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**Subsurface Analytics:  
Digital Transformation of Reservoir Management  
with Artificial Intelligence & Machine Learning**

**Shahab D. Mohaghegh**  
West Virginia University  
Intelligent Solutions, Inc.



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## Outline



- Petroleum Data Analytics - PDA
- Subsurface Analytics
- Use Cases including ***Field Validations***
  - Data-Driven Reservoir Modeling (Top-Down Modeling - TDM)
    - Case Study: Offshore Middle East
    - Case Study: Offshore Caspian Sea
    - Case Study: Onshore Middle East
  - Smart Proxy Modeling
    - Case Study: Onshore Middle East

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## Petroleum Data Analytics - PDA



- Artificial Intelligence and Machine Learning in Oil & Gas industry.
- Using “DATA” as:
  - the starting point, the foundation, and the main building blocks of analysis, workflows, modeling, and decision making.

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## Petroleum Data Analytics - PDA



- PDA is NOT an IT related discipline; it is a user of the IT services.
- PDA reverses the role of data in modeling physics:
  - Data is not there to serve our understanding of physics
  - Physics is modeled using data
- PDA is highly inspired by Physics and Geology
  - Physics and geology are **not** deterministically and rigidly **formulated**

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## Petroleum Data Analytics - PDA



- PDA uses “**hard data**” to reach its conclusions.
- PDA avoids **assumptions**, **simplifications**, **preconceived notions**, and **biases**.

- PDA integrates

Well Placement & Trajectory	Well Tests - Workovers
Geology	Completion Design
Seismic Attributes	HF Implementation
Reservoir Characteristics	Injection Details
Well Logs	Operational Conditions
Core Analysis & SCAL	Well Productivity

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## AI's Slow Progress in Petroleum Engineering



- There are three major problems associated with the application of AI&ML in our industry:
  - Lack of Domain Expertise:
    - AI experts that do not realize the application of this technology in engineering related problems
  - Traditionalists:
    - Petroleum Engineers that have a religious view of traditional technologies in the E&P
  - Lack of Scientific and realistic understanding of AI&ML by some petroleum Engineers:
    - Petroleum Engineers that mix AI&ML with mathematical equations (hybrid models) and traditional statistics

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## Subsurface Analytics



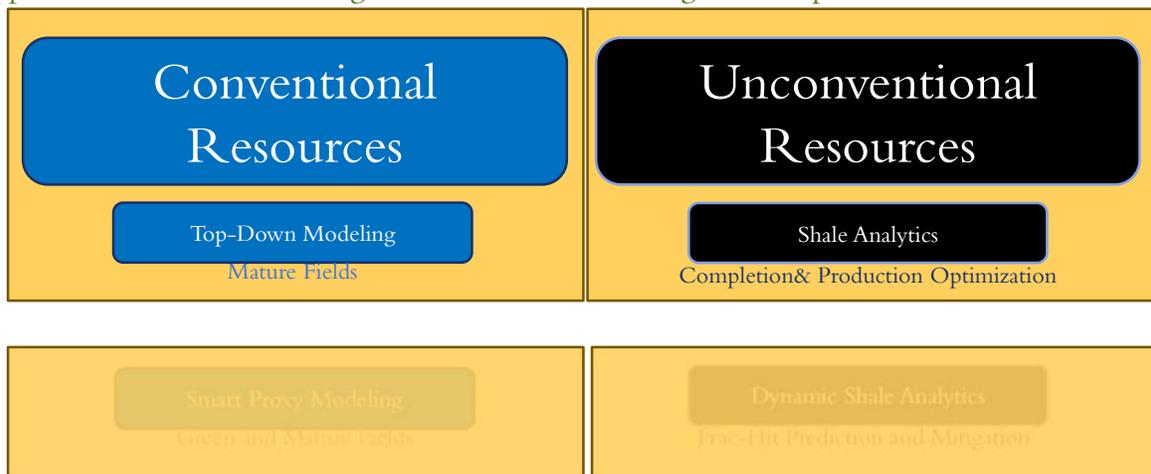
- Subsurface Analytics is a non-traditional **Physics-Based** simulation and modeling technology.
- How Physics is modeled in Subsurface Analytics:
  - Through field measurements
  - Avoiding major assumptions and simplifications
  - Based on the knowledge of Domain Experts
- Subsurface Analytics is **Data-Knowledge Fusion** Technology
- Subsurface Analytics is based on **Explainable AI (XAI)**

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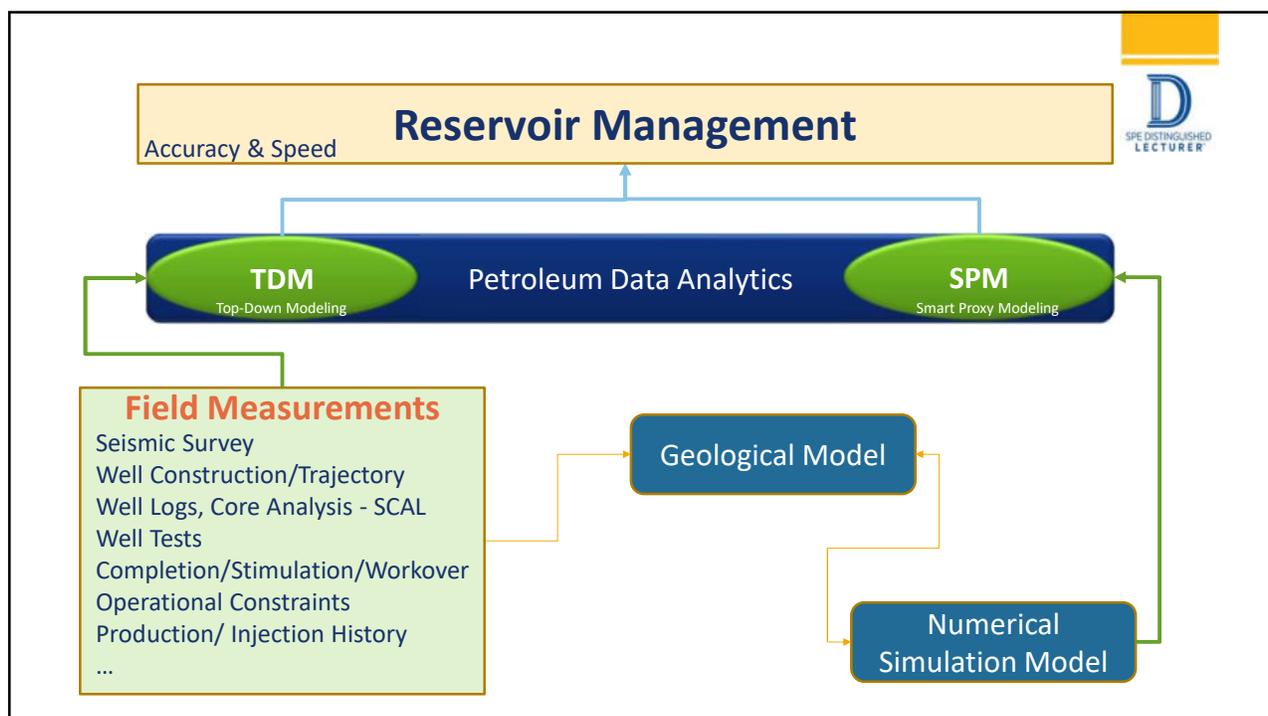
# Subsurface Analytics



Application of Artificial Intelligence & Machine Learning in the Upstream Oil and Gas Industry



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Purely Fact-Based, Field Measurement – Driven Reservoir Simulation

## TOP-DOWN MODELING

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Subsurface Analytics – Conventional Resources



## Top-Down Modeling

Coupled “Reservoir + Wellbore” Simulation Model

Purely Based on Field Measurements – (No Equations)

Fully Automated History Match

Blind Validation in Time & Space

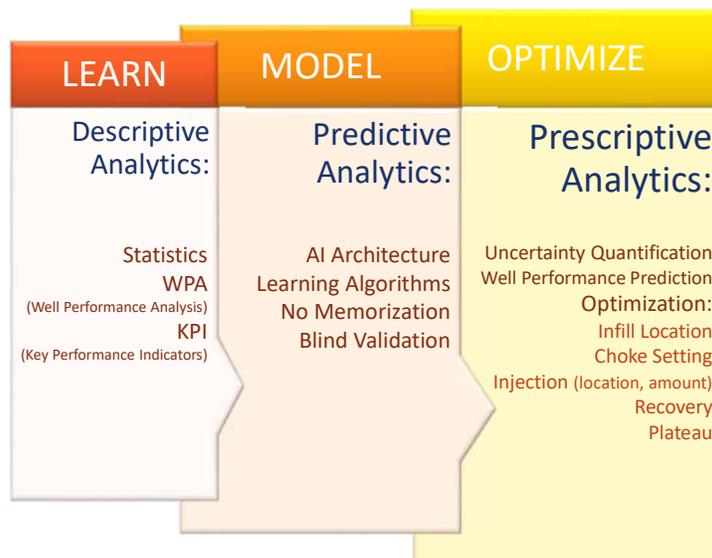
Sensitivity Analysis

Uncertainty Quantification

Field Development Planning

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## Data-Driven Reservoir Modeling (TDM) Workflow



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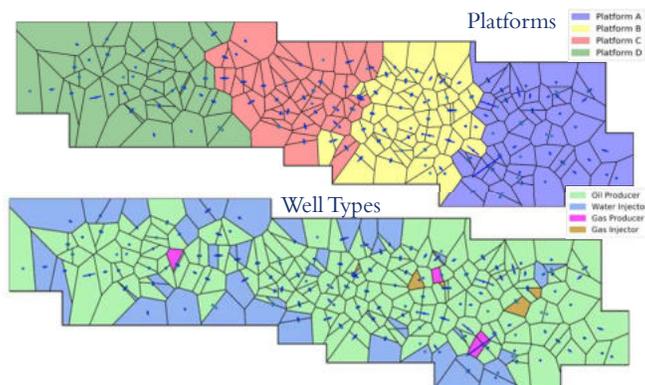
## TDM – Coupled “Reservoir + Wellbore” Model



- TDM does not require Flowing Bottom-Hole Pressure
- TDM uses “Choke Setting” and “Wellhead Pressure” as input
- TDM uses “Gas-Lift” as input
- TDM uses “Wellbore Completion” as input
- To optimize “Oil Production”, “GOR”, and “WC” all inputs can be modified.

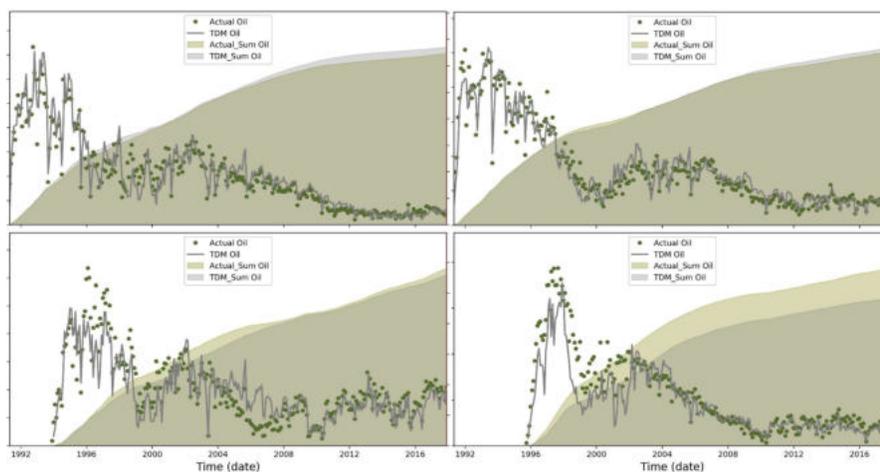
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# TDM – Fully Automated History Match

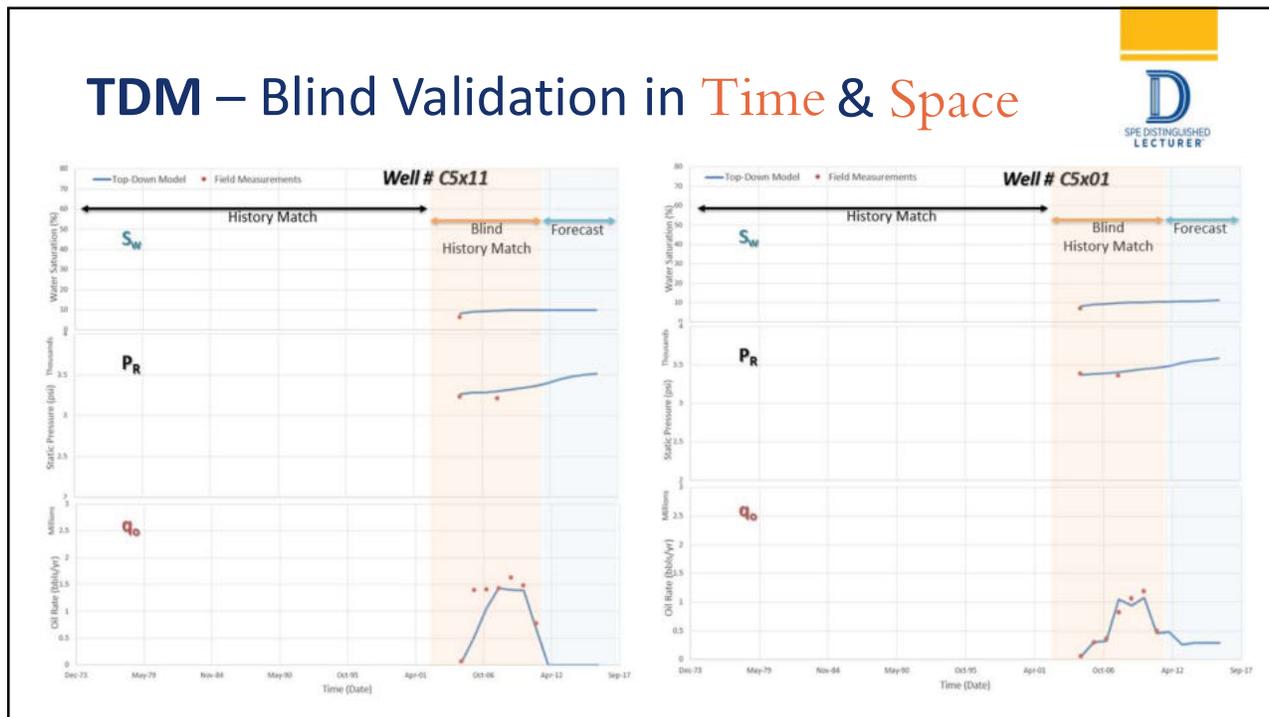


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# TDM – Fully Automated History Match



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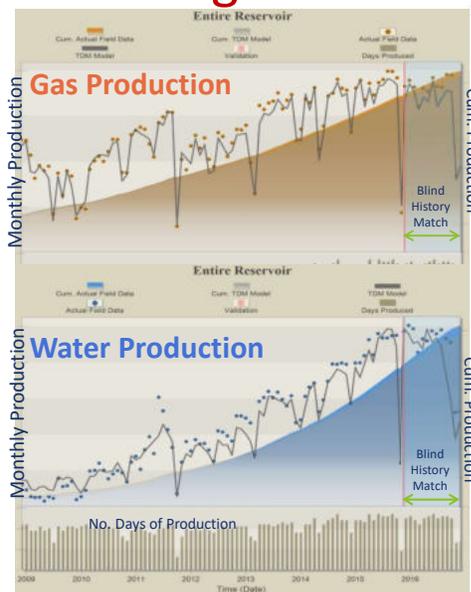
## TDM Case Study 1: Onshore-Middle East

The map shows an onshore field in the Middle East with several sub-fields labeled: Dabb'iyah, Jumayyah, Rumaytha, and others. A green box highlights the area of interest, which includes Dabb'iyah and Jumayyah. The map also shows other fields like Lab'iyah, Futa'iyah, and Arja.

- Onshore field: RA
- Offshore field: DY
- Discovered in 1969
- Producing since
  - April 1994 (EPS),
  - Dec 2005 (Phase I)
- Water, Gas and WAG Injection since
  - Mar 2006 (Phase I)

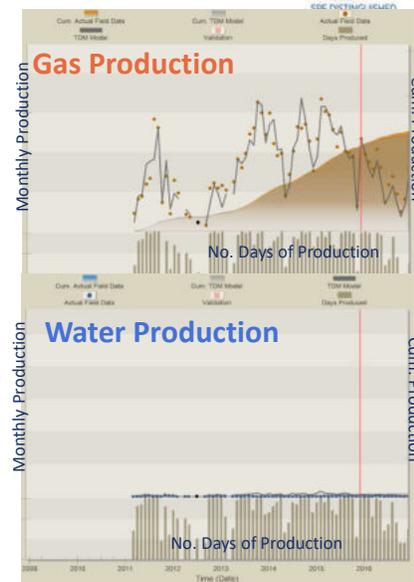
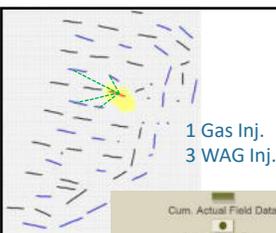
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# Automated History Matching

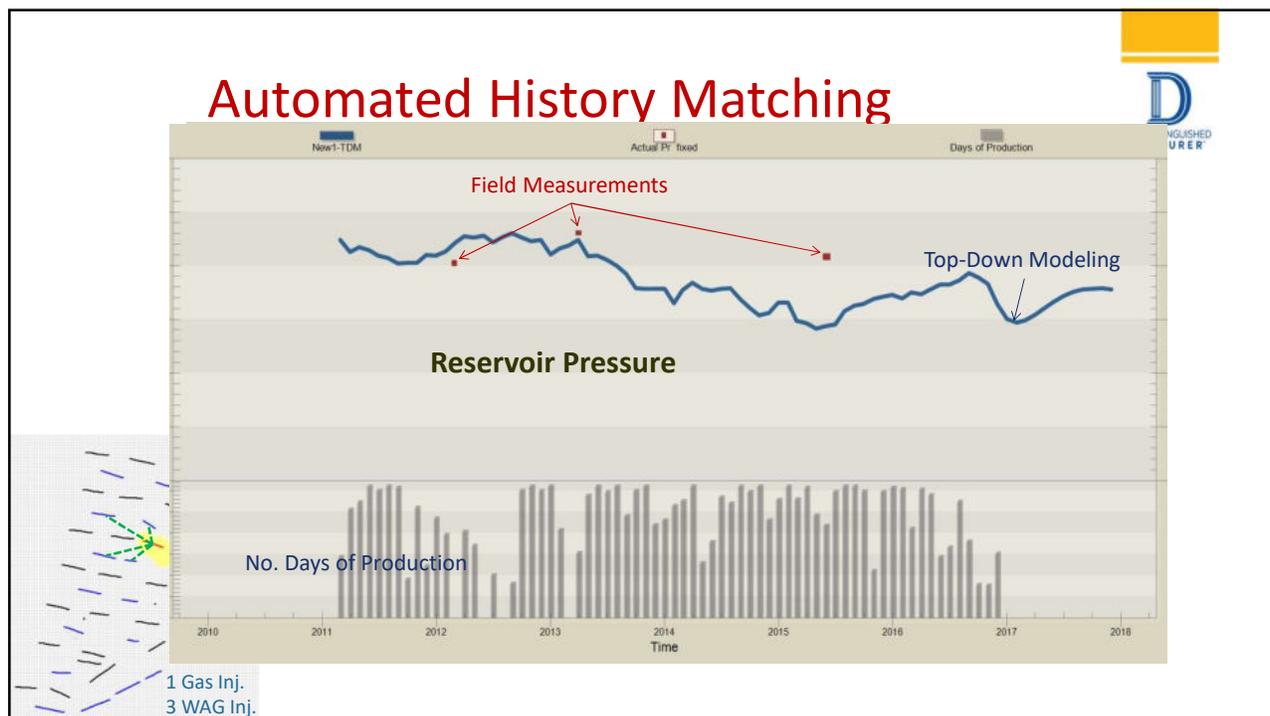


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# Automated History Matching



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## TDM Case Study 2 : Offshore - Caspian Sea

- Field: Offshore – Caspian Sea
- Variables Tested: Choke Setting Optimization
- Number of Well Locations Tested:  
Three Wells: Choke setting was modified based on TDM recommendations.

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## Choke Setting Optimization

### Results Choke Sizes for [Redacted] Wells

Wellname	LP/HP	Zones	Choke Sizes		FCT Result	TDM Result
			Case-A 1st Aug 2018	Case-B 25th Sep 2018		
[Redacted]	LP	[Redacted]	36	40	Positive	Positive
[Redacted]	LP	[Redacted]	32	34	Positive	Positive
[Redacted]	LP	[Redacted]	42	46	Positive	Positive
[Redacted]	LP	[Redacted]	42	44	Positive	Positive
[Redacted]	LP	[Redacted]	40	44	Positive	Positive
[Redacted]	HP	[Redacted]	44	46	Positive	Positive
[Redacted]	HP	[Redacted]	40	44	Positive	Positive
[Redacted]	LP	[Redacted]	44	48	Positive	Positive
[Redacted]	HP	[Redacted]	34	38	Positive	Positive
[Redacted]	HP	[Redacted]	30	34	Positive	Positive
[Redacted]	HP	[Redacted]	30	32	Positive	Positive
[Redacted]	LP	[Redacted]	34	36	Positive	Positive
[Redacted]	LP	[Redacted]	42	44	Positive	Positive
[Redacted]	LP	[Redacted]	40	42	Negative	Positive
[Redacted]	HP	[Redacted]	40	42	Negative	Positive

TDM's Choke Setting Optimization proved to be 87% accurate when compared with actual field measurements

Email of the Operating Company:

“The results also show 13 out of 15 analyses match with our recent flow test results.”

area is matching with our existing simulation model results. Furthermore, the choke analysis for A Sand na  
The results also show 13 out of 15 analyses match with our recent flow test results

- TDM choke prediction results are compared against Field Capacity Test (FCT) results.
  - 2 out of 15 TDM results from A Sand are counter intuitive to field capacity test (FCT) results

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## Production Optimization

### Forecast and Operational Recommendations by TDM

**Default System (HP System)**

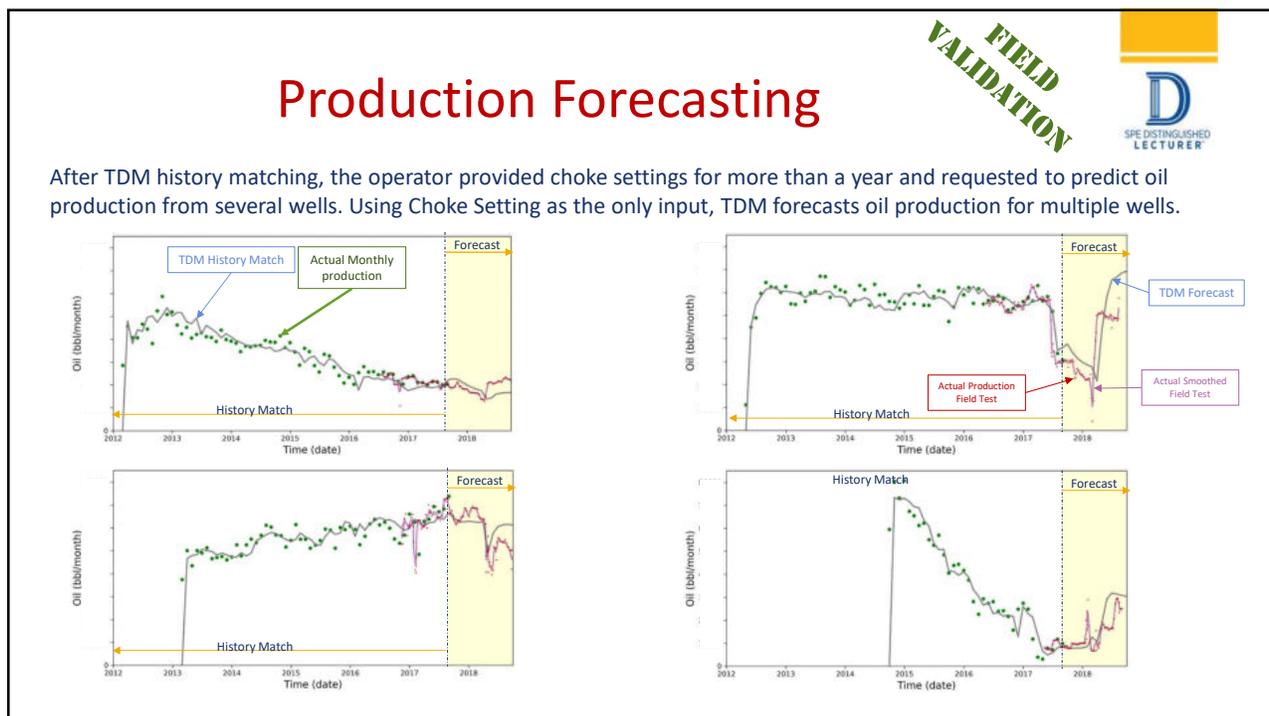
**19 Wells flow into the LP System**

Change of the wellhead system did not negatively impact GOR, WC, & Pr as was Correctly Predicted by the Top-Down Model

		Wellhead System			
Platform	Well Name	Zone	Original	Changed to	Incremental Oil (B/D)
[Redacted]	[Redacted]	[Redacted]	HP	LP	26
[Redacted]	[Redacted]	[Redacted]	HP	LP	58
[Redacted]	[Redacted]	[Redacted]	HP	LP	105

Total Incremental Oil = 189 B/D  
 Average Price of Oil = \$75.00  
 Annual Incremental Income = \$5.2 MM

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## Infill Well Location Optimization



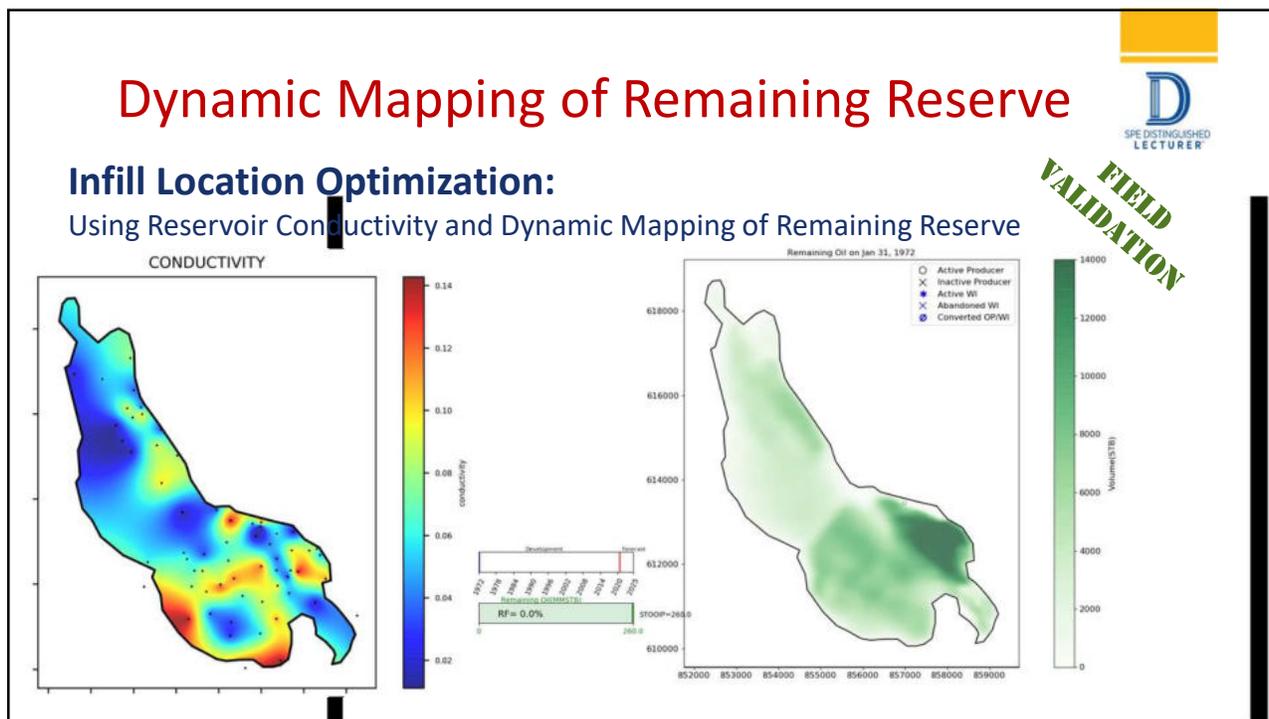

- Request to elaborate more how TDM identify location of infill wells through Fuzzy Pattern Recognition
- A plan in early 2017 to drill L28-193A where the location is similar to N-021 area. The well was drilled and completed in June 2018.
- Location of N014 area is expected inline with our new well plan based on simulation pressure and saturation maps distribution. However, we are facing slot availability problem to drill this target.



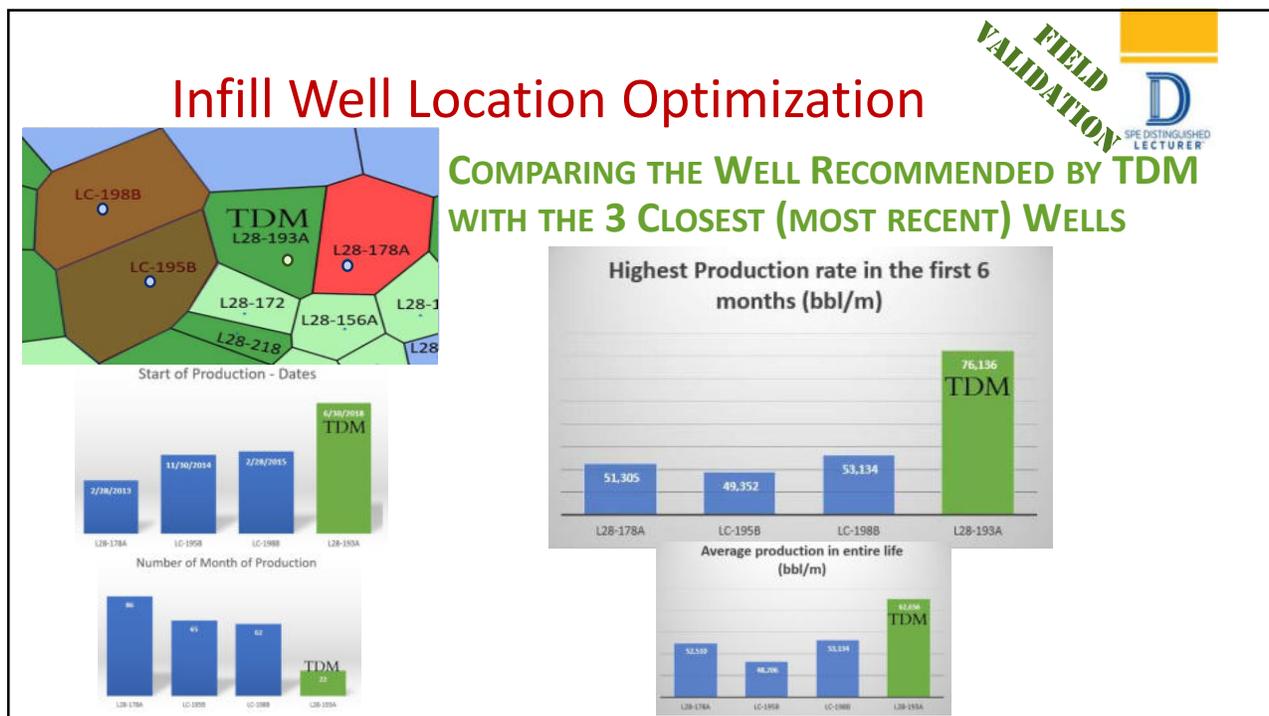
**Email of the Operating Company:**  
 “We Would like to inform you that the results of prediction scenario for ... reservoir infill wells indicate a good location for NW021. It has been proven with completed new well result in June 2018.”



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Enhancing the Utilization of Numerical Reservoir Simulation

## SMART PROXY MODELING

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## Subsurface Analytics – Conventional Resources



### Smart Proxy Modeling

Replication of Numerical Simulation Models

Cell-Based Proxy Model

Higher than 95% Accuracy

Requires only a handful of Simulation Runs

Sensitivity Analysis  
 Uncertainty Quantification  
 Field Development Planning

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## Definition of Smart Proxy Modeling - SPM



- Smart Proxy Modeling is ***teaching*** engineering problem solving to an ***open computer program*** using ***numerical simulation data***
- ***The Open Computer program*** includes a series of Machine Learning algorithms.
- ***The Numerical Simulation Data*** includes:
  - Data that is used to build the numerical simulation
  - Data that is generated by the numerical simulation (numerical solutions of the complex series of mathematical equations)

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## SPM – Replication of Numerical Simulation



- A ***complete paradigm shift*** in building a proxy model for the numerical simulation:
  - Replicate the results of the original numerical simulation:
    - with very high accuracy (above 90% accuracy)
    - at the grid-block level for every time step
  - Decrease the computational footprint by orders of magnitude:
    - Today, Smart Proxy models are run thousands of times on desktop workstations and laptops for analysis,
    - Soon, Smart Proxy Models of highly complex numerical simulation models will be run on tablets and smart phones.

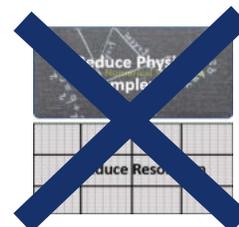
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## SPM – Non-Traditional Proxy Models

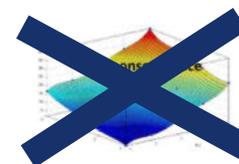


- Smart Proxy Model, unlike **ROM**:
  - Does not simplify the physics of Numerical Simulation
  - Does not reduce the Numerical Simulation resolution in space and time.
- Smart Proxy Model, unlike **RSM**, does not use statistics (curve fitting) to find correlation between few input variables and some of the output variables, only at certain times, or certain locations, using hundreds of simulation runs.

Reduced Order Modeling



Response Surface Method

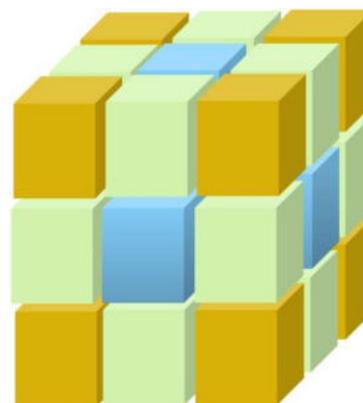


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## SPM – Cell-Based Proxy Models



- Each “Focal Block” has total of 26 neighboring blocks.
- Each “Focal Block” is connected to its neighbors through:
  - Tier One: Planes; 6 neighboring blocks
  - Tier Two: Lines; 12 neighboring blocks
  - Tier Three: Points; 8 neighboring blocks
- Therefore, each record may include static and dynamic data from 27 grid blocks
- Same idea works for CFD using Tetrahedrons



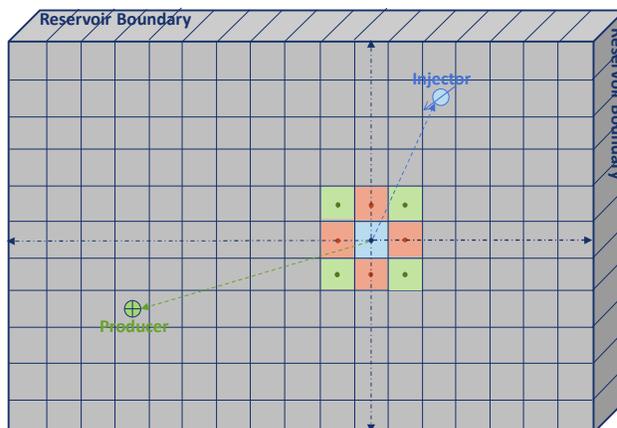
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# Spatio-Temporal Database

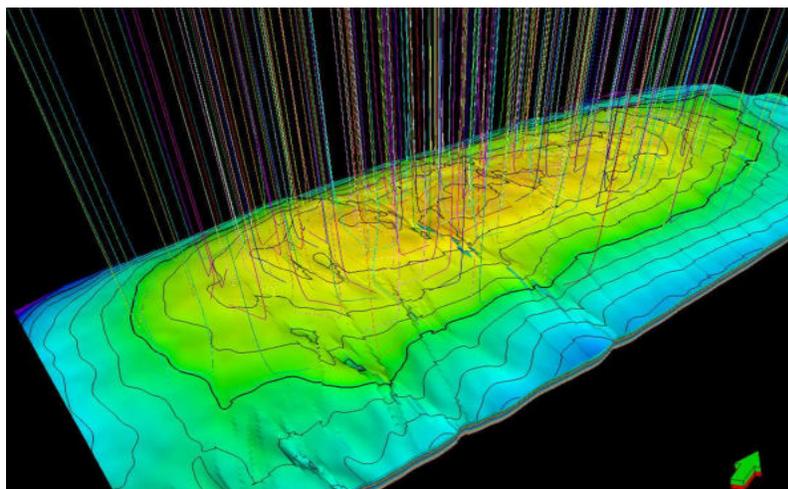
• Other information that is included in each record of the Spatio-Temporal Database are:

- Location & Characteristics of the Focal Cell
- Location & Characteristics of the Tier 1 Cells
- Location & Characteristics of the Tier 2 Cells
- Distances from the boundaries
- Production History and the Operational conditions for the producer wells
- Injection History and the Operational conditions for the Injector wells
- Distances from producers and injectors



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## SPM Case Study 1 : Onshore-Middle East



<b>Size of the Full Field Model</b>	1MM Grid Blocks
<b>Formation Type</b>	Naturally Fractured Carbonate
<b>Number of Wells</b>	167 (Horizontal)
<b>Simulation Run</b>	10 Hours on 12 parallel CPU

<b>Study Completed</b>	2005
<b>Implemented</b>	2006
<b>Look-Back Analysis</b>	2011
<b>Field Results published</b>	2014

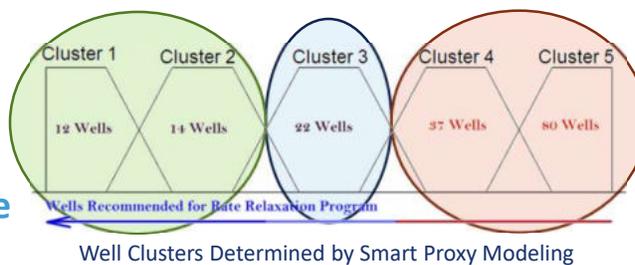
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## Field Development Planning

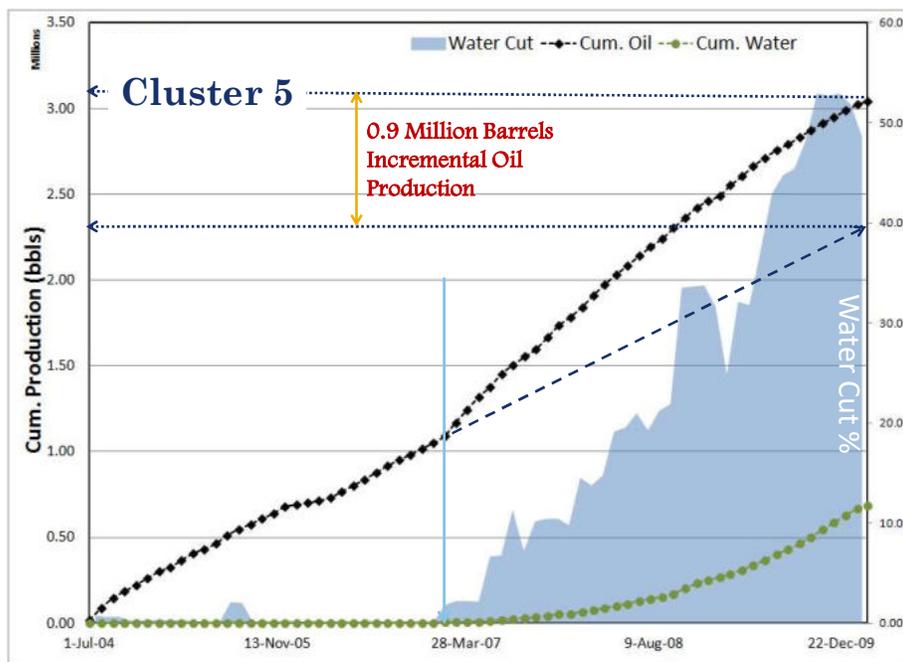


- Wells in the field were divided into five clusters for Rate Relaxation:

1. Definitely a Candidate
2. Candidate
3. May or May not be a Candidate
4. Not a Candidate
5. Definitely Not a Candidate

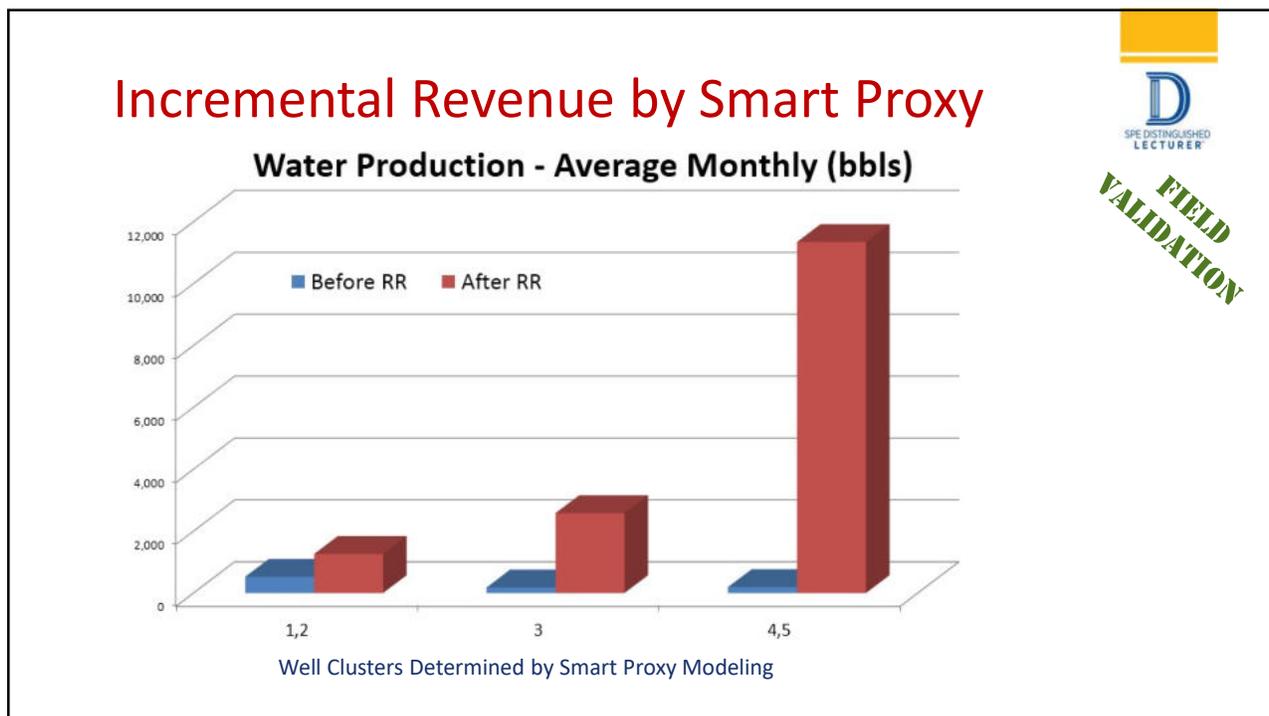


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FIELD VALIDATION

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## Incremental Revenue by Smart Proxy

Well Name	ISI Cluster #	OIL (bbls)				Revenue
		Before	After	Alt. After	Increment	
\$ 1	1	1,579,346	3,880,657	2,800,000	1,080,657	\$ 81,049,308.75
\$ 7	1	844,012	3,348,490	2,250,000	1,098,490	\$ 82,386,765.00
\$ 1	1	1,424,211	4,572,888	3,000,000	1,572,888	\$ 117,966,570.00
\$ 3	1	1,370,628	4,122,588	2,500,000	1,622,588	\$ 121,694,066.25
\$ 2	2	1,753,805	4,347,113	2,700,000	1,647,113	\$ 123,533,445.75
\$ 3	2	1,127,917	4,657,838	2,700,000	1,957,838	\$ 146,837,841.75
\$ 0	3	4,017,836	6,655,187	4,700,000	1,955,187	\$ 146,639,006.25
\$ 2	3	3,816,986	5,516,557	4,700,000	816,557	\$ 61,241,762.25
\$ 5	3	1,753,660	4,557,731	2,500,000	2,057,731	\$ 154,329,858.00
\$ 5	3	1,354,740	4,073,894	2,700,000	1,373,894	\$ 103,042,069.50
\$ 1	3	827,812	4,239,701	2,600,000	1,639,701	\$ 122,977,593.75
\$ 3	3	999,854	3,726,135	2,230,000	1,496,135	\$ 112,210,148.25
\$ 1	4	1,887,698	4,335,160	3,200,000	1,135,160	\$ 85,136,976.75
\$ 3	4	1,337,386	3,627,013	2,500,000	1,127,013	\$ 84,525,987.75
\$ 0	4	428,093	3,364,653	2,300,000	1,064,653	\$ 79,848,988.50
\$ 3	4	605,806	2,899,556	2,000,000	899,556	\$ 67,466,685.00
\$ 2	5	1,273,508	2,487,207	2,350,000	137,207	\$ 10,290,525.00
\$ 1	5	1,400,479	3,864,135	3,300,000	564,135	\$ 42,310,160.25
\$ 1	5	1,564,455	3,783,478	2,500,000	1,283,478	\$ 96,260,882.25
\$ 7	5	1,049,893	3,044,199	2,150,000	894,199	\$ 67,064,911.50
		30,418,125	81,104,181	55,680,000	25,424,181	\$ 1,906,813,552.50

Average Oil Price = \$75.00/bbl

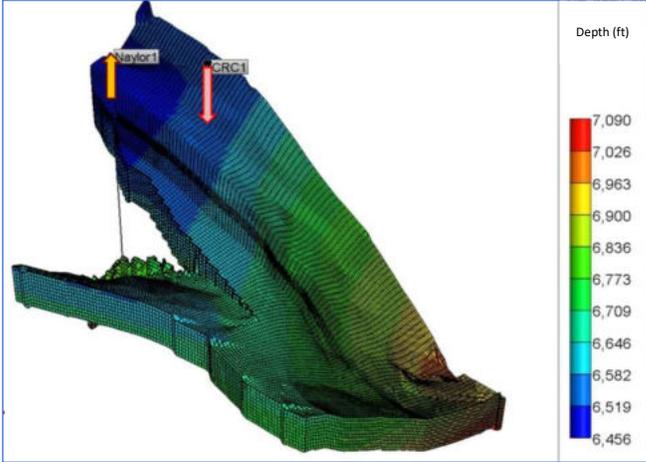
**FIELD VALIDATION**

Cluster 1&2 = \$ 673.5 MM – 6 wells  
 Cluster 3 = \$ 700.4 MM – 6 wells  
 Cluster 4&5 = \$ 532.9 MM – 8 wells

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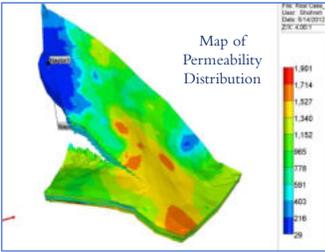
## SPM Case Study 2 : Onshore-Australia





### Geological Storage of CO<sub>2</sub>

### Otway - Australia

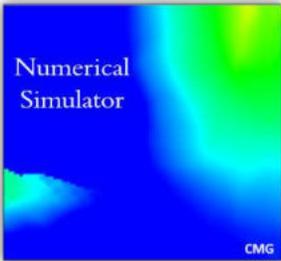


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## Pressure Distribution – Layer #1



after 1 month of injection



Numerical Simulator

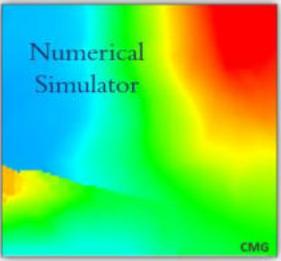
CMG



Smart Proxy

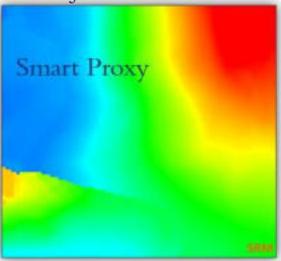
SRM

after 8 month of injection



Numerical Simulator

CMG

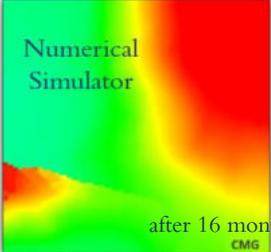


Smart Proxy

SRM

**Training Scenario#4:**  
0.7 BCF of CO<sub>2</sub> is injected into the reservoir within 16 months

after 16 month of injection



Numerical Simulator

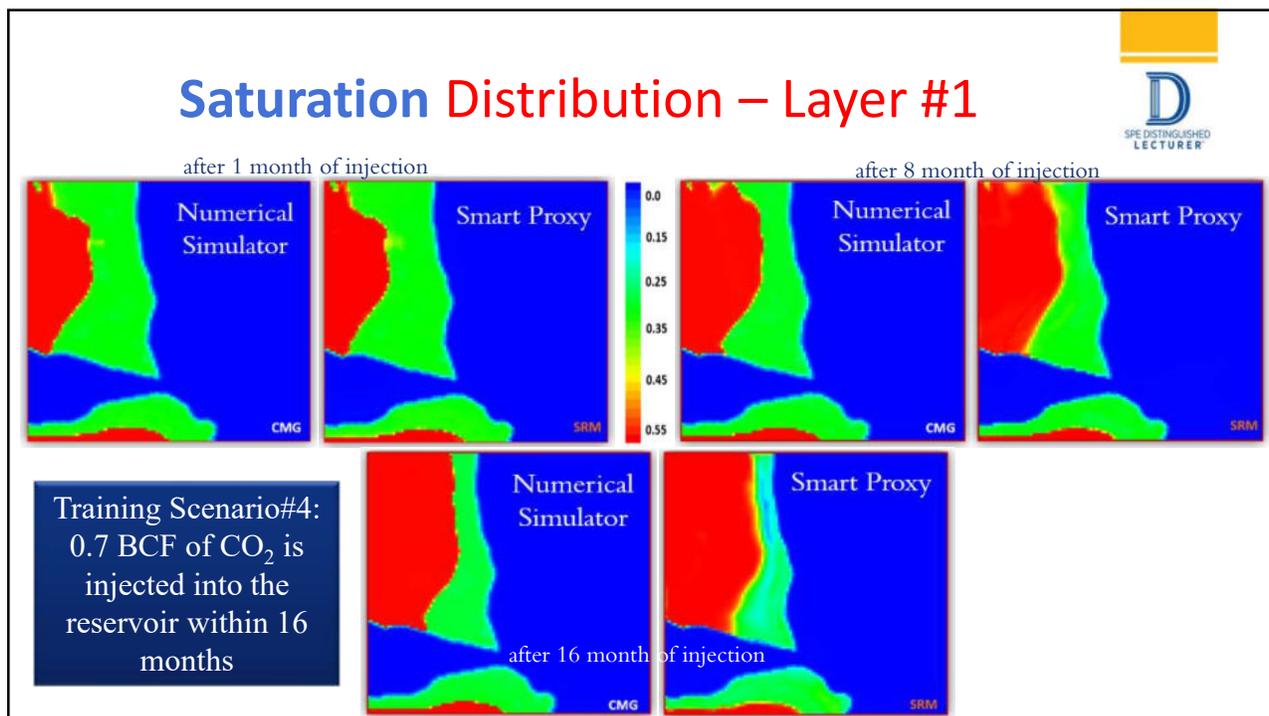
CMG



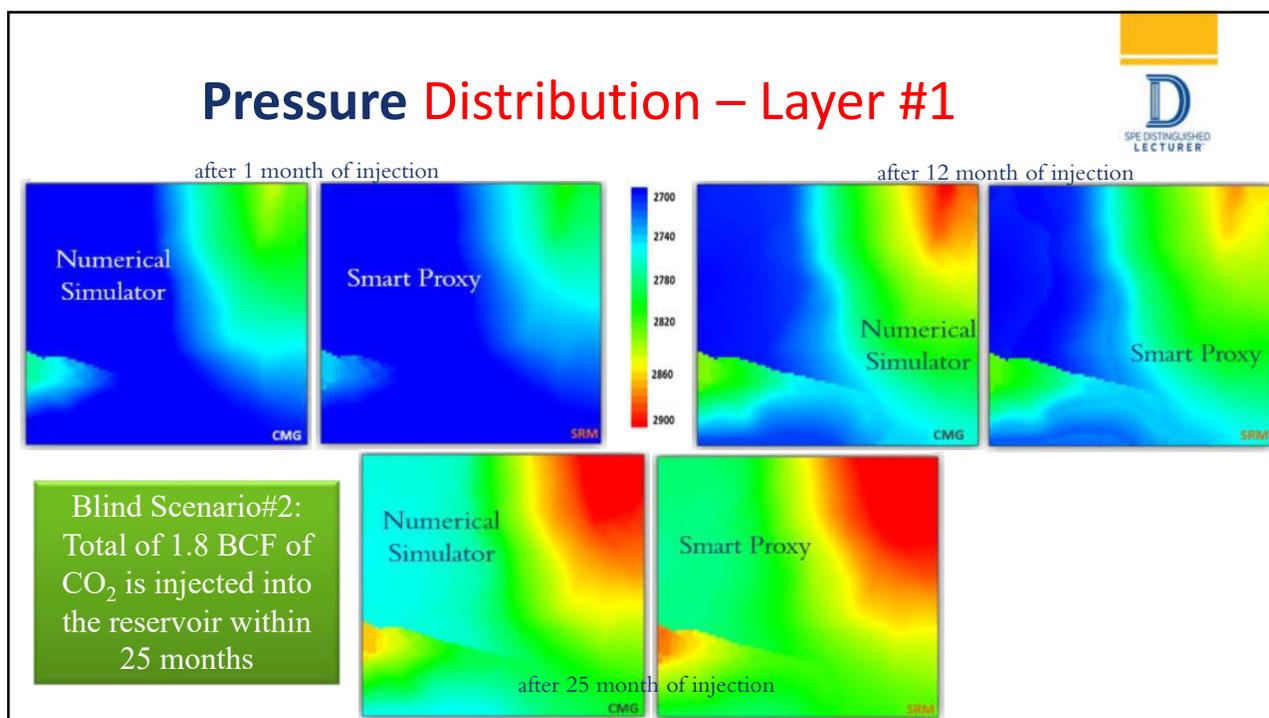
Smart Proxy

SRM

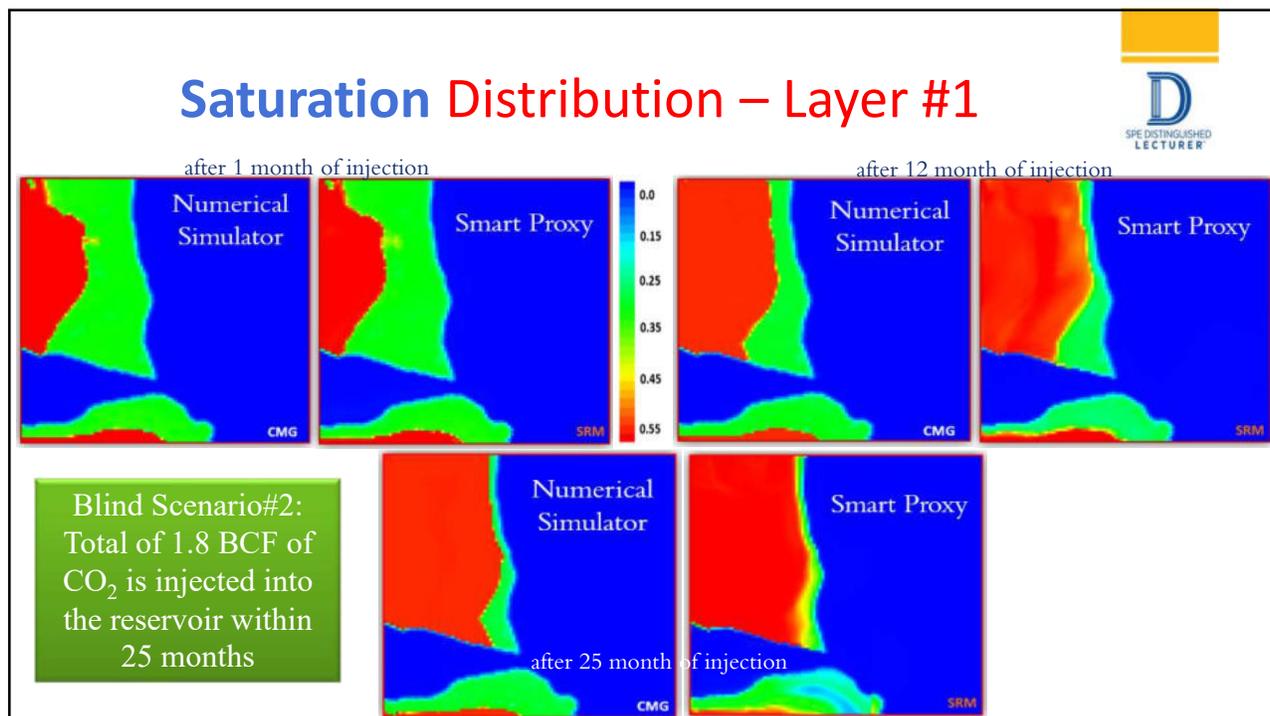
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## Conclusions

- AI&ML is changing the world, our industry is not an exception.
- The most complex and the most contributor application of AI&ML in our industry is on reservoir engineering, reservoir modeling, and reservoir management.
- Subsurface Analytics:
  - is the reality of Digital Transformation in our industry.
  - provides an alternative to traditional reservoir management technologies.
  - will Form the Future of our Industry.

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Purely Fact-Based, Field Measurement – Driven Completion and Production Optimization

## SHALE ANALYTICS

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## Shale Analytics

- Shale Analytics is the application of Artificial Intelligence and Machine Learning to Unconventional Resources.
- Shale Analytics is significantly different from using traditional modeling techniques when they are applied to highly complex unconventional resources:
  - Traditional Modeling as it applies to Shale is all about ASSUMPTIONS and GUESS WORK, and hardly has anything to do with REALITY.
  - Only SOFT DATA is used to perform traditional modeling techniques

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## Soft Data – Assumptions, Guess Work

- Since the physics of storage and transport phenomena in unconventional resources are not well understood, it cannot be explicitly modeled in detail using traditional tools without assumptions that compromise the solution integrity.
- Traditional techniques use “soft data”:
  - Fracture Half Length
  - Fracture Width
  - Fracture Height
  - Fracture Conductivity
  - Stimulated Reservoir Volume

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## Subsurface Analytics – Unconventional Resources

### Shale Analytics

Discovering Complex Patterns in Measured Data

Fact-Based Predictive Modeling of Well Productivity

Purely Based on Field Measurements – (No Equations)

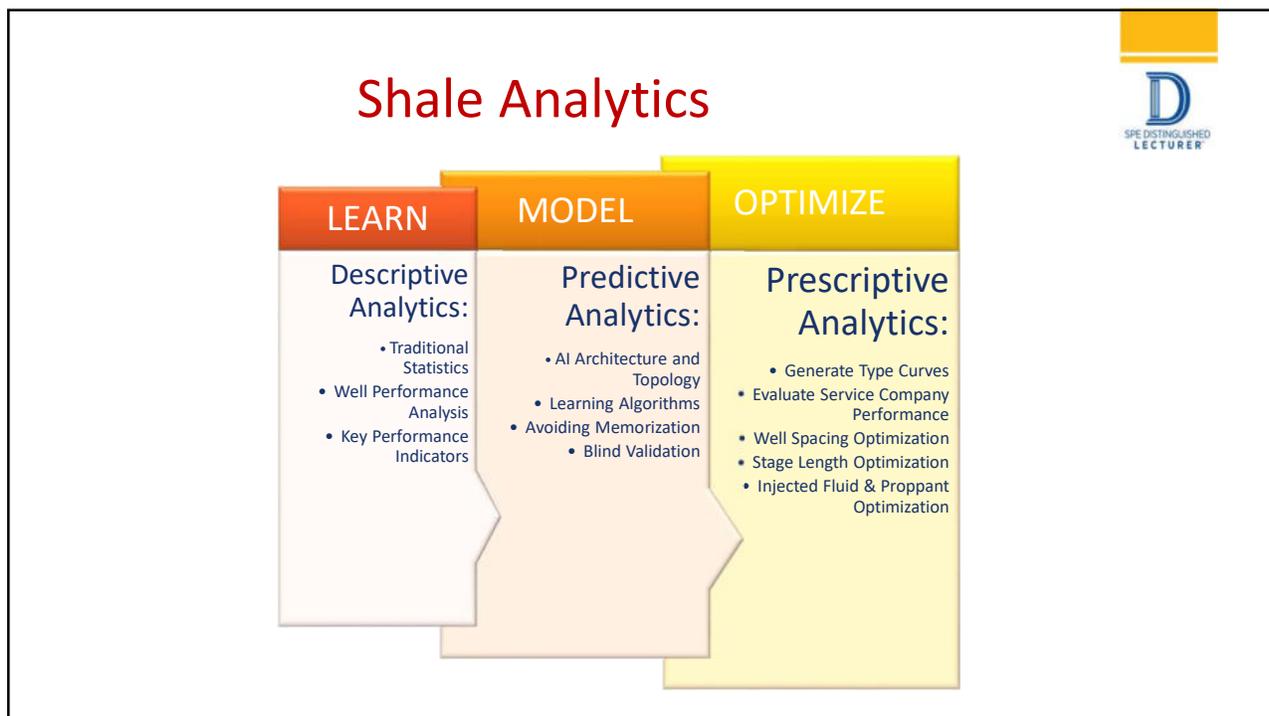
Explainable Artificial Intelligence

Sensitivity Analysis

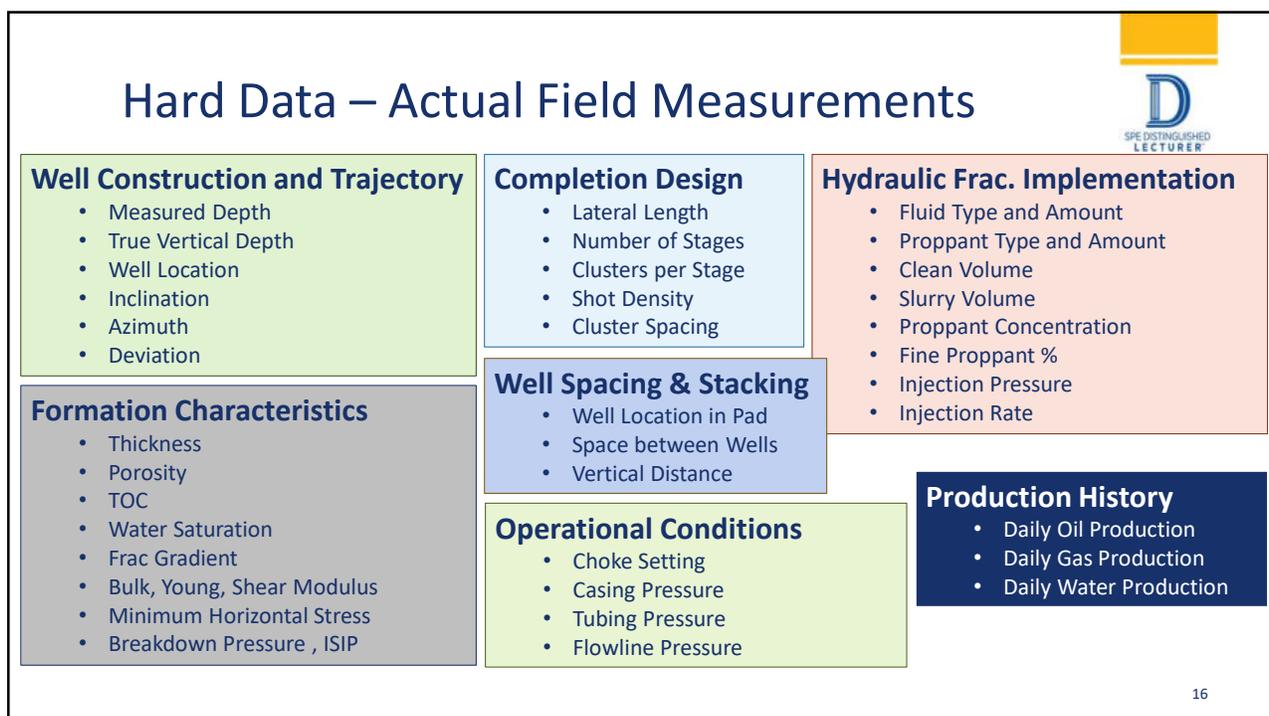
Uncertainty Quantification

Field Development Planning

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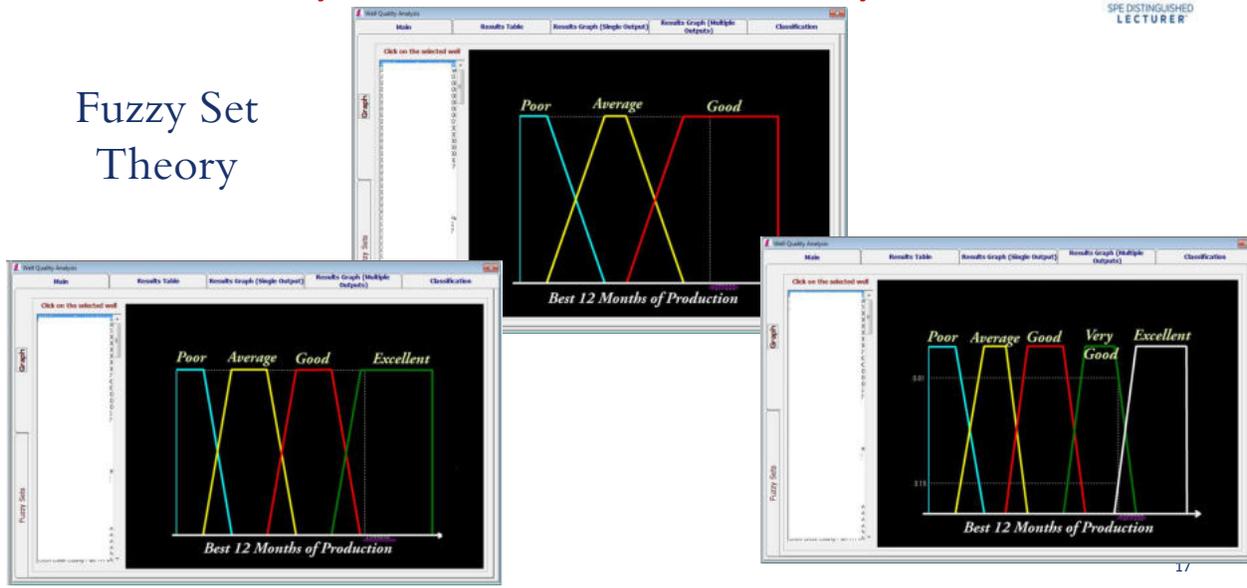
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# Shale Analytics - Pattern Discovery



## Fuzzy Set Theory

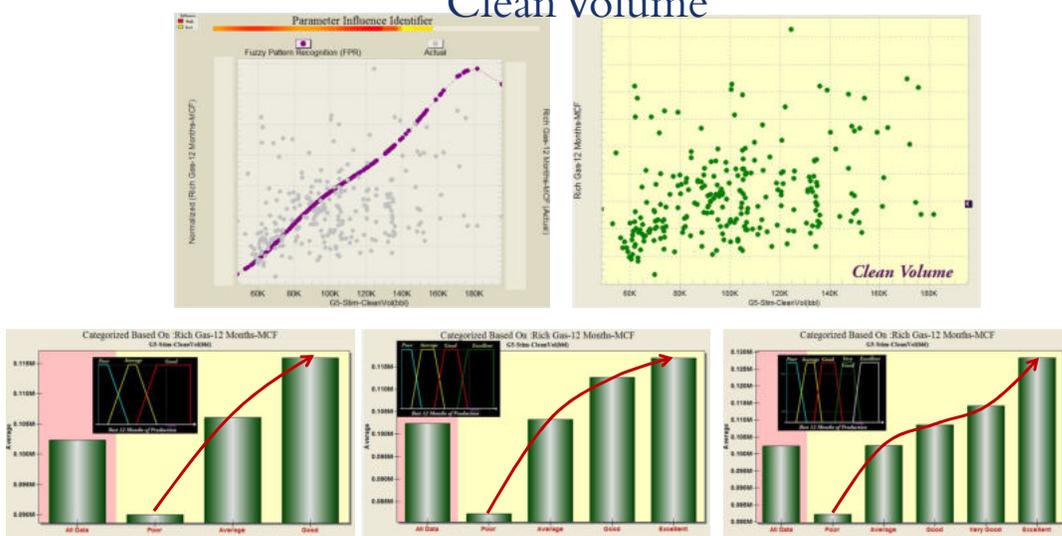


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# Shale Analytics - Pattern Discovery



## Clean Volume



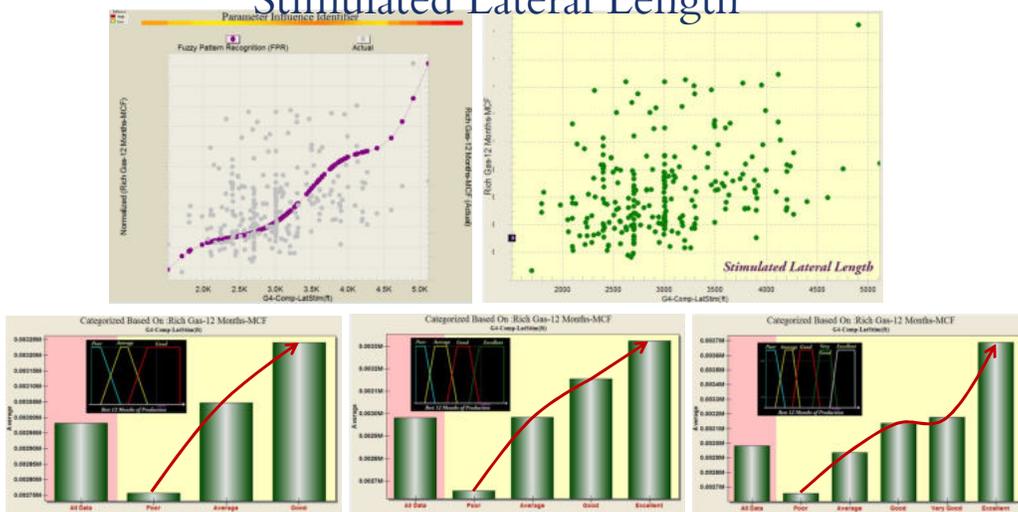
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# Shale Analytics - Pattern Discovery



## Stimulated Lateral Length



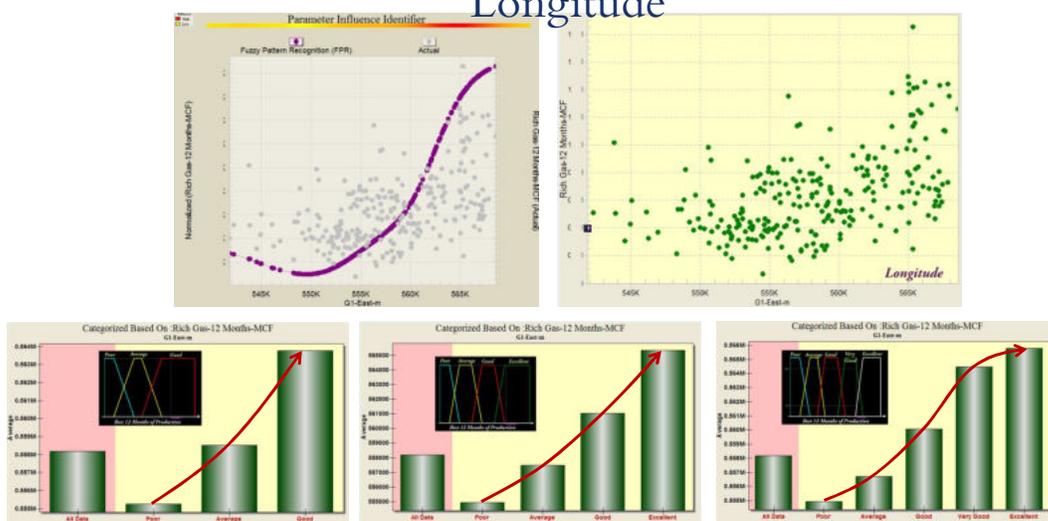
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# Shale Analytics - Pattern Discovery



## Longitude



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# Shale Analytics - Pattern Discovery



## Measured Depth



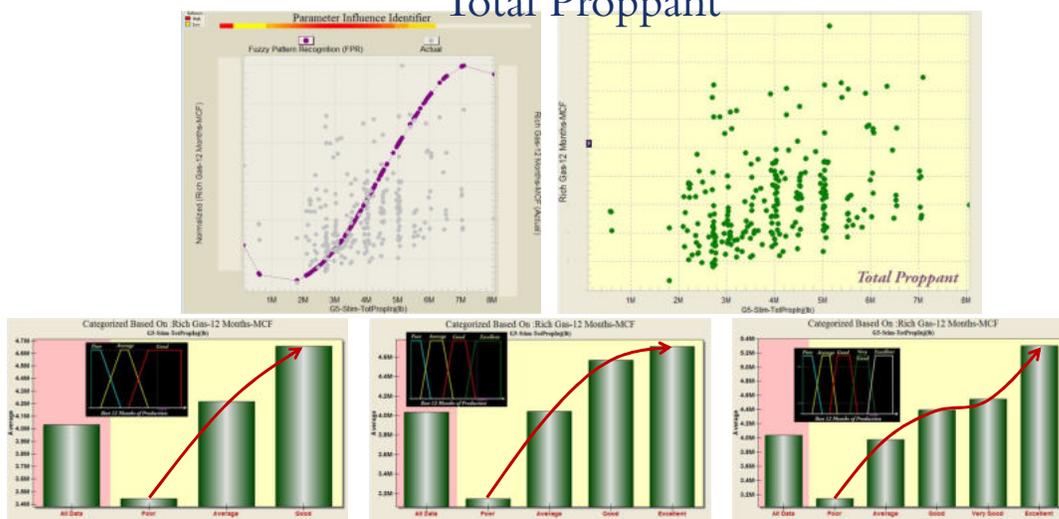
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# Shale Analytics - Pattern Discovery



## Total Proppant

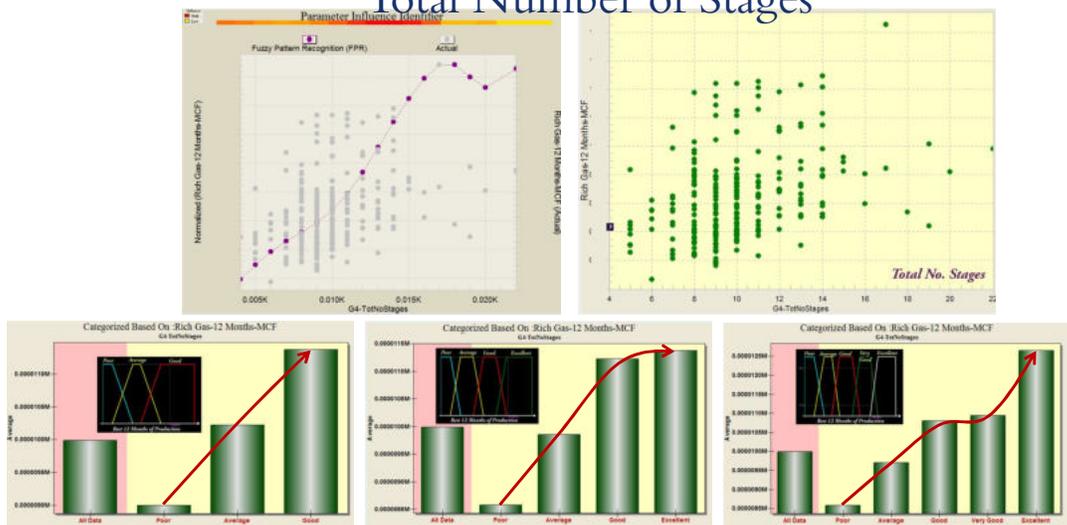


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# Shale Analytics - Pattern Discovery

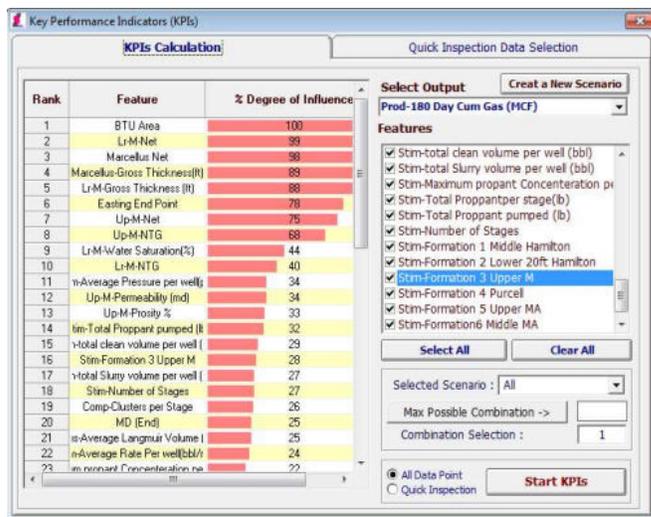
## Total Number of Stages



23

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# Key Performance Indicators - KPI



Using Fuzzy Pattern Recognition we can rank variables based on their impact (influence) on a given Production Indicator (30 or 180 days cum. production)

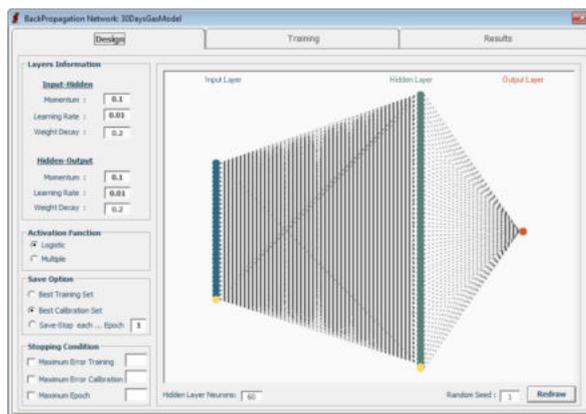
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# Machine Learning Algorithms



- Latitude
- Longitude
- Measured Depth
- TVD
- Deviation Type
- Incline
- Azimuth
- Soak Time
- Porosity
- Net Thickness
- Initial Water Saturation
- TOC
- Min. Horizontal Stress
- Stimulated Lateral Length
- Shot Density
- Total Number of Stages
- Cluster Spacing
- Average Injection Pressure
- Average Injection Rate
- Clean Volume
- Slurry Volume
- Max. Proppant Concentration
- Total Proppants
- Average Well-Head Pressure



- 30 Days Cum. Production
- 90 Days Cum. Production
- 180 Days Cum. Production
- 365 Days Cum. Production

INPUT

MODEL

OUTPUT

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25

# Characteristics of Shake Analytics

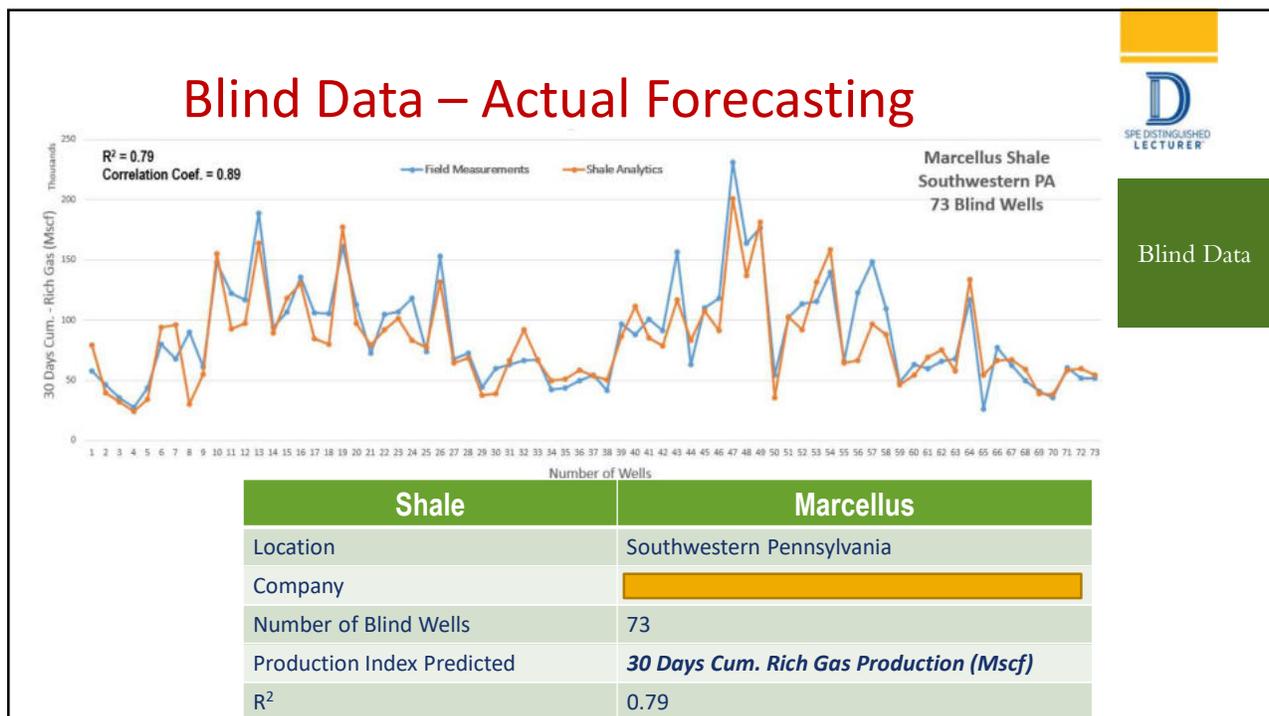


- In Shale Analytics the Data is divided into four partitions

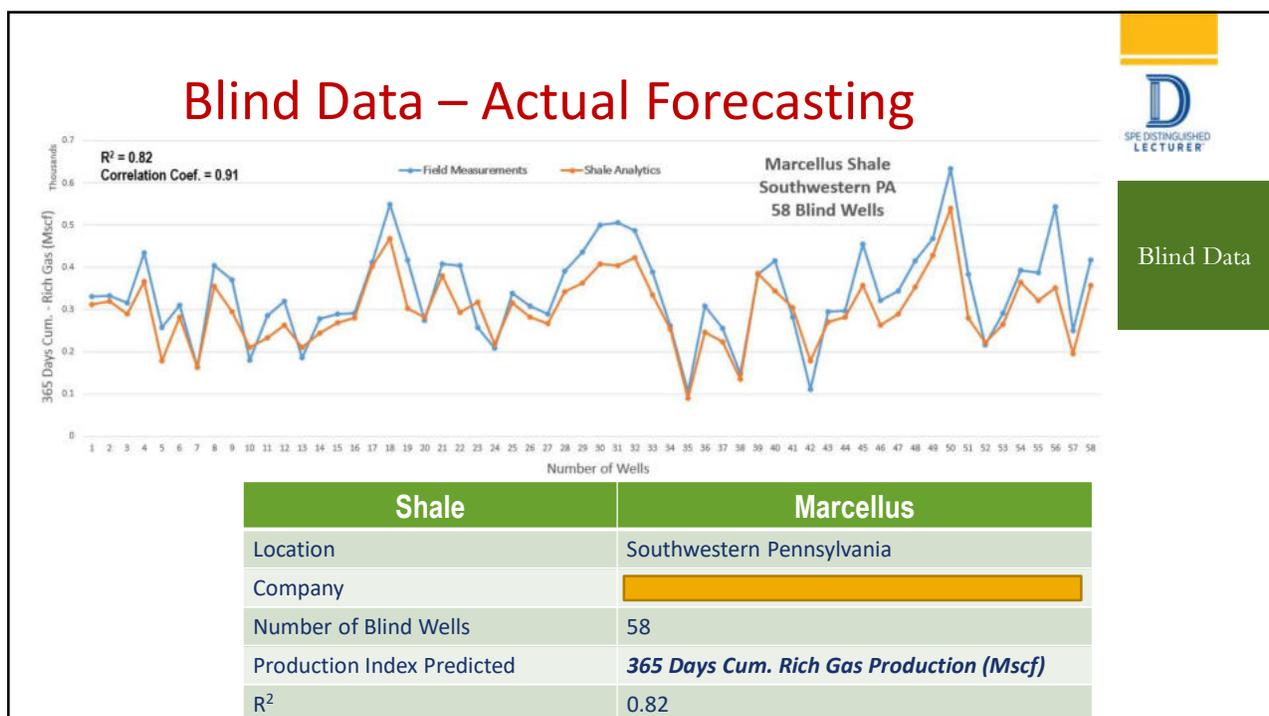


- Shale Analytics uses Explainable Artificial Intelligence (XAI)

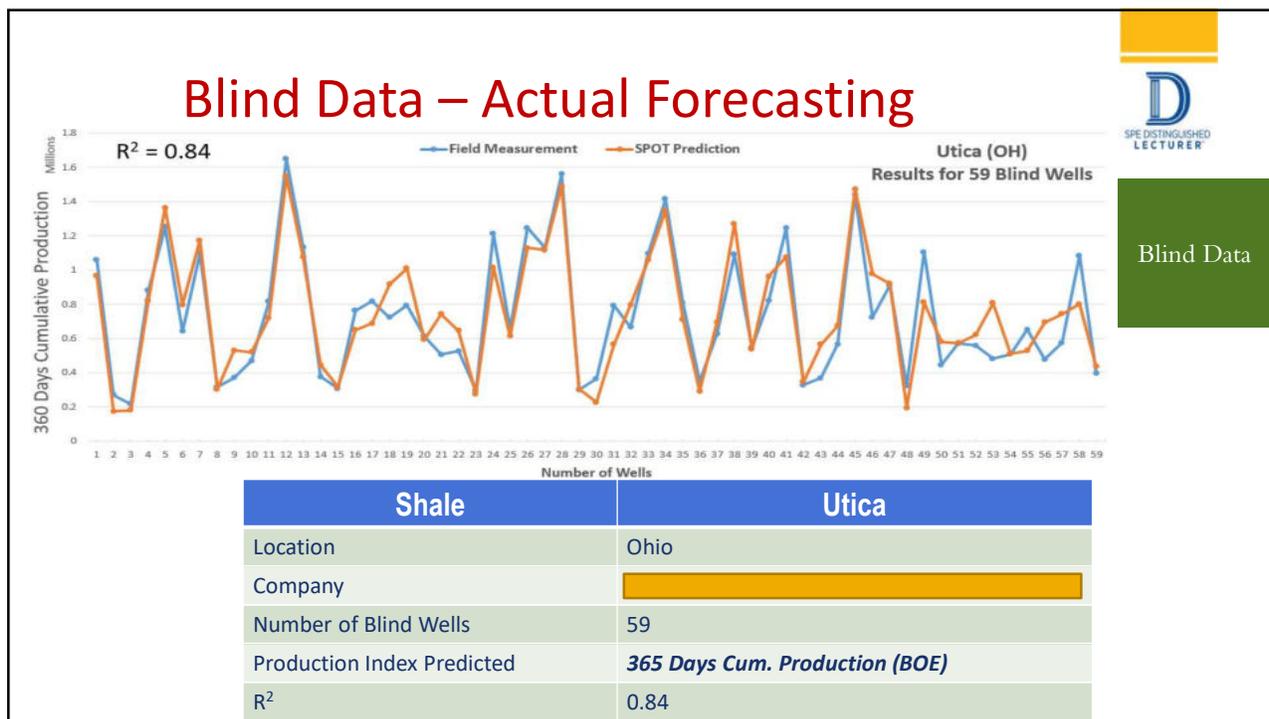
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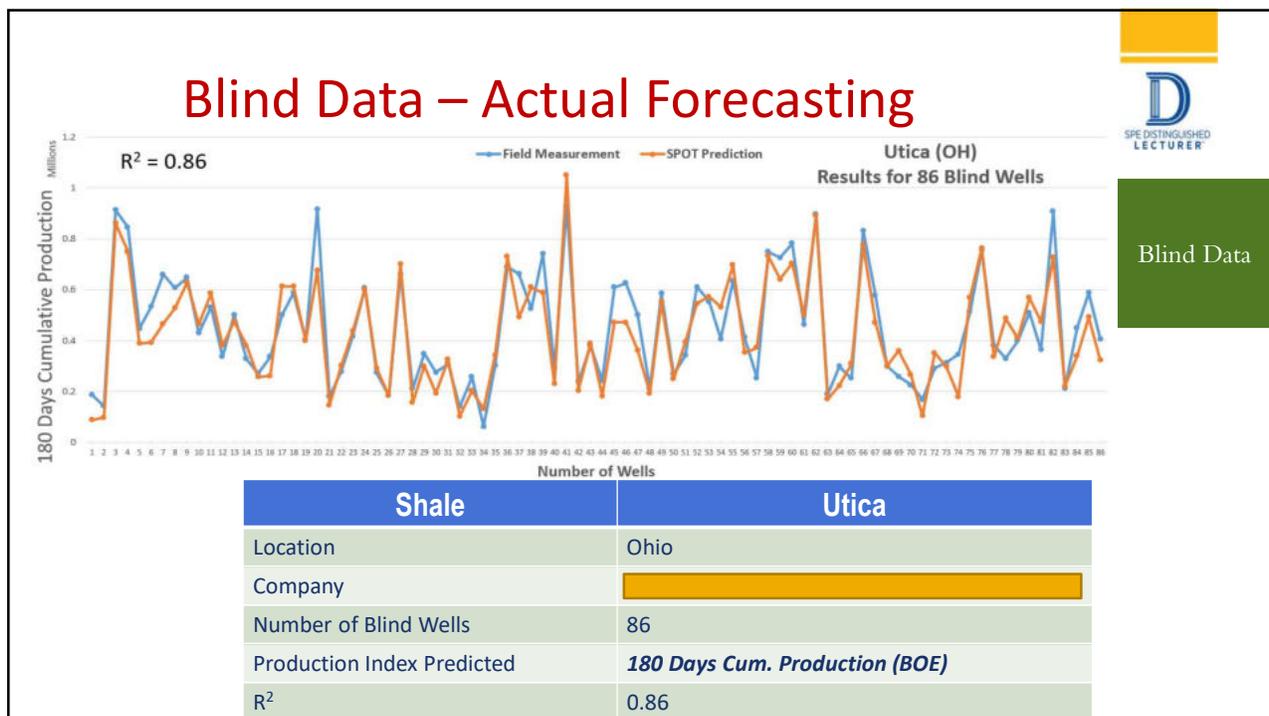
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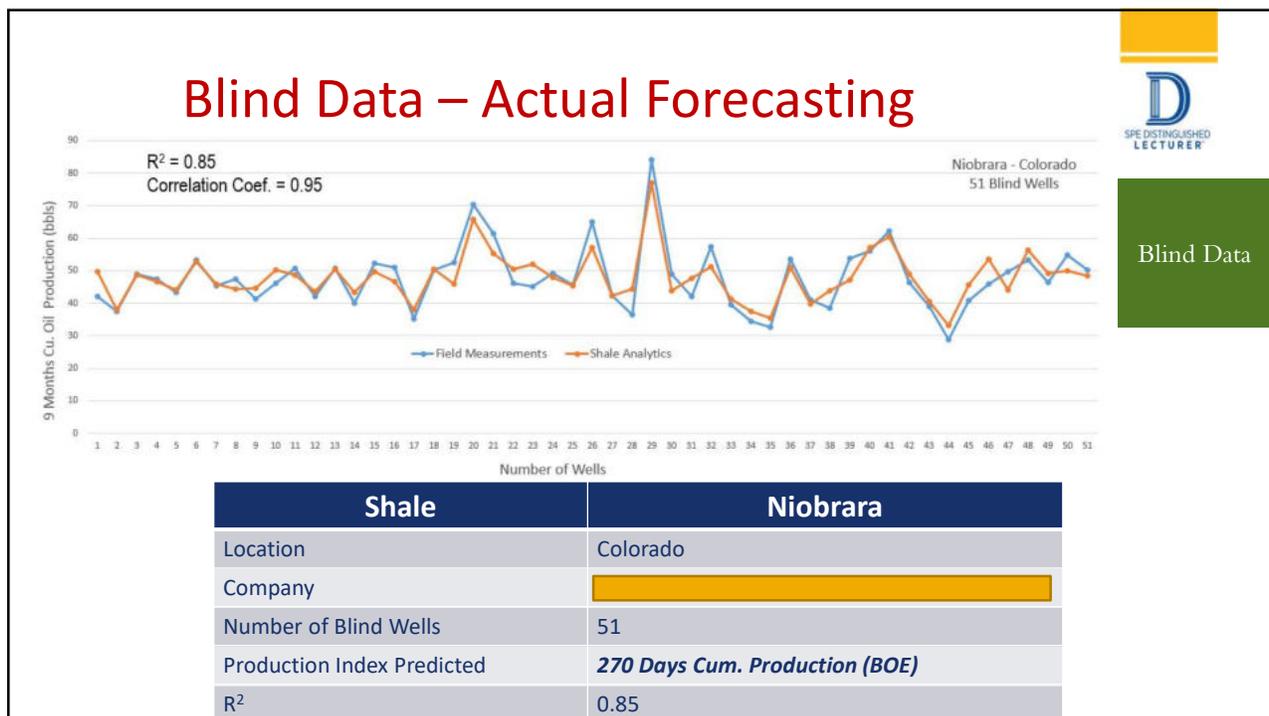
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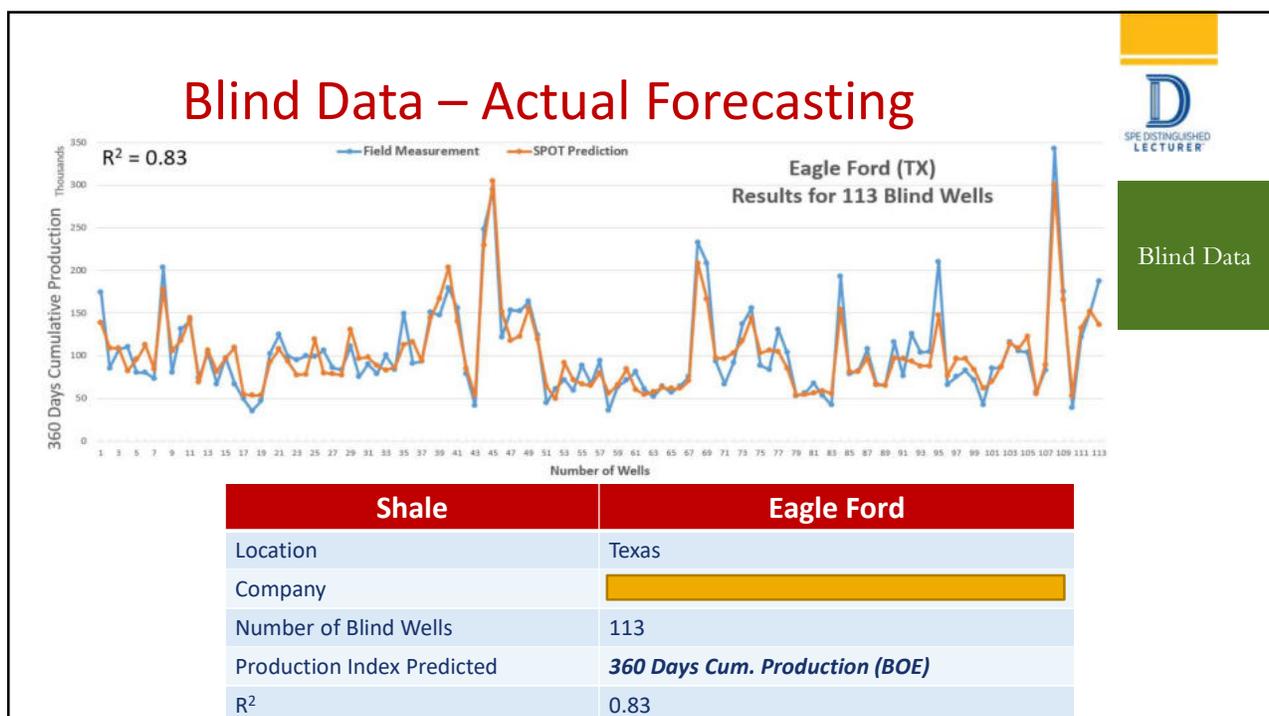
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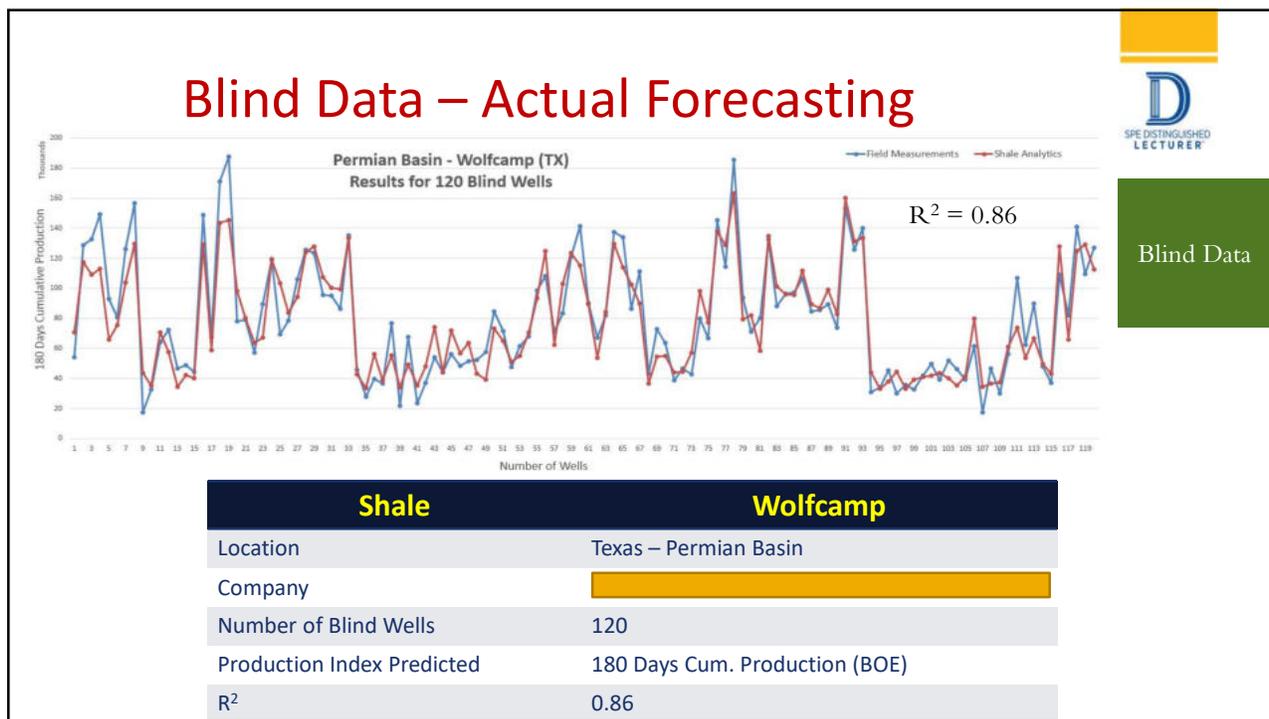
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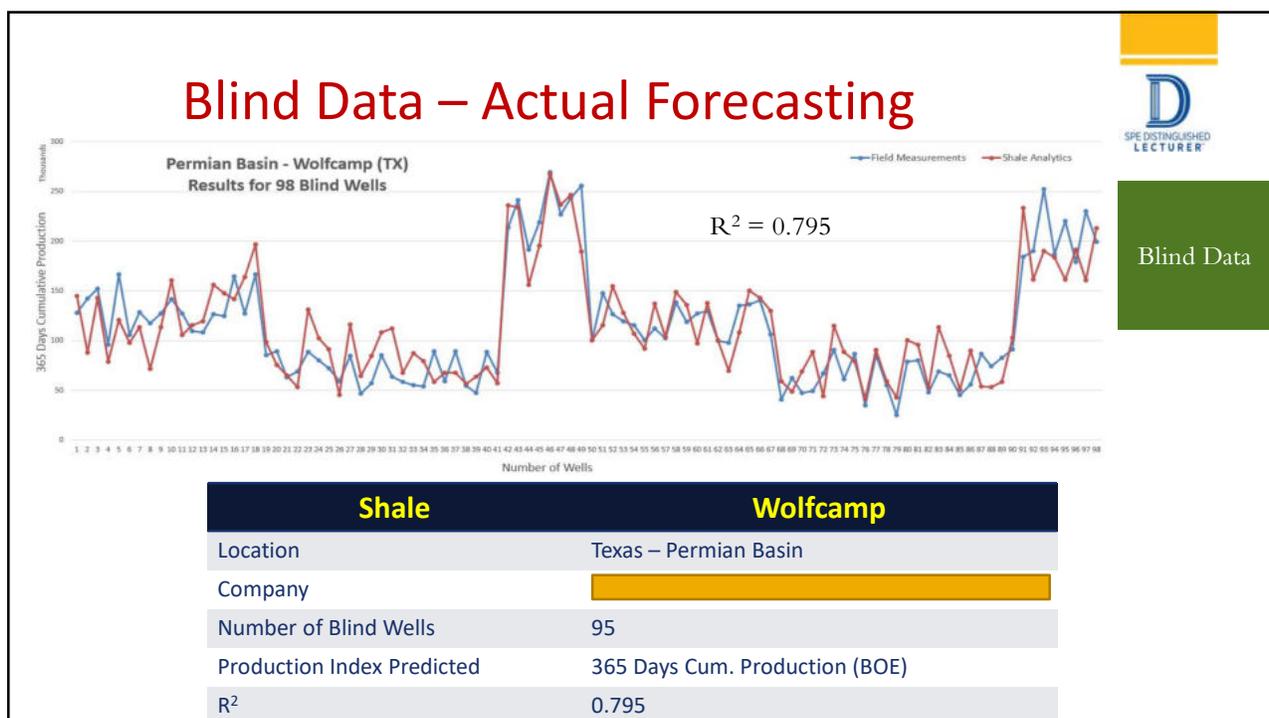
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## Shale Prescriptive Analytics



- Shale Prescriptive Analytics contributes to Field Development Planning
- During the Shale Prescriptive Analytics, the validated predictive models are used in order to:
  - Identify the quality of the historical completion designs
  - Evaluation of Service Companies Performance
  - Optimization of future Completion Designs & Implementations

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## Quality of Historical Completion



- How good and successful historical completion designs of the operating company have been?

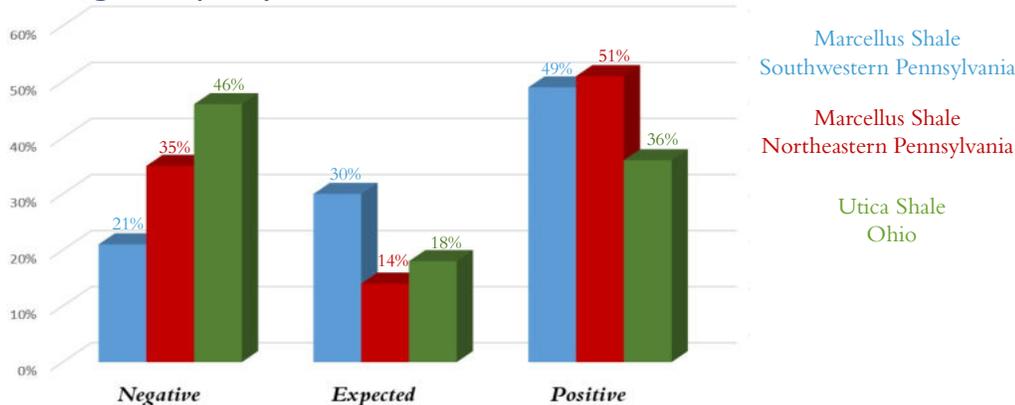


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## Quality of Historical Completion



- How good and successful historical completion designs of the operating company have been?



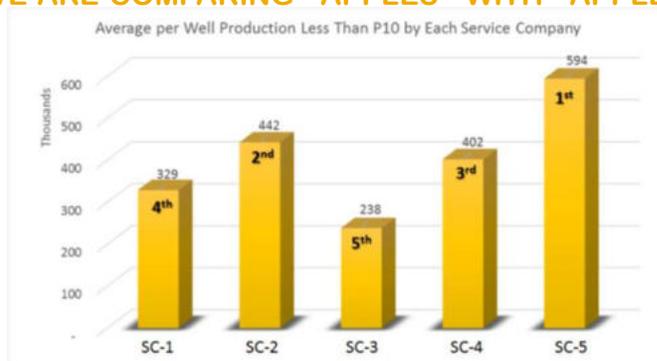
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## Service Companies Performance



- Which Service Company has performed the best?

BY ELIMINATING THE IMPACT OF RESERVOIR CHARACTERIZATION  
WE ARE COMPARING “APPLES” WITH “APPLES”

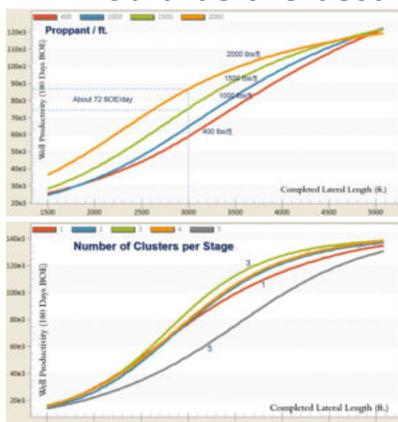


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# Completion Optimization

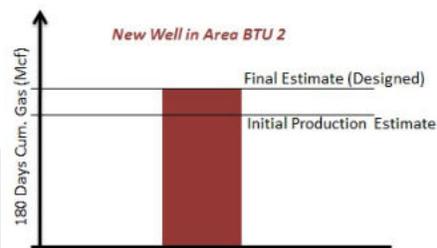


- In order to maximize the productivity of the new wells, what would be the best completion designs?



Easting End Point	1467645
Northing End Point	3886952
Measured Depth	9,329
Azimuth	123.7
Inclination	93.5
Marcellus Porosity	8.3
Marcellus Net Pay	140.2
Marcellus Sw	30.1
Marcellus TOC	3.5
Marcellus Vol. Const.	62.6
Marcellus Press. Const.	290

Lateral Length	4,565
Lateral/Stage	299
Cluster/Stage	3
Shot Density	4
Avg. Treat. Pressure	6,138
Avg. Treat. Rate	70.5
Clean Volume	150,102
Slurry Volume	117,455
Proppant/Stage	492,334
Max. Prop. Concentration	3



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