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Unified Well Spacing and Completion Design for Unconventionals – A Physics and Data-Driven Approach

Walt Dobbs, P.E.

International Reservoir Technologies, Inc.

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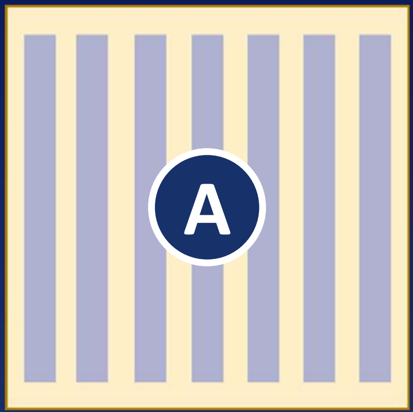
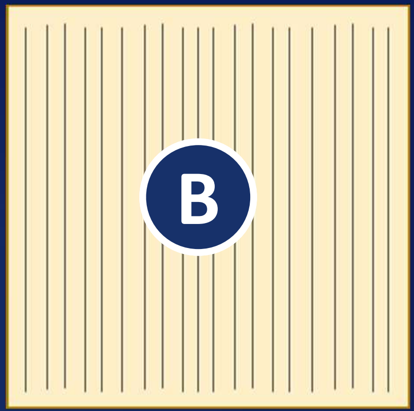
Which Design is Best?

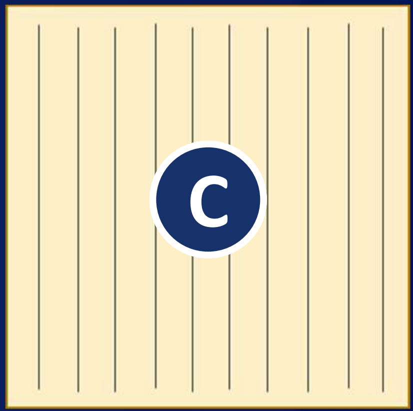
- Three design alternatives for the same campaign
- How to compare? Evaluate?



7 wells/section
72 bbl/ft



20 wells/section
21 bbl/ft



10 wells/section
19 bbl/ft

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Goal and Outline

Demonstrate a Commonsense Workflow for Unconventional Reservoir Development

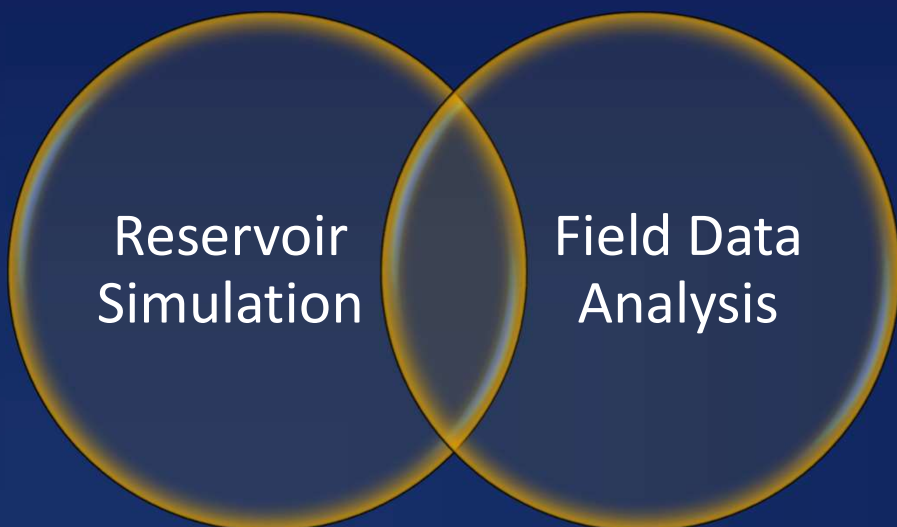


Photo by WORKSITE Ltd. on Unsplash

- Motivation
- Context
- Approach
- Applications
- Conclusions

Motivation

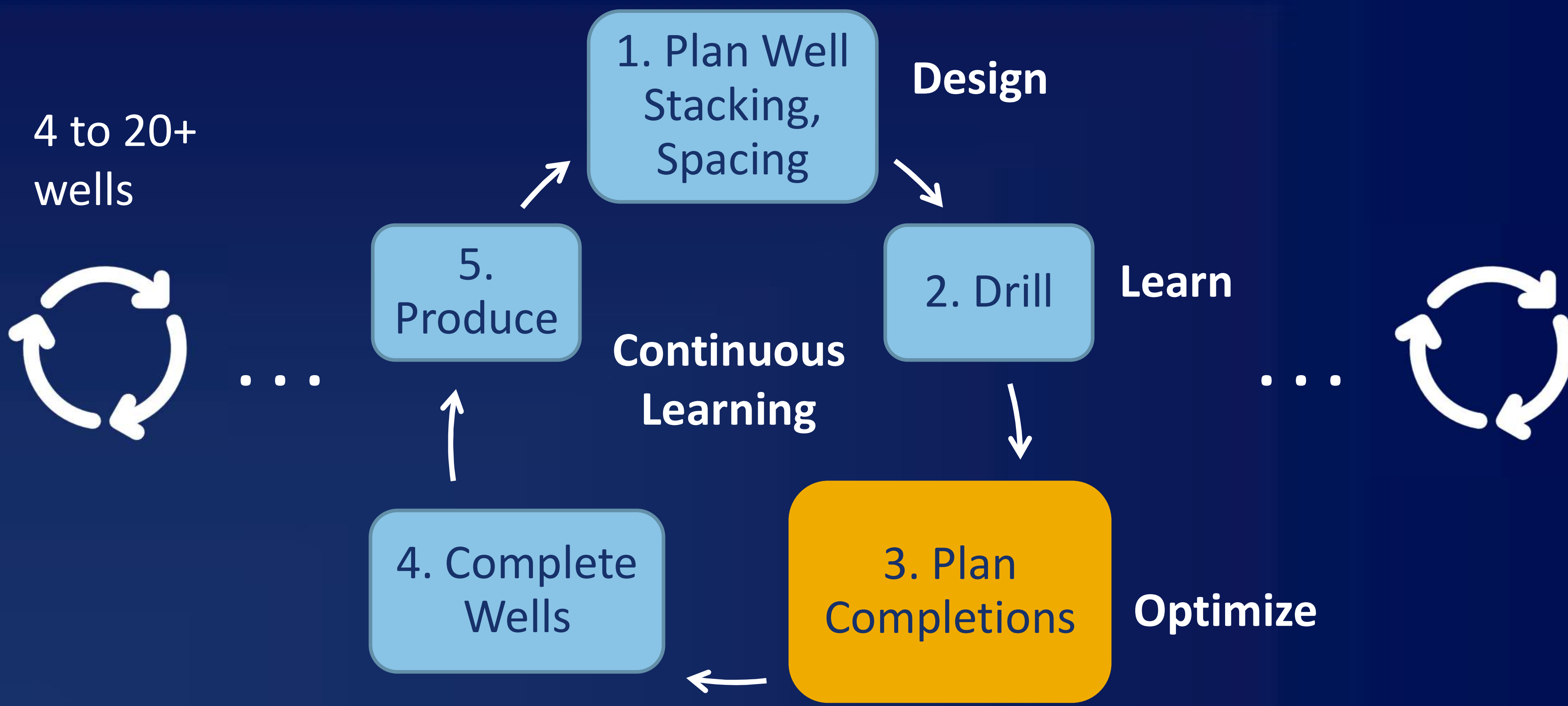
Photo by Mahir Uysal on Unsplash

"If I paint a wild horse, you might not see the horse... but surely you will see the wildness!"

— **Pablo Picasso**

- Unconventional reservoirs
  - Small scale flow physics
  - Complex fracture systems
  - Large drainage volumes
- Need for practical translation
  - Rapid campaign design
  - Efficient learning
  - Value creation

Campaign = Horizontal Well Development Cycle



Campaign Design Variables

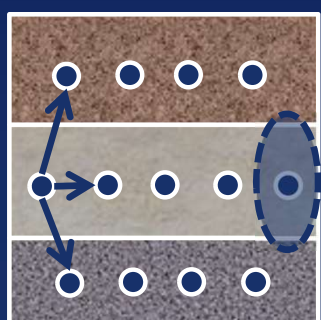
~~Drilling azimuth~~

~~Lateral length~~

~~Completion style~~

1. **Well Spacing**
2. **Well Stacking Pattern**
3. **Stimulation Size**

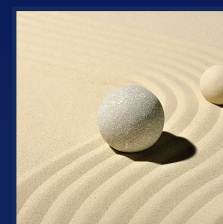
1, 2



3

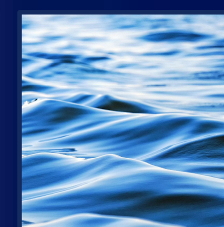
End view of well stacking pattern

Hydraulic Fracture Stimulation



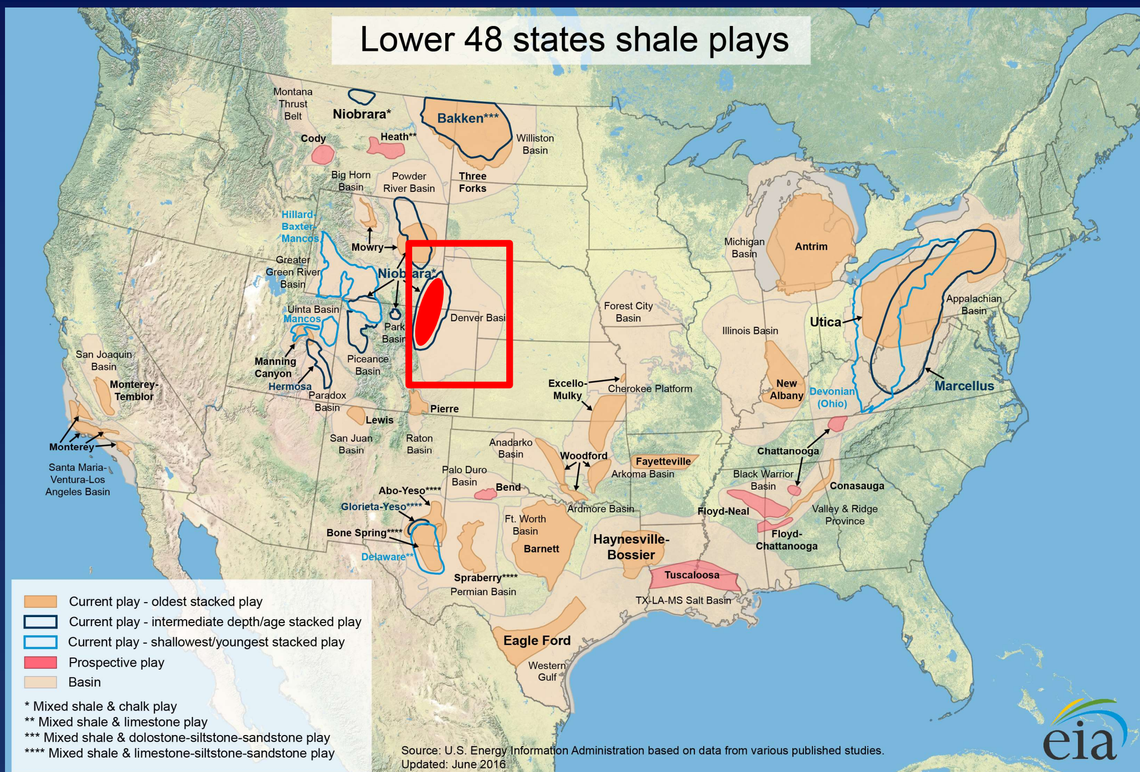
Proppant Mass

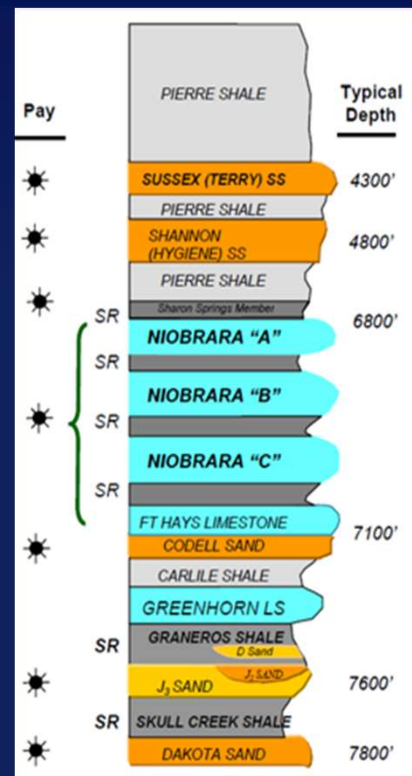
Fluid Volume



Fluid Loading or Intensity (volume per lateral length)

Proving Ground: Denver Basin Niobrara Play





Type log (Sonnenberg, 2011)

Depth (ft)	6800
Thickness (ft)	250 to 350
Porosity (%)	5 to 8
Perm. (md)	1E-6 to 1E-4
Temp. (°F)	220 to 250
Initial pressure	overpressure
Fluid type	black oil to gas condensate
No. horizontal wells	**5000**

Analogs for Knowledge Transfer:

3D well stacking patterns, Multiple Targets, Potential for interference

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Global Potential of Tight Oil and Gas

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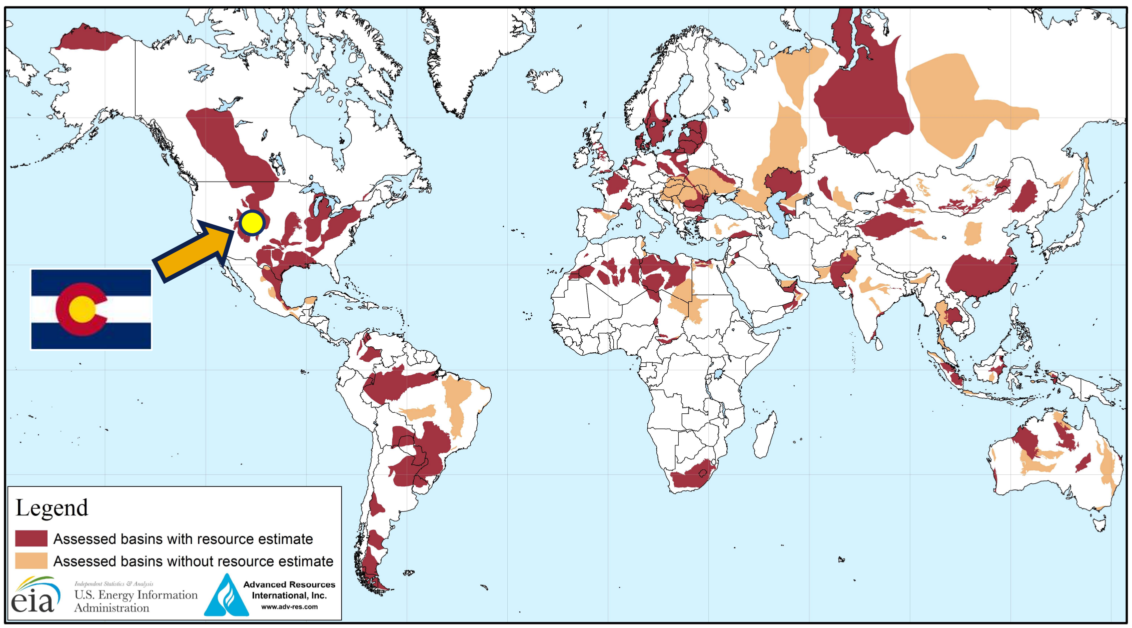
Tight oil and gas represent resources in low-permeability reservoirs, including shale and chalk formations. Natural gas production represents dry gas.
- US Energy Information Administration.

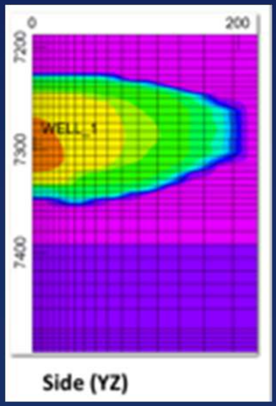


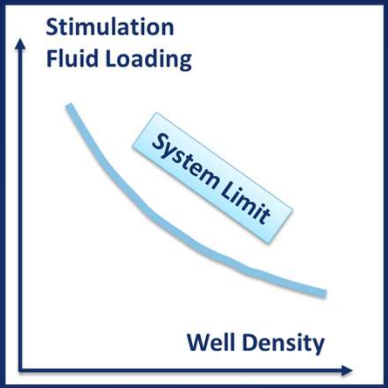
Basins with assessed shale oil and shale gas formations, 2013

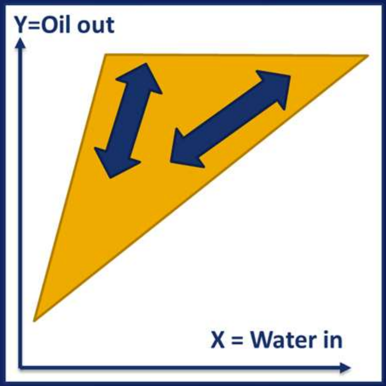
- 8% of global crude supply, 14% natural gas, mostly US-based (2019)
- Material global resource
- Similarities among basins promotes knowledge transfer

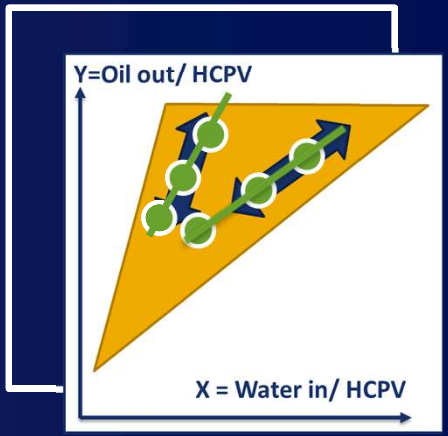
Approach

Modeling Foundations → Stimulation Limits → Prediction Sensitivities → Unified Design





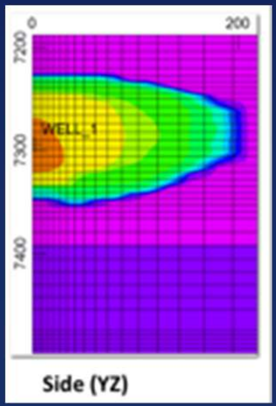




After SPE-194312-MS Tanner et al. 2019

Step 1

Modeling Foundations | Stimulation Limits | Prediction Sensitivities | Unified Design



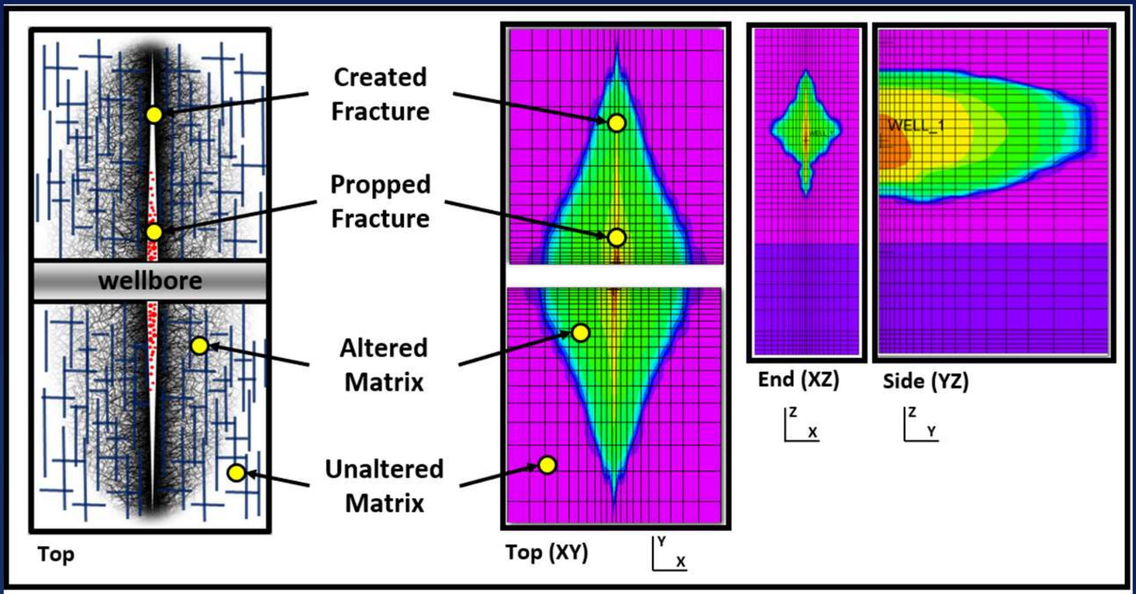
Dynamic Stimulated Reservoir Volume (DSRV) Model

Colors represent transmissibility multiplier along a fracture plane at time of injection

Dynamic Stimulated Reservoir Volume Model

Coupled injection-production solution

Stimulation = Planar fracture + enhanced matrix



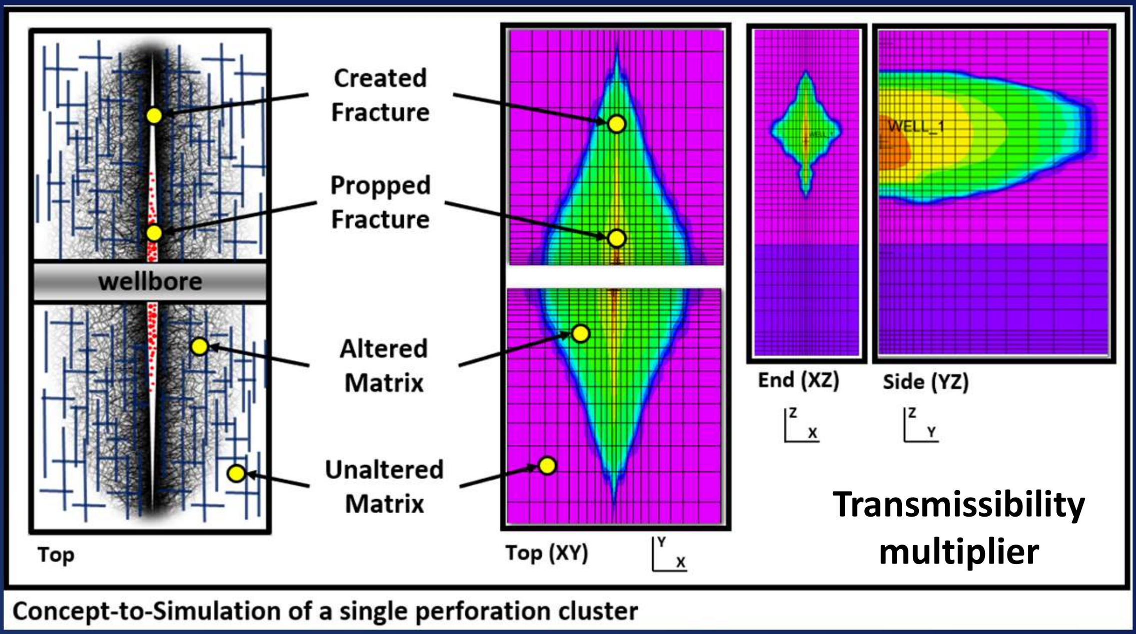
Concept-to-Simulation of a single perforation cluster

SPE 191571-MS Sen et al. 2018

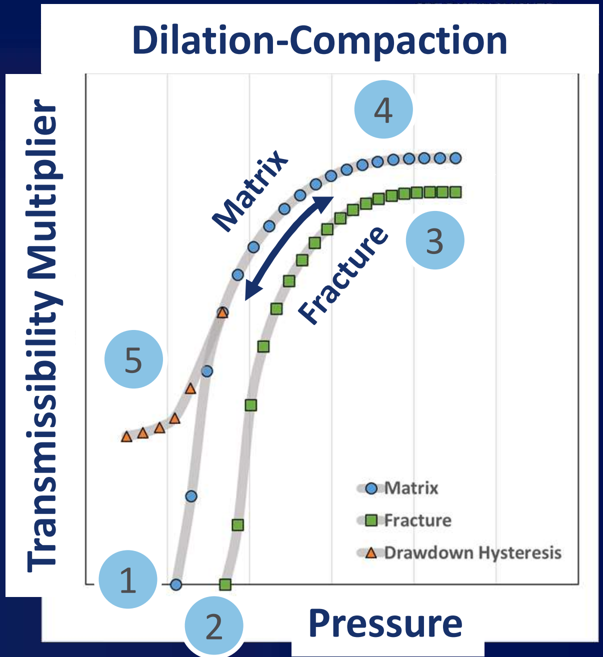
Dynamic Stimulated Reservoir Volume Model

Coupled injection-production solution

Stimulation = Planar fracture + enhanced matrix

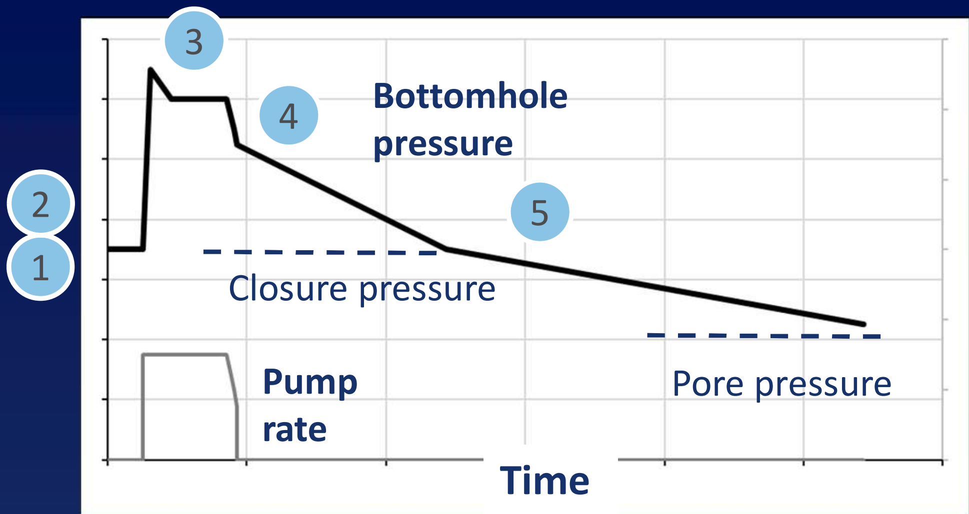


SPE 191571-MS Sen et al. 2018

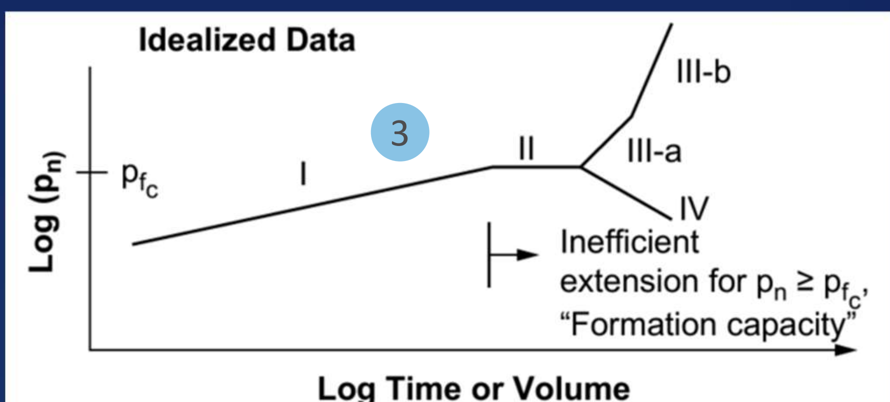


1. Injection: Matrix entry threshold
2. Fracture initiation
3. Fracture extension
4. Drawdown: Fracture function replaced with propped feature
5. Retained enhancement

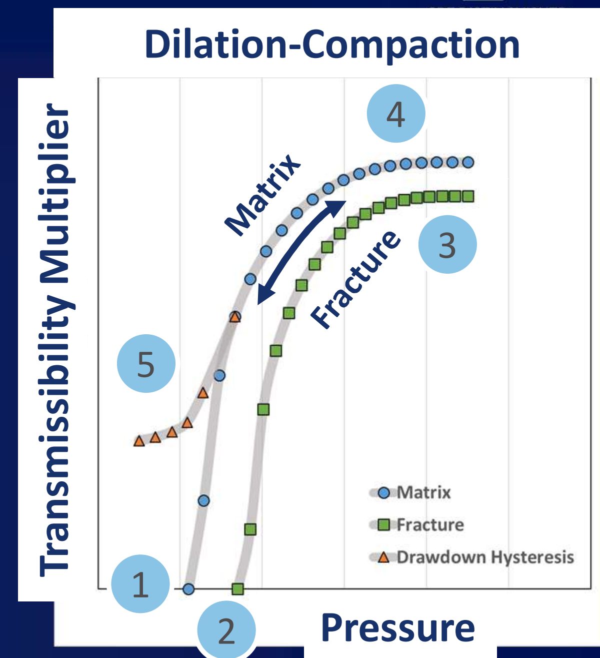
Enhancement Mechanism



After Weijers, de Pater, Miskimins ed. 2019



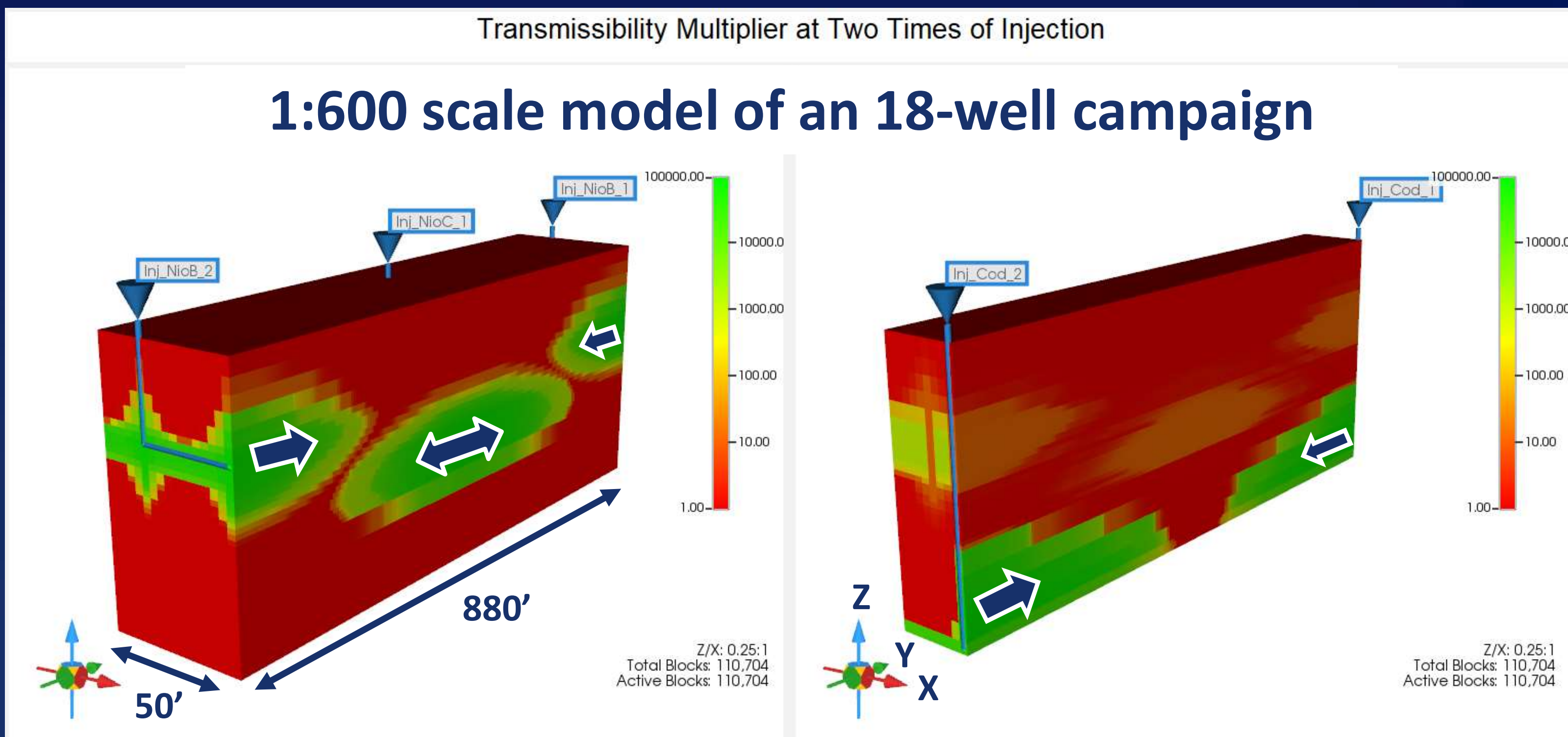
Nolte, 1979



1. Injection: Matrix entry threshold
2. Fracture initiation
3. Fracture extension
4. Drawdown: Fracture function replaced with propped feature
5. Retained enhancement

Pattern Element

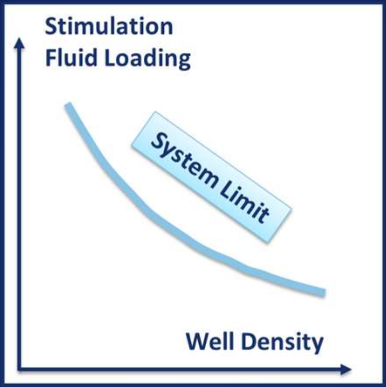
- Smallest repeating part of larger system
- Scale model allows focus on inter-well dynamics



Time 1 – Upper Zone Injection **Time 2 – Lower Zone Injection**

Step 2

Modeling Foundations → **Stimulation Limits** → Prediction Sensitivities → Unified Design

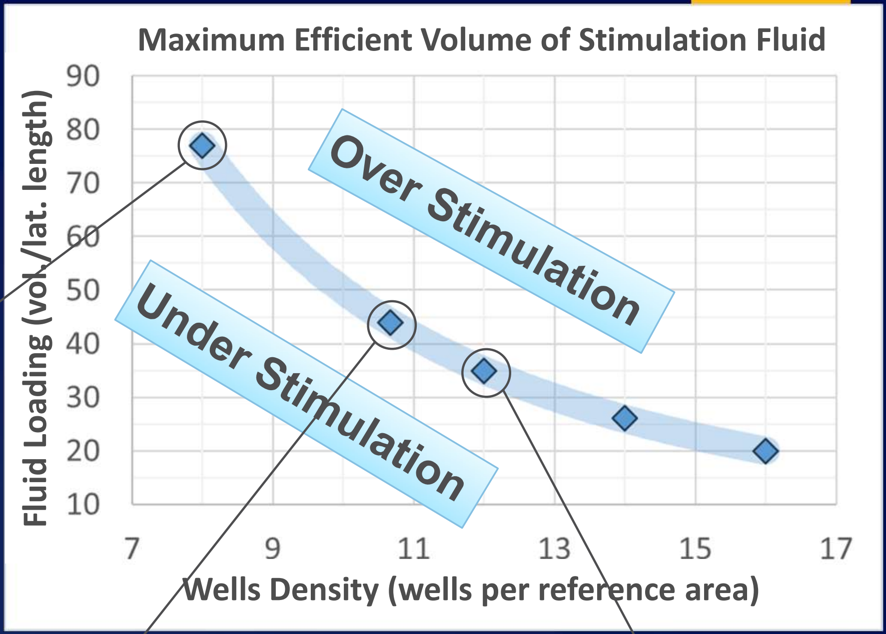


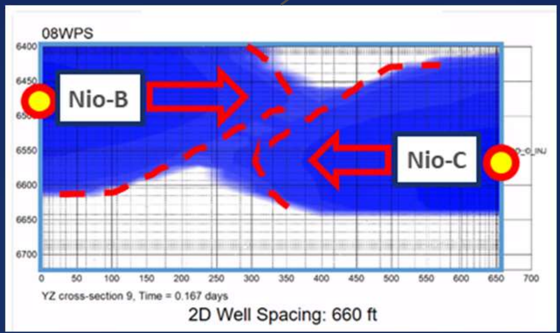
Maximum Efficient Volume of stimulation fluid (MEV)

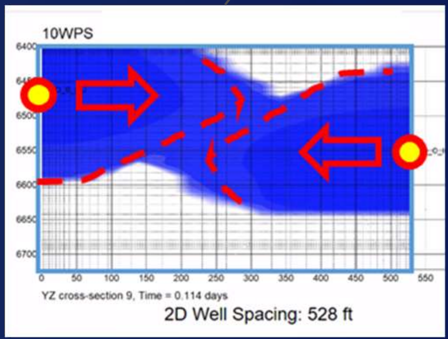
After SPE-194312-MS Tanner et al. 2019

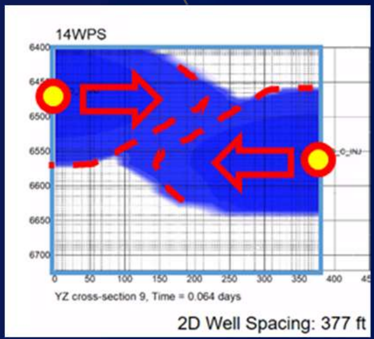
Maximum Efficient Volume

- Two-well, two-target cross section
- Stimulation pressure front at onset of interference
- Threshold of effective stimulation







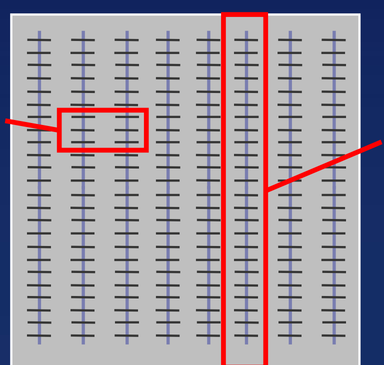


Well density:	8 well/section	10 wells/section	12 wells/section
Fluid loading:	75 bbl/ft	50 bbl/ft	35 bbl/ft

Well-level Predictions: Variable Spacing, at MEV

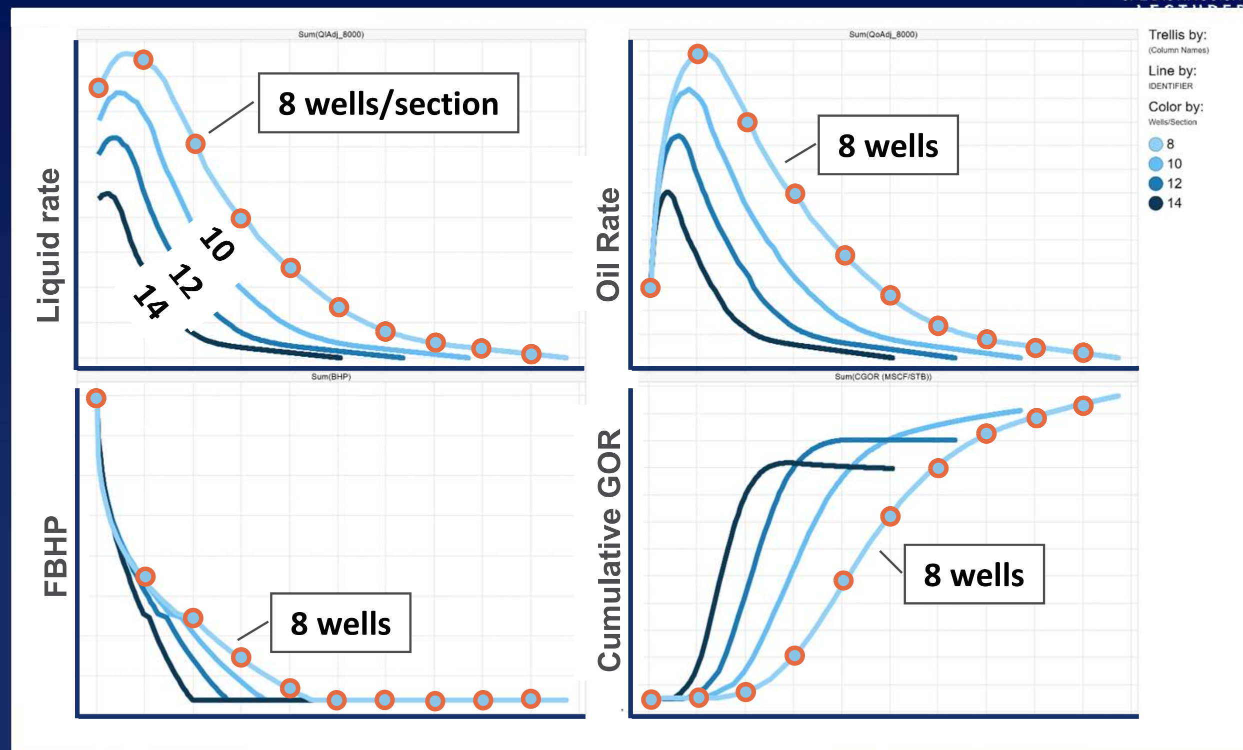
Design element	Values
Geology	fixed
Reservoir fluid	45 API
Well density (wells/section)	8, 10, 12, 14
Fluid loading (bbl/ft)	MEV

Pattern Element



Well

Scale-up



Cumulative Oil (all X-axes)

Best well performance for given spacing
… but how to assess campaign-level design?

Step 3

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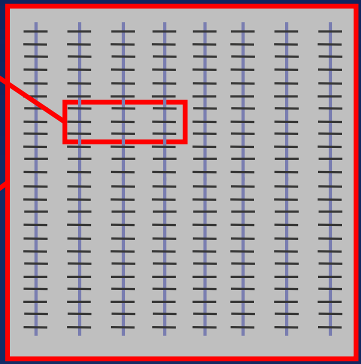
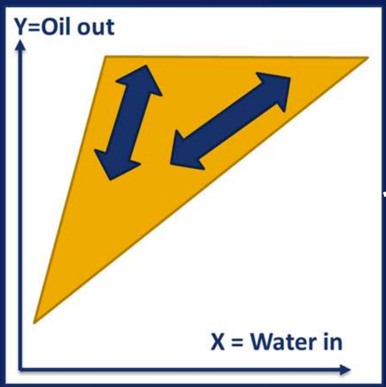
Modeling Foundations → Stimulation Limits → **Prediction Sensitivities** → Unified Design

Pattern Element

1 SECTION*
1 mi^2
640 ac
259 hectare
2.59 km^2



Scale-up



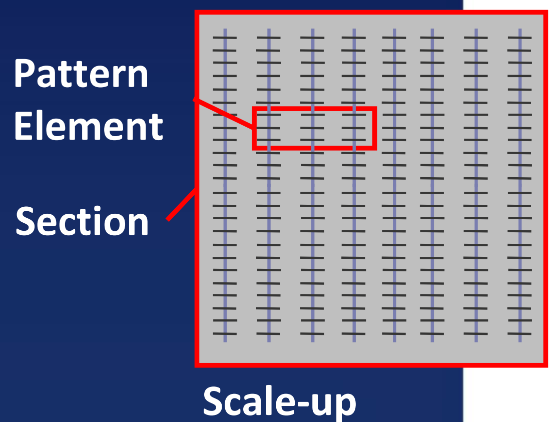
Design Space

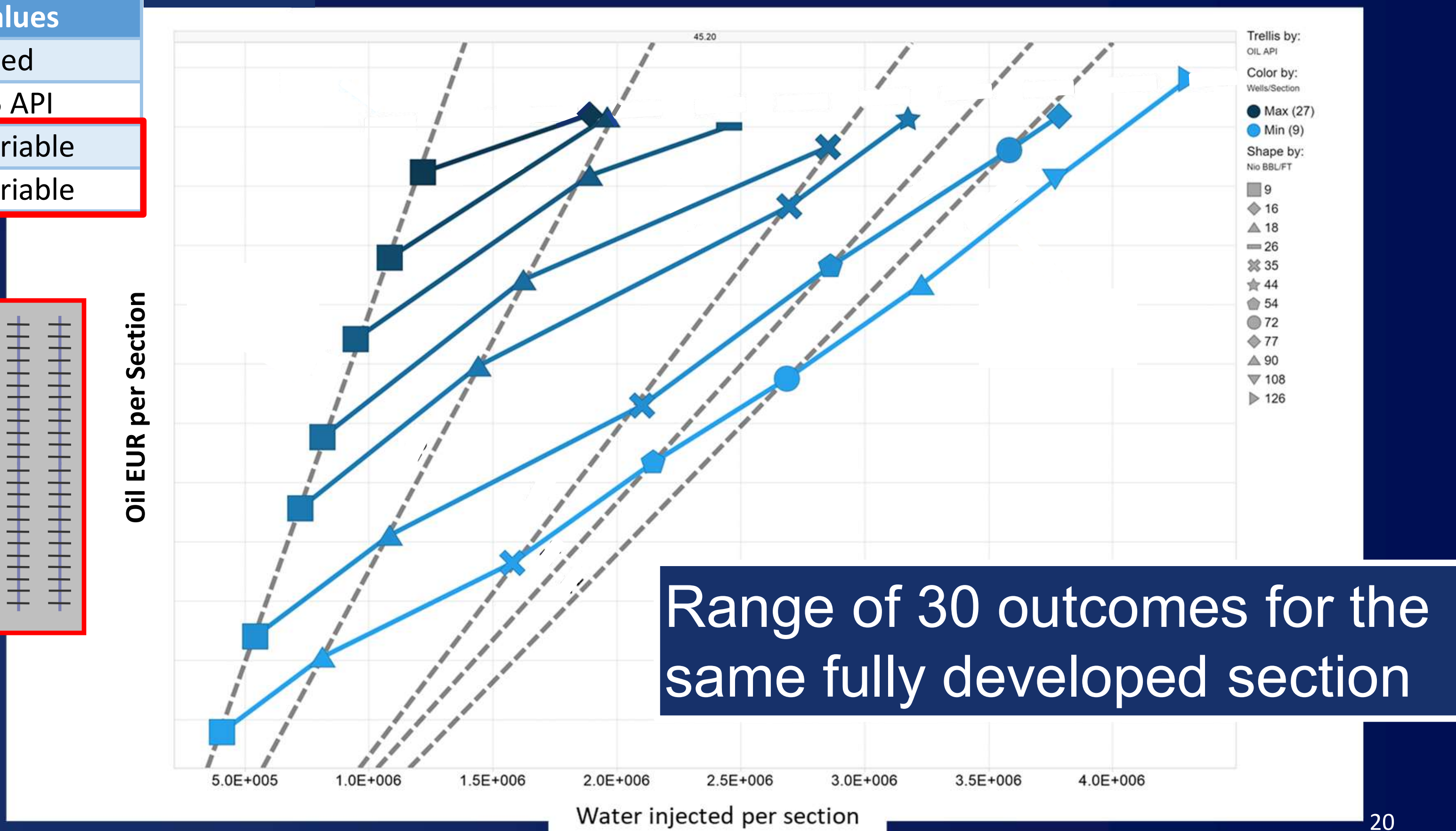
Classical Waterflood Surveillance technique

*US Federal Land Survey Grid

Well Group-Level Predictions

Design element	Values
Geology	fixed
Reservoir fluid	45 API
Well density (wells/section)	variable
Fluid loading (bbl/ft)	variable





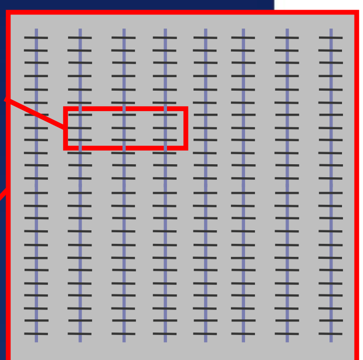
After SPE-194312-MS Tanner et al. 2019

Recovery Limit

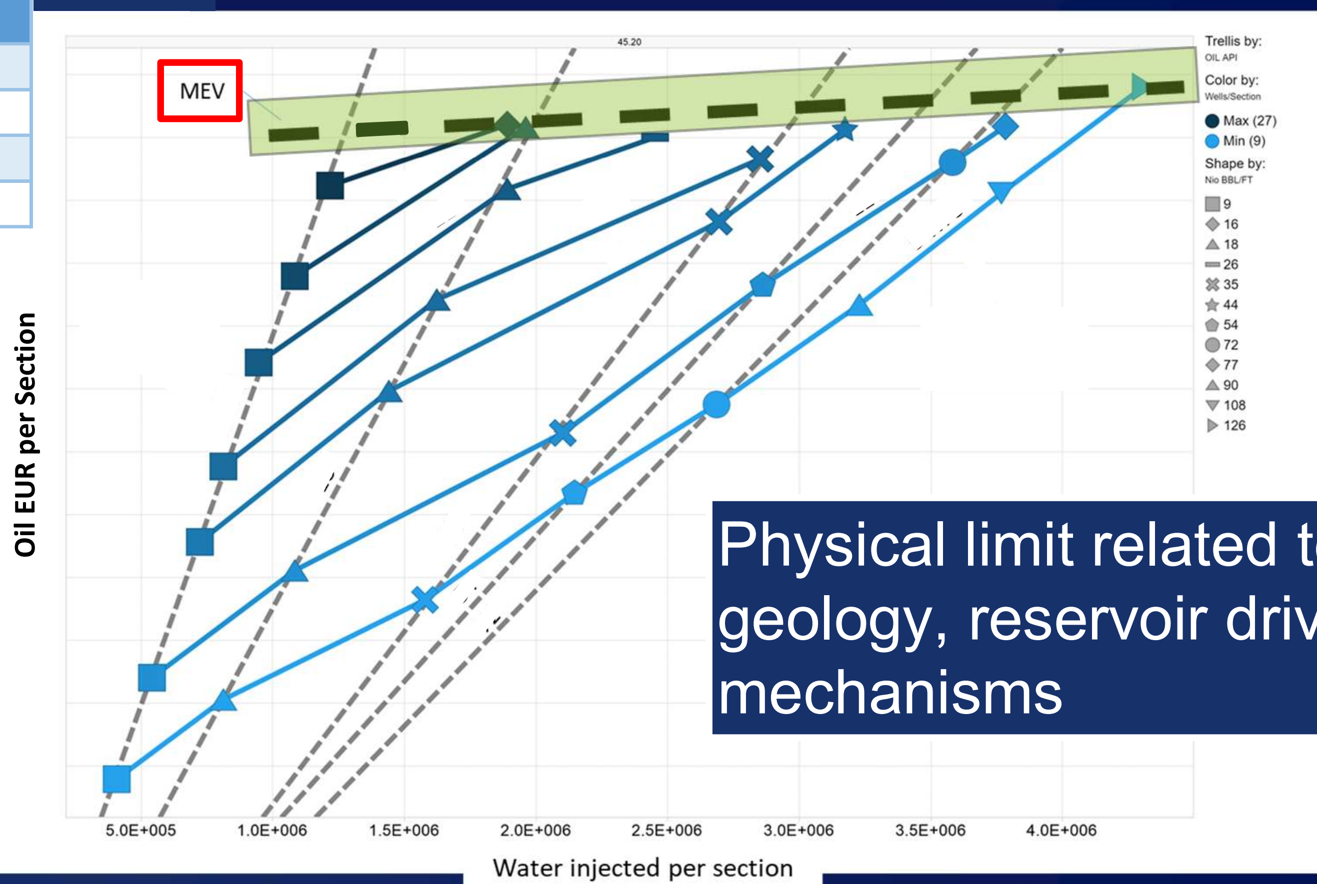
Design element	Values
Geology	fixed
Reservoir fluid	45 API
Well density (wells/section)	variable
Fluid loading (bbl/ft)	variable

Pattern Element

Section



Scale-up



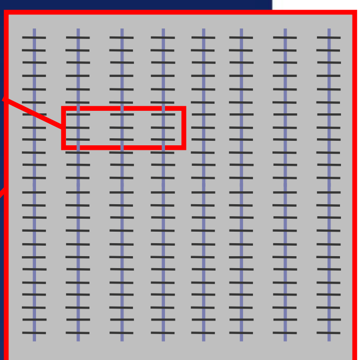
Physical limit related to geology, reservoir drive mechanisms

High Slope Path – Add Wells

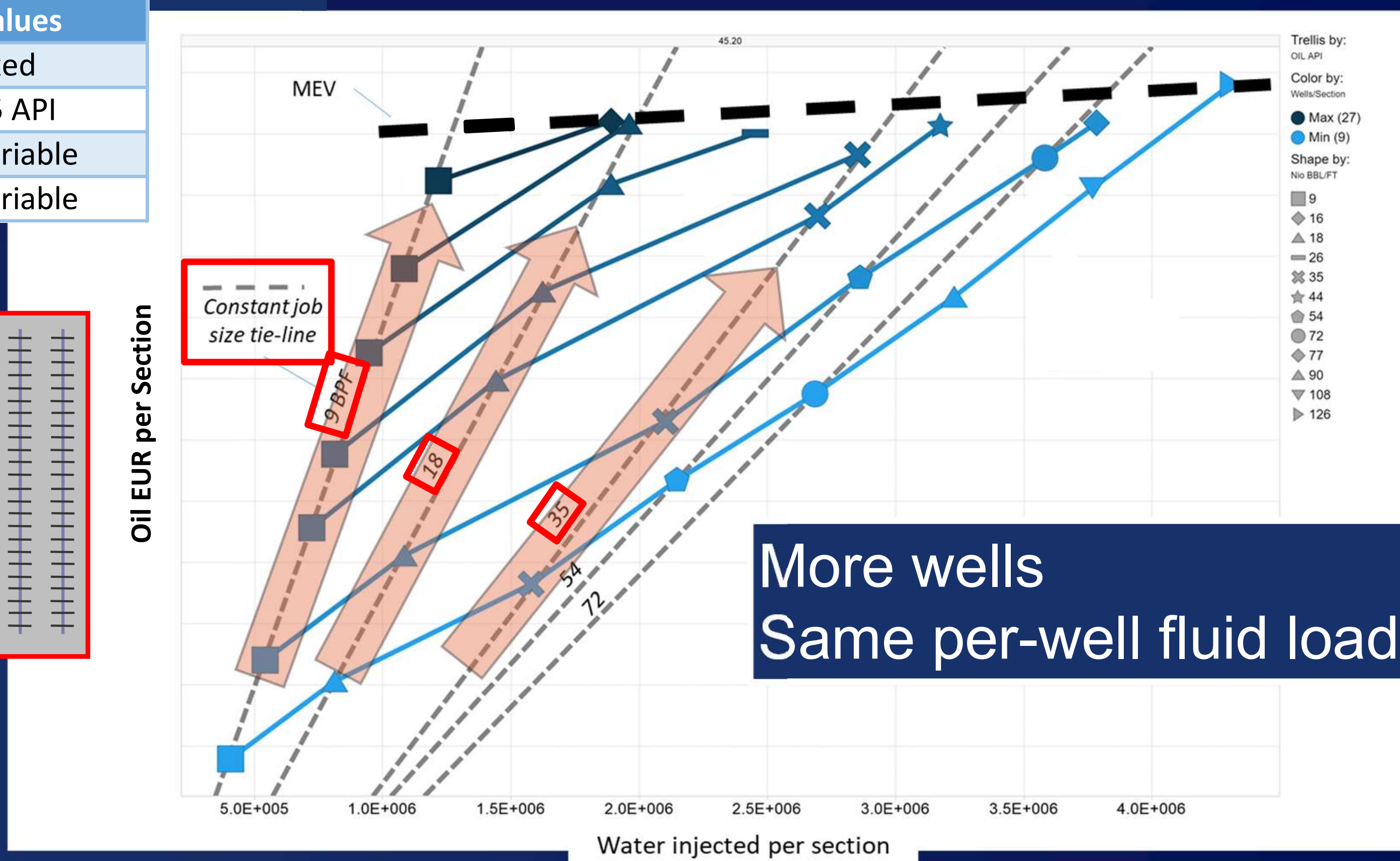
Design element	Values
Geology	fixed
Reservoir fluid	45 API
Well density (wells/section)	variable
Fluid loading (bbl/ft)	variable

Pattern Element

Section



Scale-up



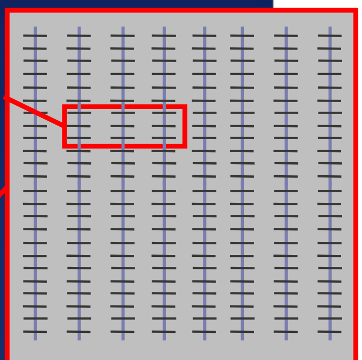
More wells
Same per-well fluid loading

Low Slope Path – Add Fluid

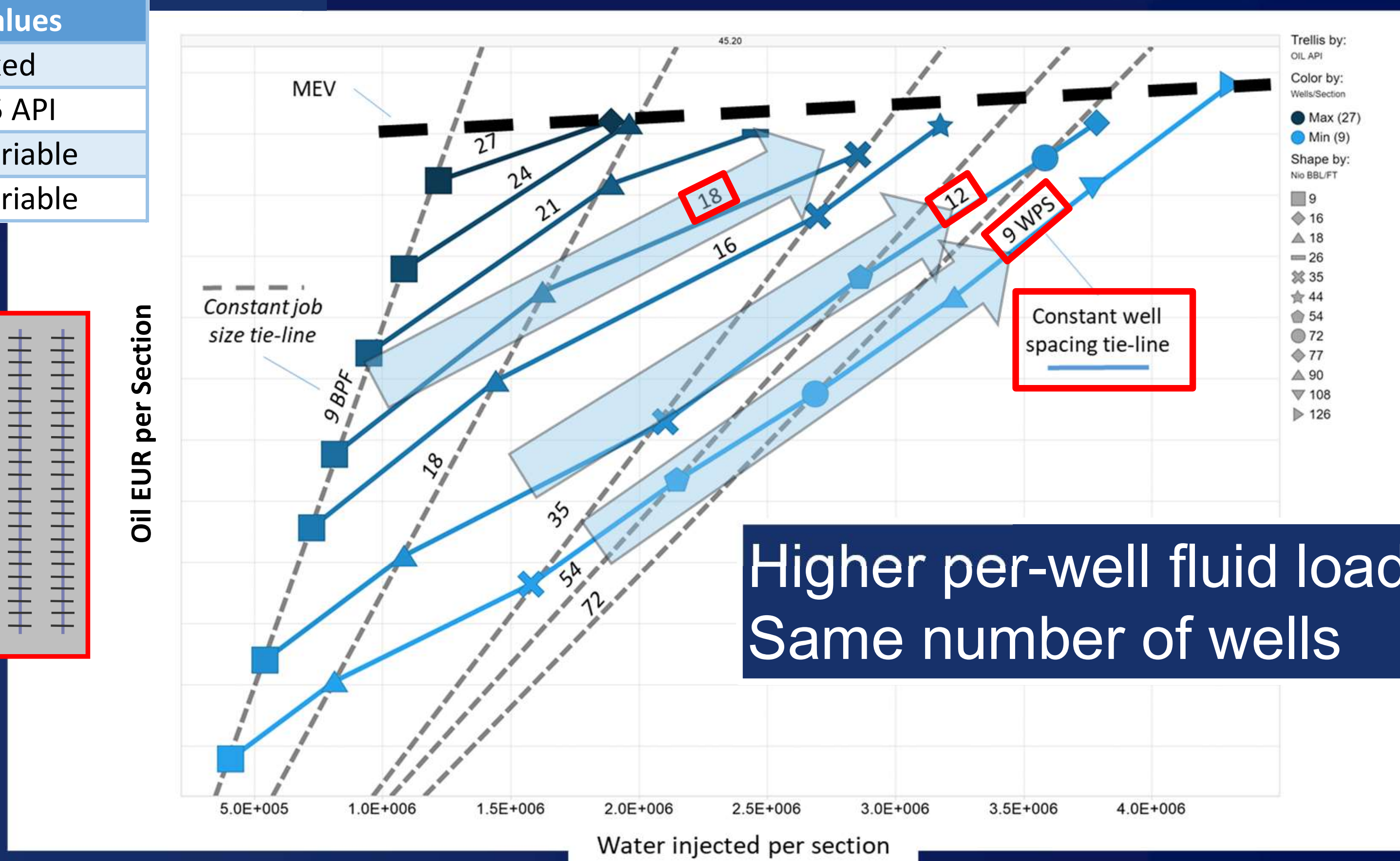
Design element	Values
Geology	fixed
Reservoir fluid	45 API
Well density (wells/section)	variable
Fluid loading (bbl/ft)	variable

Pattern Element

Section



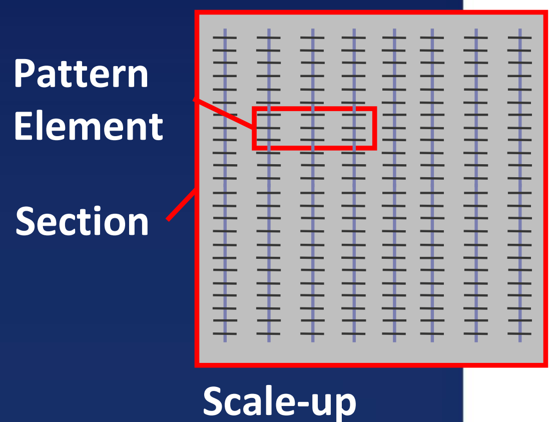
Scale-up

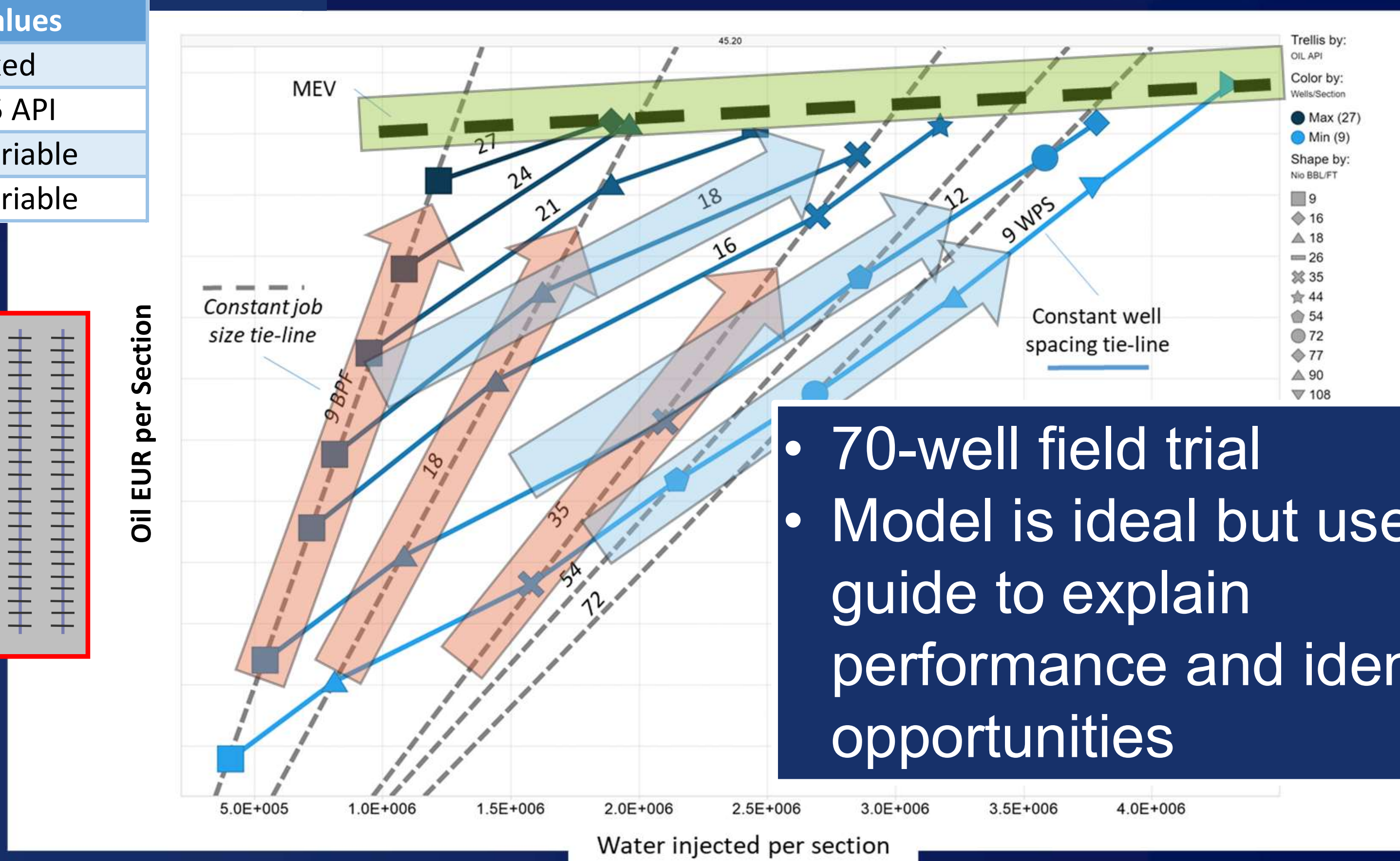


Higher per-well fluid loading
Same number of wells

Validation from Field

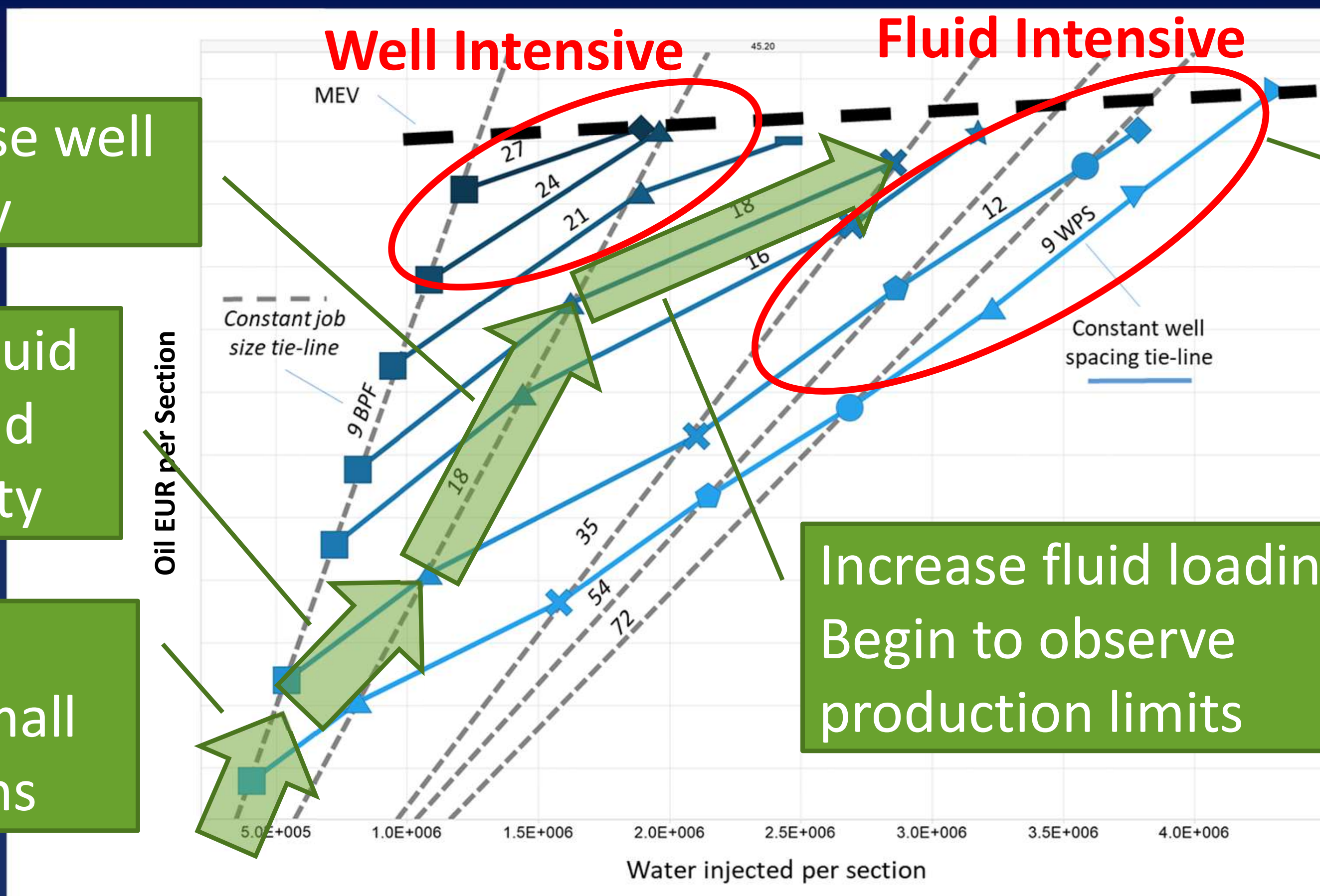
Design element	Values
Geology	fixed
Reservoir fluid	45 API
Well density (wells/section)	variable
Fluid loading (bbl/ft)	variable





- 70-well field trial
- Model is ideal but useful guide to explain performance and identify opportunities

Denver Basin Historical Trends Explained



Increase well density

Increase fluid loading and well density

Wide well spacing, small completions

Increase fluid loading
Begin to observe production limits

Custom optimization

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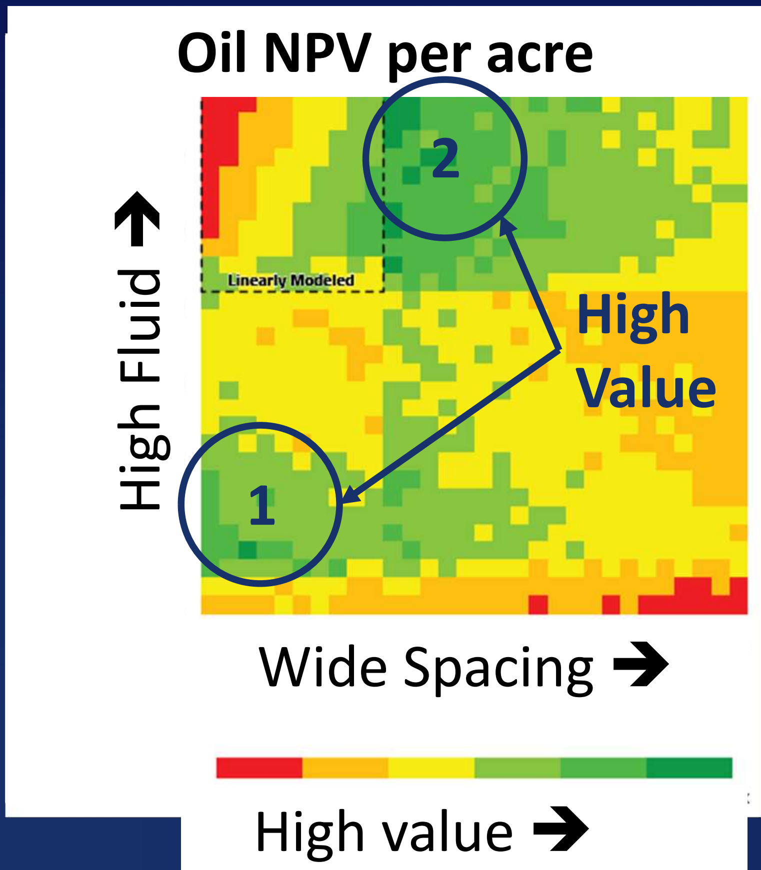
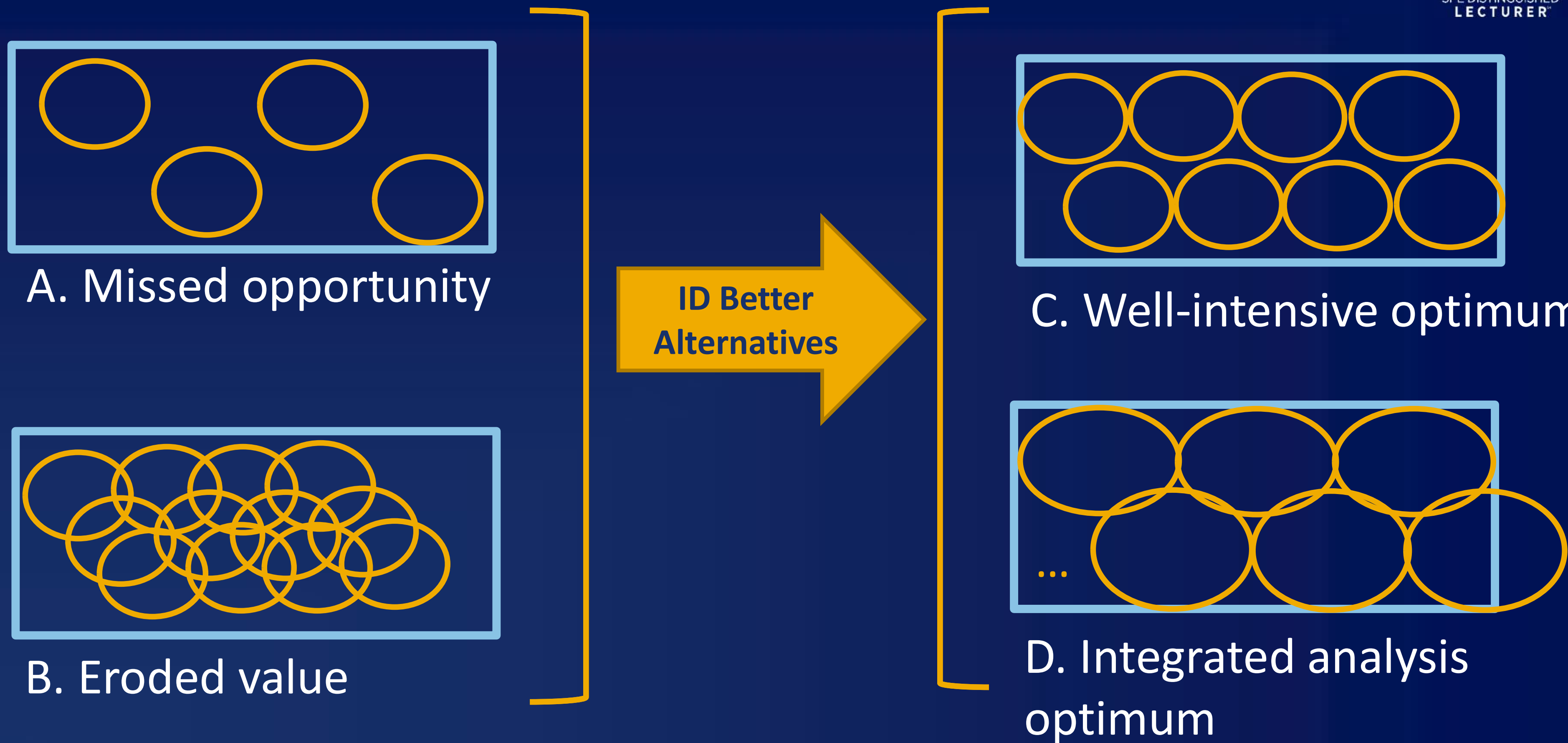
Denver Basin Niobrara Oil Net Present Value



- Industry-wide dataset
- Confirms two alternative designs for maximum oil NPV
  1. Well-Intensive: Small completion-tight well spacing
  2. Fluid-Intensive: Large completion-wide well spacing

SOURCE | RS Energy Group, a Part of Enverus

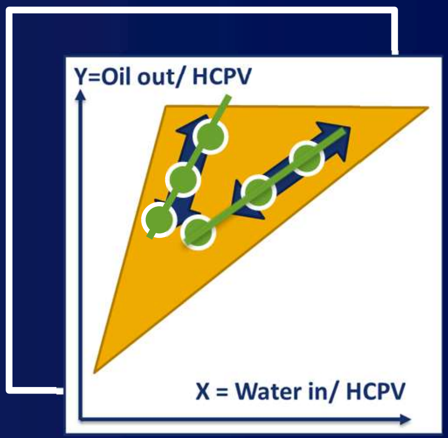
Must Use Physics with Field Data for Best Designs



Step 4

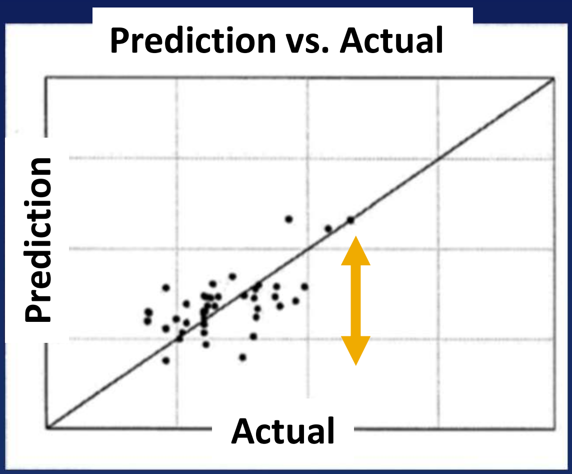
Modeling Foundations → Stimulation Limits → Prediction Sensitivities → **Unified Design**

Unconventional Resource Normalization Plot (N-Plot)



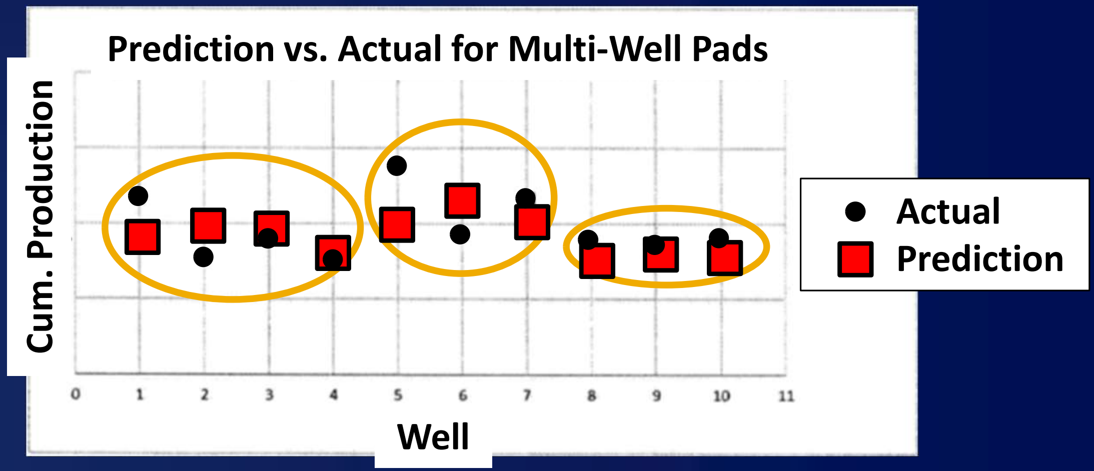
The Case for Averaging

Single-well approach inadequate



+-40% error

Group level interpretation more representative



Pattern A parent-child

Pattern B parent-child

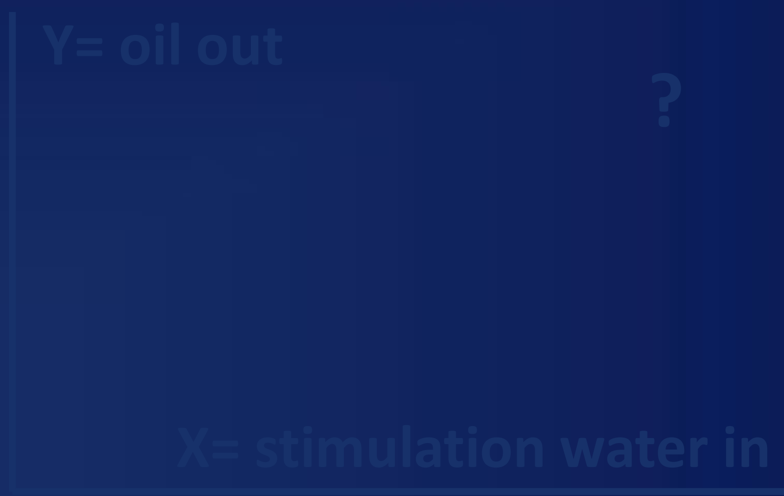
Pattern C simultaneous

after URTEC-2897656 Min et al. 2018

Group-Level Interpretation

Goals

- Smooth out local effects of uneven geology, well spacing, and timing.
- Readily deployed and cross-checked on a large dataset and models.



Group-Level Interpretation

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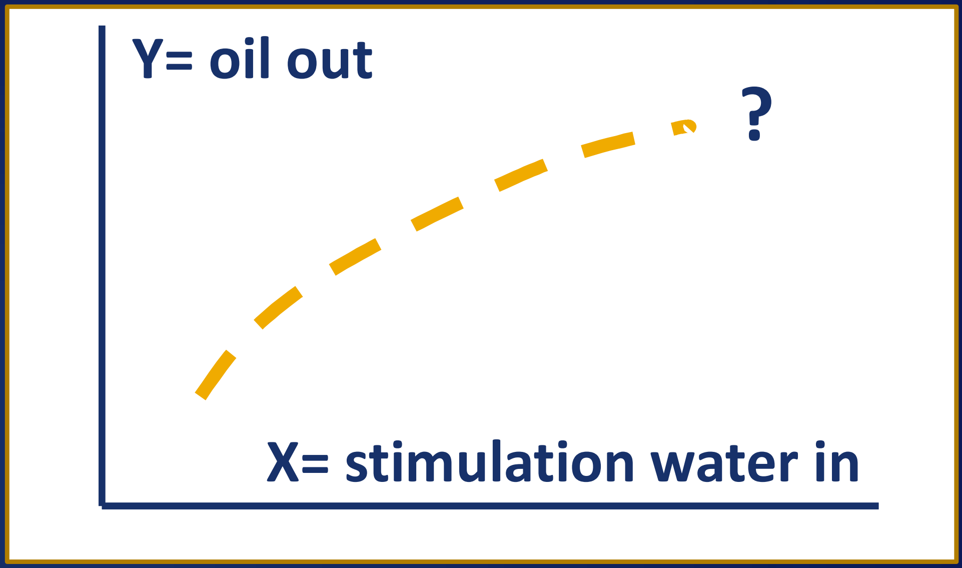
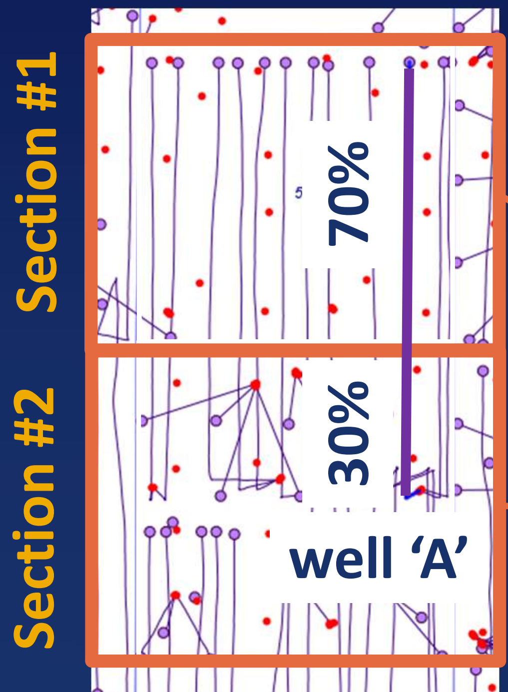
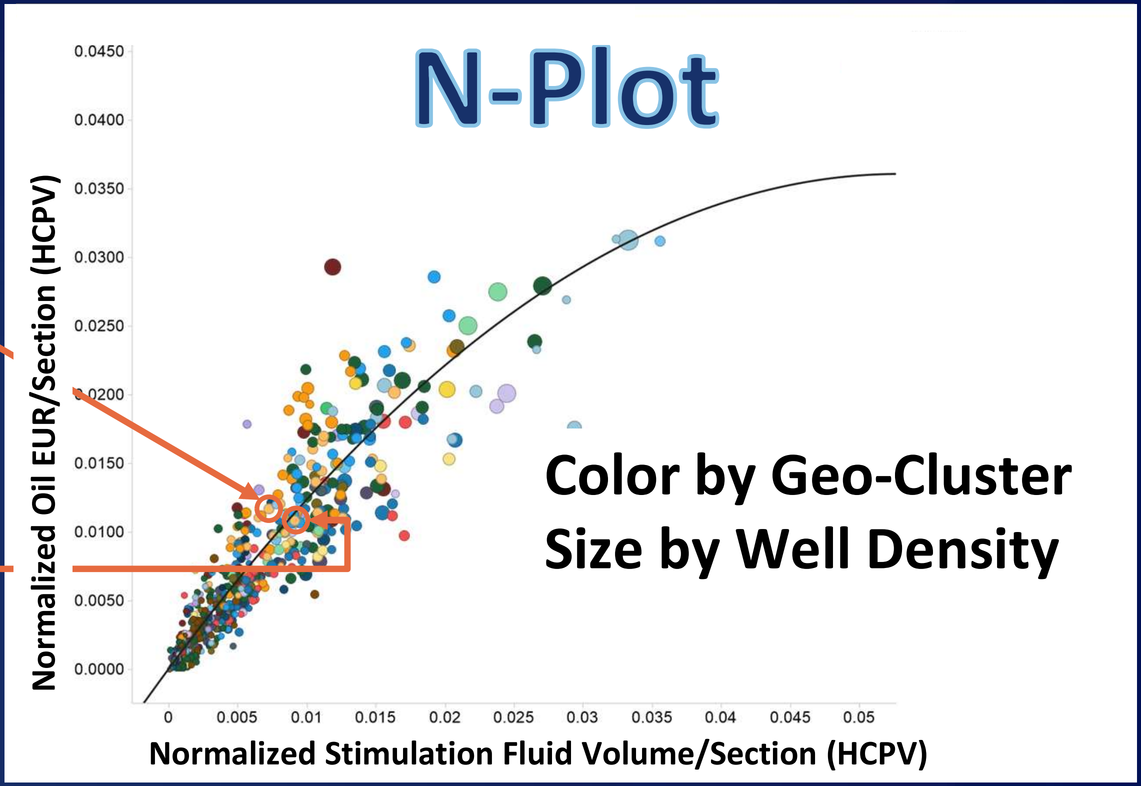


Grand Averaging of Play-Level Well Performance

Well-level stimulation and production Volumes are **allocated** to each **Section**, **summed**, **normalized** by HCPV, and plotted as one point per section.

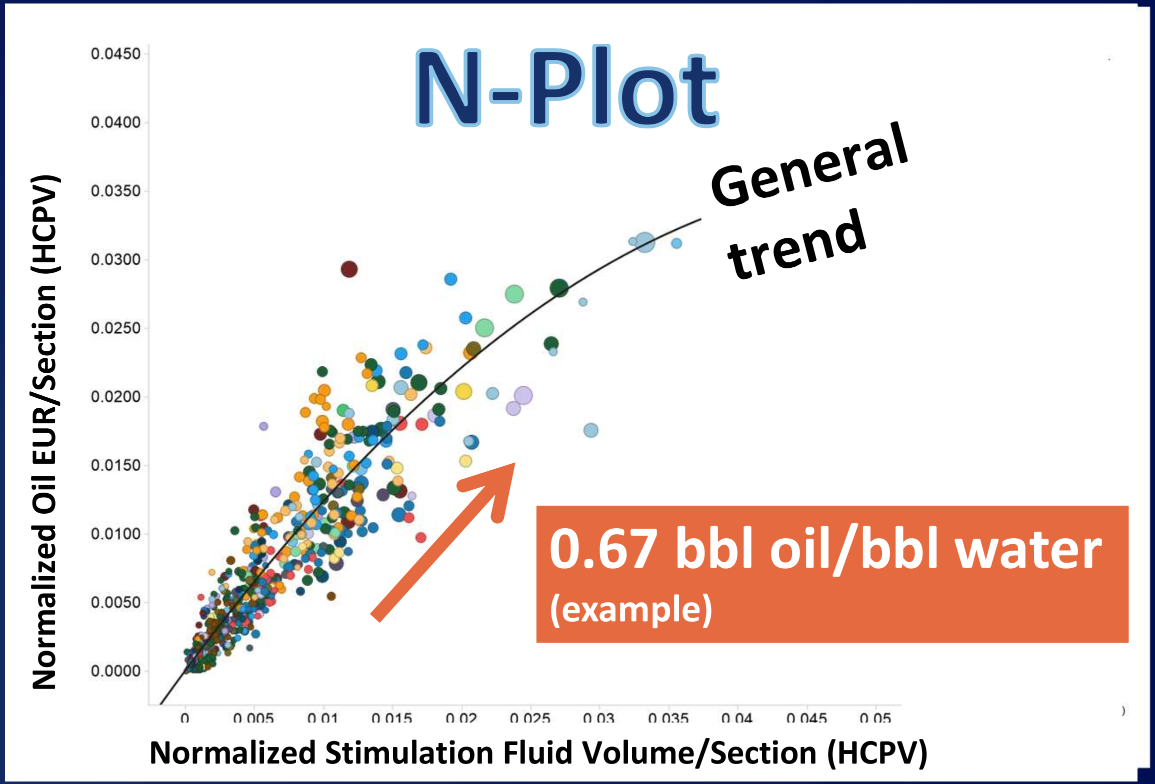


195204-MS Rosenhagen et al. 2019



What Does the N-Plot Tell Us?

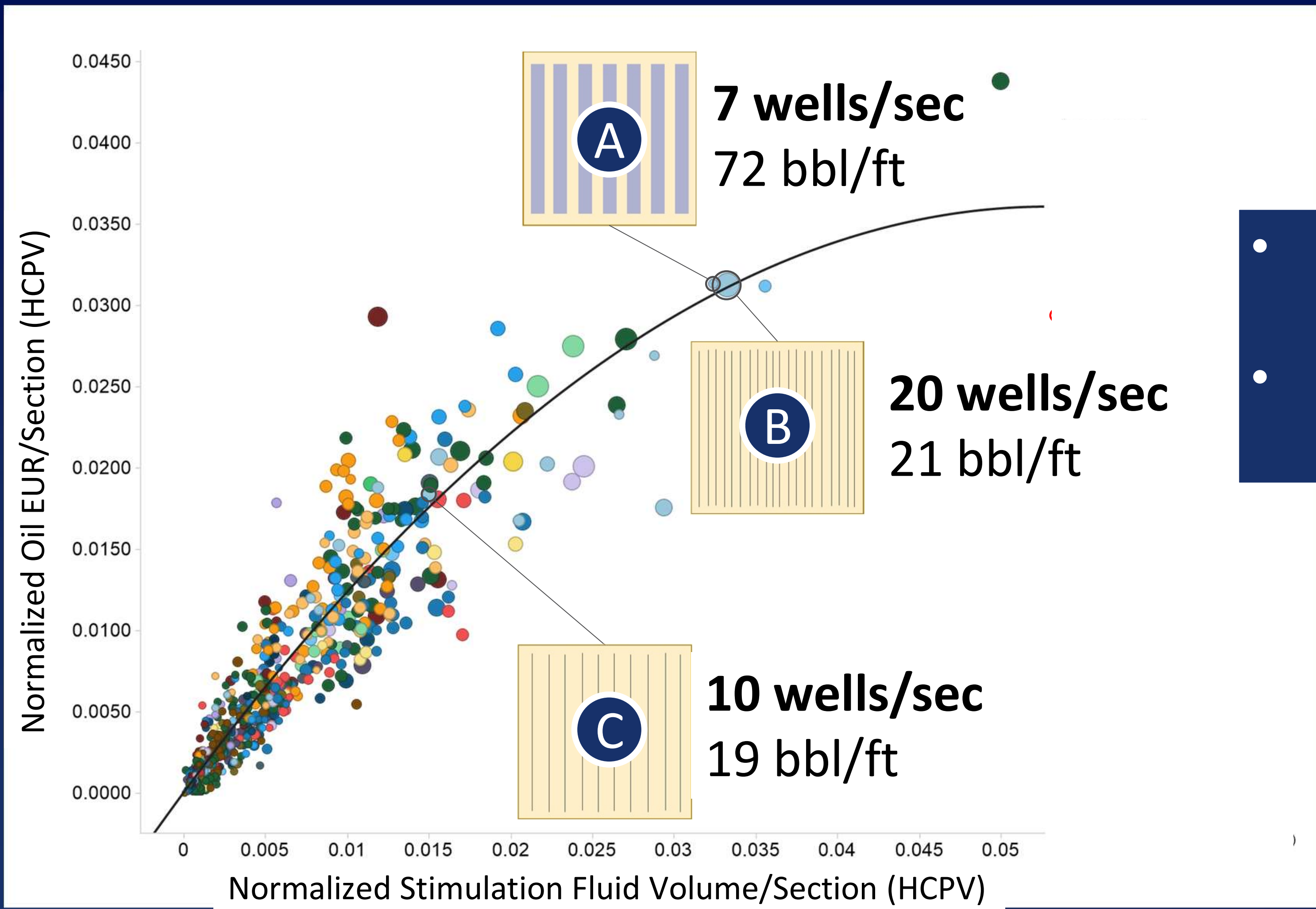
1. Strong correlation: **Response slope directly linked to economics of adj. fluid intensity.**
2. More heterogeneity and well interference than model
3. Model-based trends can be discerned



Use of N-Plot with Model Guidance offers most interpretive power

195204-MS Rosenhagen et al. 2019

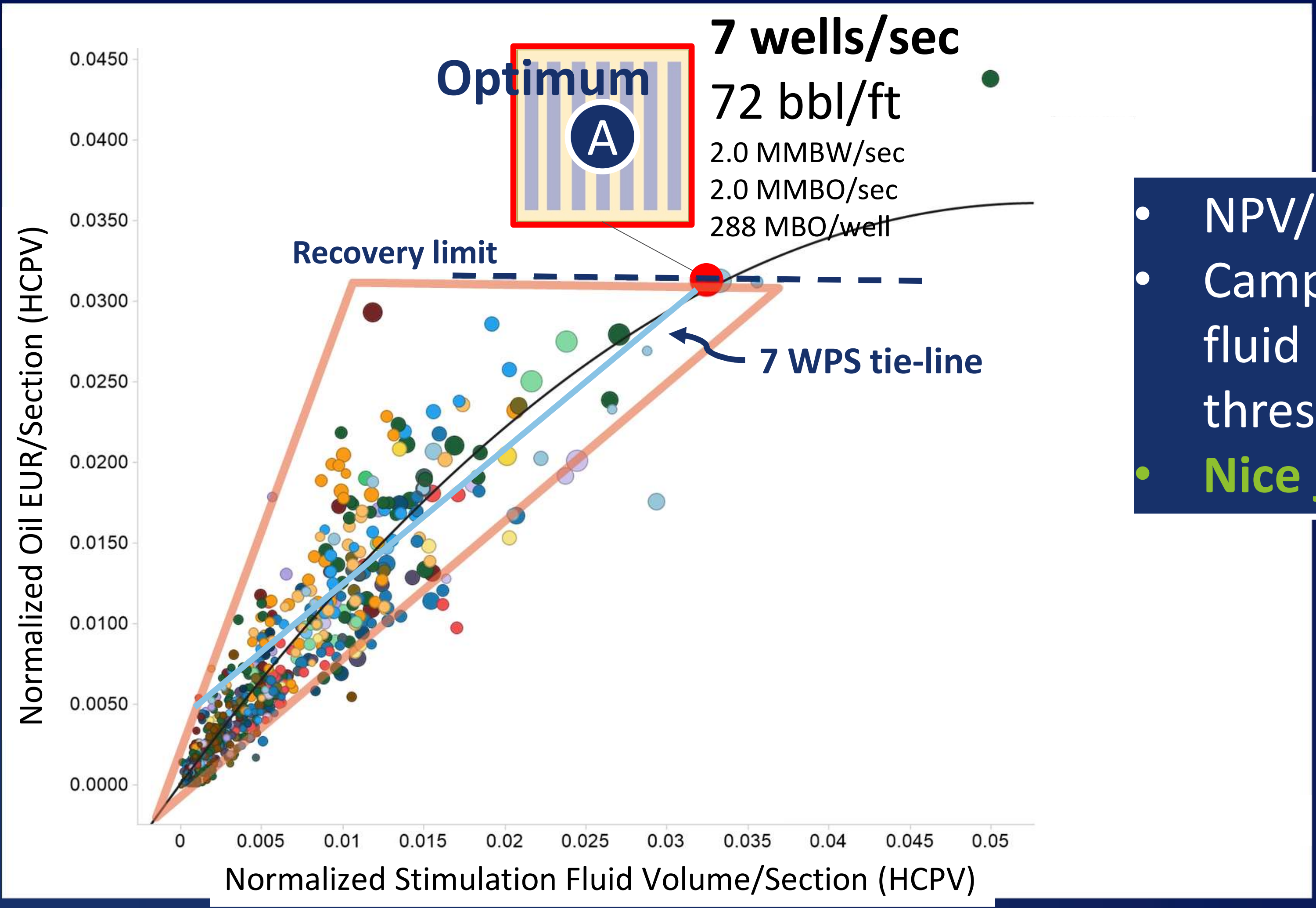
Application #1: Post-Appraisal



- Three designs from same geo-cluster
- Appropriately or poorly developed?

After 195204-MS Rosenhagen et al. 2019

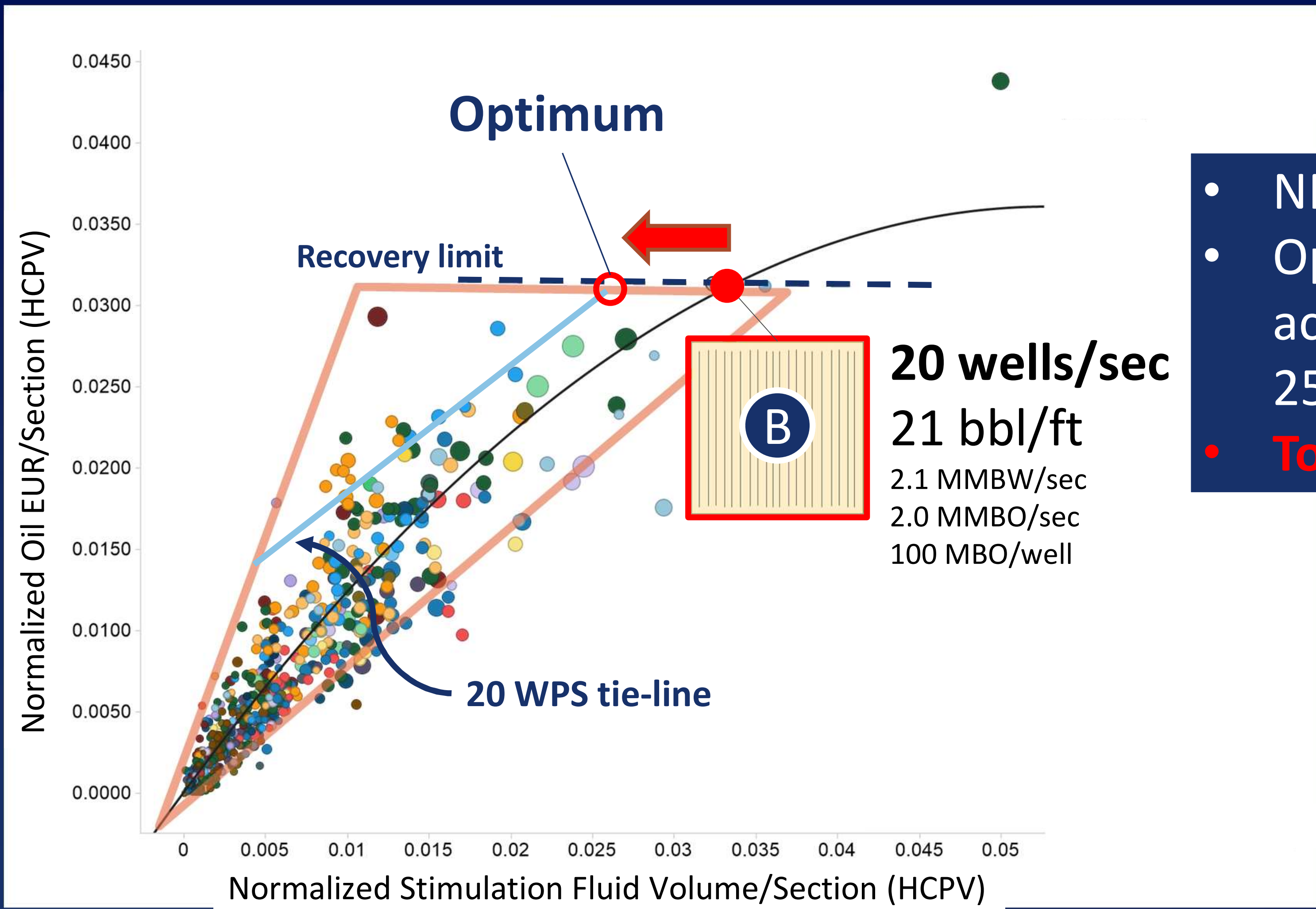
Operator A



- NPV/Section = $33 MM
- Campaign optimized its fluid loading to hit threshold oil target.
- **Nice job!**

After 195204-MS Rosenhagen et al. 2019

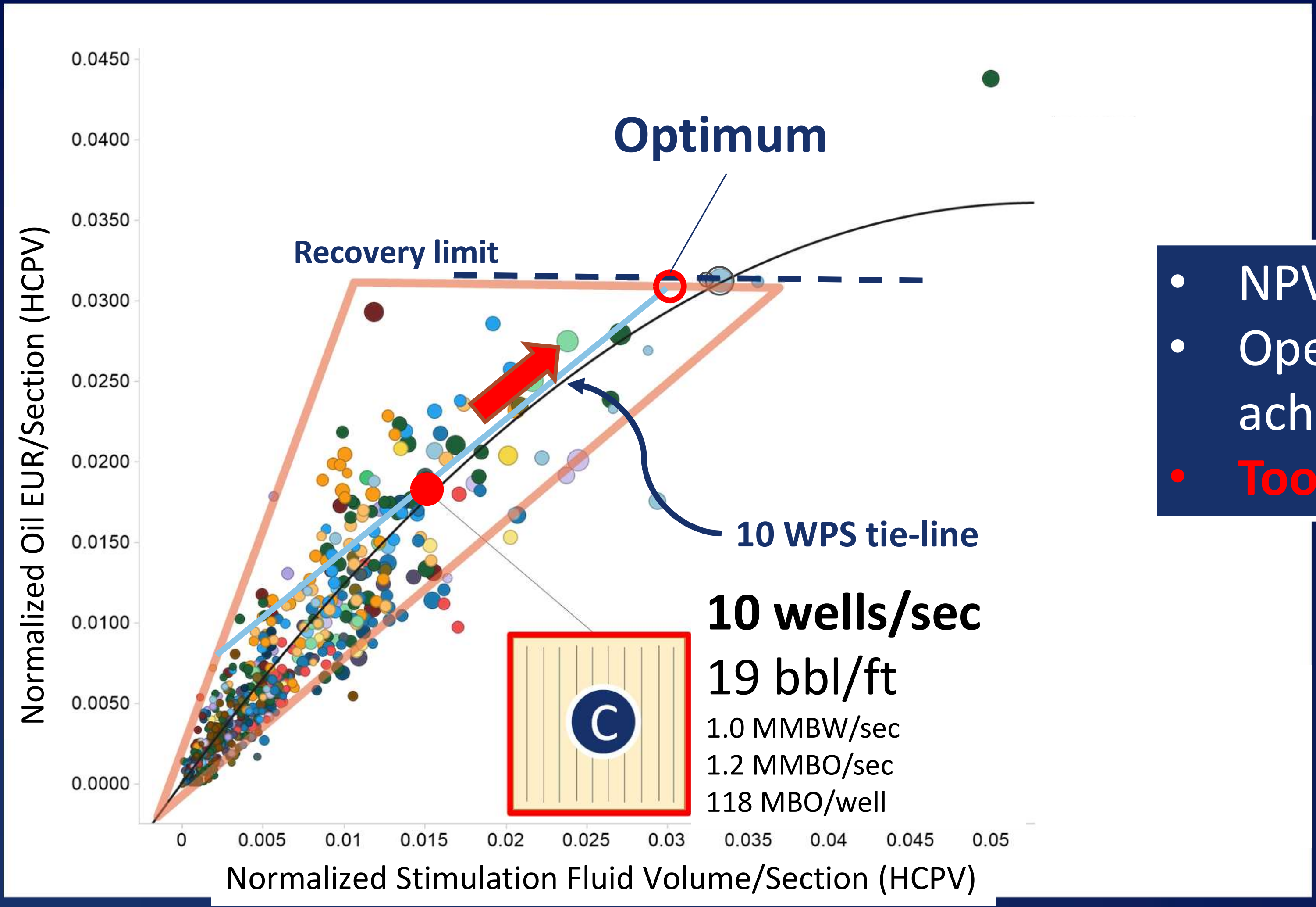
Operator B



- NPV/Section = $1.9 MM
- Operator might have achieved same oil with 25% less water
- **Too much fluid loading**

After 195204-MS Rosenhagen et al. 2019

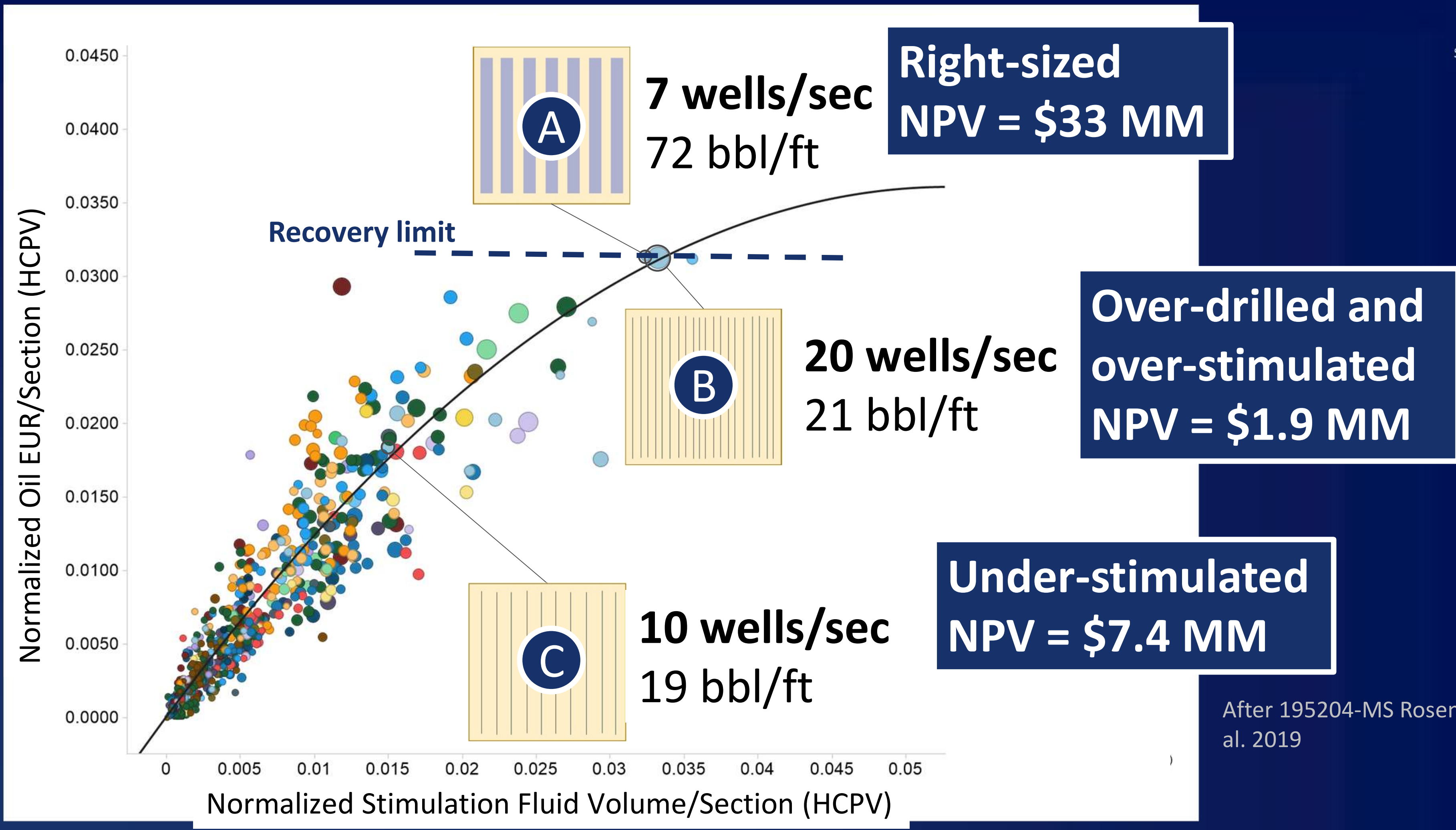
Operator C



- NPV/Section = $7.4 MM
- Operator could have achieved 50% more oil.
- **Too little fluid loading**

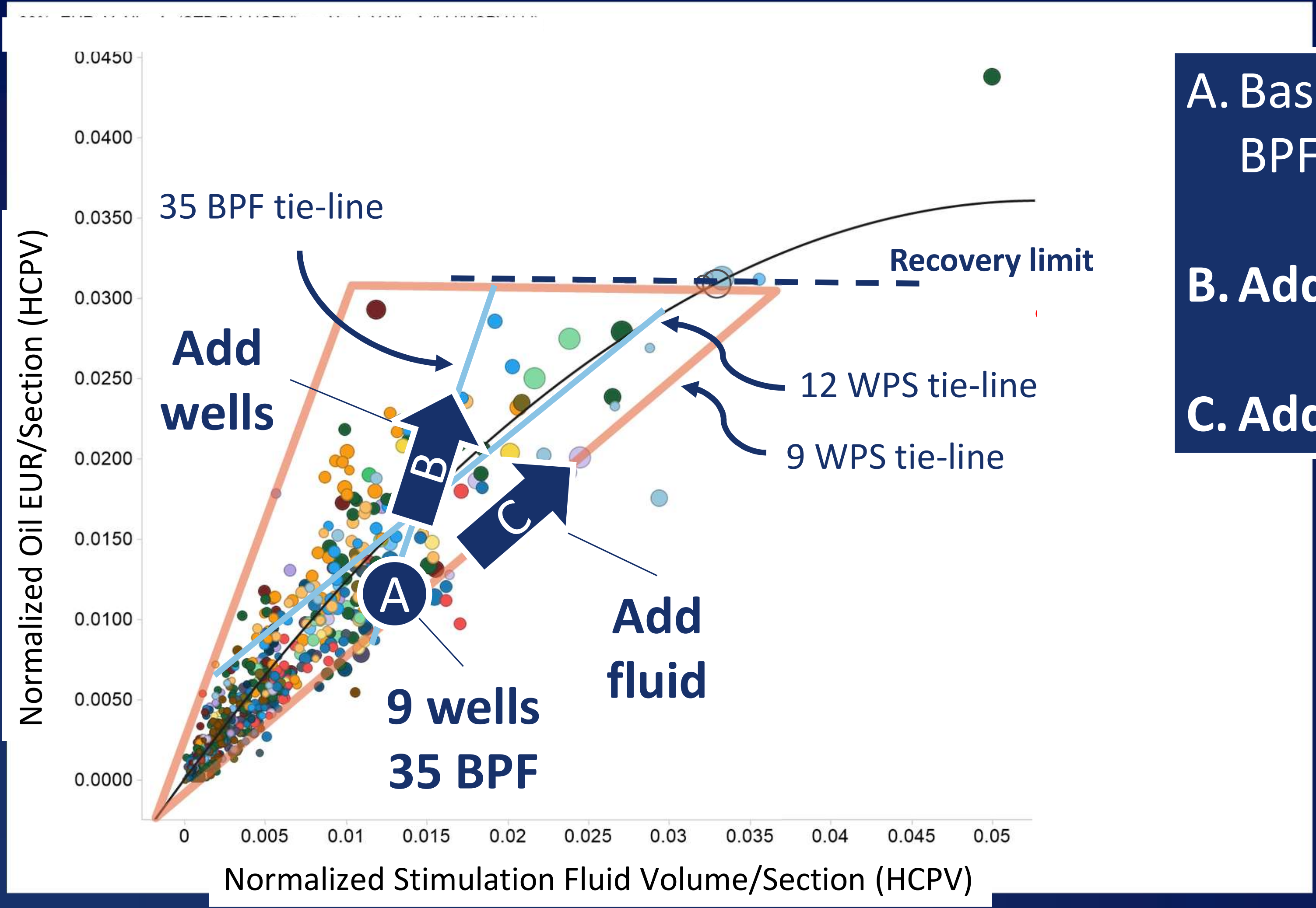
After 195204-MS Rosenhagen et al. 2019

Post-Appraisal Results



After 195204-MS Rosenhagen et al. 2019

Application #2: New Campaign Design

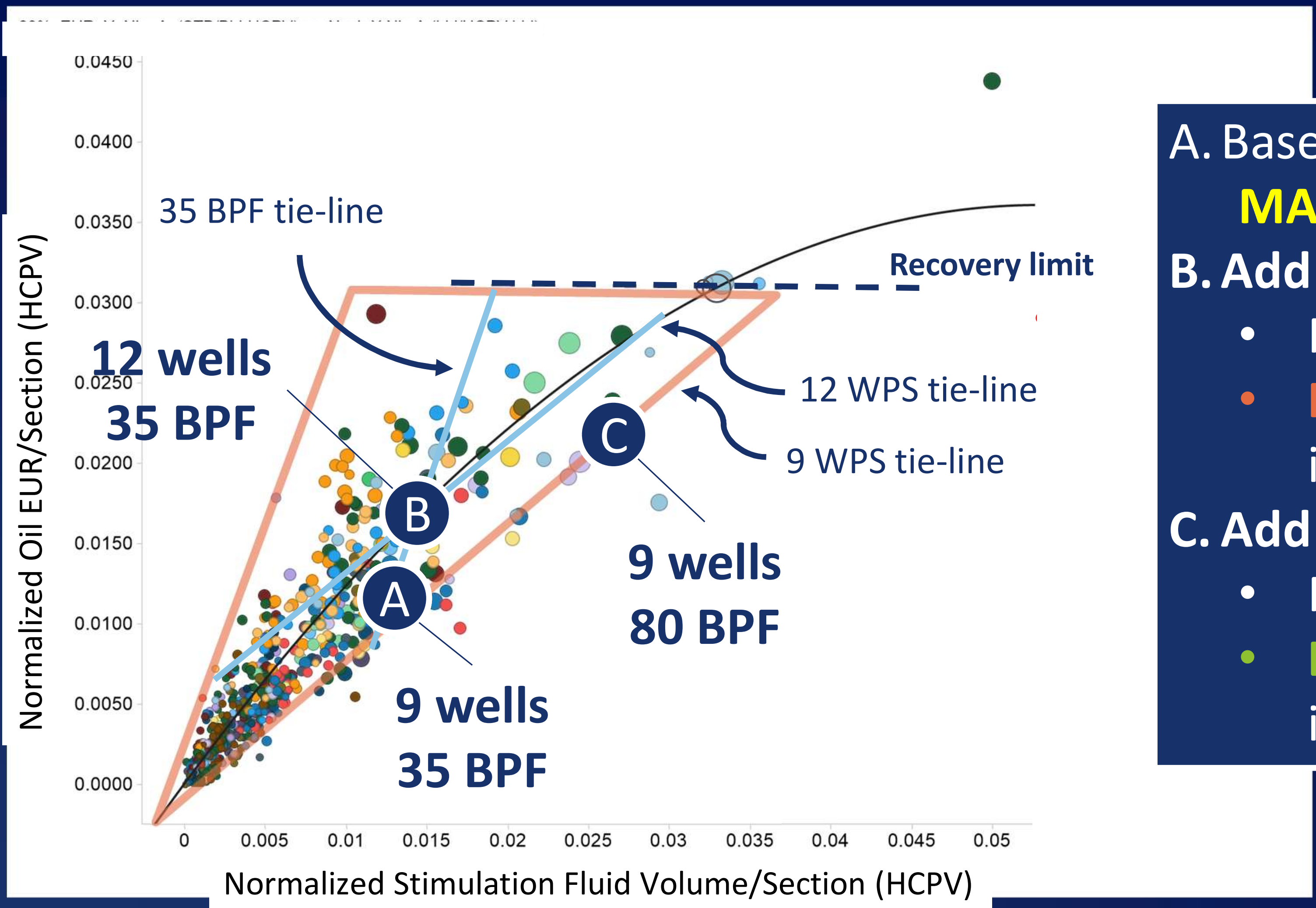


A. Base design (9 wells, 35 BPF). **MAKE IT BETTER**

B. Add wells?

C. Add fluid?

New Campaign Design Results



A. Base design

MAKE IT BETTER

B. Add wells

- More recovery, value
- **FAIL** incremental investment efficiency

C. Add fluid

- More recovery, value
- **EXCEED** incremental investment efficiency

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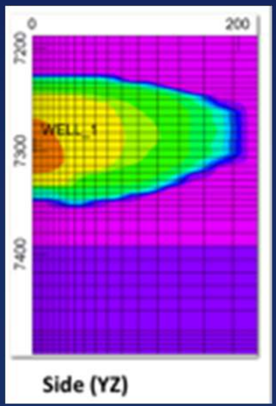
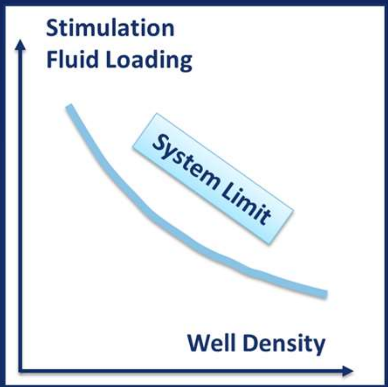
Review

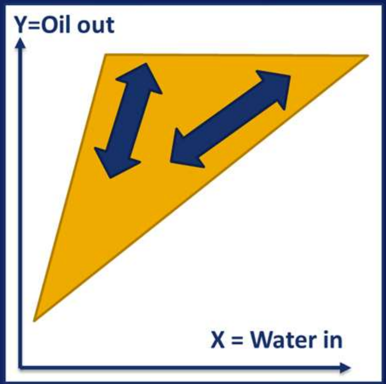
Modeling Foundations → Stimulation Limits → Prediction Sensitivities → Unified Design



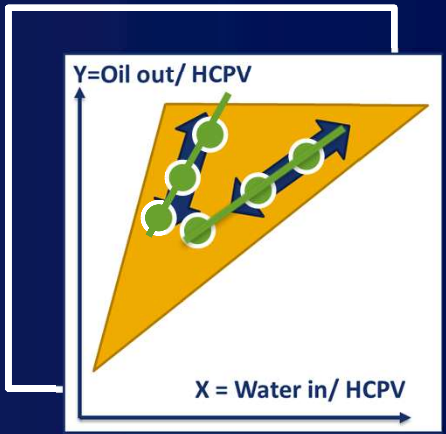
DSRV



MEV



Design Space



N-Plot

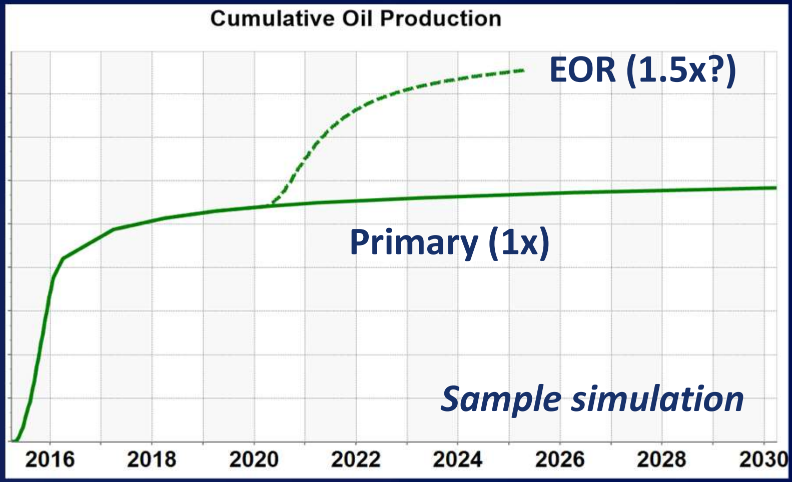
After SPE-194312-MS Tanner et al. 2019

What's Next?

Huge Well Stock

Effective Reservoir Characterization

EOR Potential



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Questions

- Remaining oil distribution
- Effects of changing stress, temperature, and fluid chemistry?
- Impacts of geology, depth, reservoir fluid type, well patterns, stimulations?
- Drive mechanisms for both IOR and EOR?

Conclusions

1. Practical approach

Combination of physics and data-driven techniques allows engineers to create, interpret, and improve integrated well spacing - completion designs

2. The power of Hydraulic Fracturing design

A force for campaign-level optimization

3. Just ONE WAY to rein in a wild problem

Successfully and economically manage a physically complex asset

Photo by Daniel Bonilla on Unsplash

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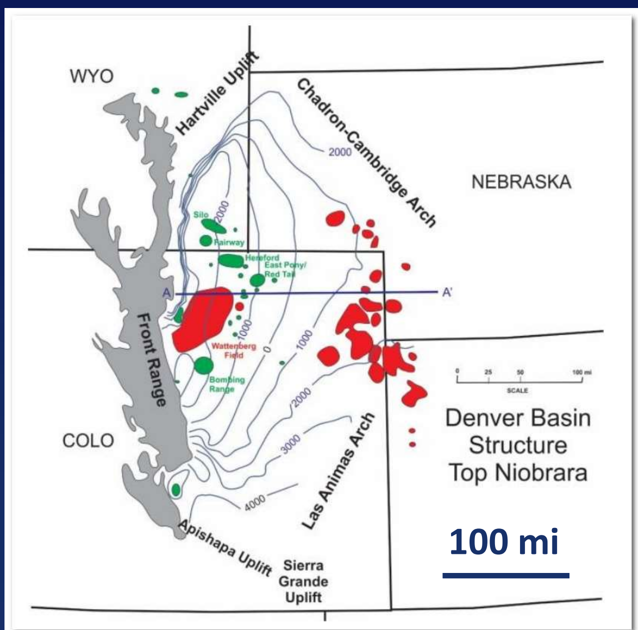
21-22

BACKUP

Sample Play Comparison

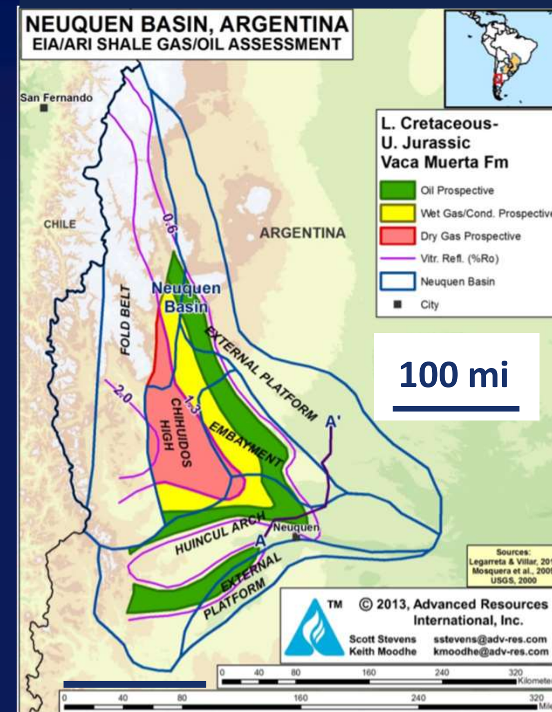
Niobrara



Structure map of Denver Basin, with Niobrara oil and gas fields (from Sonnenberg, 2016)

Formation	Niobrara	Vaca Muerta
Age	Late Cretaceous	Late Jurassic-Early Cretaceous
Lithology	organic-rich marine carbonate mudstone and shale	
Average Depth (ft)	6800	6500
Net Thickness (ft)	300	1000
Reservoir Pressure	over-pressured	highly over-pressured
Total Organic Content (wt. %)	5%	6%
Reservoir Fluid	Varies with maturity	

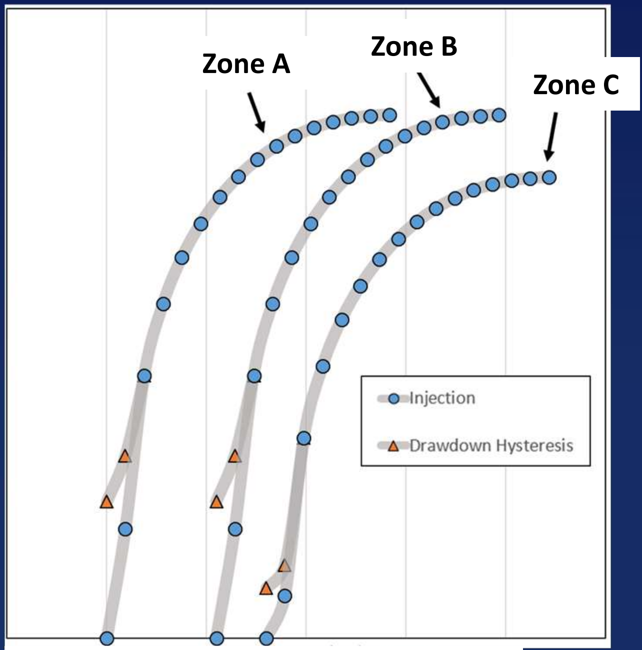
Vaca Muerta



Prospective shale gas and oil areas, Vaca Muerta Formation, Neuquen Basin (Advanced Resources International, 2013 and U.S. Energy Information Administration, 2015)

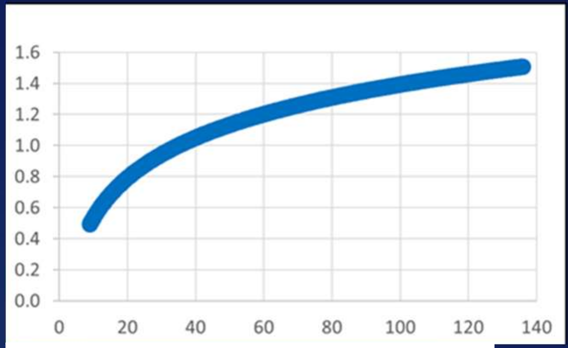
Workflow Extensions

1. Zone-specific matrix transmissibility functions



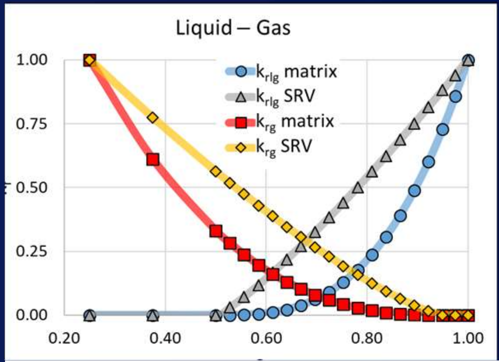
Trasmissibility Multiplier vs. Pressure

2. Propped fracture length proxy



Normalized Fracture Half-Length vs. Stimulation Fluid Loading

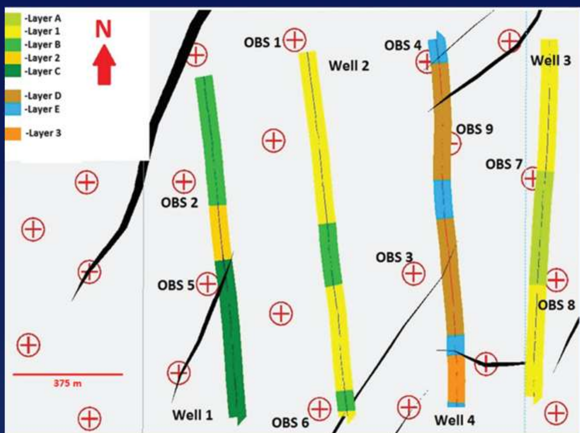
3. Matrix and SRV relative permeability

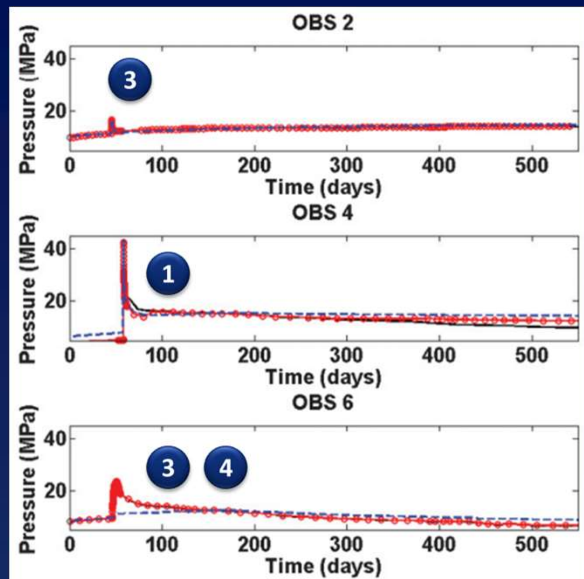


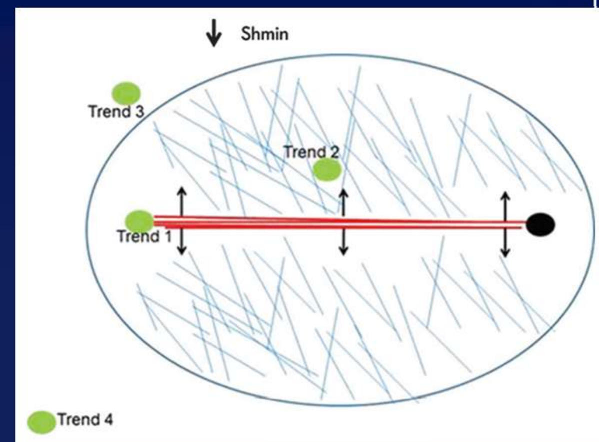
Liquid-Gas Relative Permeability vs. Sw

All features set through calibration

Drainage Volume Characterization Project







Study

Pressure observations of four-HZ well hydraulic fracturing program

Mechanisms

1. induced fractures
2. natural fractures
3. pore space
4. matrix (poroelastic)

Conclusions

1. Drainage volume is complex
2. Fluid compressibility can overshadow poroelastic effects
3. Hydraulic connections more widespread than retained propped connections

Griffith and McClure, 2016. Society of Exploration Geophysicists and American Association of Petroleum Geologists, 13 October.

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Hydro-Fracture Model Types: Where Does DSRV Fit?

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Some Modeling Options:

Mechanical fracture models
- 2D
- Pseudo-3D
- Gridded
- Complex (DFN, non-planar)

Reservoir simulators
- Enhanced skin
- Local Grid Refinement
- Dual Permeability

Coupled simulators
- Precise
- Approximate ✓
- Varied

What Features are Coupled?

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Typical Fracturing Models

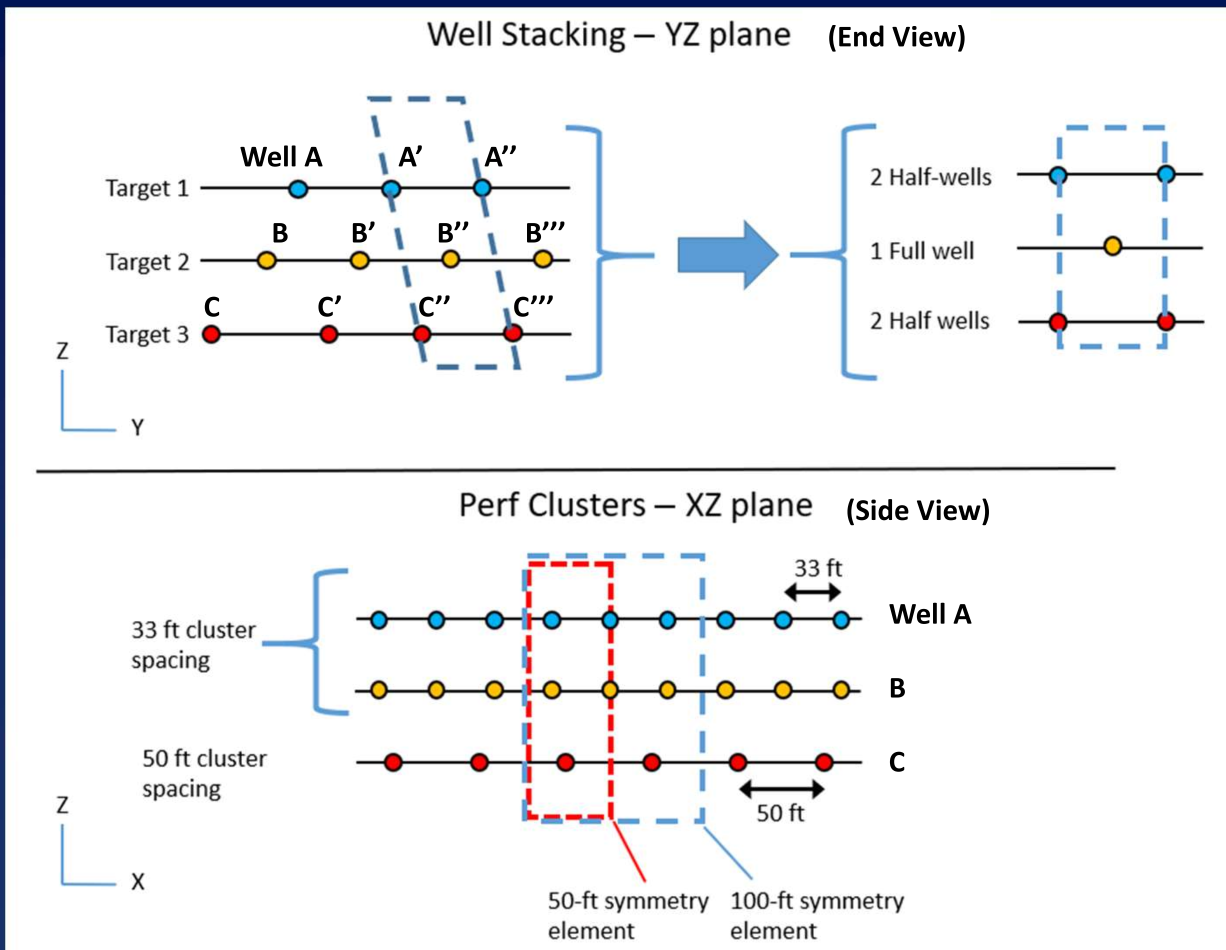
- ✓ Pressure
- ✓ Stress (+time) ✗
- ✗ Displacement
- ✓ Conductivity
- ✓ Fractured well
- ✓ Well Geometry

Typical Reservoir models

- ✓ Pressure
- ✓ Transmissibility
- ✓ Saturations
- ✓ Production
- ✓ Reservoir geometry

✓ **DSRV model**

Scale Model: Pattern Element Selection



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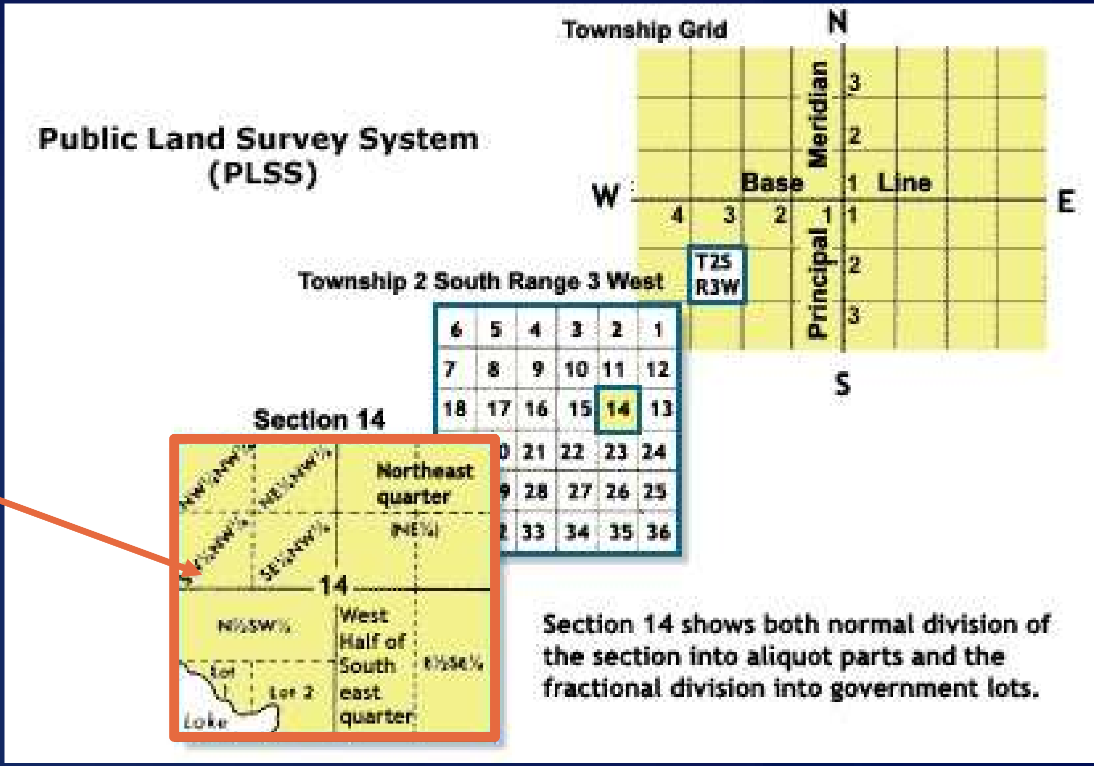
Convenient Well Group Level for Averaging Western USA

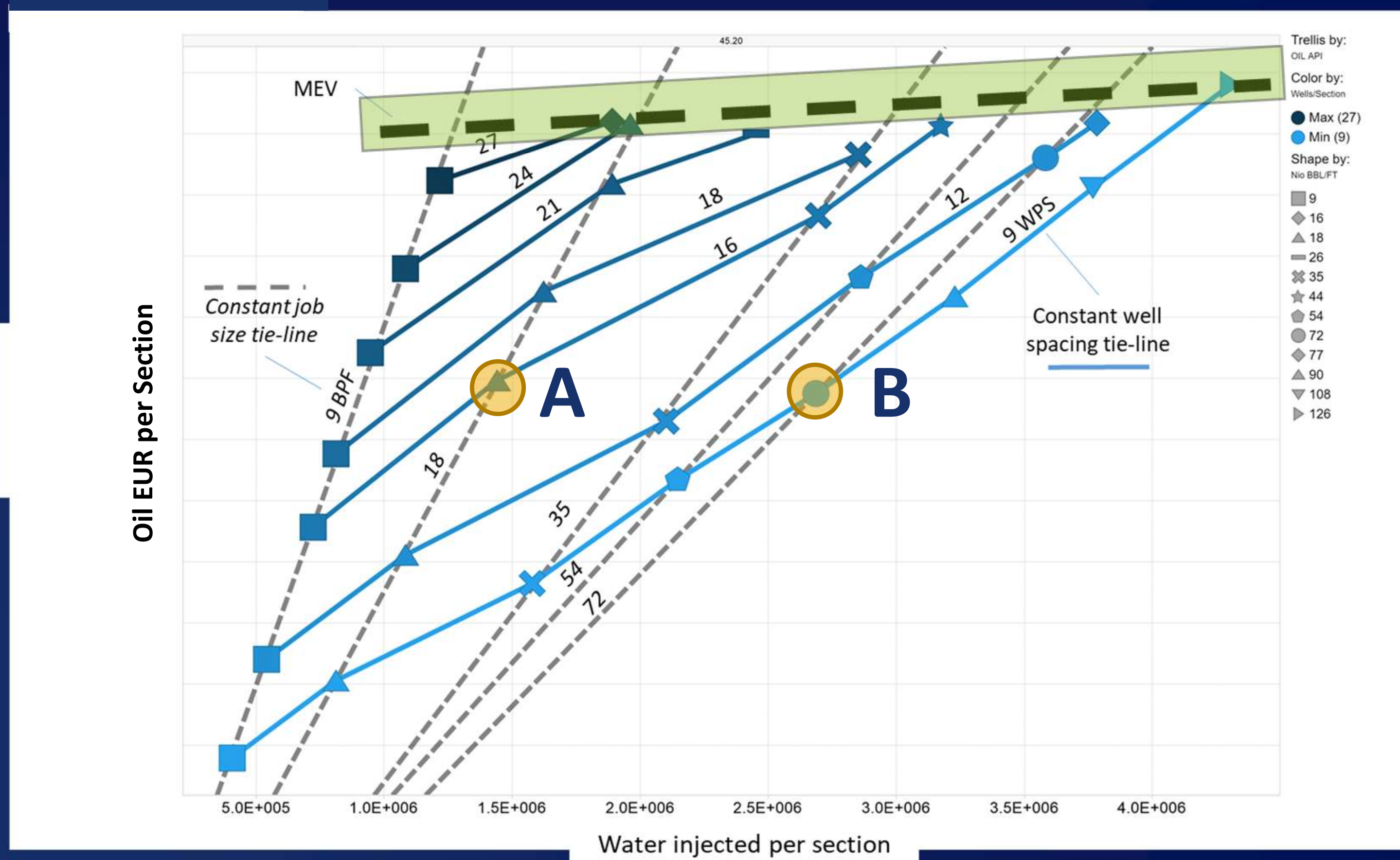
The PLSS is a method used in the United States to survey and identify land parcels. Its basic units of area are the

- Section: one square mile or 640 acres
- Township: 36 sections



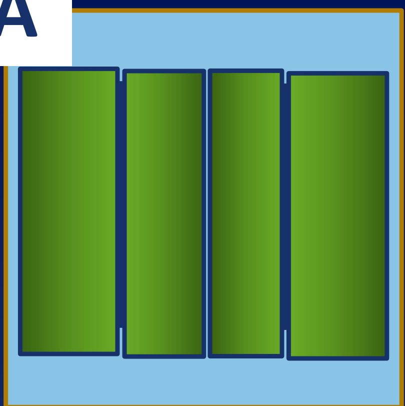
USGS

Why Different Slopes?

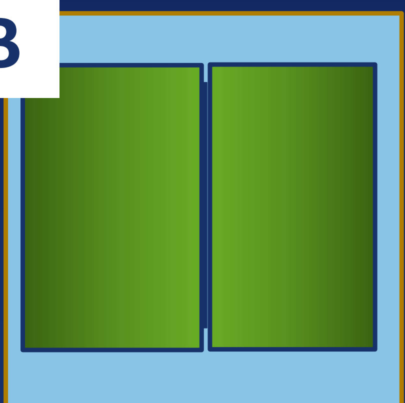


Why Different Slopes?

A



B



Same section oil, different well spacing

<u>Assumptions</u>

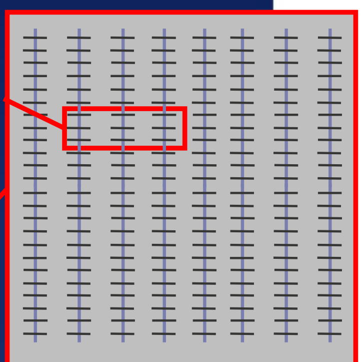
OOIP (STB/section)	2.50E+07
Oil RF per section	5.00E-02
Oil EUR (STB/section)	1.25E+06

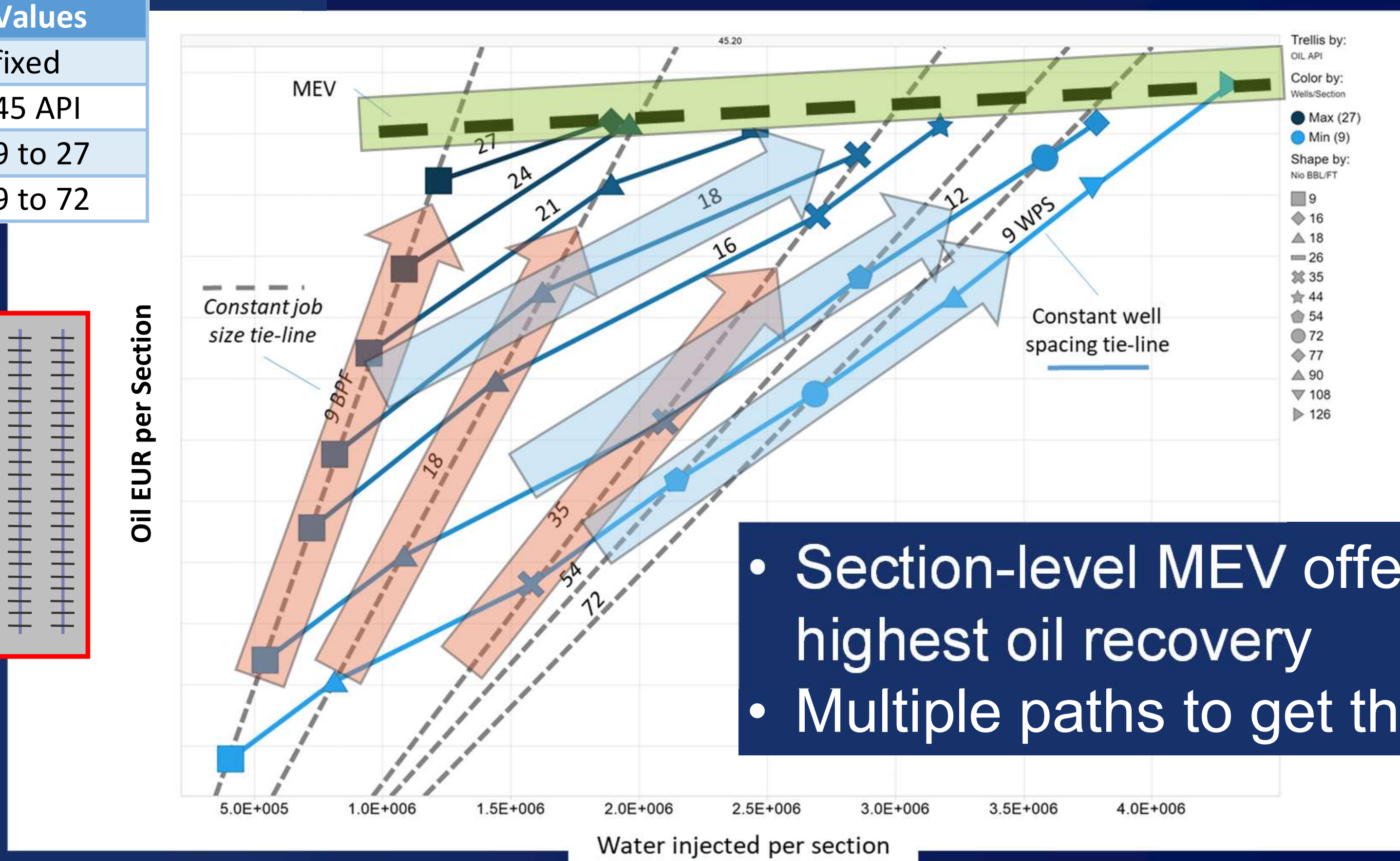
Scenario	Well Density (wells/section)	Fluid Loading (bbl/ft)	Water inj (bbl/section)	Water inj (bbl/section) norm	Oil EUR/section	Oil EUR/well (STB)	Oil EUR/well norm 2	Oil RF/well
A	16	18	1.44E+06	1	1.25E+06	78,125	1	0.05
B	9	72	3.24E+06	2.25	1.25E+06	138,889	1.78	0.05

- All SRV not created equal
- Larger well box requires more WI to achieve same RF as small well box – to capture resources further afield.

Group-level Predictions (below & at MEV)

Design element	Values
Geology	fixed
Reservoir fluid	45 API
Wells per section	9 to 27
Fluid intensity (BPF)	9 to 72





- Section-level MEV offers highest oil recovery
- Multiple paths to get there

Custom MEV from Modeling

Geology, Well geometry,

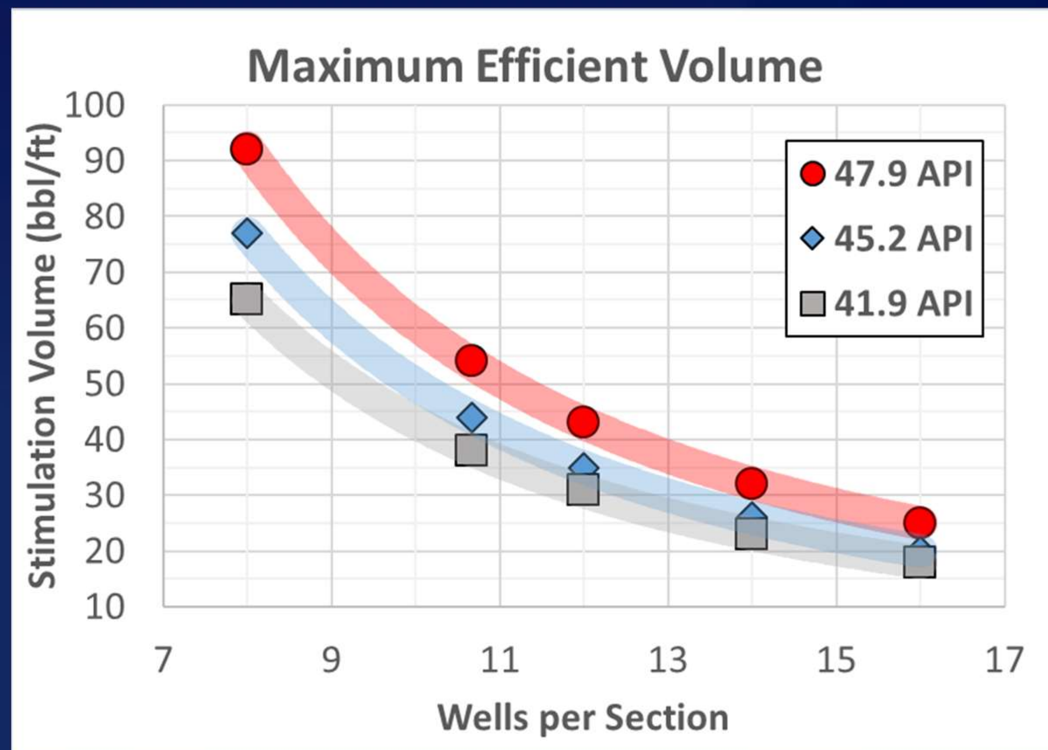
Reservoir fluid type

System compressibility drives SRV creation, resulting in different MEV trends

40 44 47 50

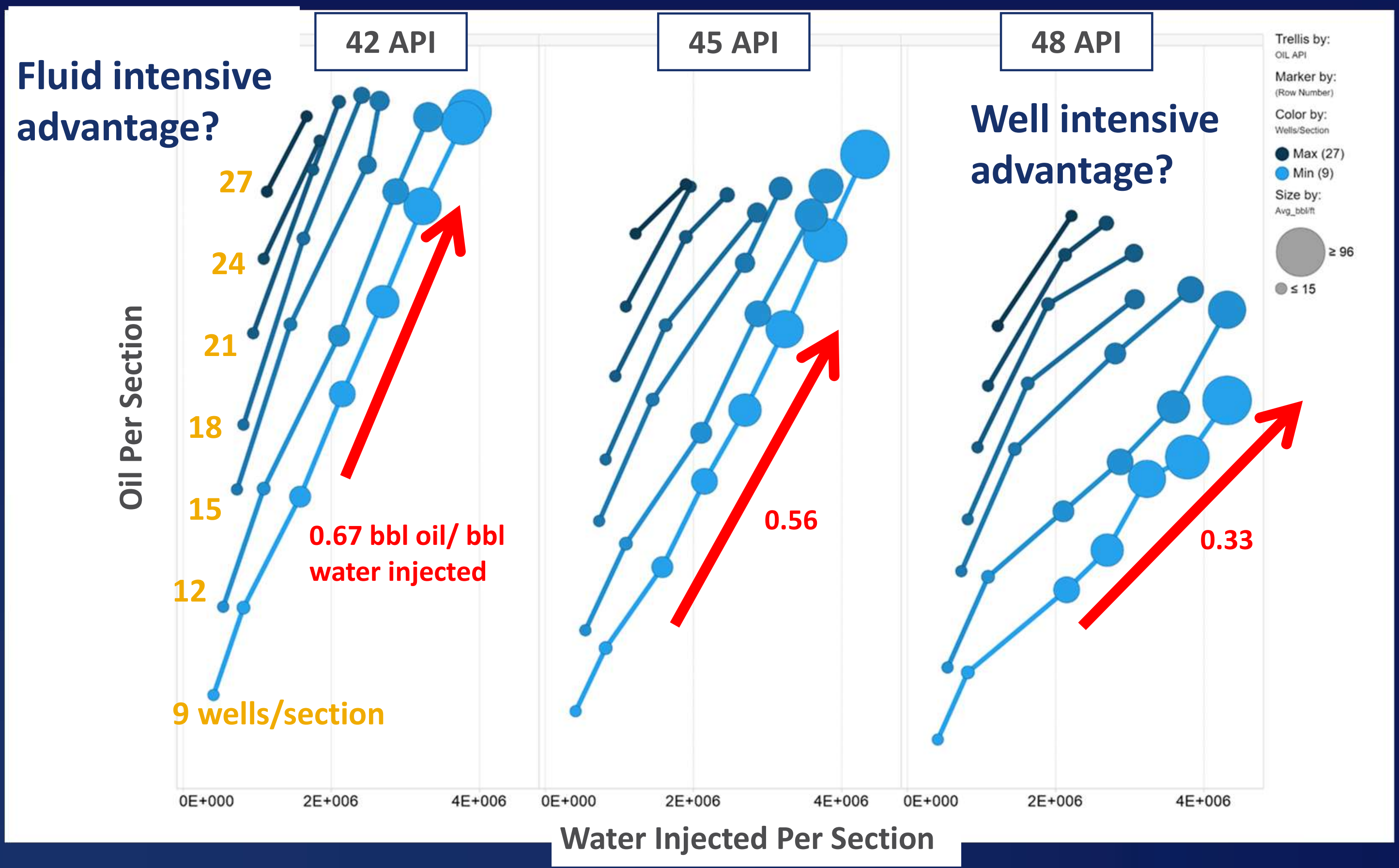
API gravity

Courtesy Core Lab Reservoir Fluid Services



Prediction Sensitivity to Reservoir Fluid

Tie lines of constant WPS

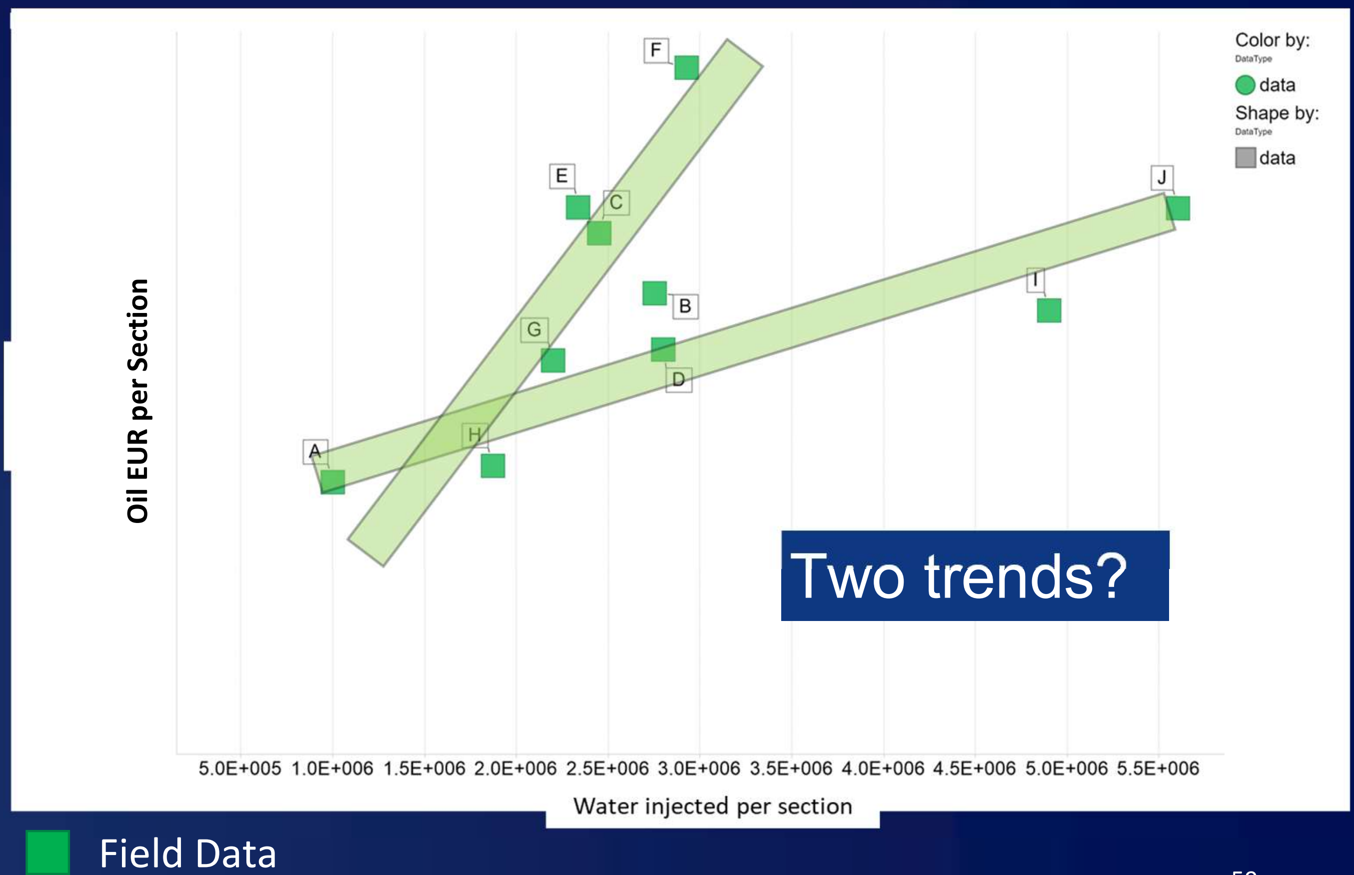


Response slope directly linked to economics of adjusting fluid intensity

Field Data: 10-Pattern Well Spacing Test

Area	Well Density (WPS)	Stim Fluid (BPF)	Actual Wtr/Sec (MMbbl)
A	10	20	1
B	10	55	2.8
C	14	35	2.5
D	16	35	2.8
E	17	28	2.3
F	18	33	2.9
G	20	22	2.2
H	22	17	1.9
I	28	35	4.9
J	32	35	5.6

Spacing Test Detail



Interpretation of Field Data (1)

Area	Well Density (WPS)	Stim Fluid (BPF)	Actual Wtr/Sec (MMbbl)
A	10	20	1
B	10	55	2.8
C	14	35	2.5
D	16	35	2.8
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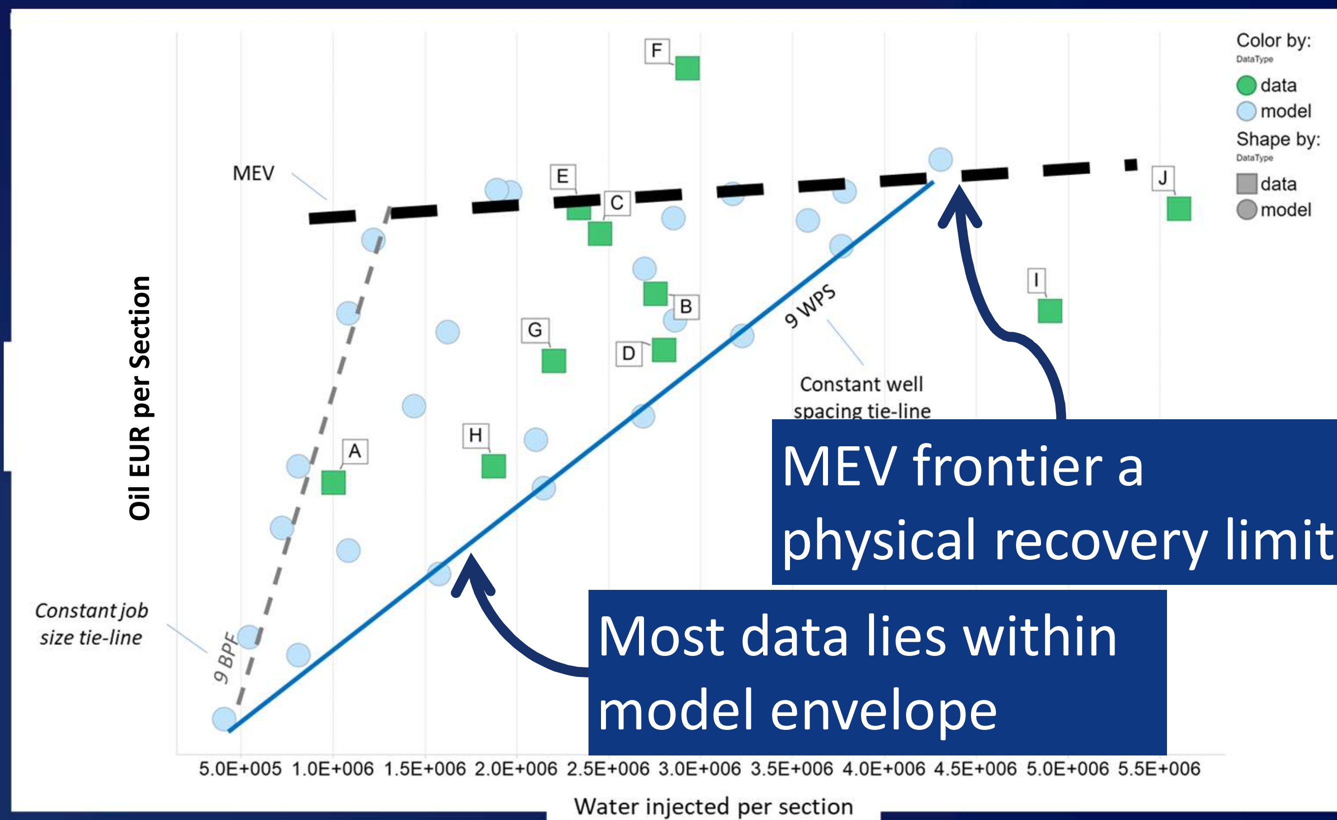
F	18	33	2.9
G	20	22	2.2
H	22	17	1.9
I	28	35	4.9
J	32	35	5.6

Spacing Test Detail

Field Data

Simulation



Interpretation of Field Data (2)

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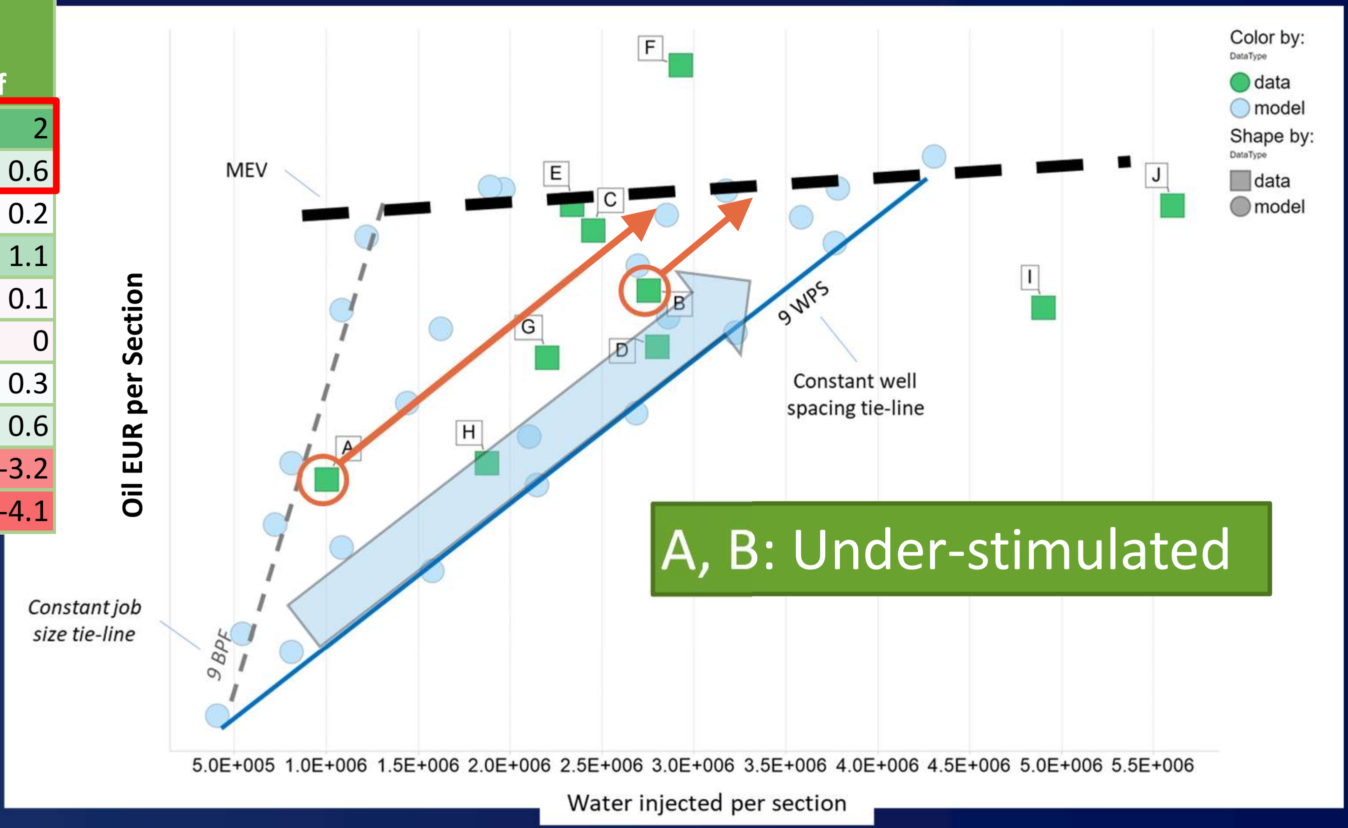
Area	Well Density (WPS)	Stim Fluid (BPF)	Actual Wtr/Sec (MMbbl)	Right-Sized Wtr/Sec	Diff
A	10	20	1	3	2
B	10	55	2.8	3.4	0.6
C	14	35	2.5	2.7	0.2
D	16	35	2.8	3.9	1.1
E	17	28	2.3	2.4	0.1
F	18	33	2.9	2.9	0
G	20	22	2.2	2.5	0.3
H	22	17	1.9	2.5	0.6
I	28	35	4.9	1.7	-3.2
J	32	35	5.6	1.5	-4.1

Field Data

Simulation

Design opportunity



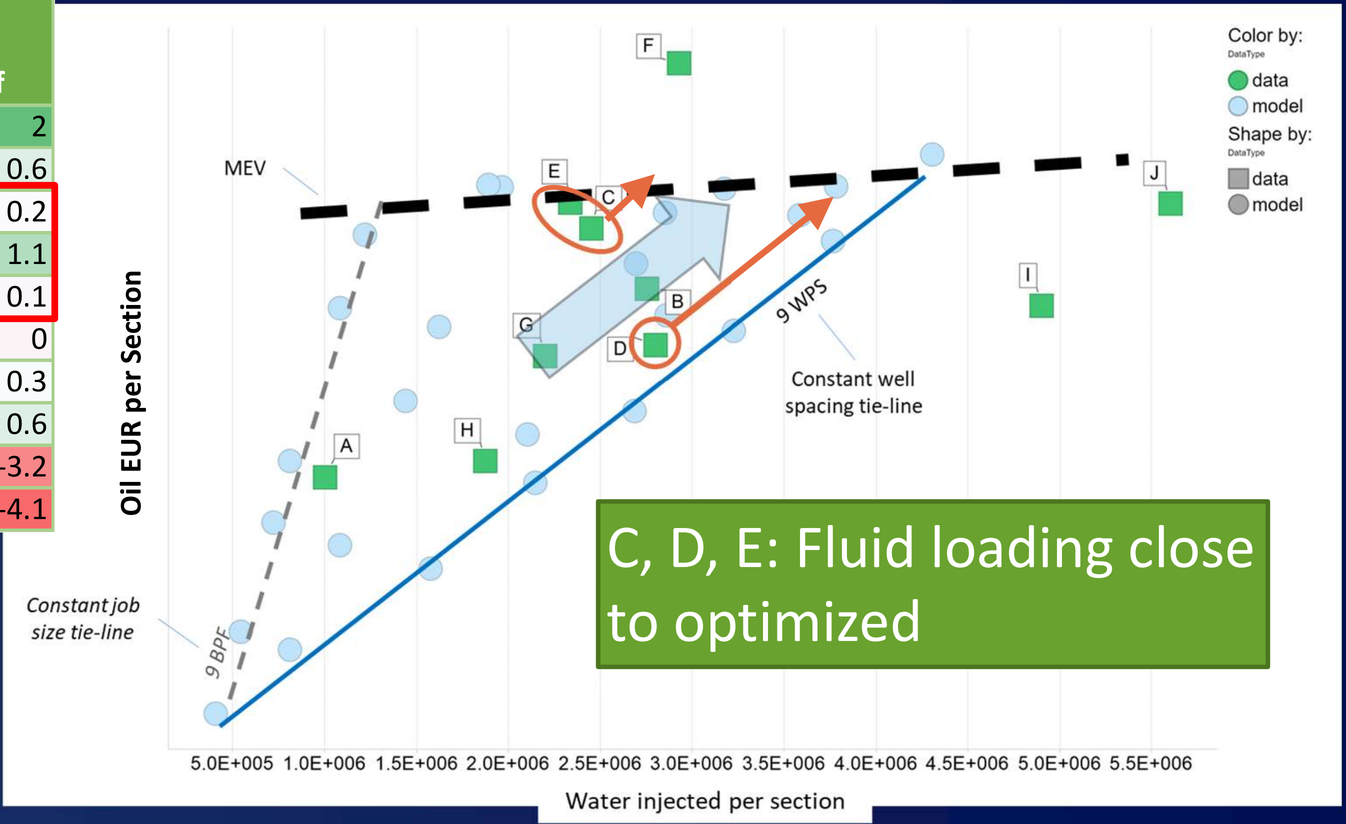
Interpretation of Field Data (3)

Area	Well Density (WPS)	Stim Fluid (BPF)	Actual Wtr/Sec (MMbbl)	Right-Sized Wtr/Sec	Diff
A	10	20	1	3	2
B	10	55	2.8	3.4	0.6
C	14	35	2.5	2.7	0.2
D	16	35	2.8	3.9	1.1
E	17	28	2.3	2.4	0.1
F	18	33	2.9	2.9	0
G	20	22	2.2	2.5	0.3
H	22	17	1.9	2.5	0.6
I	28	35	4.9	1.7	-3.2
J	32	35	5.6	1.5	-4.1

Field Data

Simulation

Design opportunity

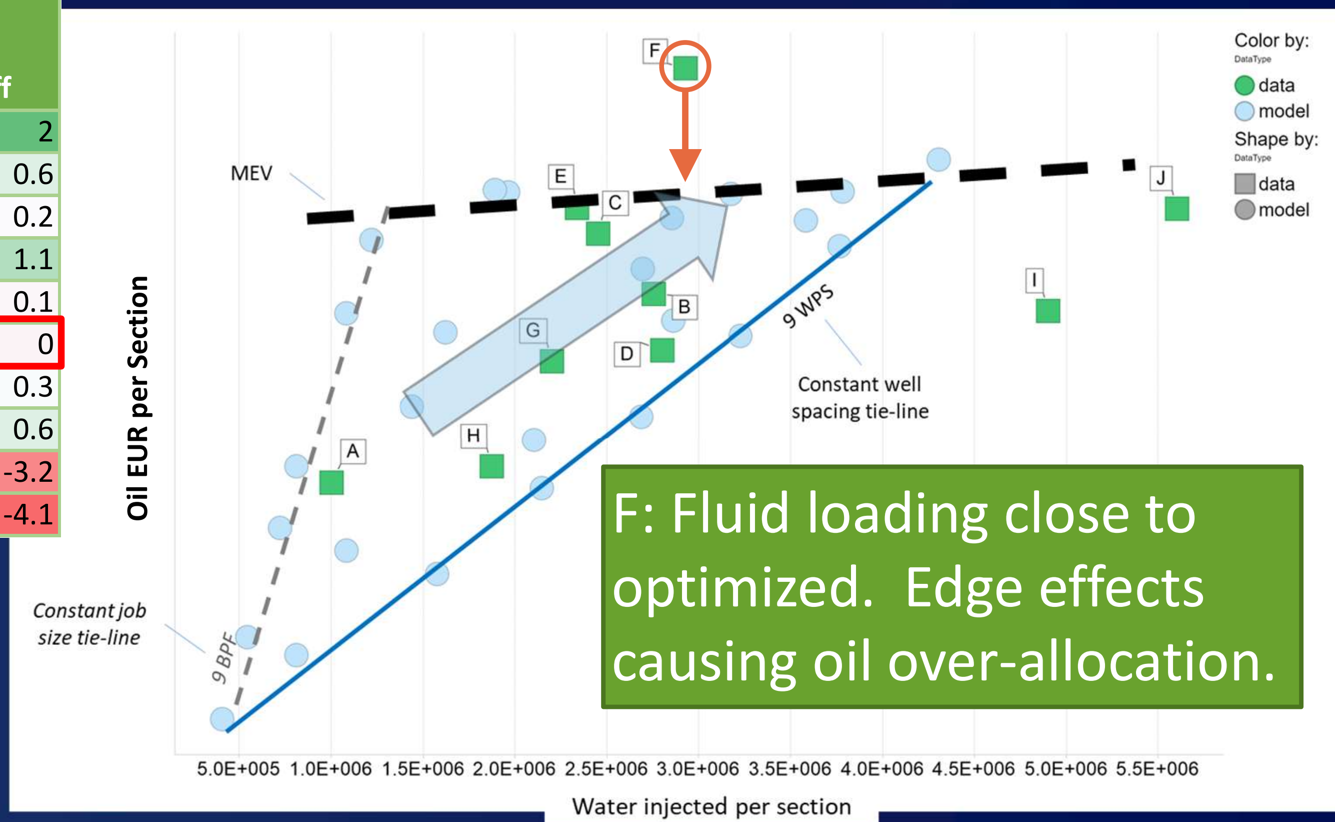


C, D, E: Fluid loading close to optimized

Interpretation of Field Data (4)

Area	Well Density (WPS)	Stim Fluid (BPF)	Actual Wtr/Sec (MMbbl)	Right-Sized Wtr/Sec	Diff
A	10	20	1	3	2
B	10	55	2.8	3.4	0.6
C	14	35	2.5	2.7	0.2
D	16	35	2.8	3.9	1.1
E	17	28	2.3	2.4	0.1
F	18	33	2.9	2.9	0
G	20	22	2.2	2.5	0.3
H	22	17	1.9	2.5	0.6
I	28	35	4.9	1.7	-3.2
J	32	35	5.6	1.5	-4.1

- Field Data
- Simulation
- Design opportunity



F: Fluid loading close to optimized. Edge effects causing oil over-allocation.

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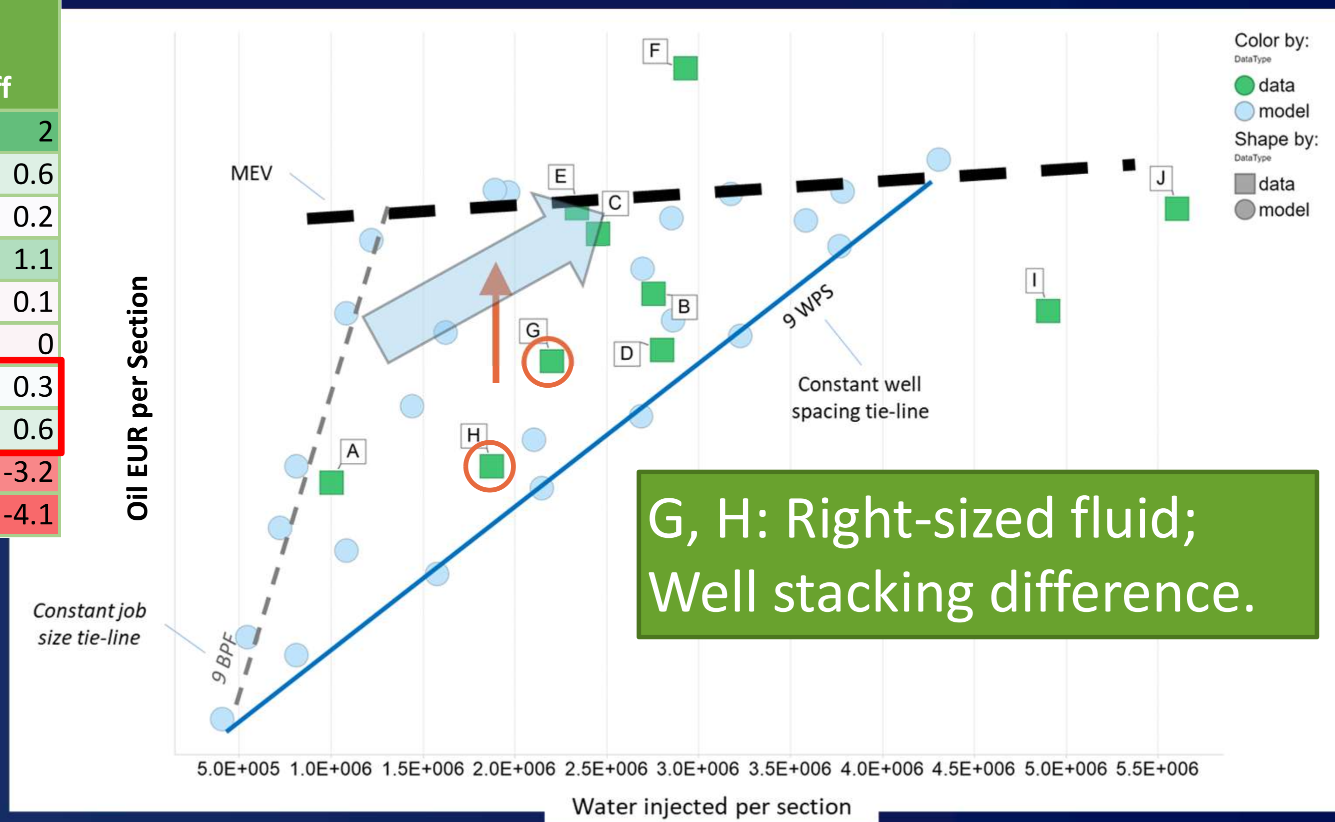
Interpretation of Field Data (5)

Area	Well Density (WPS)	Stim Fluid (BPF)	Actual Wtr/Sec (MMbbl)	Right-Sized Wtr/Sec	Diff
A	10	20	1	3	2
B	10	55	2.8	3.4	0.6
C	14	35	2.5	2.7	0.2
D	16	35	2.8	3.9	1.1
E	17	28	2.3	2.4	0.1
F	18	33	2.9	2.9	0
G	20	22	2.2	2.5	0.3
H	22	17	1.9	2.5	0.6
I	28	35	4.9	1.7	-3.2
J	32	35	5.6	1.5	-4.1



Field Data

Simulation

Design opportunity

Interpretation of Field Data (6)

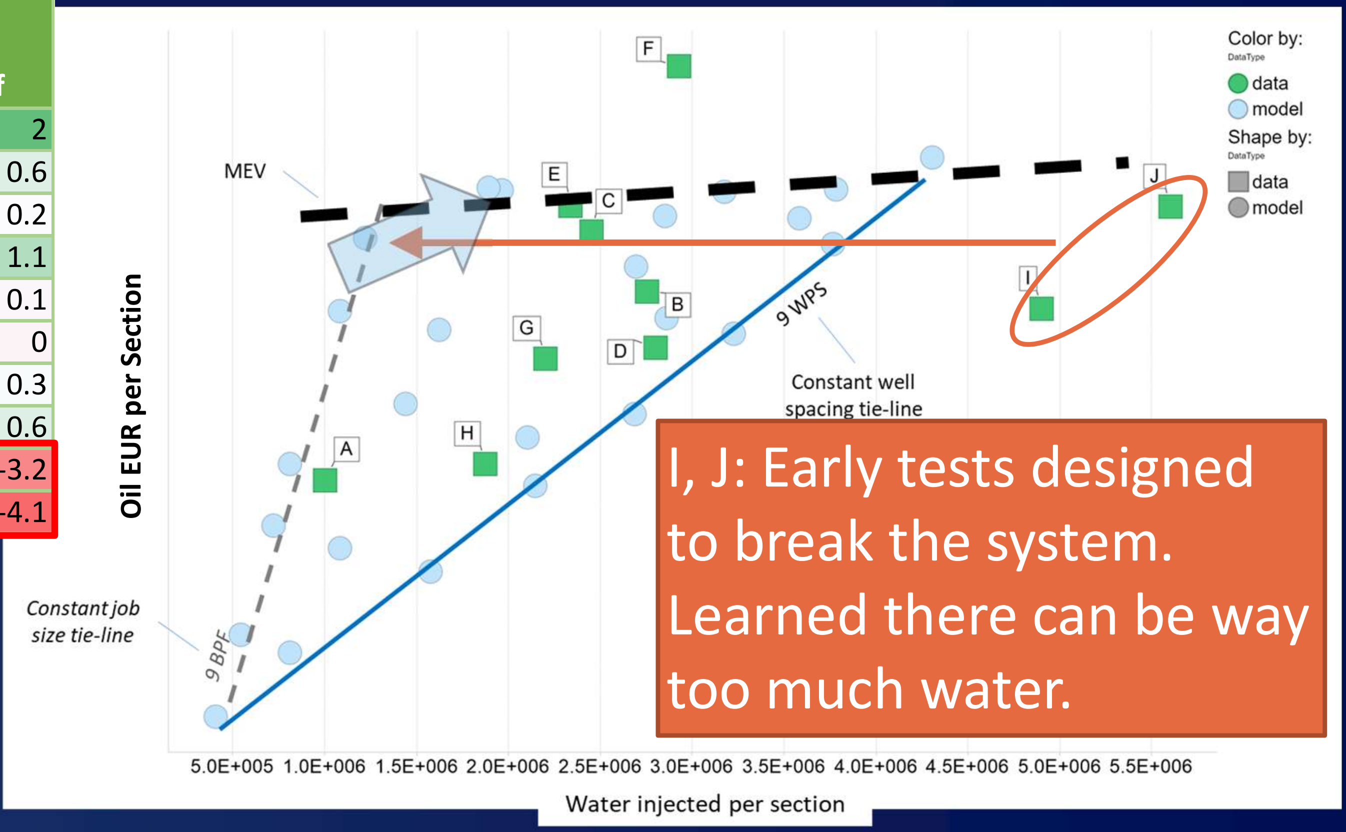
SPE DISTINGUISHED LECTURER

Area	Well Density (WPS)	Stim Fluid (BPF)	Actual Wtr/Sec (MMbbl)	Right-Sized Wtr/Sec	Diff
A	10	20	1	3	2
B	10	55	2.8	3.4	0.6
C	14	35	2.5	2.7	0.2
D	16	35	2.8	3.9	1.1
E	17	28	2.3	2.4	0.1
F	18	33	2.9	2.9	0
G	20	22	2.2	2.5	0.3
H	22	17	1.9	2.5	0.6
I	28	35	4.9	1.7	-3.2
J	32	35	5.6	1.5	-4.1

Field Data

Simulation

Design opportunity



HF Fundamentals – selections Planar Fracture Assumption

- 4.12.1 p.113: The paradigm of planar fracture was chosen more for convenience than for an accurate description of fractures in geological formations.
- p.119 Because fractures grow perpendicular to the least principal stress, most hydraulic fractures can be approximated as planar.

Hydraulic Fracturing: Fundamentals and Advancements, SPE Monograph, Miskimins editor-in-chief, 2019, Ch.4 – Wiejers and de Pater.

HF Fundamentals – selections DFN Modeling

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- 4.12.1 p.117: Detailed shale stimulation studies with DFN simulations could be useful for characterizing the formations, but it appears more productive to develop much simpler modeling techniques that can be used for designing routine well stimulations.
- 4.12.1 p.119: DFN models contain many parameters that need to be calibrated on the basis of full reservoir characterization and microseismic mapping and treatment records. Given the large number of input parameters, it is impossible to make reliable, detailed predictions of fracture geometry in offset wells. At best, an average fracture geometry can be obtained from model calibration.

Hydraulic Fracturing: Fundamentals and Advancements, SPE Monograph, Miskimins editor-in-chief, 2019, Ch.4 – Wiejers and de Pater.

HF Fundamentals – selections
Coupled Models

- 4.13.1 …using only limited coupling will be more practical in many cases compared with full coupling. For instance, coupling of a fractured well to the reservoir is now routinely done with explicit fractures in 3D simulation models, but ignoring detailed stress changes. Stress evolution by depletion might be a necessary component to include because depletion tends to give a strong stress effect, and this has a big influence on fracture geometry.
- Different levels of coupling can be applied: The simplest way is to couple pressure to stress and displacements, but full coupling of flow properties (transmissibility) with stress and its impact on flow and pressure can also be performed.
- **Porosity is often a function of the stress, but more importantly permeability will nearly always exhibit a strong stress dependency. Fracture propagation by fluid injection will change the permeability in the fracture plane by orders of magnitude because of fracture opening. Also, permeability might change because of shear strain and compaction that occurs over a large volume.**
- The simplest method to incorporate a fracture into an FEM is the so-called "smeared crack" method. Instead of explicitly modeling the fracture opening displacement, the element properties are modified to describe the fracture opening. In some models, the opening is even neglected and only fracture transmissibility is included because that is most important.
- The capability to accurately include the filtrate fluid in the reservoir-simulation input is very important when trying to accurately model (or history match) the initial post-fracture cleanup period, which can be of critical importance especially in tight gas reservoirs.

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