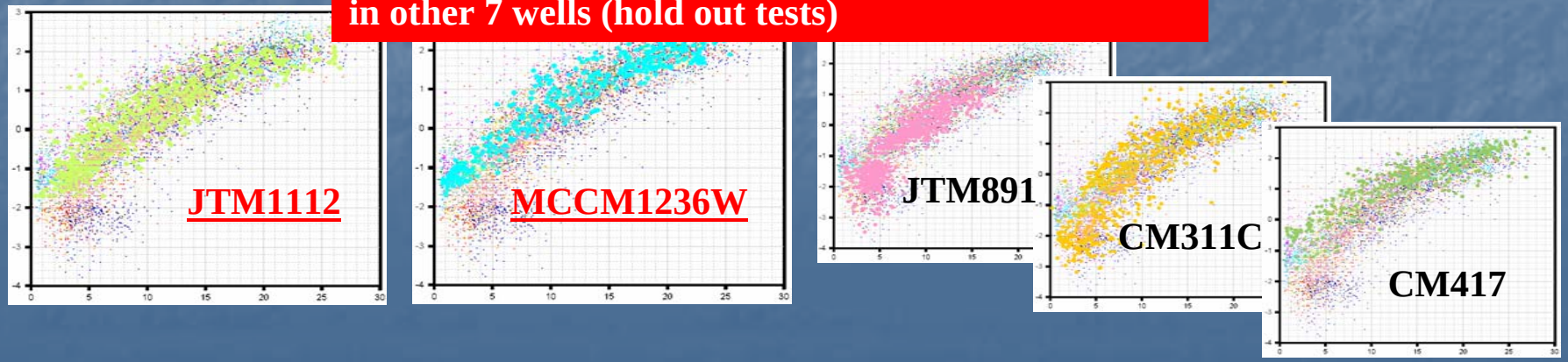
Permeability (log 10) vs Porosity for 11 Cored Wells



Core Perm (log 10) vs Core Por (red, underlined font = wells used in prediction models)



6 wells selected as model wells; predict por & perm in other 7 wells (hold out tests)

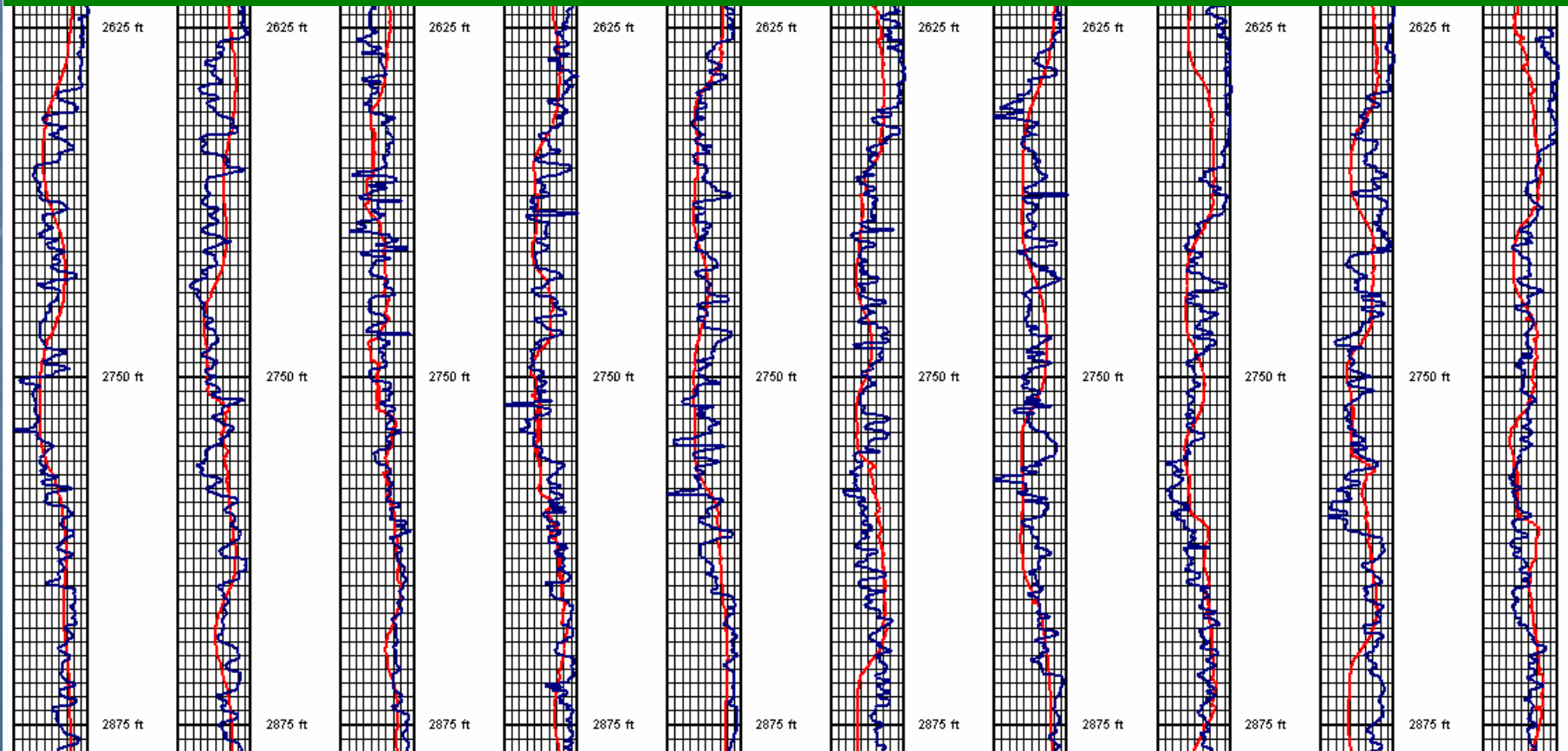


Log vs. SS Porosity Predictions

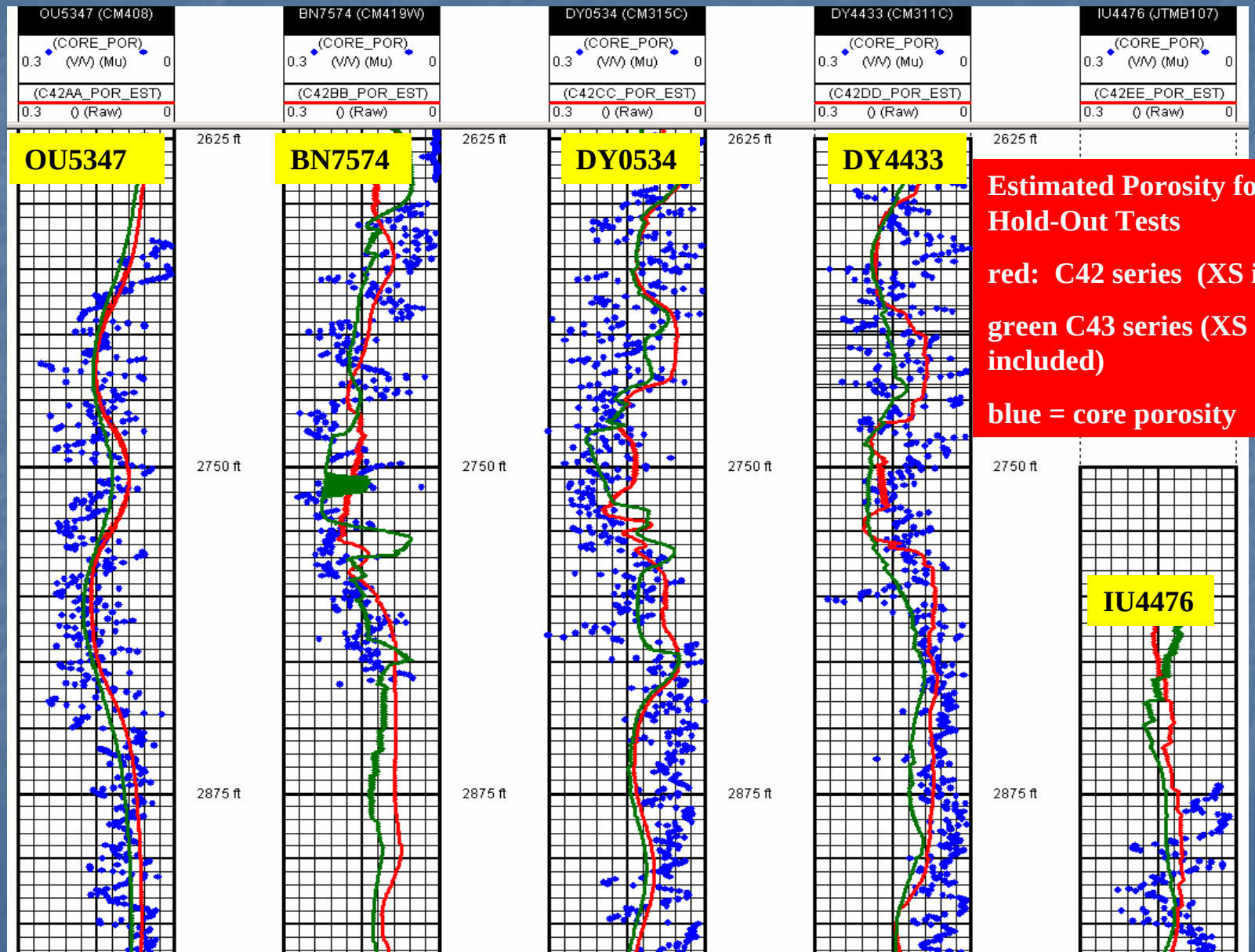
purple = predicted porosity using well logs only (Por_P10, C12 [ME8])

red = estimated porosity using only SS atributes and C45 (C45 was initialized using MC-1 (C23 model cluster) using all four data types [well logs, core data, SS, and XS])

OU5348 DY0434 IU4814 BO3825 IU4815 BN4693 IU4715 OU5345 DY0234 OU5354



Porosity Predictions from Surface Seismic, w/ and w/o Xwell



Estimated Porosity for 10 Hold-Out Tests

red: C42 series (XS included)

green C43 series (XS not included)

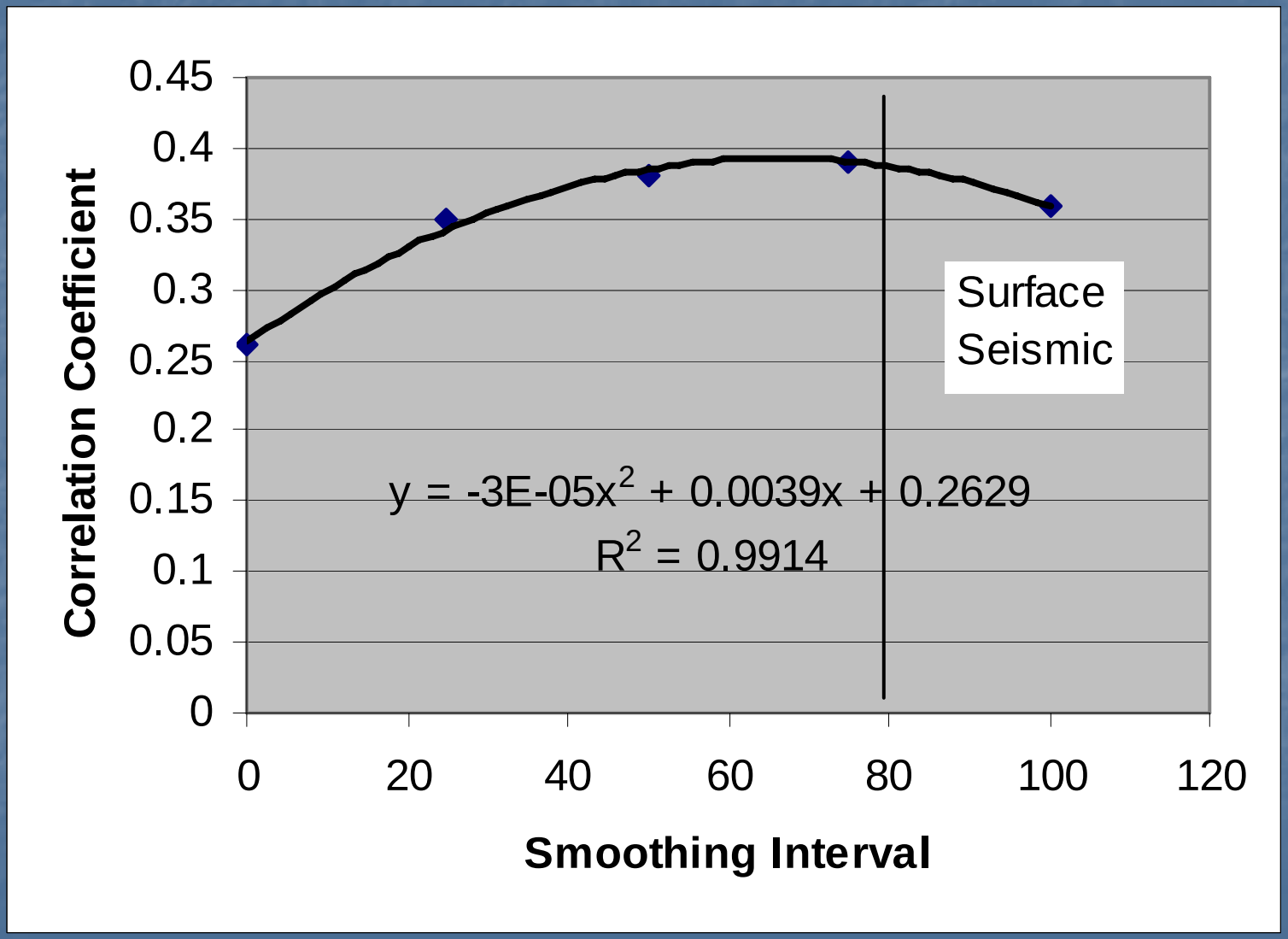
blue = core porosity

Correlation Coefficients for OU5347

R values are given using raw (unsmoothed) estimated core porosity values ("none") and for values after smoothing using median filters for 25, 50, 75, and 100 points

	R				
Test Cluster	**none**	**25 pt**	**50 pt**	**75 pt**	**100 pt**
C42 (XS included)	**0.26**	**0.34**	**0.37**	**0.39**	**0.37**
C43 (XS excluded)	**0.26**	**0.35**	**0.38**	**0.39**	**0.36**

Some Improvement in Vertical Resolution Achieved



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Model 2 Conclusions

- Despite low absolute correlation coefficients, Model 2 provides reasonable predictions of P&P using surface seismic attributes.
- The inclusion of crosswell data did not improve the results – this may be due to the quality of the crosswell data.
- Some improvement in vertical resolution of P&P predictions was achieved over the surface seismic frequency.

Areas of Difficulty

- Time/depth transform was not robust.
  - Use “depth windowing” strategy in future
- Quality of Xwell data may have limited resolution improvement sought.
- Seismic response to reservoir properties is more difficult in carbonate than in clastic formations.
- Data acquisition was not on consistent time basis.

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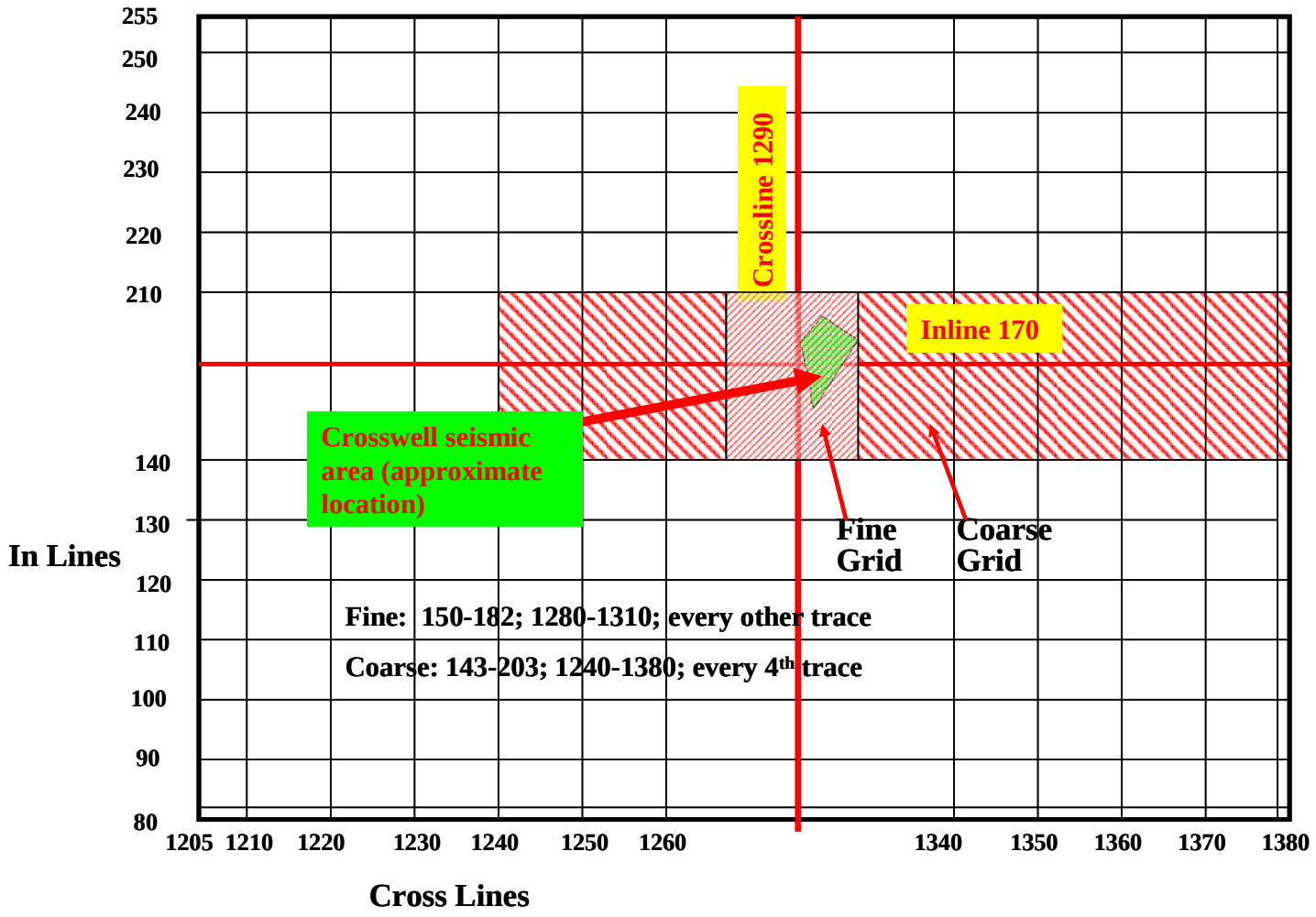
Inline/Crossline Scheme

LayOut of InLines and CrossLines Grid (176 inlines and 176 crosslines)

Notes: NOT TO SCALE; top inline and left crossline in grid are not at 10-line interval



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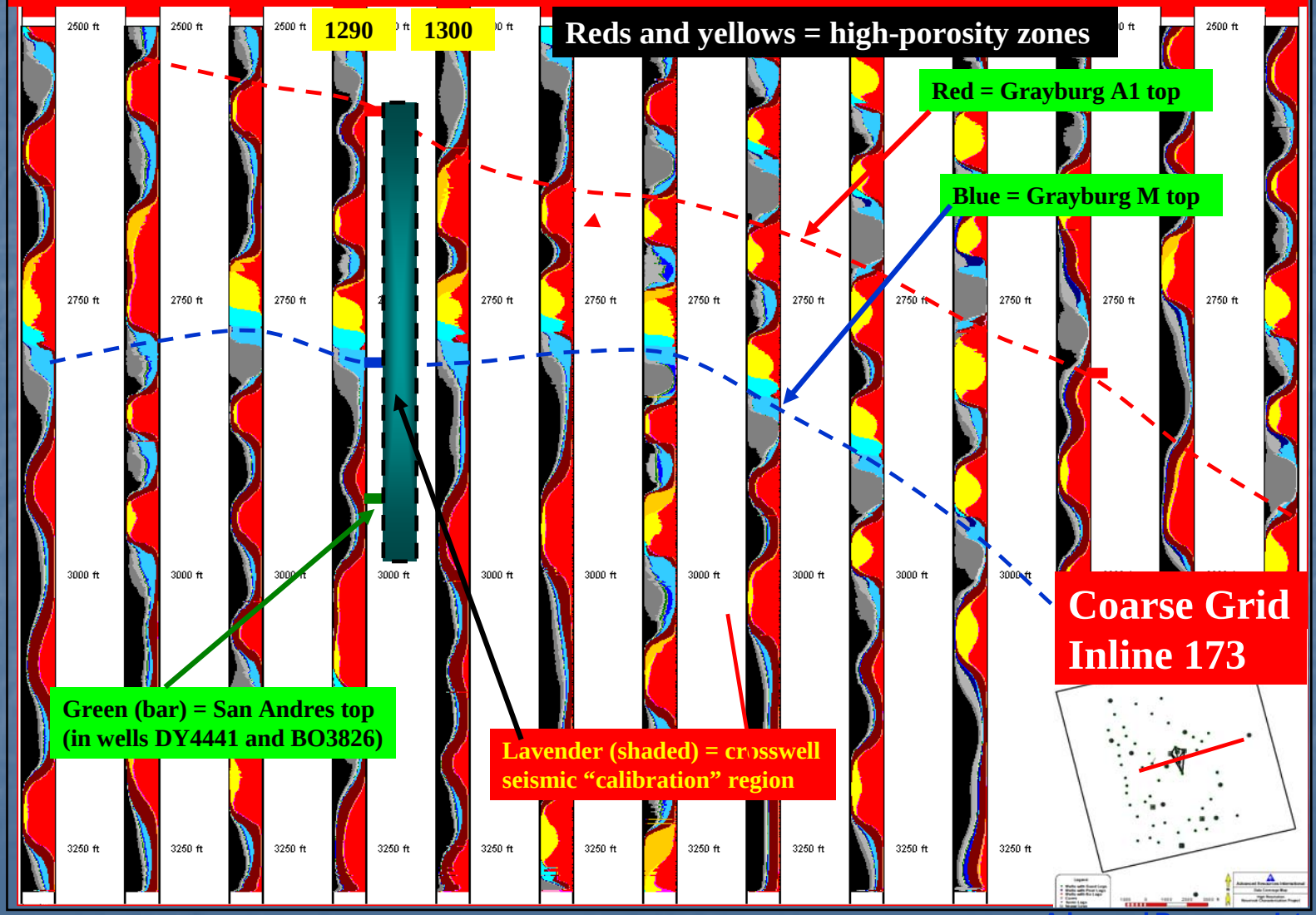
E-W Cross-Section

C30 CMP (cumulative mode probability) plots; 13 traces East-to-West (left-to-right) along Inline 173, Xlines 1260 - 1380



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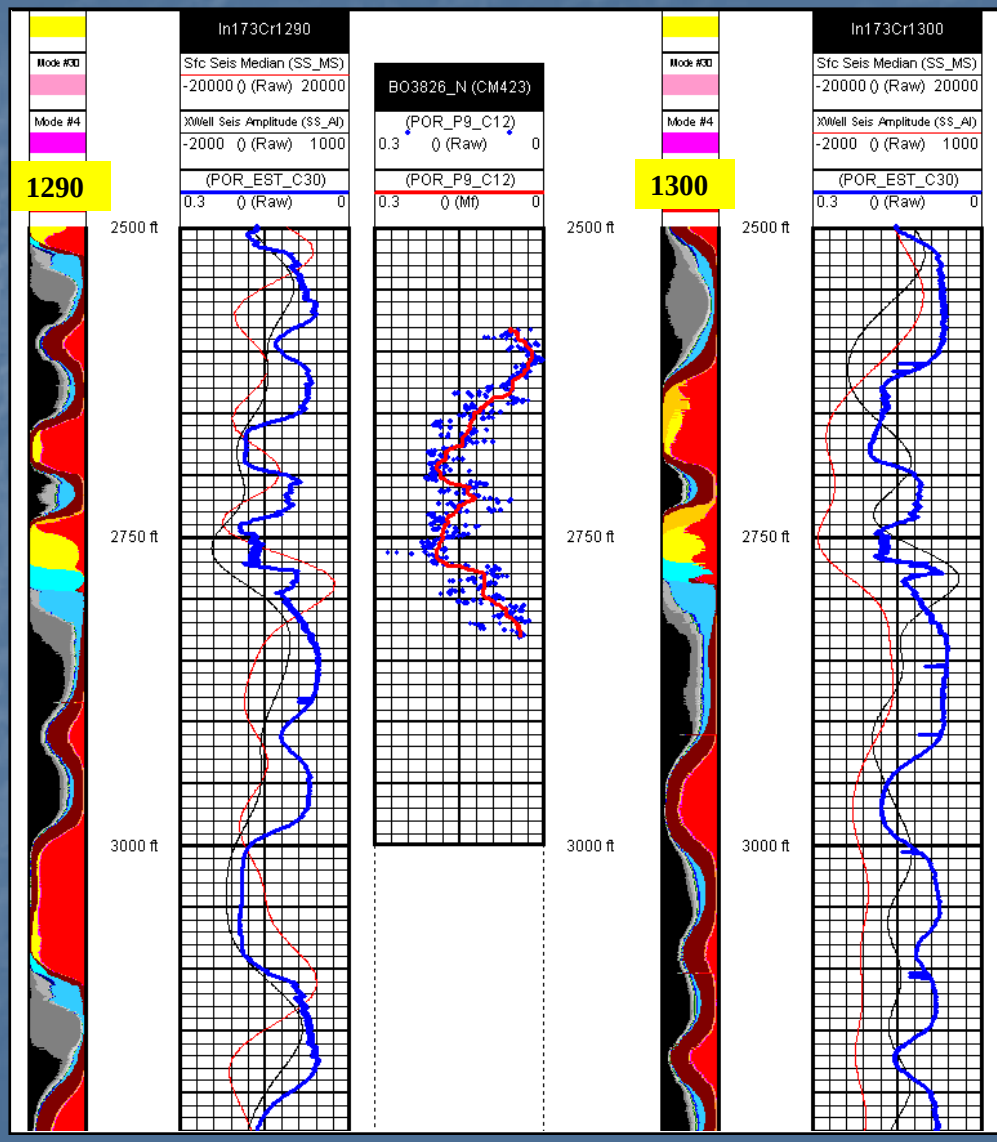
Close-Up in Crosswell Area



Tracks 1 and 4:

C30 CMPs for Xline 1290 and 1300

tracks 2 and 5:

blue = estimated porosity generated with C30 (profiles for the positions of the two SS traces)

black = SS_MS (median smoother)

red = SS_AI (acoustic impedance)

track 3:

blue dots = porosity (predicted earlier) for well BO3826

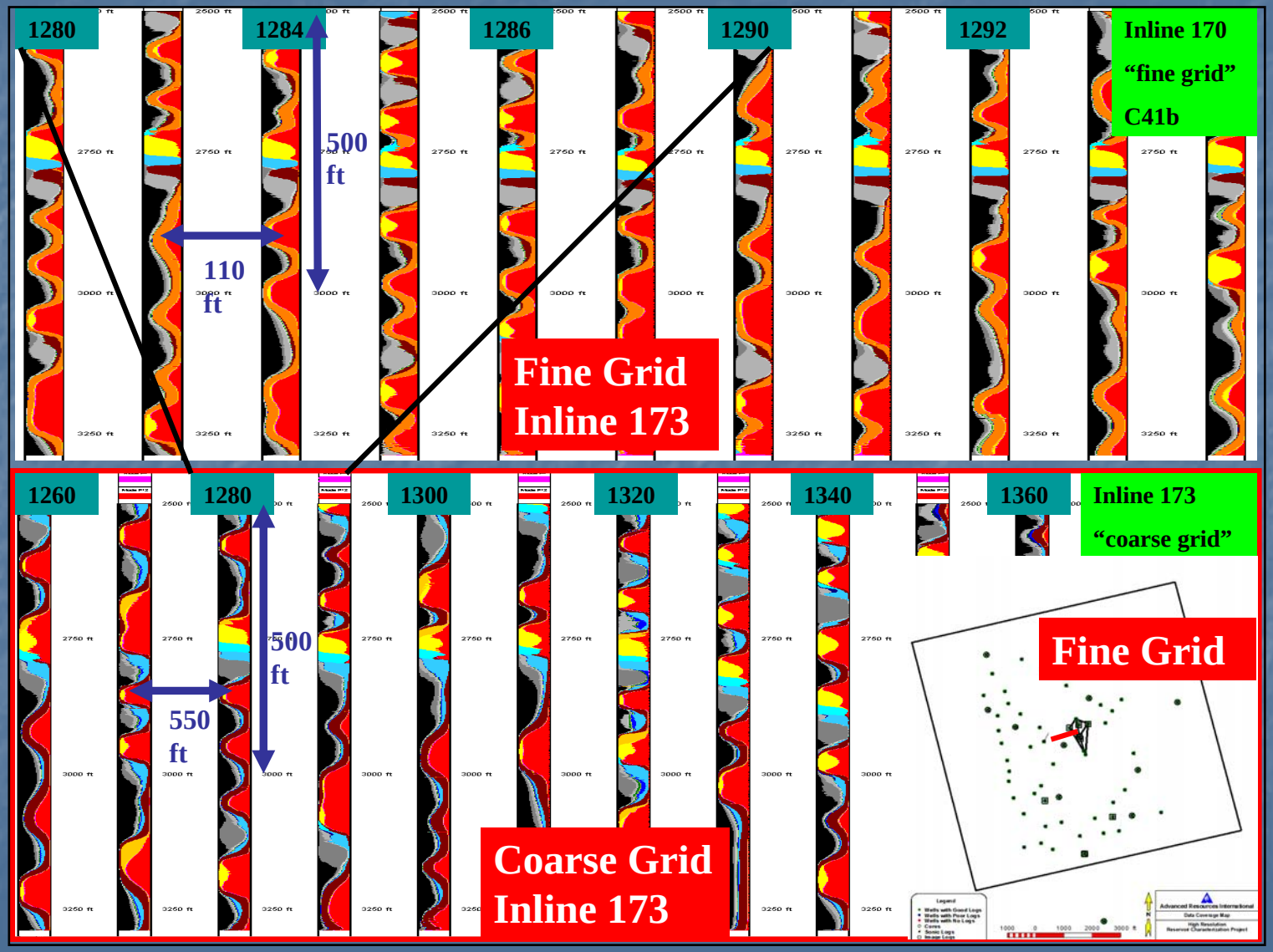
red line = predicted porosity with a 50-point median filter (smoother)

NOTE:

correlations of CMP plots and estimated porosity curves from C30 and the "actual" (predicted) porosity for well BO3826

this well is the closest one (although not cored) to these 2 SS traces

Fine Grid vs. Coarse Grid



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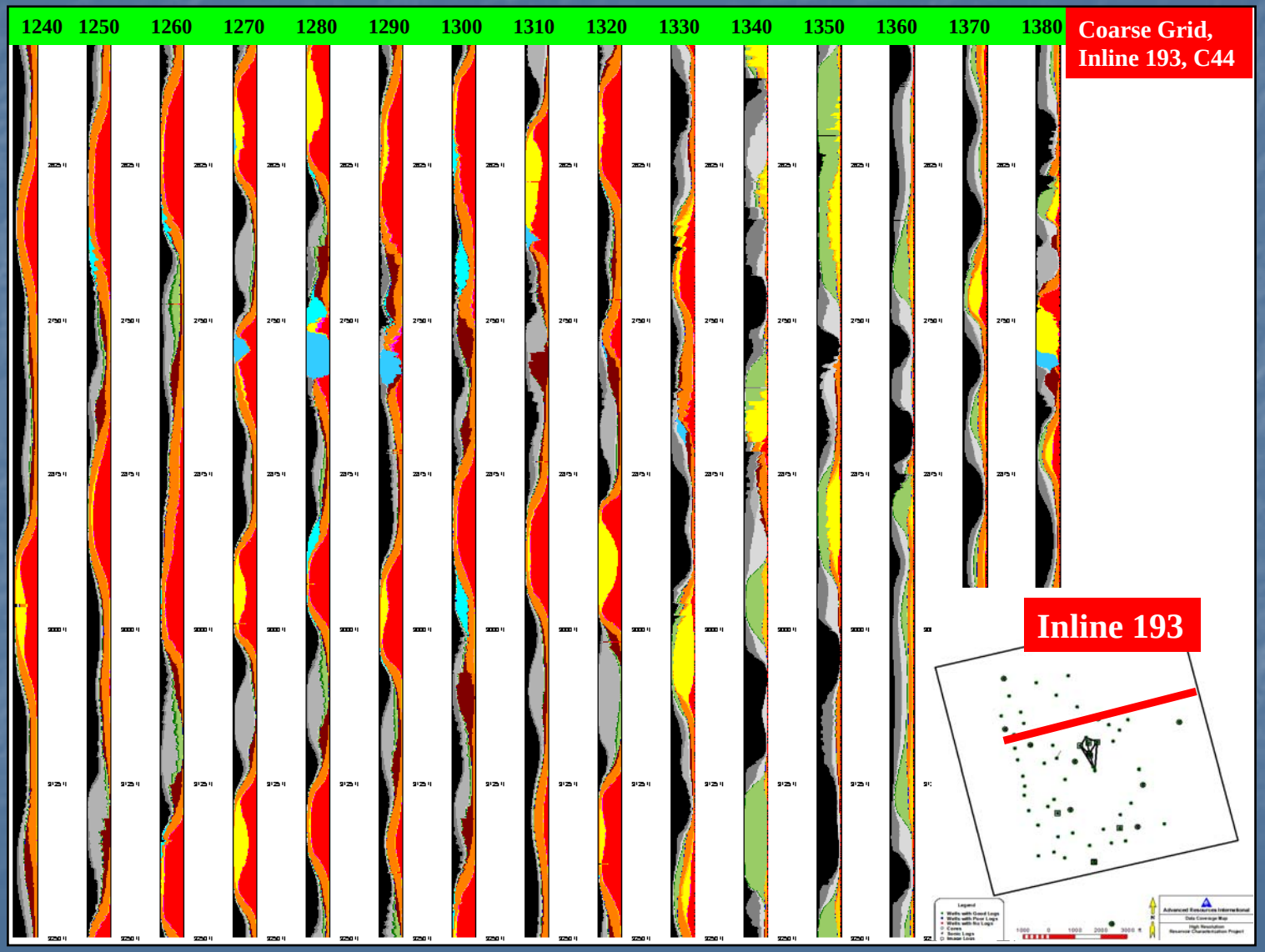
Low RQ Areas Identified



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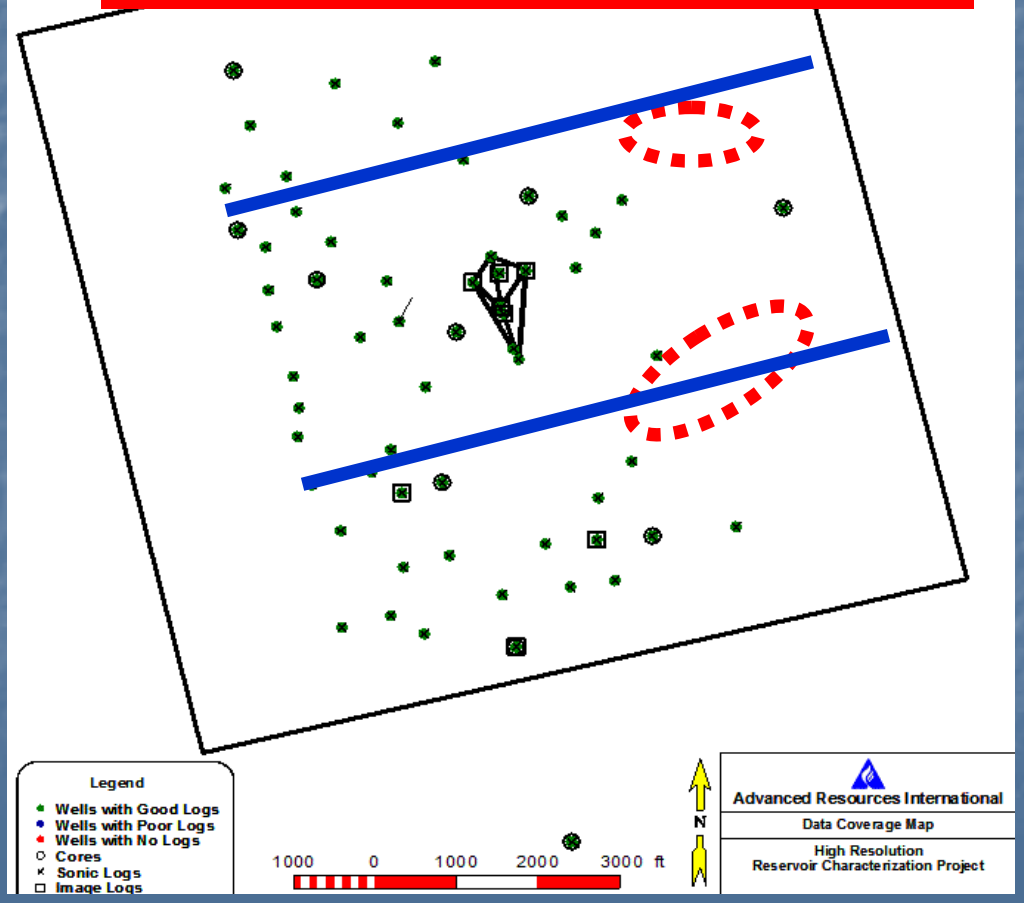
Implied Poor Quality Reservoir Areas

Red = low RQ

Blue = limits of prediction area



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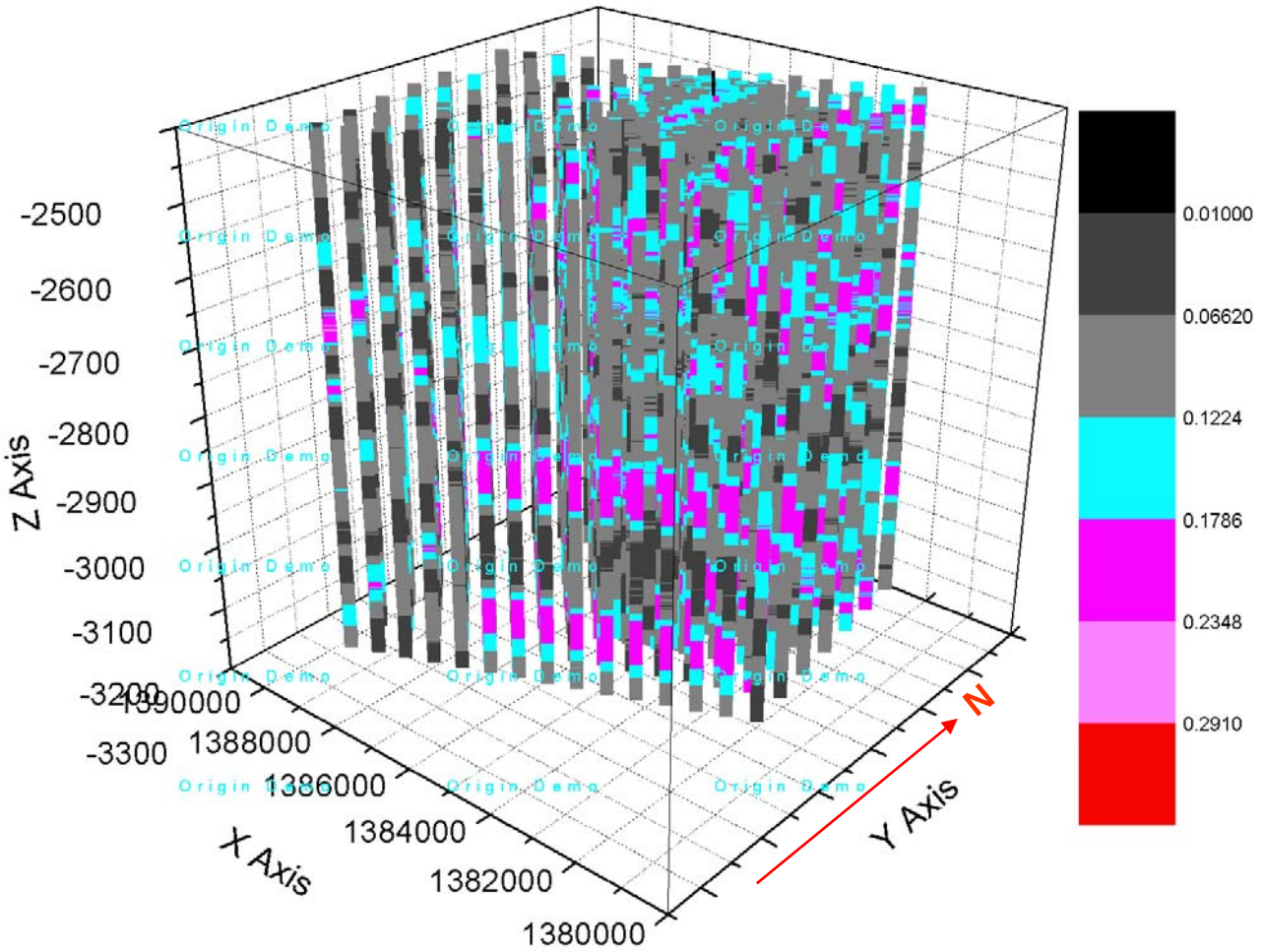
3D Porosity Cube



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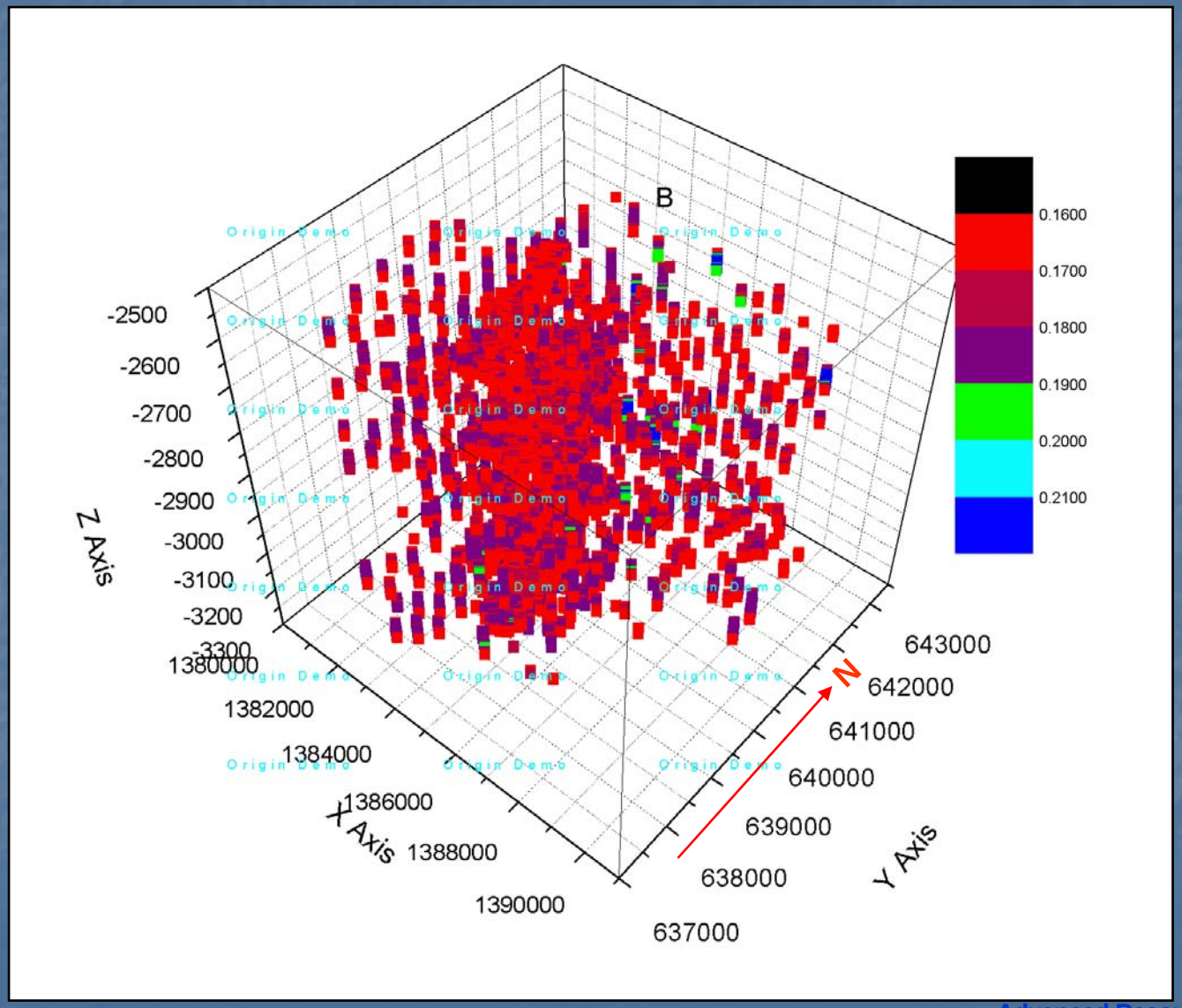
Regions with High Porosity



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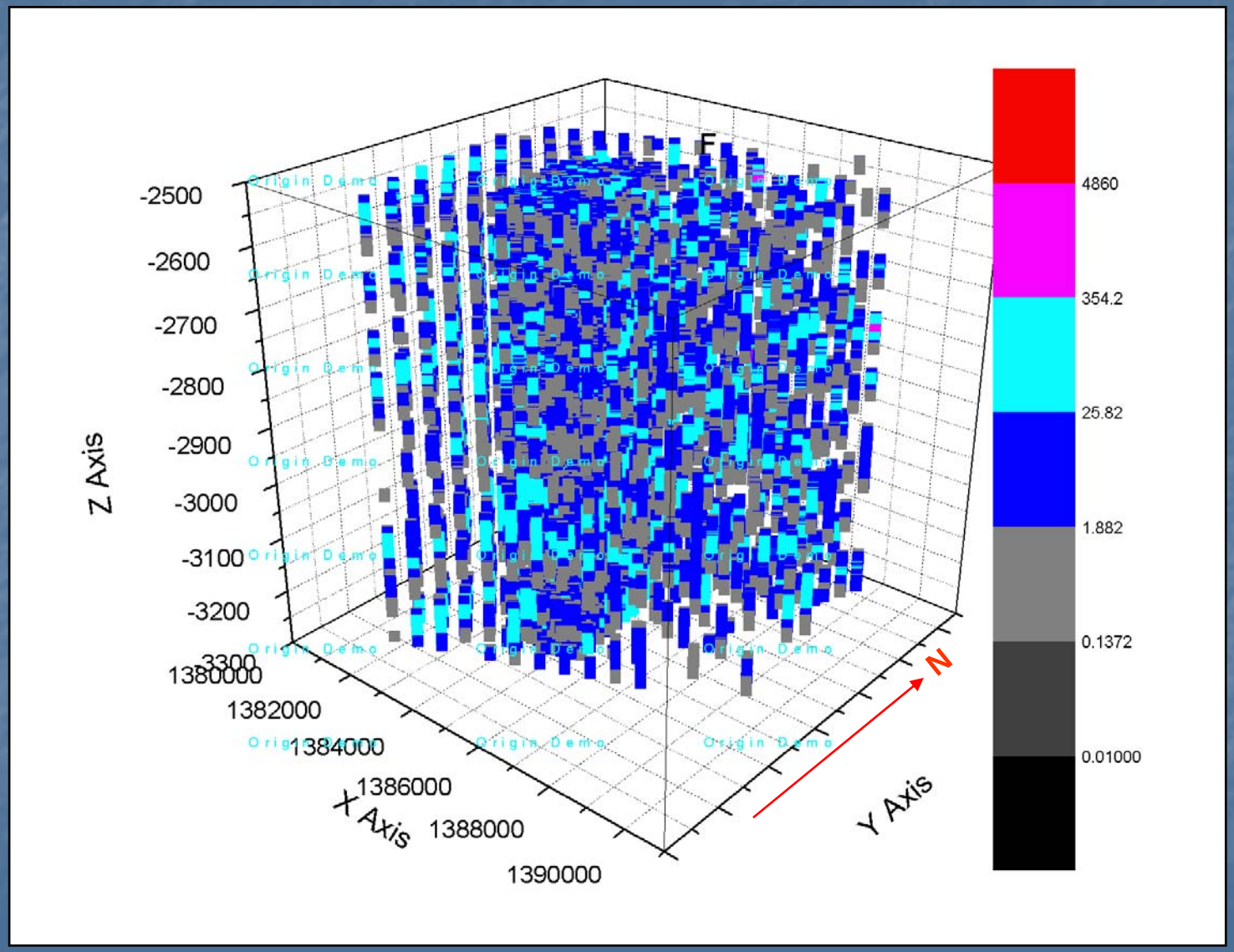
3D Permeability Cube



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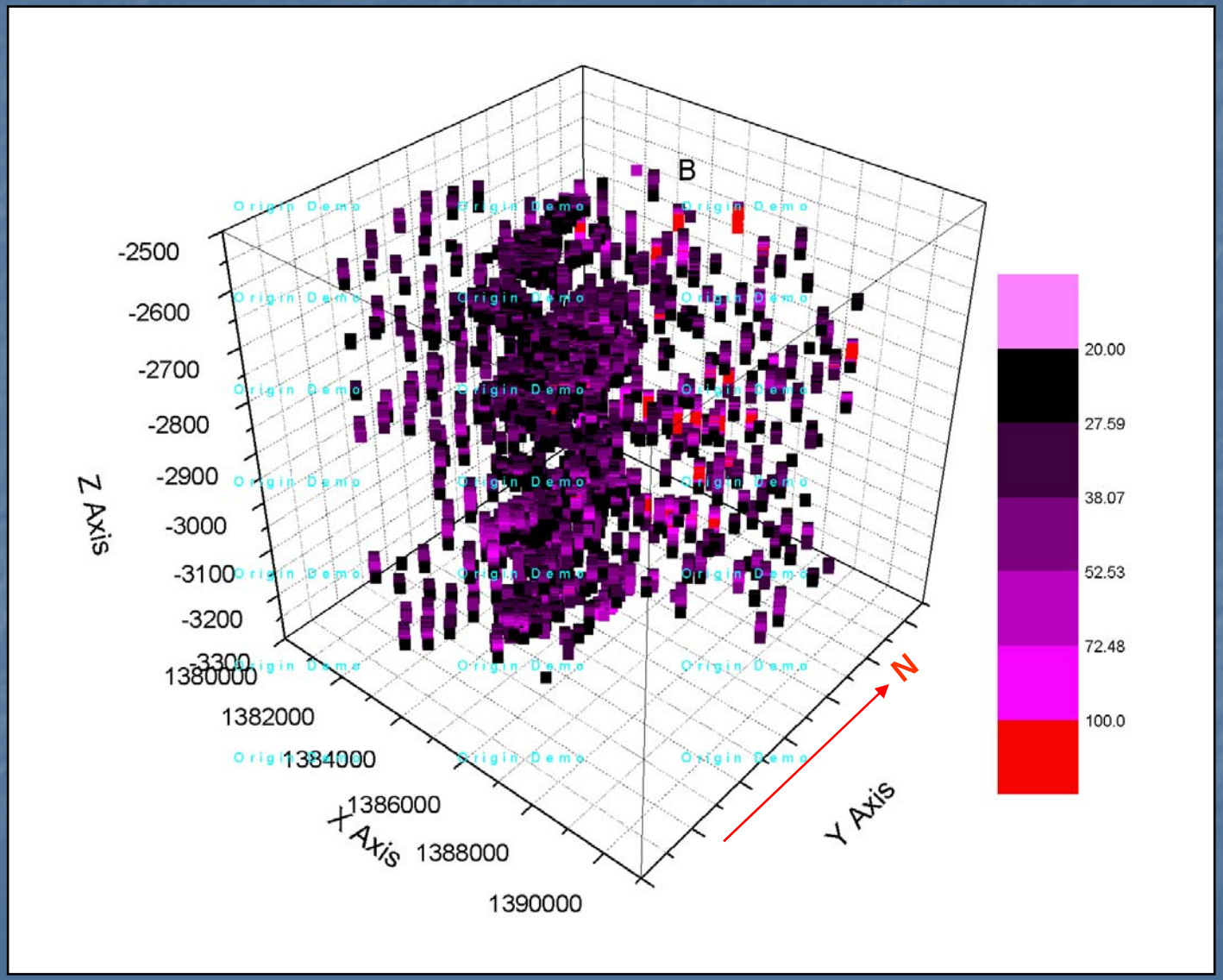
Regions with High Permeability



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Conclusions

- A cluster model has been developed to predict permeability and porosity based on surface seismic data at McElroy.
- The method yields good trends of reservoir properties on a vertical resolution of +/- 10-35 ft. This is a modest improvement over surface seismic frequency.
- The procedure may have been compromised by uncertain time/depth transform, poor-quality cross-well data, inconsistent data acquisition timing, and it's application in a carbonate reservoir.

Final Steps

- Check/validate ø/k predictions against ChevronTexaco's existing knowledge of reservoir properties.

- Final reporting:
  - Cluster Model
  - Final Report

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Questions?