Smart Fields; A Data-Driven Approach to Making Oilfields Smart

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Summary

- The concept of Smart Field has come a long way since its inception.
- Overwhelming majority of accomplishments have been in hardware.
- Comparatively, very little has been accomplished in the realm of software.
- How do we bridge this gap?
- This presentation addresses the software aspects of "Smart Fields".

Outline

- Objective
- Definitions
  - Smart Completion, Smart Well, Smart Field
- Technology
  - A Paradigm Shift in Problem Solving
- Applications / Case Studies
  - Data Cleansing & Abstraction
  - Data-Driven Reservoir Simulation & Modeling

Objective

- Propose technologies that have the potential to transform "Smart Fields" from concept to reality.
- Provide case studies to demonstrate the capabilities of such technologies.

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DEFINITIONS

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Common Misconceptions

- Automation IS **NOT** Intelligence.
- "Smart Field" does not mean "Smart" people managing "Fields" using automated tools.
- "Smart Fields" is a vision that can become reality. It needs bold and innovative people and technologies.

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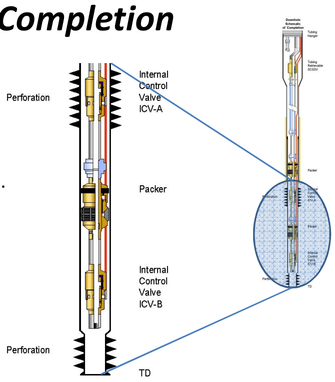
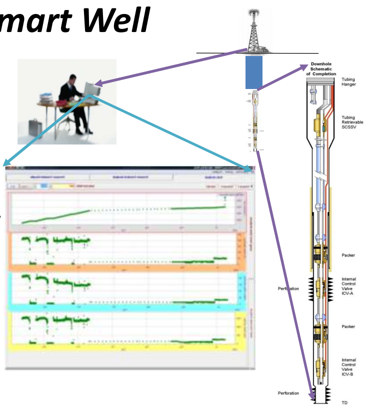
Smart Completion

- Smart Completion:
  - Remotely monitor & control downhole fluid production or injection.
  - Downhole control to adjust flow distributions along the wellbore to correct undesirable fluid front movement.



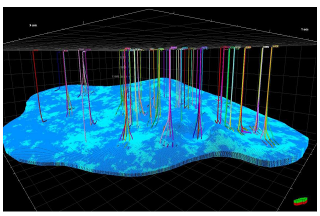
Smart Well

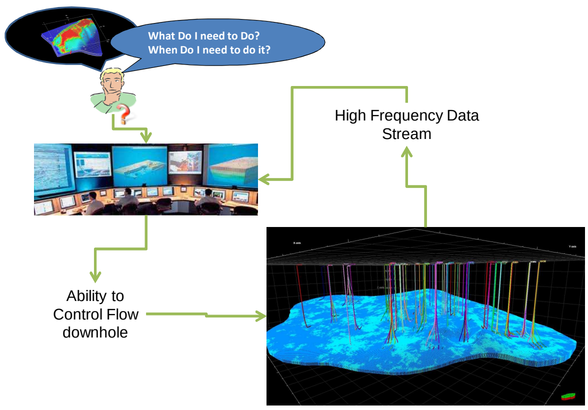
- Smart Well:
  - Using permanent downhole gauges for continuous monitoring of pressure, flow rates, … and automatic flow controls.
  - Capability of automatic interaction using extensive downhole communication.



Smart Field

- Smart Field:
  - Includes multiple Smart Wells & Smart Completions.
  - Reservoir model is updated in real-time.
  - Fluid flow in the reservoir is visualized in real-time.
  - Reservoir Management decisions are made and executed in real-time.





The Technology Gap

- Existing technology was developed for data frequency that used to be annual, monthly, or daily.
- Adapting this technology to data frequency that is now in seconds, has caused serious issues.
- How do we bridge this technology gap caused essentially by time-resolution?

Characteristics of Smart Fields

- Availability of high frequency data.
- Possibility of intervention, control and management from a distance, in real-time.
- The missing Link?

Making Real-Time reservoir management decisions based on Real-Time data from the field.

Characteristics of Smart Fields

- Making real-time reservoir management decisions based on real-time data from the field.
- Considerations:
  - Reservoir surveillance technology.
  - Reservoir management tools.
  - Uncertainties associated with the geological model.
  - Predicting the consequences of decisions.
  - Real-time feedback from the reservoir on decisions made.
  - Real-time optimization.

Smart Field

- Automation is necessary but not sufficient.
- Automation IS NOT Intelligence.
- Hardware:
  - Permanent Downhole Gauges
  - Fiber Optic and Wireless Communication
  - Data Warehousing
- Software:
  - Field of Dreams …

TECHNOLOGY

Technology

- Smart Fields constitute a ***Paradigm Shift*** in how we operate and manage oilfields.
- A *Paradigm Shift* in operation and management requires a *Paradigm Shift* in solution methods.

Technology

- Using data as the main building block of models is the new paradigm in science and technology.
- It has been called "Fact-Based" decision making.

Technology

- Data-Driven Analytics is a way of mimicking how human brain works.
- Human brain is 10,000,000 times slower than the chips in your smart phone.
  - Imagine combining the intelligence of human brain with the speed of computers.

Paradigm Shift

- ***First Paradigm:*** Thousands of years ago
  - Science was ***Empirical*** (describing the natural phenomena)
- ***Second Paradigm:*** Last few hundred years
  - ***Theoretical*** branch (using models, generalizations)
    - Kepler's Law, Newton's Law of Motion, Maxwell's Equation
- ***Third Paradigm:*** Last few decades
  - ***Computational*** branch (simulating complex phenomena)
    - Theoretical models grew too complicated to solve analytically

Jim Gray: (1944-2007) Legendary American computer scientist , received the Turing Award for seminal contributions to computer science.

Paradigm Shift

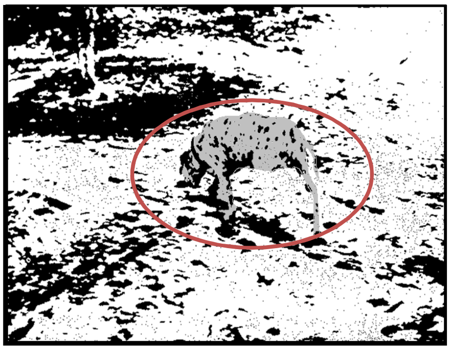
- ***Fourth Paradigm:*** Today:
  - ***Data-Intensive***, ***Data Exploration***, ***eScience***
  - Unify theory, experiment, and simulation
  - Data captured by instruments or generated by simulator
  - Processed by Software
  - Information/Knowledge stored in computer
  - Scientists analyze database/files using data management tools and statistics

Jim Gray: (1944-2007) Legendary American computer scientist , received the Turing Award for seminal contributions to computer science.

Artificial Intelligence & Data Mining

- Inspired by functionalities of human brain.
- Human brain has remarkable pattern recognition capabilities.
- Using Machine Learning, we build computer software that can learn from experience.
- This is called "Data-Driven Solutions"

Artificial Intelligence & Data Mining



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Artificial Intelligence & Data Mining

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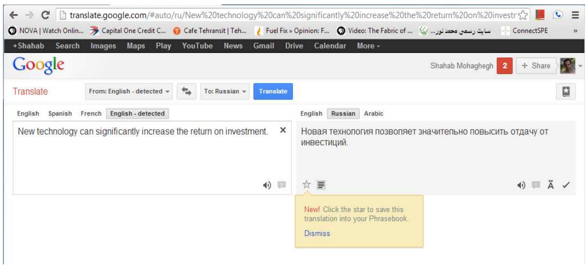
Machine Learning in Action



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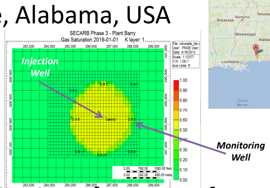
APPLICATIONS & CASE STUDIES

Real-Time Pressure Analysis (USA)

- Site: Citronelle, Alabama, USA

- CO_2 injection



- Real-time monitoring of pressure from an offset well to track the CO_2 plum movement & detection of possible leakage from existing abandoned wells.

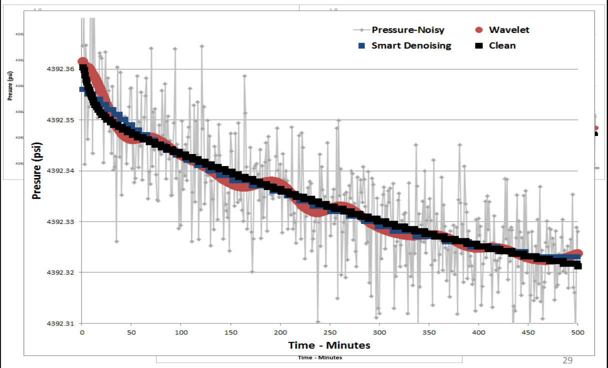
Real-Time Pressure Analysis (USA)

- Real-Time Data (Big Data):
  – Very Large Volume (needs abstraction & summarization)
  – Noisy (needs clean up while preserving the information content)

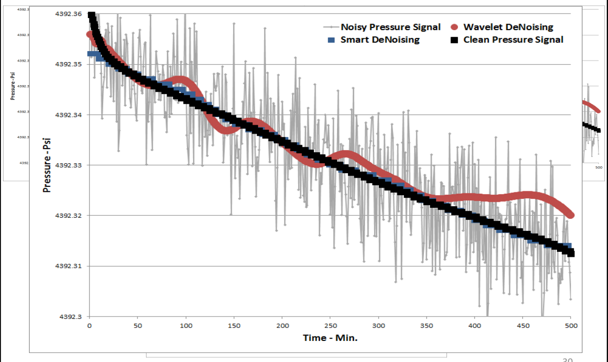
Real-Time Pressure Analysis (USA)

- Real Time Data is Noisy
  - Most available tools use Wavelet approach to de-noise & summarize the high frequency data received from the downhole gauges.
  - Smart Data Abstraction & De-Noising using Machine Learning technology.

Real-Time Pressure Analysis (USA)



Real-Time Pressure Analysis (USA)



Real-Time Pressure Analysis (USA)

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1. Real-time pressure data from a CO_2 injection site; USA
2. *Real-time execution of a full field numerical reservoir simulation model, UAE*

APPLICATIONS & CASE STUDIES

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Challenges

- There is a technology gap in smart fields between ***Fast Data*** and ***Slow Models***.
  - Speed of reservoir simulation models needs to catch up with the speed at which data is collected, transformed, and prepared in smart fields.

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Challenges - Models

- We need to entertain a ***Paradigm Shift*** in how we build reservoir models.
  - Analytical Models: Too Simplistic
  - Numerical Models: Too Slow & Sluggish
- Is there an alternative to "Analytical" and "Numerical" models?

YES, There is

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Challenges - Models

- Data-Driven Modeling is an alternative to conventional, physics-based modeling.
- Characteristics of Data-Driven Models:
  - Robust and reliable performance
  - Small computational footprint
  - Updatable, online and in real-time

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Real-Time, Data-Driven Models

Smart Models continuously and autonomously observe well and reservoir behavior and adapt their parameters to match the observed behavior, in real-time.
They Learn From Data

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Data-Driven Reservoir Model

- ***DATA** as the main building blocks of* reservoir simulation models:

Source of Data	Data-Driven Model
Measured Field Data	Top-Down Model (TDM)
Simulated Data	Surrogate Reservoir Model (SRM)

Data-Driven Reservoir Model

- Surrogate Reservoir Models (SRM) are developed to address the software need of smart fields.
- SRMs are reservoir management tools for smart fields:
  - Real-time full field reservoir simulation & modeling
    - Predictive modeling
    - Uncertainty analysis
    - Real-time optimization

This Case Study, although not an actual Smart Field, shows how a very large and complex numerical reservoir simulation model can be executed and provide detail results in fractions of a second, rather than hours, mirroring the application in a Smart Field.

SURROGATE RESERVOIR MODEL

SURROGATE RESERVOIR MODEL *Definition*

- Surrogate Reservoir Models are *replicas* of numerical simulation models (full field flow models) that ***run in real-time;***
  - SRM is highly accurate
  - SRM is built based on pattern recognition capabilities of Artificial Intelligence & Data Mining (AI&DM)

Characteristics of SRM

- SRMs ***are not***
  - response surfaces
  - statistical representations of simulation models
- SRMs ***are***
  - engineering tools
  - honor the physics of the problem
  - adhere to the definition of "System Theory"

SRM Case Study

- A giant oil field in the Middle East
- Complex carbonate formation
- 165 horizontal wells
- Total field production capped at 250,000 BOPD
- Each well is capped at 1,500 BOPD
- Water is injected for pressure maintenance

Background

- Management Concerns:
  - Wells are choked back (rate Restriction) to avoid bypassing oil & water production
  - Numerical models include uncertainty
- Technical Team's Concerns:
  - May be able to produce more oil from some wells ***(which ones? How much increase?)*** without significant increase in water cut
  - Increasing well rate may actually help recovery

Objective

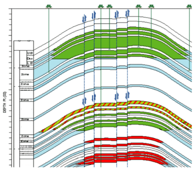
- Identify the collection of wells in this asset that will produce more oil without significant increase in water cut upon rate relaxation.

Objective

- Accomplishing this objective requires:
  - Exhaustive search of the solution space, examining all possible production (rate relaxations) scenarios, while considering uncertainties associated with the geological model.
  - Requires hundreds of thousands of simulation runs.

Numerical Model Characteristics

- Full Field Model Characteristics:
  - Complex Geological Model
  - Industry Standard Commercial Reservoir Simulator
  - ***165*** Horizontal Wells
  - About ***1,000,000*** grid blocks
  - Single Run = ***10*** Hours on a cluster of ***12*** CPUs



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SRM Development

- Generate required data from the numerical model;
  - Requires 10 to 25 simulation runs,
- Assimilate the required spatio-temporal database;
  - Requires solid and deep understanding of reservoir engineering and reservoir modeling,
- Train, Calibrate, and Validate a set of data-driven models;
  - Requires solid and deep understanding of machine learning,
- Data driven models will form the SRM;
  - Usually requires development of intelligent agents.

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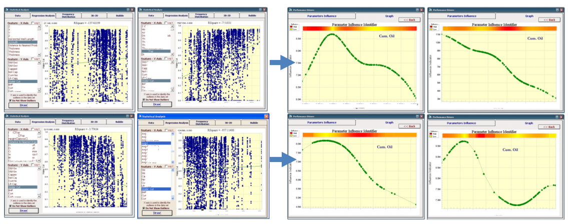
Curse of Dimensionality

- To address curse of dimensionality, we have developed ***Fuzzy Pattern Recognition*** technology;



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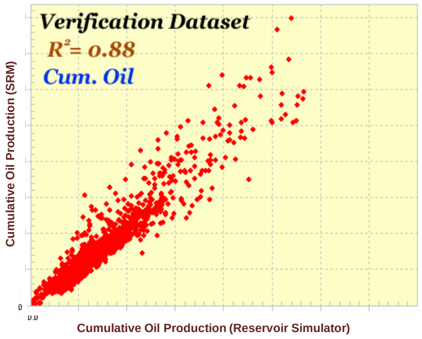
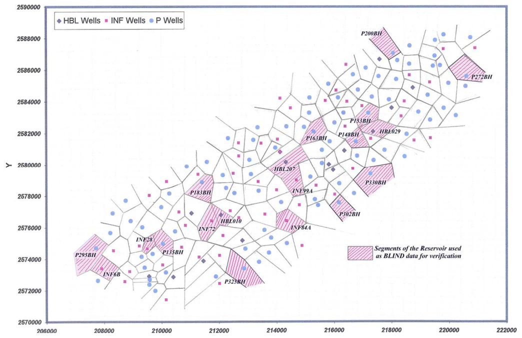
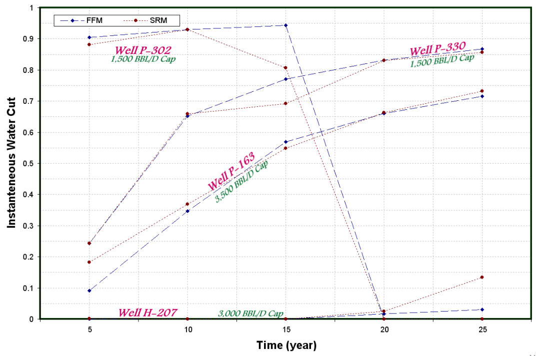
Validation of the SRM - 1



Validation of the SRM - 2



Validation of the SRM - 2



Using SRM for Analysis

- Address uncertainties associated with the simulation model;
  – Monte Carlo Simulation
- Identify wells that benefit from a rate relaxation program;

To perform the above analyses millions of simulation runs were required.

Upon development & validation, SRM provides accurate results in fraction of a second.

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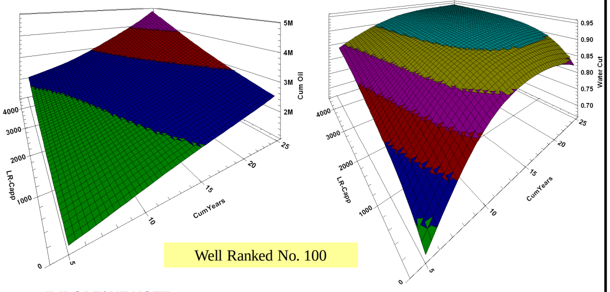
Optimal Production Strategy



IMPORTANT NOTE:

This is NOT a Response Surface – SRM was run hundreds of times to generate these figures.

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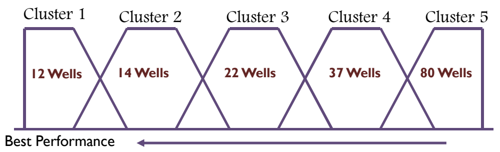
Optimal Production Strategy

- Wells were divided into 5 clusters
- Rate relaxation recommended for wells in clusters 1&2 without significant increase in water production



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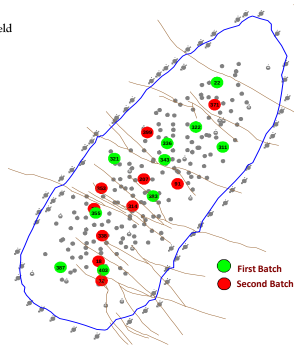
Results From the Field

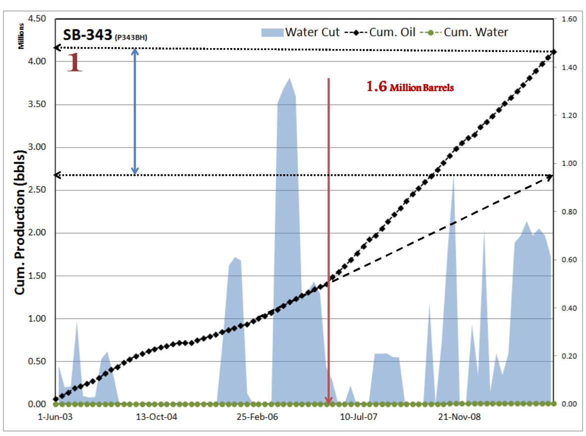
- Upon completion of the project management decided on allowing rate relaxation of some wells.
- From Jan. 1, 2006 to Feb. 17, 2007 production cap was relaxed on a total of 20 wells.

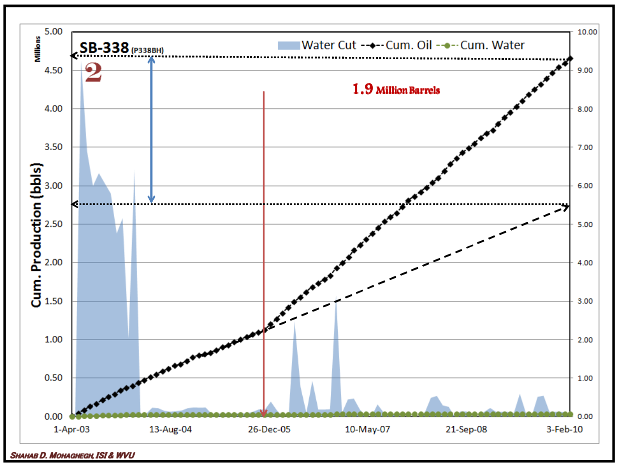
Results From the Field

Rate Relaxation performed on 12% of Wells in the field

ISI Cluster	No. Wells Subjected to Rate Relaxation	%
1	4	20%
2	2	10%
3	6	30%
4	4	20%
5	4	20%
	20	*100%*






SB-338 (P338BH)
Water Cut
Cum. Oil
Cum. Water
2
1.9 Million Barrels
Millions
Cum. Production (bbls)
1-Apr-03
13-Aug-04
26-Dec-05
10-May-07
21-Sep-08
3-Feb-10
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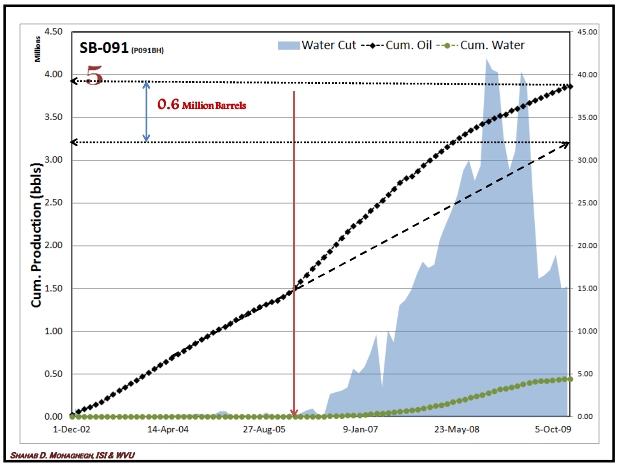
SB-091 (P091BH)
Water Cut
Cum. Oil
Cum. Water
5
0.6 Million Barrels
Millions
Cum. Production (bbls)
1-Dec-02
14-Apr-04
27-Aug-05
9-Jan-07
23-May-08
5-Oct-09
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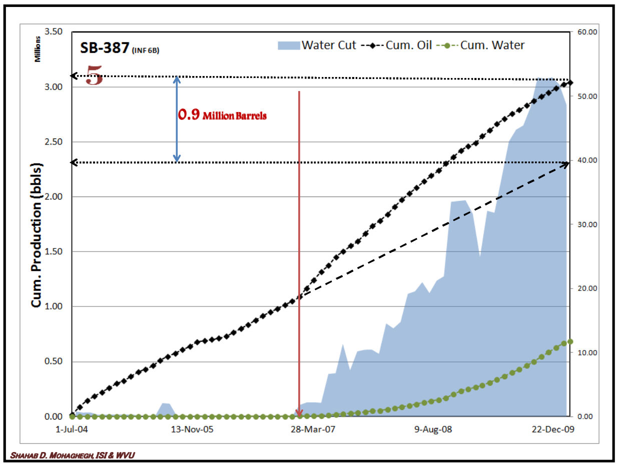
SB-387 (INF 6B)
Water Cut
Cum. Oil
Cum. Water
5
0.9 Million Barrels
Millions
Cum. Production (bbls)
1-Jul-04
13-Nov-05
28-Mar-07
9-Aug-08
22-Dec-09
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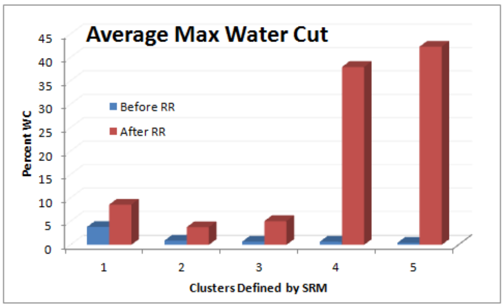
Impact of Rate Relaxation on WC



Incremental Revenue
Post-Rate Relaxation

Well Name	ISI Cluster #	OIL (bbls) Before	After	Alt. After	Increment	Revenue
SB-018	1	1,579,346	3,880,657	2,800,000	1,080,657	$ 81,049,308.75
SB-207	1	844,012	3,348,490	2,250,000	1,098,490	$ 82,386,765.00
SB-314	1	1,424,211	4,572,888	3,000,000	1,572,888	$ 117,966,570.00
SB-343	1	1,370,628	4,122,588	2,500,000	1,622,588	$ 121,694,066.25
SB-322	2	1,753,805	4,347,113	2,700,000	1,647,113	$ 123,533,445.75
SB-338	2	1,127,917	4,657,838	2,700,000	1,957,838	$ 146,837,841.75
SB-020	3	4,017,836	6,655,187	4,700,000	1,955,187	$ 146,639,006.25
SB-022	3	3,816,986	5,516,557	4,700,000	816,557	$ 61,241,762.25
SB-336	3	1,753,660	4,557,731	2,500,000	2,057,731	$ 154,329,858.00
SB-355	3	1,354,740	4,073,894	2,700,000	1,373,894	$ 103,042,069.50
SB-371	3	827,812	4,239,701	2,600,000	1,639,701	$ 122,977,593.75
SB-383	3	999,854	3,726,135	2,230,000	1,496,135	$ 112,210,148.25
SB-311	4	1,887,698	4,335,160	3,200,000	1,135,160	$ 85,136,976.75
SB-353	4	1,337,386	3,627,013	2,500,000	1,127,013	$ 84,525,987.75
SB-399	4	428,093	3,364,653	2,300,000	1,064,653	$ 79,848,988.50
SB-403	4	605,806	2,899,556	2,000,000	899,556	$ 67,466,685.00
SB-012	5	1,273,508	2,487,207	2,350,000	137,207	$ 10,290,525.00
SB-091	5	1,400,479	3,864,135	3,300,000	564,135	$ 42,310,160.25
SB-321	5	1,564,455	3,783,478	2,500,000	1,283,478	$ 96,260,882.25
SB-387	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

Conclusions

- Smart Fields constitute a paradigm shift in operations and management of oilfields;
- To take maximum advantage of hardware installed, a paradigm shift in how we solve problems is required;

Conclusions

- This is the main barrier toward comprehensive Smart Field technology is the disparity between ***fast data*** and ***slow models***;
- Data-Driven Predictive Analytics promises to be the key that will unlock the potential of smart fields;

Conclusions

- In the case study it was demonstrated that a large and complex numerical reservoir simulation model can be executed in real-time, using the SRM technology;
- Using SRM numerical models may be updated in real-time, creating realistic opportunities for Real-Time Reservoir Management (RRM) in Smart Fields

QUESTIONS?

EXTRA SLIDES

Artificial Intelligence & Data Mining

D

Artificial Intelligence & Data Mining

- What was the phrase that you just saw (in pieces)?
- You were forced to process information like a machine.
- Now process the same information in a parallel, distributed fashion (like you always do).

Artificial Intelligence & Data Mining

- Parallel, distributed processing of information

A PENNY SAVED
IS A
PENNY EARNED

Analysis of Uncertainty

- Objective:
  - To address and analyze the uncertainties associated with the Full Field Model using Monte Carlo simulation method.

Analysis of Uncertainty

- Motivation:
  - The Full Field Model is a reservoir simulator that is based on a geologic model.
  - The geologic model is developed based on a set of measurements (logs, core analysis, seismic, …) and corresponding geological and geophysical interpretations.

Analysis of Uncertainty

- Motivation:
  - Therefore, like any other reservoir simulation and modeling effort, it includes certain obvious uncertainties.
  - One of the outcomes of this project has been the identification of a small set of reservoir parameters that essentially control the production behavior in the horizontal wells in this field (KPIs).

Analysis of Uncertainty

- Following are the steps involved:
  1. Identify a set of key performance indicators that are most vulnerable to uncertainty.
  2. Define probability distribution function for each of the performance indicators.
     a. Uniform distribution
     b. Normal (Gaussian) distribution
     c. Triangular distribution
     d. Discrete distribution

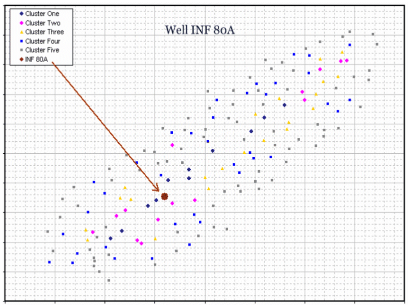
Analysis of Uncertainty

- Following are steps involved:
  3. Run the neural network model hundreds or thousands of times using the defined probability distribution functions for the identified reservoir parameters. *Performing this analysis using the actual Full Field Model is impractical.*
  4. Produce a probability distribution function for cumulative oil production and the water cut at different time and liquid rate cap.

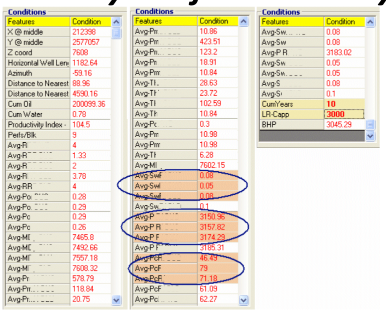
Analysis of Uncertainty

- Following are steps involved:
  5. Such results bounds to be much more reliable and therefore, more acceptable to the management or skeptics of the reservoir modeling studies.

Analysis of Uncertainty

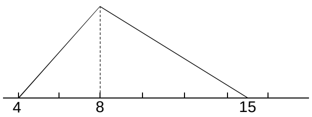


Analysis of Uncertainty



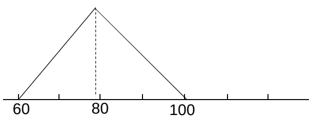
Analysis of Uncertainty

- Average S_w @ Reference point in Top Layer II
  - Value in the model = 8%
  - Lets use a minimum of 4% and a maximum of 15% with a triangular distribution

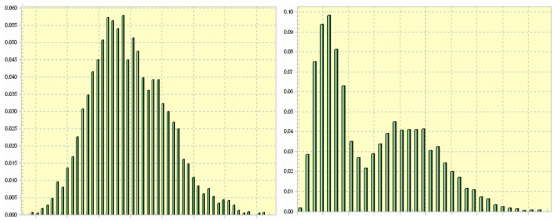


Analysis of Uncertainty

- Average Capillary Pressure @ Reference point in Top Layer III
  - Value in the model = 79 psi
  - Lets use a minimum of 60 psi and a maximum of 100 psi with a triangular distribution



Analysis of Uncertainty



PDF for HB001 Cumulative Oil and Cumulative Water production at the rate of 3,000 blpd cap after 20 years.

Actual Models are available & can be demonstrated after the presentation.

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Type Curves

- Type curves can be generated in seconds to address sensitivity of oil and water production to all involved parameters.
- Type curves can be generated for:
  - Individual wells
  - Each cluster of wells
  - Entire field

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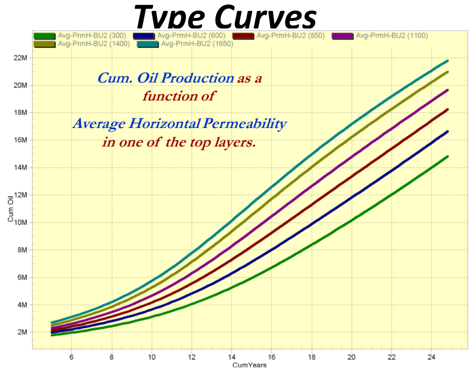
Type Curves



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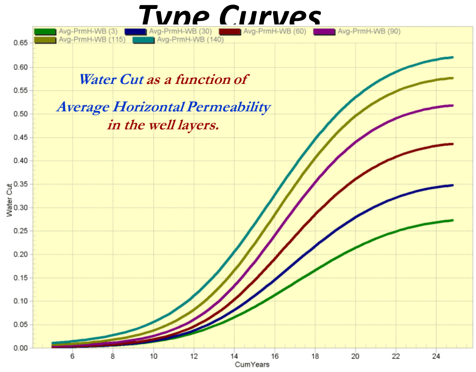
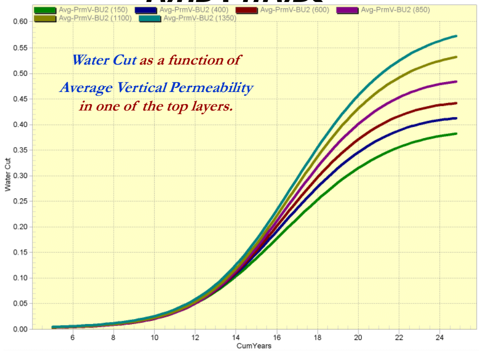
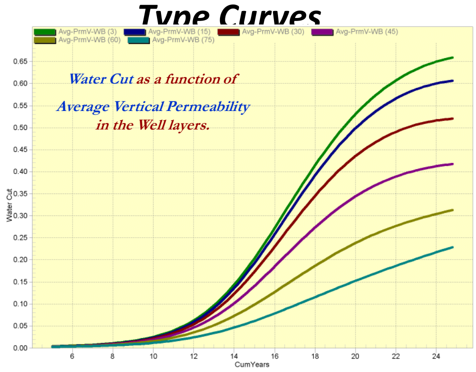
Type Curves



Type Curves



Type Curves



Results & Conclusions

- Upon completion of the project management allowed production increase in six cluster one wells.
- After 8 months of successful production rest of the cluster one wells were also put on higher production.
- It has been more than 15 months since the results were implemented with success.

Results & Conclusions

- A successful surrogate reservoir model was developed for a giant oil field in the Middle East.
- The surrogate model was able to accurately mimic the behavior of the actual full field flow model in real-time.

CONCLUSIONS

- Development of successful surrogate reservoir model is an important and essential step toward development of next generation of reservoir management tools that would address the needs of smart fields.

Smart Oil Field Technology

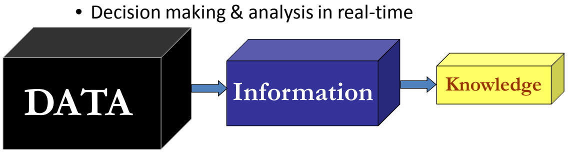
- Smart Completion:
  - Downhole control to adjust flow distributions along the wellbore to correct undesirable fluid front movement.
- Smart Well:
  - Using permanent gauges and automatic flow controls for continuous monitoring of events and automatic interaction using extensive downhole communication.
- Smart Field:
  - Digital Oil Field, Field of Future, Intelligent Field, *i* Field, ...

Smart Fields – Automation & Intelligence

- Are Automation and Intelligence synonyms?
- Automation in the smart field is achieved though:
  - Placing permanent gauges downhole.
  - Making large volumes of data available in real-time.
  - Capability to control well and completion operations from a remote location (office).

Smart Fields – Automation & Intelligence

- Are Automation and Intelligence synonyms?
- Data has to be transformed into information, then knowledge, to be used as a tool for:
  - Analysis under uncertain conditions
  - Process optimization in real-time
  - Decision making & analysis in real-time



The Challenge

- Make the most important reservoir management tools (Complex Numerical Solutions) available at the same time scale as the (high frequency) data.
- Surrogate Reservoir Models (SRM)

How Do You Build an SRM?

- Define concrete objectives.
  - The objective determines the ***Type & Scale*** of SRM.
- Generate required data.
- Use the " ***right tool*** " to build the SRM.
- Test and validate the accuracy of the SRM.

Surrogate Reservoir Models are developed using State-Of-The-Art in Intelligent Systems (NN-FL-GA)

How Do You Build an SRM?

- ***Clearly identify the objective of the project and how the SRM is going to be used***.
- SRMs are developed to address very specific issues such as:
  - Production/injection (rate & pressure) profiles of wells in reservoir/filed.
  - Changes in pressure and saturation throughout reservoir/field (Flood Fronts).
  - Interaction between wells.

How Do You Validate SRMs?

- A considerable volume of data must be used as blind data for validation purposes.
- SRMs must be validated in their accuracy before they are used for analysis.
- This is possible since the data generation engine is accessible.

In our case studies we have used 40-95% of the data as blind dataset for validation.

Types of SRM

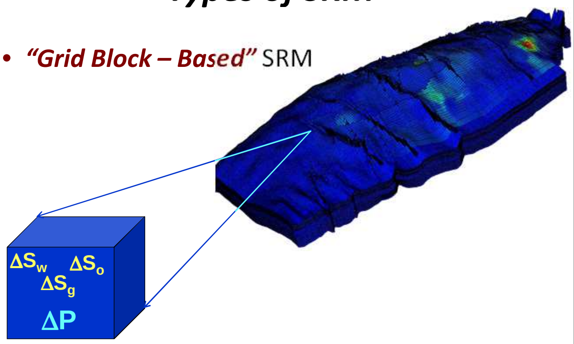
- SRMs are developed on different ***SCALES*** in order to address specific needs of a project.
  - The key to development of SRM is the recognition that numerical models are built based on discrete mathematics (small and manageable sub-models that are repeated over and over).
  - Our success is based on recognizing this fact and taking full advantage of its consequences.

Types of SRM

- SRMs are classified based on the size of their elemental volume.
  - ***"Grid Block – Based"*** SRM
  - ***"Well – Based"*** SRM
  - ***"Domain – Based"*** SRM

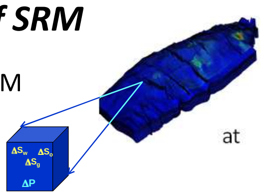
Types of SRM

- ***"Grid Block – Based"*** SRM



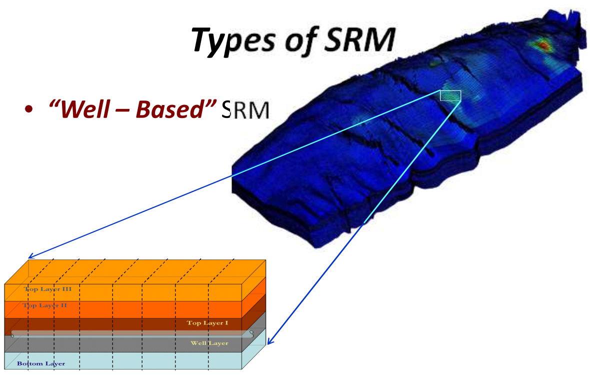
Types of SRM

- ***"Grid Block – Based"*** SRM
  - Tracking changes in pressure and saturation at the grid block level.
  - Detect by-passed oil.
  - Has been used successfully to model ΔS and ΔP as a function of time-lapsed seismic attributes.
  - May be used for:
    - Flood front monitoring.
    - Optimization of rock-typing in flow models.
    - Populating geological models.

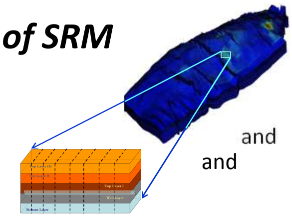


Types of SRM

- ***"Well – Based"*** SRM



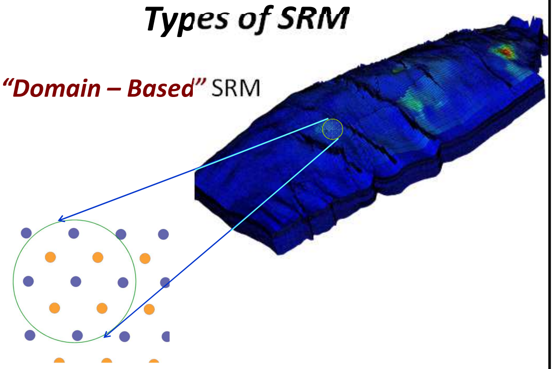
Types of SRM



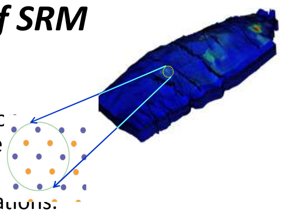
- ***"Well – Based"*** SRM
  - Monitoring pressure and rate at the injection and production wells.
  - Rate optimization.
  - New well placements in complex reservoirs.
  - Quantify uncertainties associated with geological model.
  - Selective injection and production into portions of reservoir.

Types of SRM

- ***"Domain – Based"*** SRM



Types of SRM

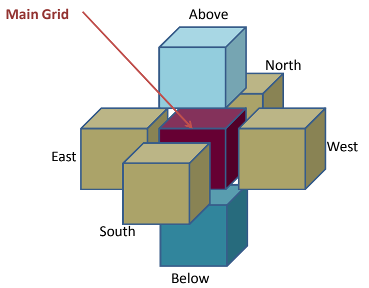


- ***"Domain – Based"*** SRM
  - Monitoring the interaction of wells with one another.
  - Monitoring flood front during water flood operations.
  - Optimizing injection rates for maximum sweep efficiency.
  - New well placement to optimize enhance recovery.
  - Developing new strategies for field development.

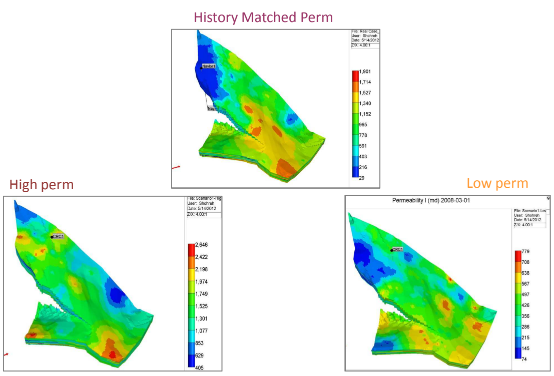
Intelligent System; the Foundation of SRM

- Intelligent Systems
  - Artificial Neural Networks
  - Genetic Algorithms
  - Fuzzy Logic

Anatomy of SRM

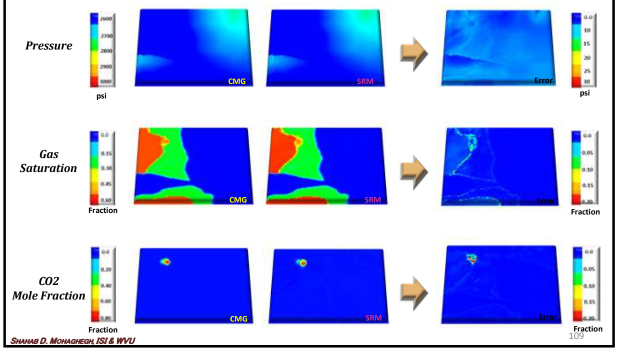


Permeability Maps



SRM Results

- 1 Month after injection



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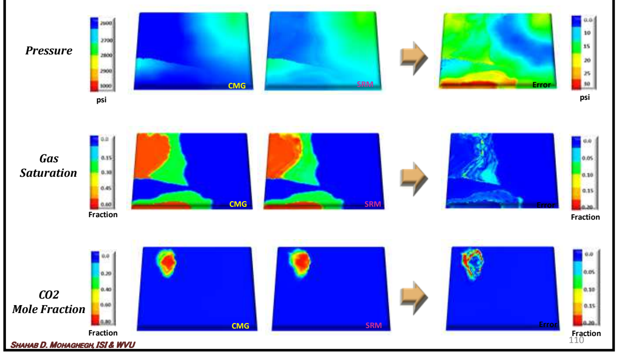
SRM Results

- 4 Months after injection



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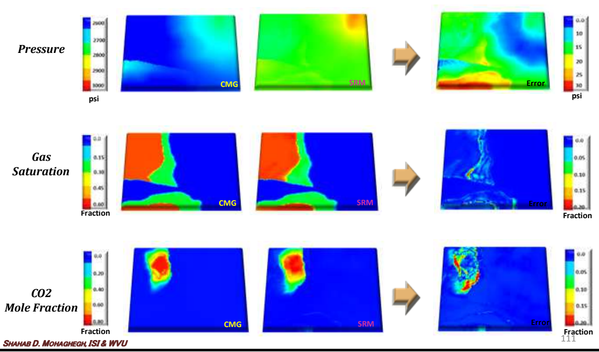
SRM Results

- 8 Months after injection



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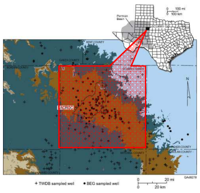
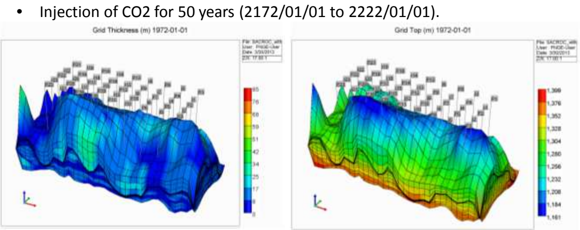
SACROC Unit Location

- SACROC Unit in Permian Basin of Western Texas



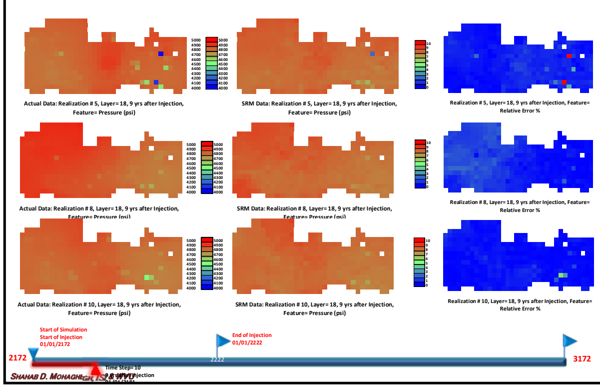
SACROC Unit- Base Reservoir Model

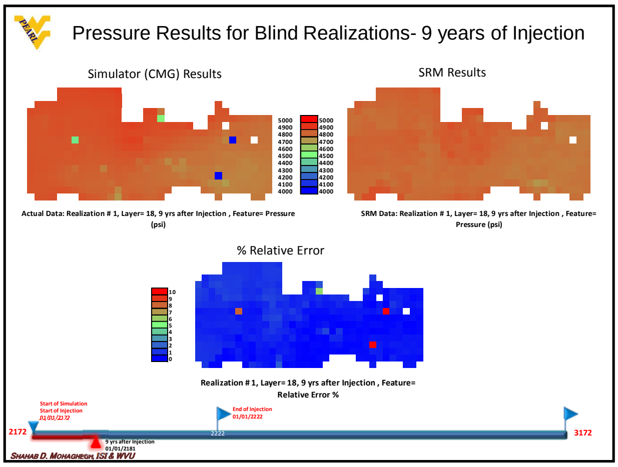
- Simulation starts at 2172/01/01 and ends at 3172/01/01.
- 34 by 16 Cartesian grids in X and Y directions (including null and active blocks).
- 25 layers with 45 wells perforated in single layer.
- Perforation layers: 19 (one well), 20 (40 wells), 21 (one well) and 22 (three wells) .
- Injection of CO2 for 50 years (2172/01/01 to 2222/01/01).



Pressure Results for Training Realizations- 9 years of Injection

Simulator (CMG) Results | SRM Results | % Relative Error




PEARL
Pressure Results for Blind Realizations- 9 years of Injection
Simulator (CMG) Results
SRM Results
Actual Data: Realization # 1, Layer= 18, 9 yrs after Injection , Feature= Pressure (psi)
SRM Data: Realization # 1, Layer= 18, 9 yrs after Injection , Feature= Pressure (psi)
% Relative Error
Realization # 1, Layer= 18, 9 yrs after Injection , Feature= Relative Error %
Start of Simulation
Start of Injection
End of Injection
01/01/2222
2172
2222
3172
9 yrs after Injection
01/01/2181
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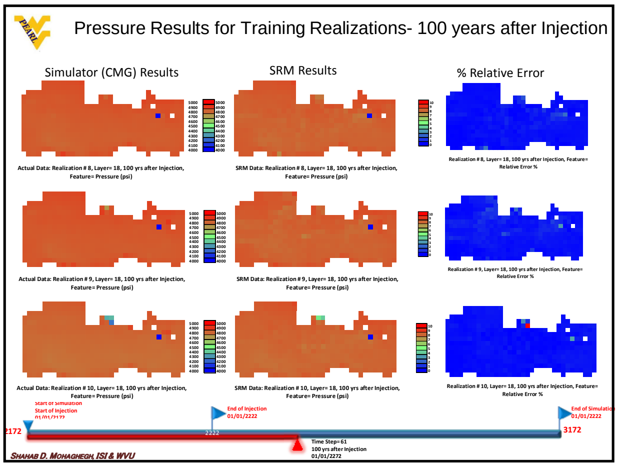
PEARL
Pressure Results for Training Realizations- 100 years after Injection
Simulator (CMG) Results
SRM Results
% Relative Error
Actual Data: Realization # 8, Layer= 18, 100 yrs after Injection, Feature= Pressure (psi)
SRM Data: Realization # 8, Layer= 18, 100 yrs after Injection, Feature= Pressure (psi)
Realization # 8, Layer= 18, 100 yrs after Injection, Feature= Relative Error %
Actual Data: Realization # 9, Layer= 18, 100 yrs after Injection, Feature= Pressure (psi)
SRM Data: Realization # 9, Layer= 18, 100 yrs after Injection, Feature= Pressure (psi)
Realization # 9, Layer= 18, 100 yrs after Injection, Feature= Relative Error %
Actual Data: Realization # 10, Layer= 18, 100 yrs after Injection, Feature= Pressure (psi)
SRM Data: Realization # 10, Layer= 18, 100 yrs after Injection, Feature= Pressure (psi)
Realization # 10, Layer= 18, 100 yrs after Injection, Feature= Relative Error %
Start of Injection
End of Injection
01/01/2222
2222
3172
Time Step= 61
100 yrs after Injection
01/01/2272
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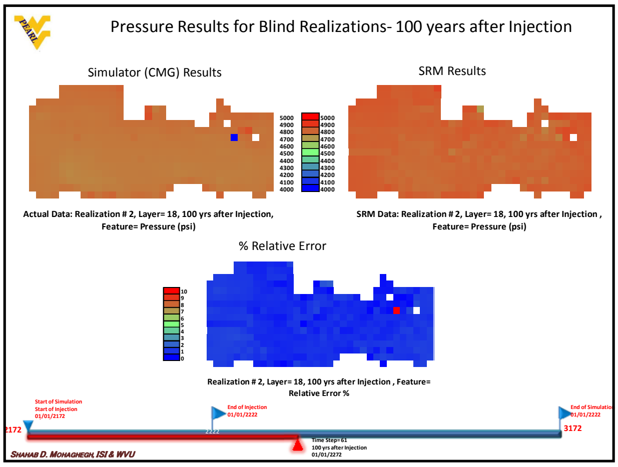
PEARL
Pressure Results for Blind Realizations- 100 years after Injection
Simulator (CMG) Results
SRM Results
Actual Data: Realization # 2, Layer= 18, 100 yrs after Injection, Feature= Pressure (psi)
SRM Data: Realization # 2, Layer= 18, 100 yrs after Injection , Feature= Pressure (psi)
% Relative Error
Realization # 2, Layer= 18, 100 yrs after Injection , Feature= Relative Error %
Start of Simulation
Start of Injection
01/01/2172
End of Injection
01/01/2222
2222
3172
Time Step= 61
100 yrs after Injection
01/01/2272
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SRM Development-Water Saturation

- 16 Realizations were used to develop SW models.
- The models were validated using 2 blind realizations.
- For Water Saturation models, Back-Propagation gave the best results.
- Generally absolute errors were less than 5 %.

Scenarios	2	3
Inputs	i	i
	j	j
	Porosity	Porosity
	Thickness(m)	Thickness(m)
	Top (m)	Top (m)
	Permeability (md)	Permeability (md)
	Initial Pressure (kPa)	Initial Pressure (kPa)
	Initial SW	Initial SW
	Initial SG	Initial SG
	Porosity , avergae of Injection Layers	Porosity , avergae of Injection Layers
	Thickness (m), avergae of Injection Layers	Thickness (m), avergae of Injection Layers
	Top (m), avergae of Injection Layers	Top (m), avergae of Injection Layers
	Permeability (md), avergae of Injection Layers	Permeability (md), avergae of Injection Layers
	Initial P(kPa), avergae of Injection Layers	Initial P(kPa), avergae of Injection Layers
	Initial SW,avergae of Injection Layers	Initial SW,avergae of Injection Layers
	Initial SG,avergae of Injection Layers	Initial SG,avergae of Injection Layers
	BHP (kPa)- Offset Well 1	BHP (kPa)- Offset Well 1
	BHP (kPa)- Offset Well 2	BHP (kPa)- Offset Well 2
	BHP (kPa)-Offset Well 3	BHP (kPa)-Offset Well 3
		SW at the end of Injection Period

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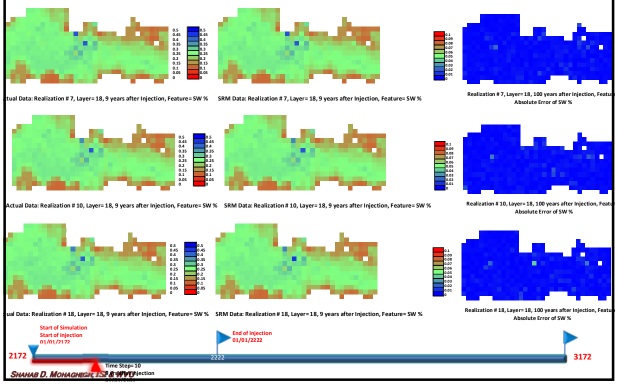
Water Saturation Results for Training Realizations- 9 years of Injection

Simulator (CMG) Results SRM Results Absolute Error



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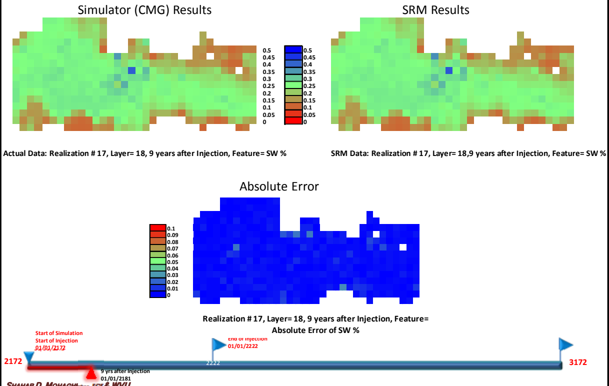
Water Saturation Results for Blind Realizations- 9 years of Injection

Simulator (CMG) Results SRM Results



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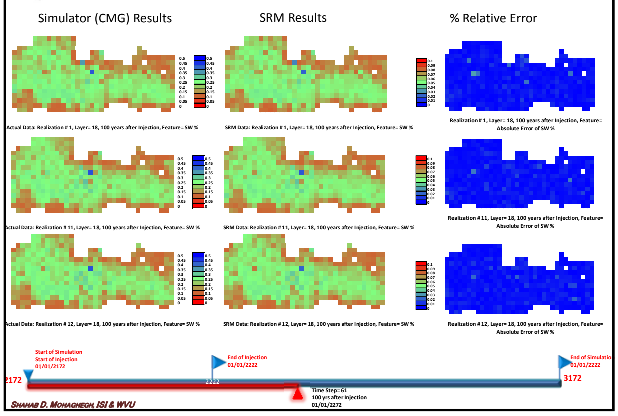
Water Saturation Results for Training Realizations- 100 years after Injection



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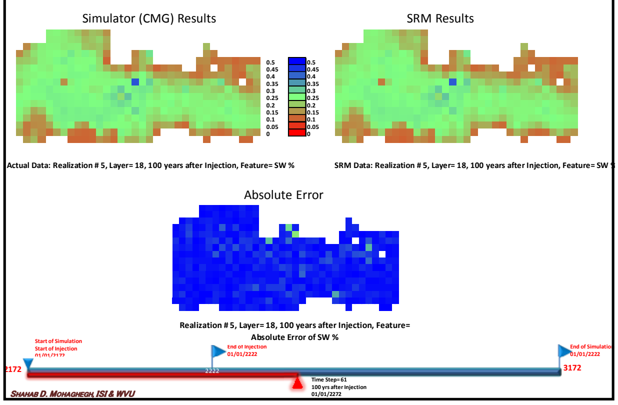
Water Saturation Results for Blind Realization- 100 years after Injection



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SRM Development-CO2 Mole Fraction

- 16 Realizations were used to develop the models.
- The SRM were validated using 2 blind realizations.
- For CO2 models, Back-Propagation gave the best results.
- Generally absolute errors were less than 5 %.

Scenarios	4	5	6
Inputs	i	i	i
	j	j	j
	Porosity	Porosity	Porosity
	Thickness(m)	Thickness(m)	Thickness(m)
	Top (m)	Top (m)	Top (m)
	Permeability (md)	Permeability (md)	Permeability (md)
	Initial Co2 Global Mole Fraction	Porosity , avergae of Injection Layers	Porosity , avergae of Injection Layers
	Porosity , avergae of Injection Layers	Thickness (m), avergae of Injection Layers	Thickness (m), avergae of Injection Layers
	Thickness (m), avergae of Injection Layers	Top (m), avergae of Injection Layers	Top (m), avergae of Injection Layers
	Top (m), avergae of Injection Layers	Permeability (md), avergae of Injection Layers	Permeability (md), avergae of Injection Layers
	Permeability (md), avergae of Injection Layers	Initial CO2 Global Mole Fraction at Injection Layers	Initial CO2 Global Mole Fraction at Injection Layers
	Initial CO2 Global Mole Fraction at Injection Layers	BHP (kPa)- Offset Well 1	Grid Block Distance to Offset Well 1
	Grid Block Distance to Offset Well 1	BHP (kPa)- Offset Well 2	Grid Block Distance to Offset Well 2
	Grid Block Distance to Offset Well 2	BHP (kPa)-Offset Well 3	Grid Block Distance to Offset Well 3
	Grid Block Distance to Offset Well 3	CO2 Global Mole Fraction at the end of Injection Period	BHP (kPa)- Offset Well 1
	BHP (kPa)- Offset Well 1		BHP (kPa)- Offset Well 2
	BHP (kPa)- Offset Well 2		BHP (kPa)-Offset Well 3
	BHP (kPa)-Offset Well 3		CO2 Global Mole Fraction at the end of Injection Period

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Curse of Dimensionality, Dynamic

- Well productivity is identified through following simulation runs:
  - All wells producing at 1500, 2500, 3500, & 4500 bpd (nominal rates)
    - No cap on field productivity (4 simulation runs)
    - Cap the field productivity (4 simulation runs)

Need to understand reservoir's response to changes in imposed constraints.

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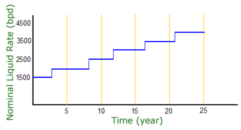
Curse of Dimensionality, Dynamic

- Well productivity through following simulation runs:
  - Step up the rates for all wells
    - No cap on field productivity (1 simulation runs)
    - Cap the field productivity (1 simulation runs)



Need to understand reservoir's response to changes in imposed constraints.

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Fuzzy Pattern Recognition

- In order to address the "Curse of Dimensionality" one must understand the behavior and contribution of each of the parameters to the process being modeled.
- Not a simple and straight forward task. !!!

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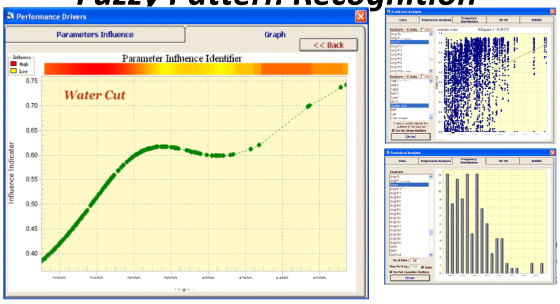
Fuzzy Pattern Recognition



Parameter: Pressure @ Reference

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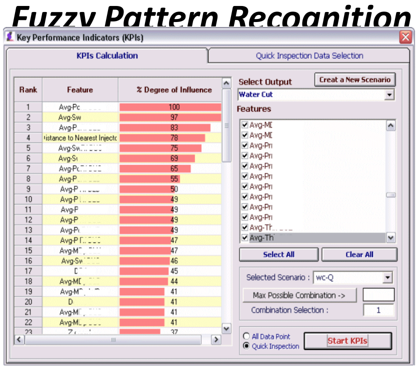
Fuzzy Pattern Recognition



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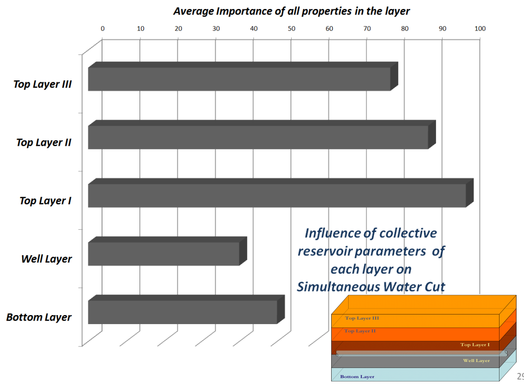
Key Performance Indicators



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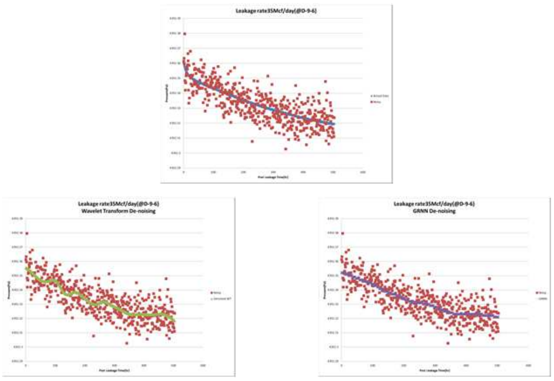
Noise and De-noising



Curse of Dimensionality, Static

- Potential list of parameters that can be collected on a "per-well" basis.

Parameters Used on a per well basis	
Latitude	Longitude
Deviation	Azimuth
Horizontal Well Length	Productivity Index
Distance to Free Water Level	Water Cut @ Reference Point
Flowing BHP @ Reference Point	Oil Prod. Rate @ Reference Point
Cum. Oil Prod. @ Reference Point	Cum. Water Prod. @ Reference Point
Distance to Nearest Producer	Distance to Nearest Injector
Distance to Major Fault	Distance to Minor Fault

16 Parameters

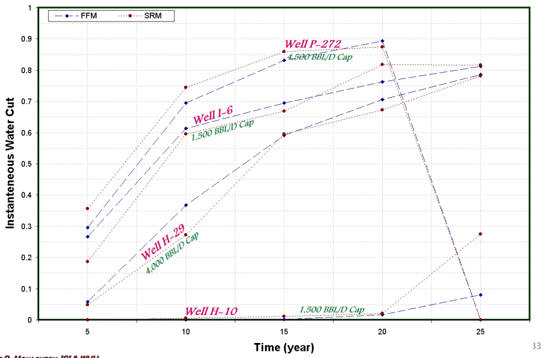
Curse of Dimensionality, Static

- Potential list of parameters that can be collected on a "per-SRM block" basis.

Parameters Used on a per segment basis	
Mid Depth	Thickness
Relative Rock Ttype	Porosity
Initial Water Saturations	Stylolite Intensity
Horizontal Permeability	Vertical Permeability
Sw @ Reference Point	So @ Reference Point
Capillary Pressure/Saturation Function	Pressure @ Reference Point

12 Parameters

Validation of the SRM



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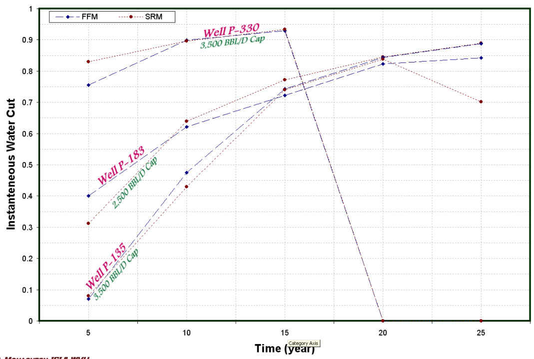
Validation of the SRM



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Cost of Water Production

Post-Rate Relaxation

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Incremental Revenue

Post-Rate Relaxation

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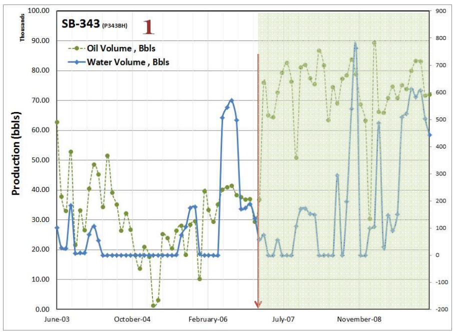
Results From the Field



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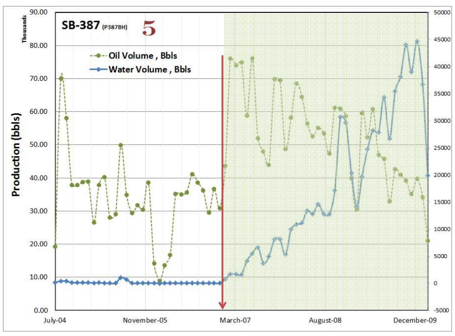
Results From the Field



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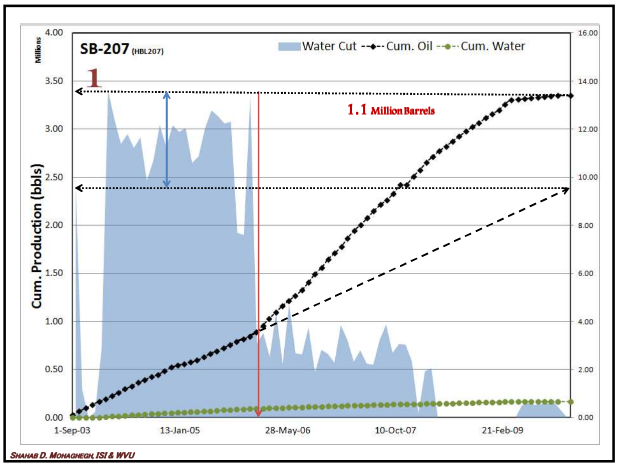
SB-207 (HBL207)
Water Cut
Cum. Oil
Cum. Water
1
1.1 Million Barrels
Cum. Production (bbls)
Millions
1-Sep-03
13-Jan-05
28-May-06
10-Oct-07
21-Feb-09
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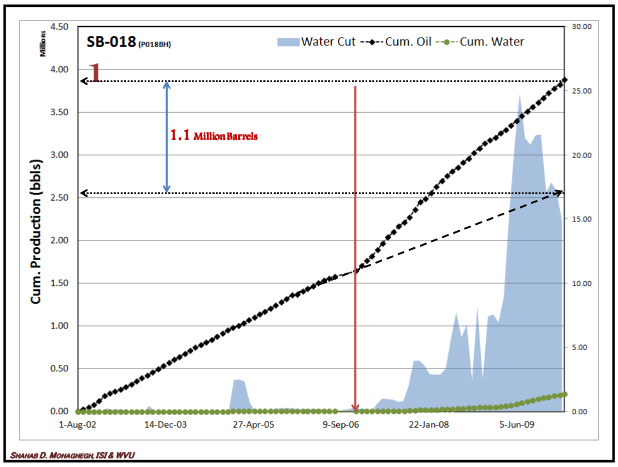
SB-018 (P018BH)
Water Cut
Cum. Oil
Cum. Water
1
1.1 Million Barrels
Cum. Production (bbls)
Millions
1-Aug-02
14-Dec-03
27-Apr-05
9-Sep-06
22-Jan-08
5-Jun-09
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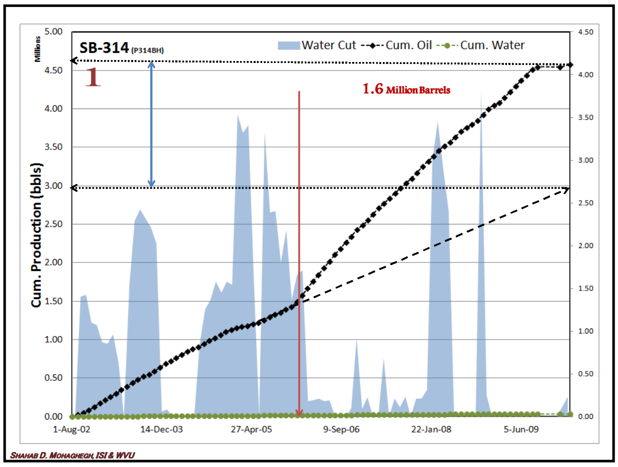
SB-314 (P314BH)
Water Cut
Cum. Oil
Cum. Water
1
1.6 Million Barrels
Cum. Production (bbls)
Millions
1-Aug-02
14-Dec-03
27-Apr-05
9-Sep-06
22-Jan-08
5-Jun-09
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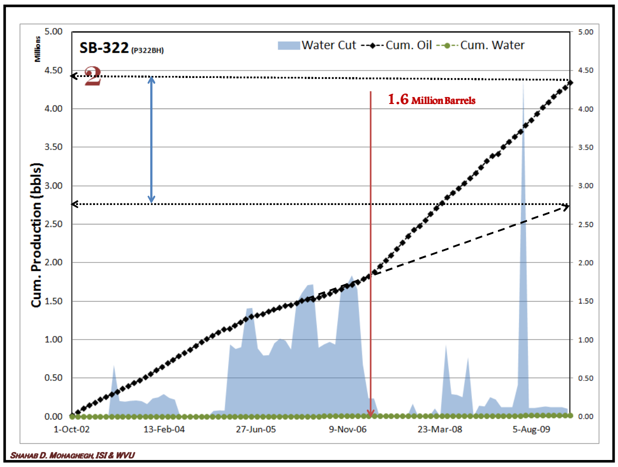
SB-322 (P322BH)
Water Cut
Cum. Oil
Cum. Water
Millions
Cum. Production (bbls)
2
1.6 Million Barrels
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1-Oct-02
13-Feb-04
27-Jun-05
9-Nov-06
23-Mar-08
5-Aug-09
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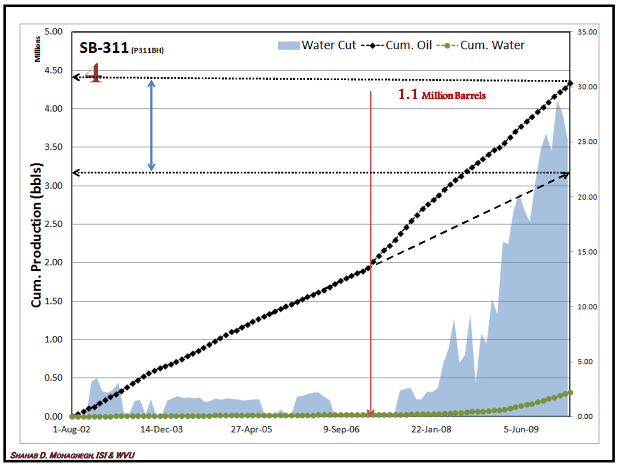
SB-311 (P311BH)
Water Cut
Cum. Oil
Cum. Water
Millions
Cum. Production (bbls)
4
1.1 Million Barrels
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1-Aug-02
14-Dec-03
27-Apr-05
9-Sep-06
22-Jan-08
5-Jun-09
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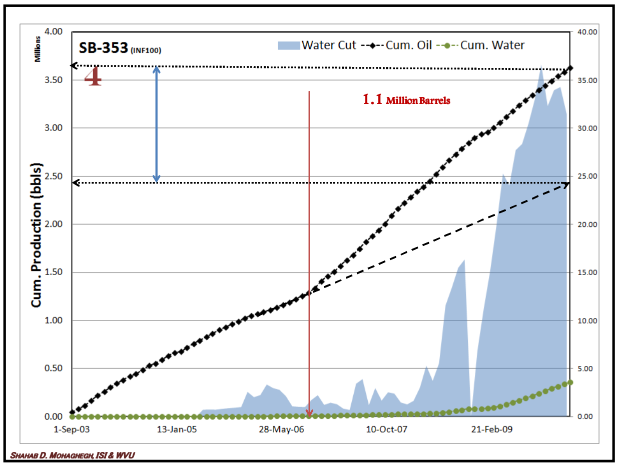
SB-353 (INF100)
Water Cut
Cum. Oil
Cum. Water
Millions
Cum. Production (bbls)
4
1.1 Million Barrels
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1-Sep-03
13-Jan-05
28-May-06
10-Oct-07
21-Feb-09
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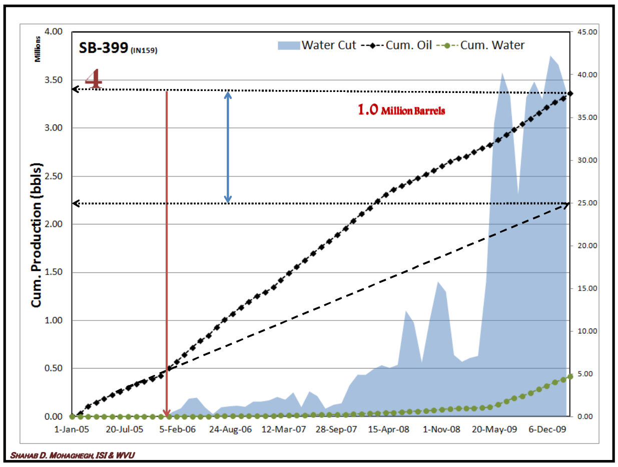
SB-399 (IN159)
Water Cut
Cum. Oil
Cum. Water
4
1.0 Million Barrels
Millions
Cum. Production (bbls)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1-Jan-05
20-Jul-05
5-Feb-06
24-Aug-06
12-Mar-07
28-Sep-07
15-Apr-08
1-Nov-08
20-May-09
6-Dec-09
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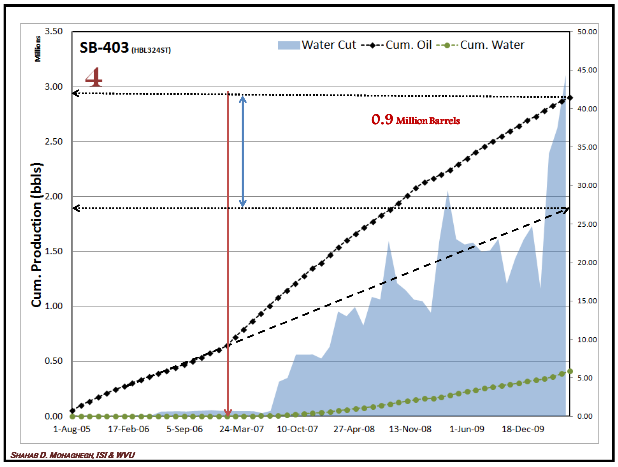
SB-403 (HBL324ST)
Water Cut
Cum. Oil
Cum. Water
4
0.9 Million Barrels
Millions
Cum. Production (bbls)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1-Aug-05
17-Feb-06
5-Sep-06
24-Mar-07
10-Oct-07
27-Apr-08
13-Nov-08
1-Jun-09
18-Dec-09
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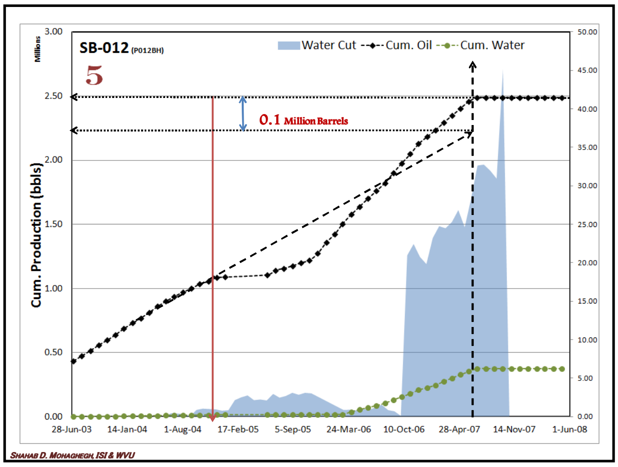
SB-012 (P012BH)
Water Cut
Cum. Oil
Cum. Water
5
0.1 Million Barrels
Millions
Cum. Production (bbls)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
28-Jun-03
14-Jan-04
1-Aug-04
17-Feb-05
5-Sep-05
24-Mar-06
10-Oct-06
28-Apr-07
14-Nov-07
1-Jun-08
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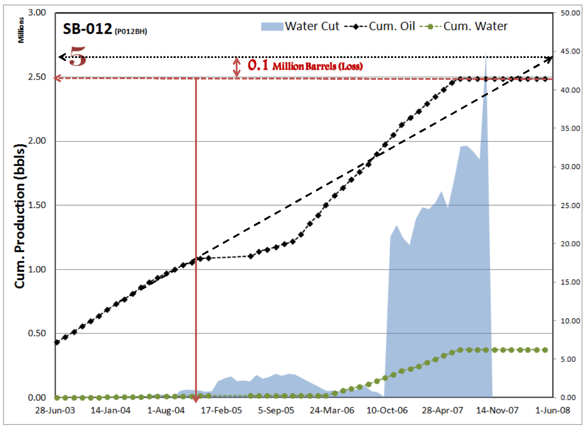

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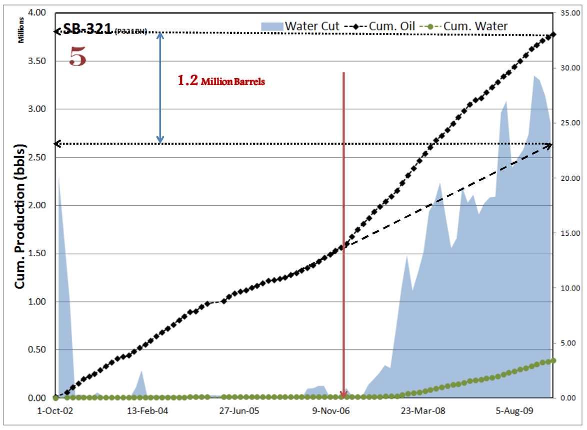

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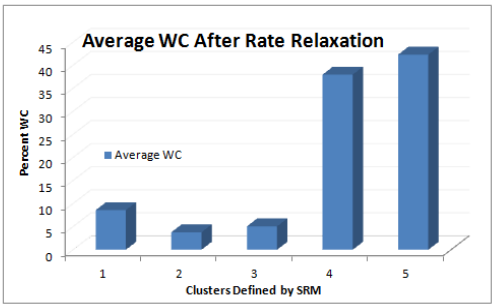
Impact of Rate Relaxation on WC



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