

# **The Intersection of Environment and EOR: How Carbon Capture is Changing Tertiary Recovery**

**Dr. Robert S. Balch  
Petroleum Recovery Research Center  
New Mexico Tech**

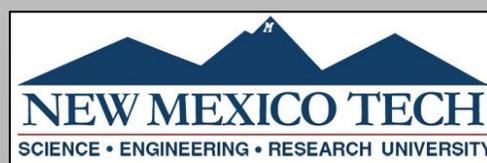


Society of Petroleum Engineers  
Distinguished Lecturer Program  
[www.spe.org/dl](http://www.spe.org/dl)

# ACKNOWLEDGMENTS

Funding for this project is provided by the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) through the Southwest Regional Partnership on Carbon Sequestration (SWP) under Award No. DE-FC26-05NT42591. Additional support was provided by Chaparral Energy, LLC, Perdure Petroleum, LLC, and Schlumberger Carbon Services.

The presenters gratefully acknowledge the contributions of more than 50 SWP scientists and engineers, working at New Mexico Tech, the University of Utah, the University of Missouri, Los Alamos National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories.

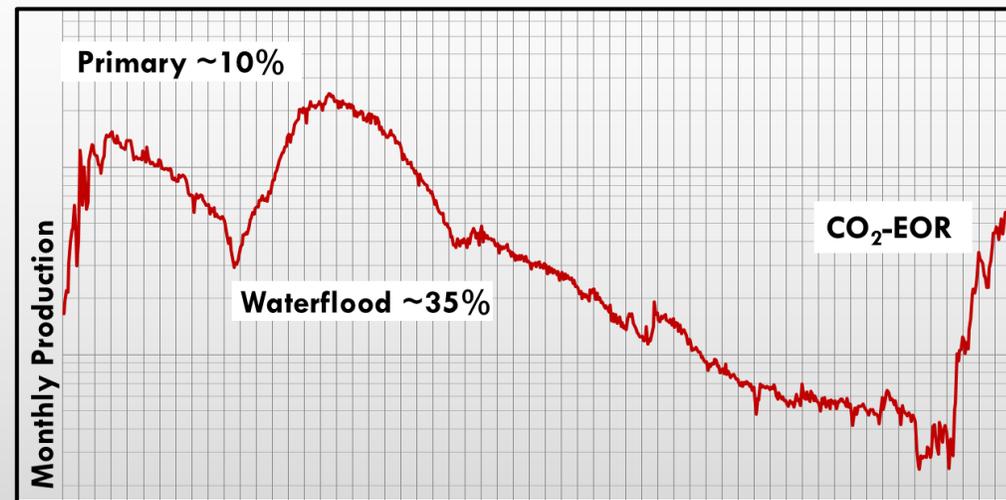


# OUTLINE

1. A brief history of CO<sub>2</sub> Enhanced Oil Recovery (EOR)
2. Carbon Capture and Storage (CCS) vs utilization (CCUS)
3. Case Studies of Carbon capture and utilization for EOR
4. Southwest Partnership demonstration at Farnsworth unit
  - a) Introduction to Farnsworth
  - b) Characterization of the reservoir and seals
  - c) Models and Simulation
  - d) Monitoring, Verification and Accounting (carbon storage security)
5. Final thoughts and takeaways

# CO<sub>2</sub> ENHANCED OIL RECOVERY

- CO<sub>2</sub> acts as a solvent at the right pressure and temperature conditions
  - Impact on production – typical response to a CO<sub>2</sub> flood is equivalent to the response of a waterflood.
  - Extends life of fields: CO<sub>2</sub> EOR can add an additional 30+ years after the end of a waterflood.
- Limited by
  - Natural supply
  - Limited by infrastructure
  - Minimum miscibility pressure

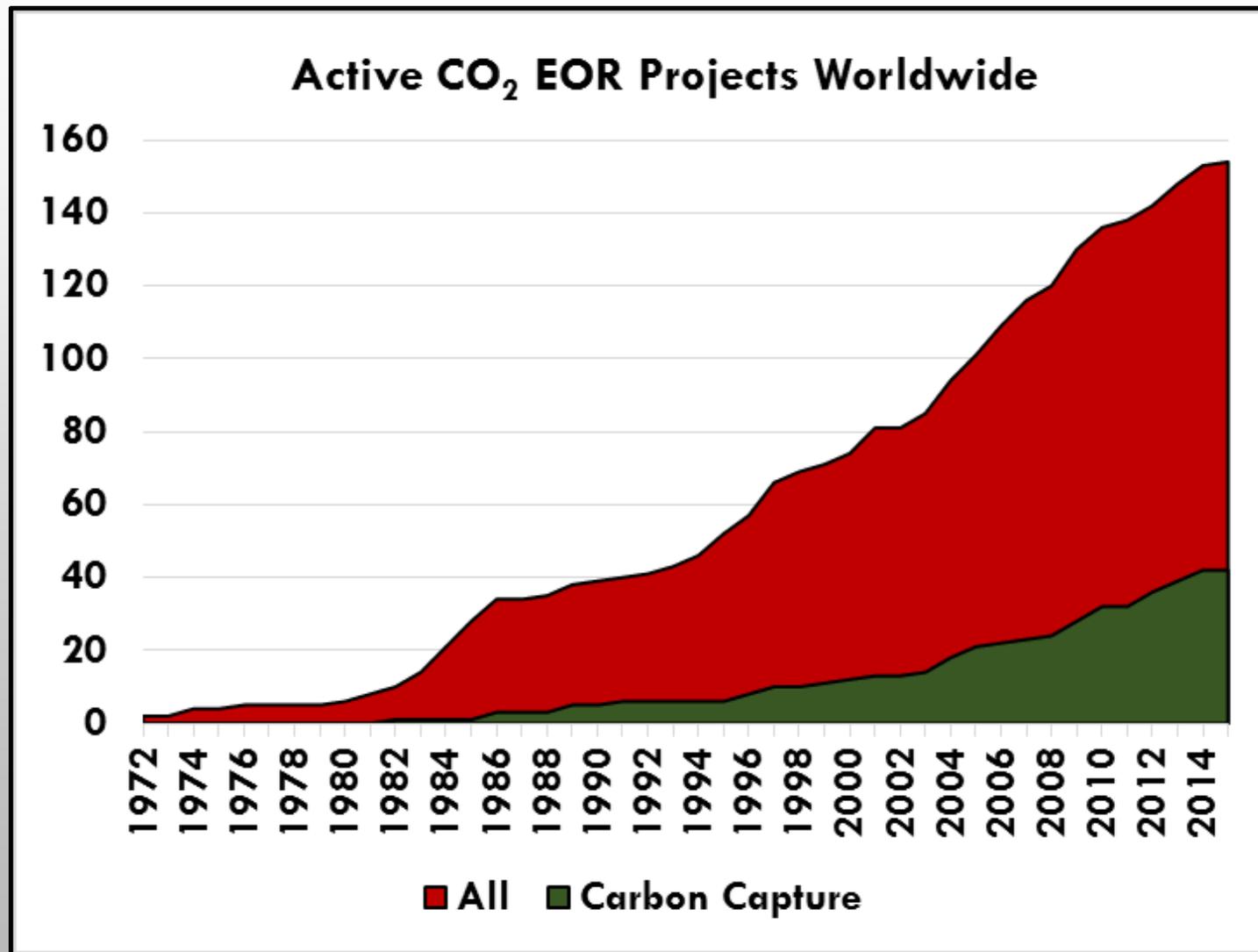


## Criteria for Screening Reservoirs for CO<sub>2</sub> EOR

Temperature, °F	< 250, not critical
Pressure, PSIA	>1200, varies
Permeability, mD	>1
Oil Gravity, °API	> 27
Viscosity, cp	< 10
Residual Oil Saturation, %	>25
Depth, ft	<9800 and >2000

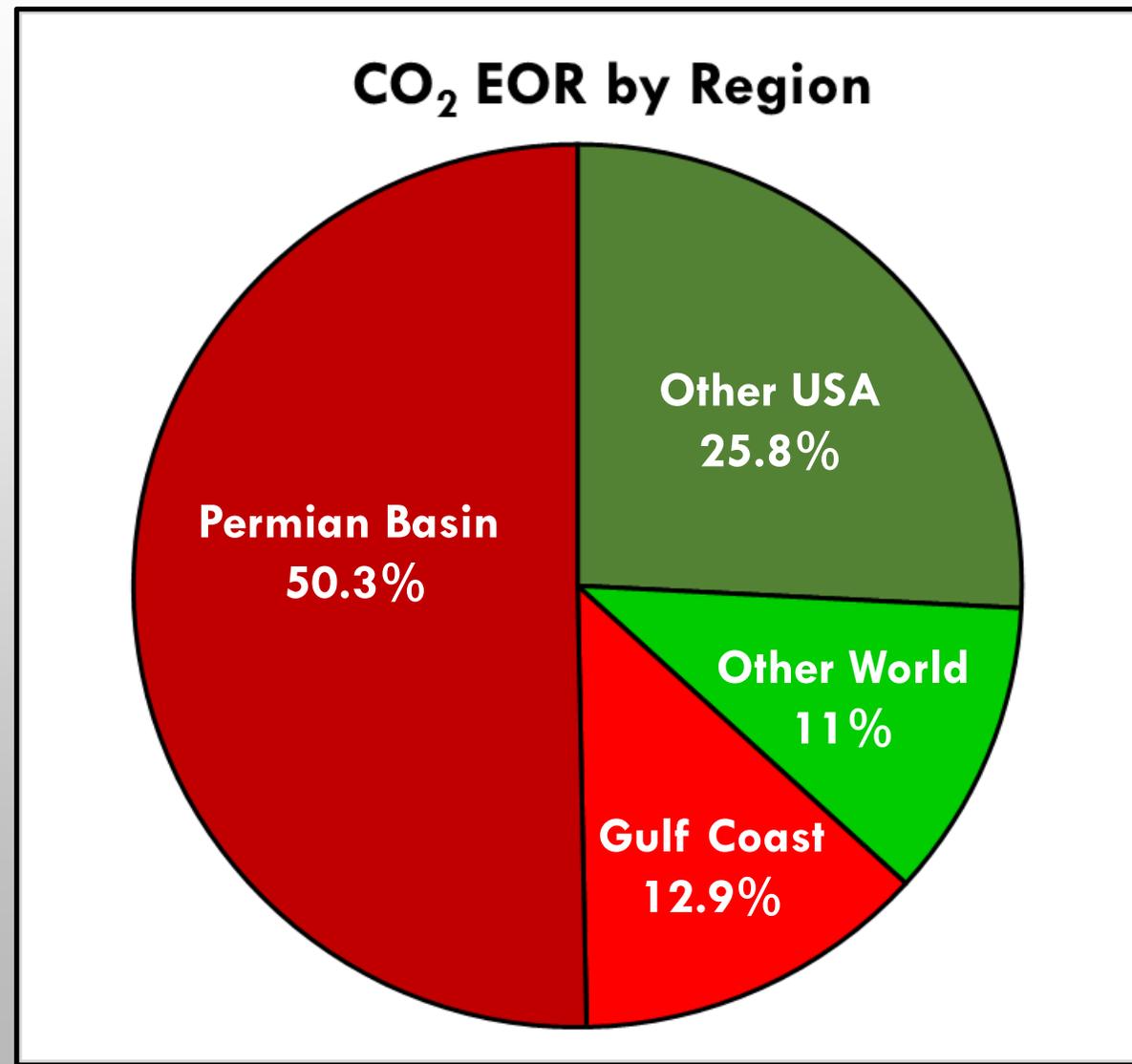
# CO<sub>2</sub> EOR PROJECTS

- First CO<sub>2</sub> EOR project started in 1972 at SACROC unit in Texas
- Since then 154 additional projects have been emplaced, initially in the Permian basin and Gulf coast areas of the United States
  - Availability of Natural CO<sub>2</sub>
- Carbon capture has enabled additional projects in the USA and the World

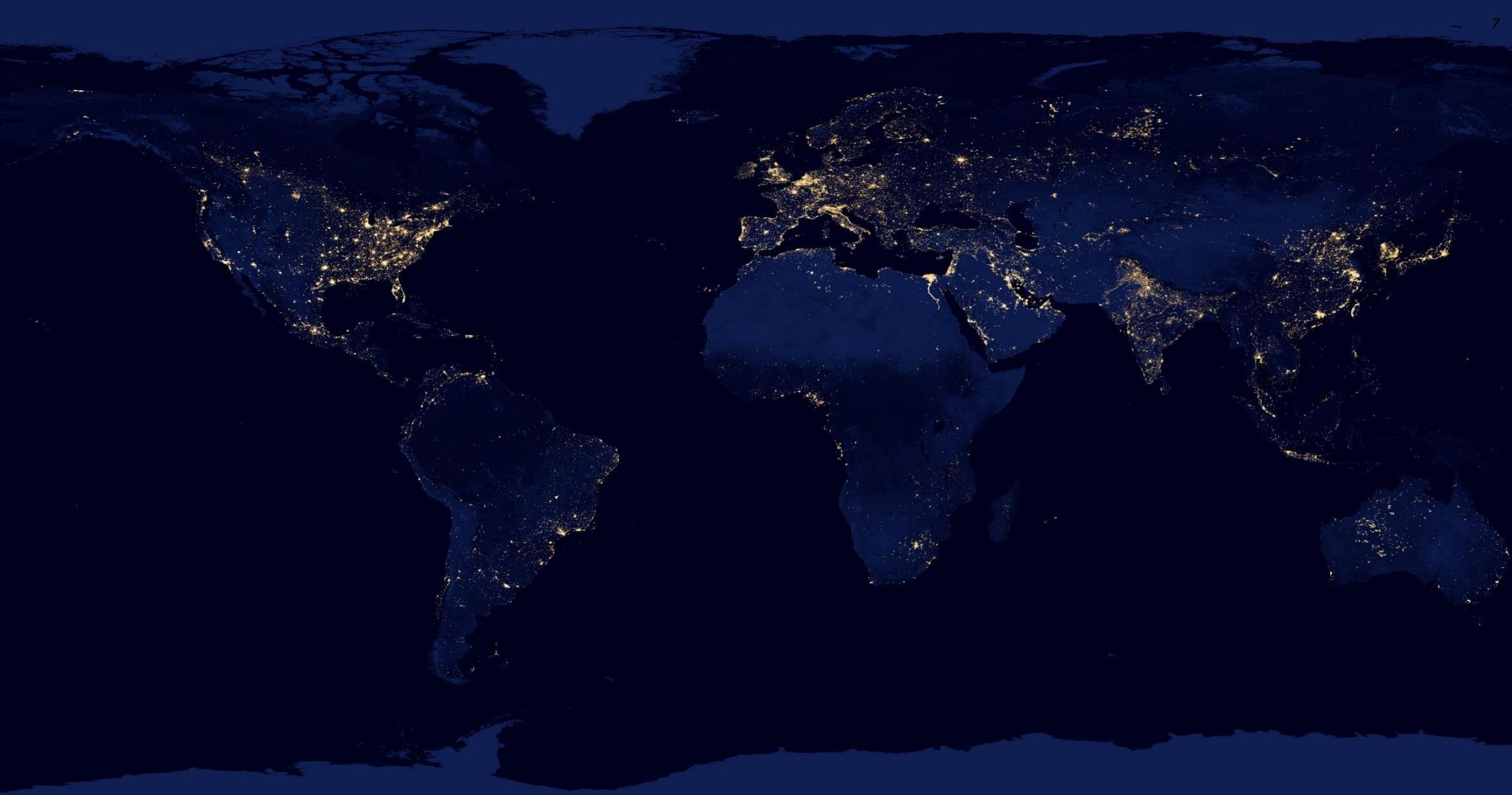


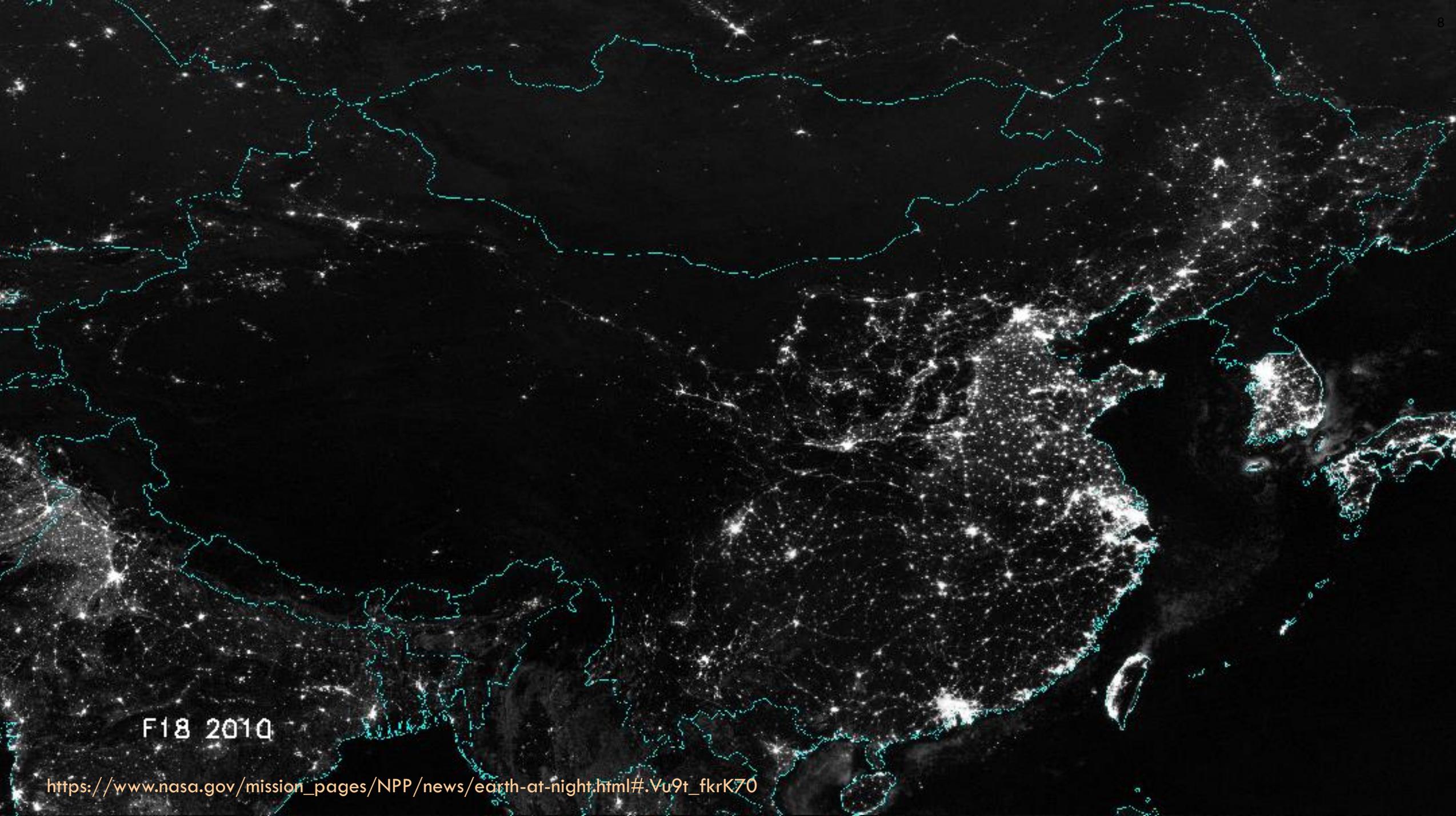
# CARBON CAPTURE, (UTILIZATION) AND STORAGE

- Concerns over CO<sub>2</sub> in the atmosphere is prompting governments to investigate CCS/CCUS
- For large point sources (coal plants) looking at saline aquifers
- For smaller point sources use for EOR is growing due to:
  - Proximity to mature fields
  - Purity of CO<sub>2</sub>
  - Existing oil field infrastructure



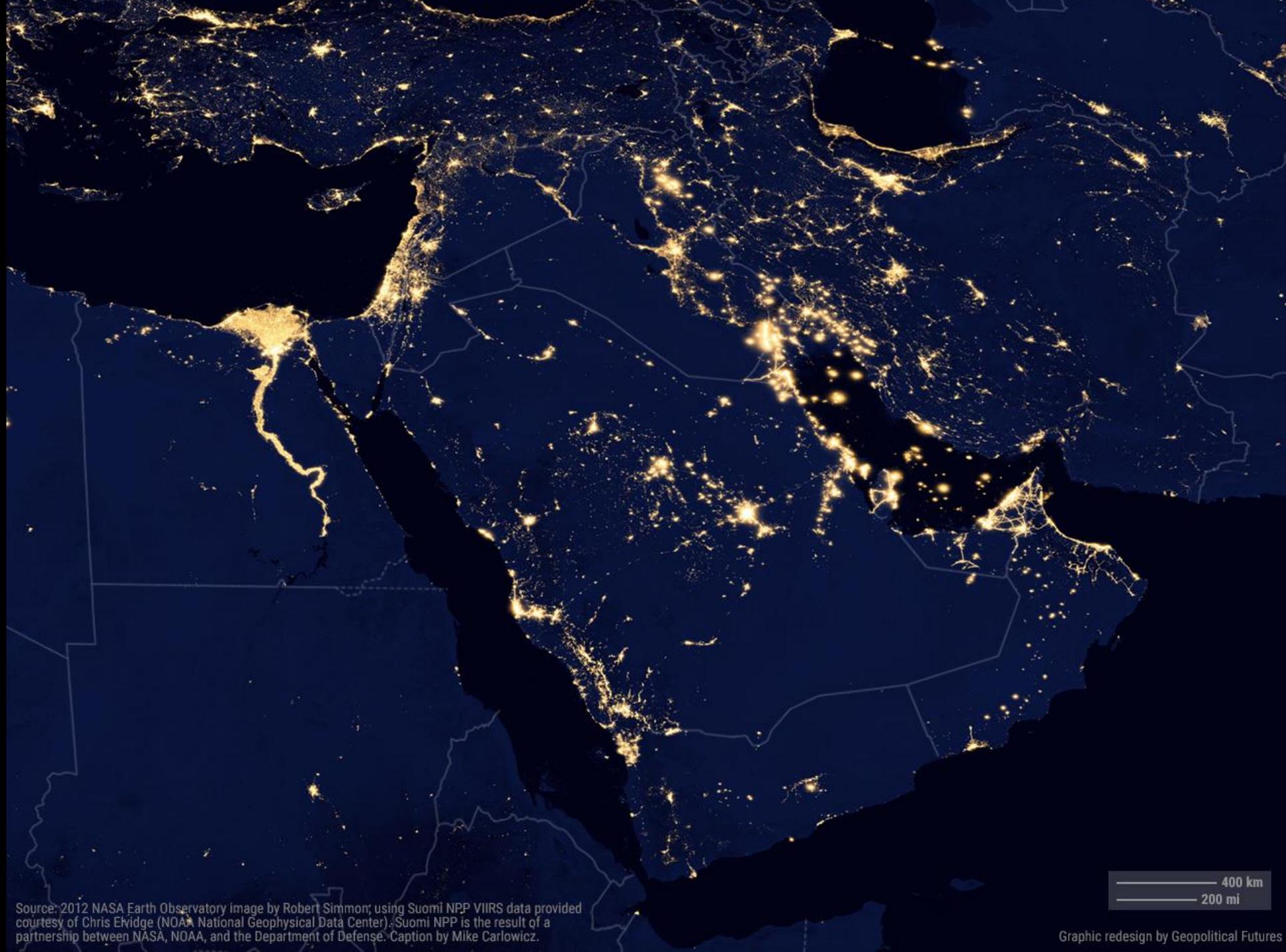
Plotted using data tabulated in Oil and Gas Journal April, 2014





F18 201Q

[https://www.nasa.gov/mission\\_pages/NPP/news/earth-at-night.html#.Vu9t\\_fkrK70](https://www.nasa.gov/mission_pages/NPP/news/earth-at-night.html#.Vu9t_fkrK70)



Source: 2012 NASA Earth Observatory image by Robert Simmon; using Suomi NPP VIIRS data provided courtesy of Chris Elvidge (NOAA National Geophysical Data Center). Suomi NPP is the result of a partnership between NASA, NOAA, and the Department of Defense. Caption by Mike Carlowicz.



Graphic redesign by Geopolitical Futures

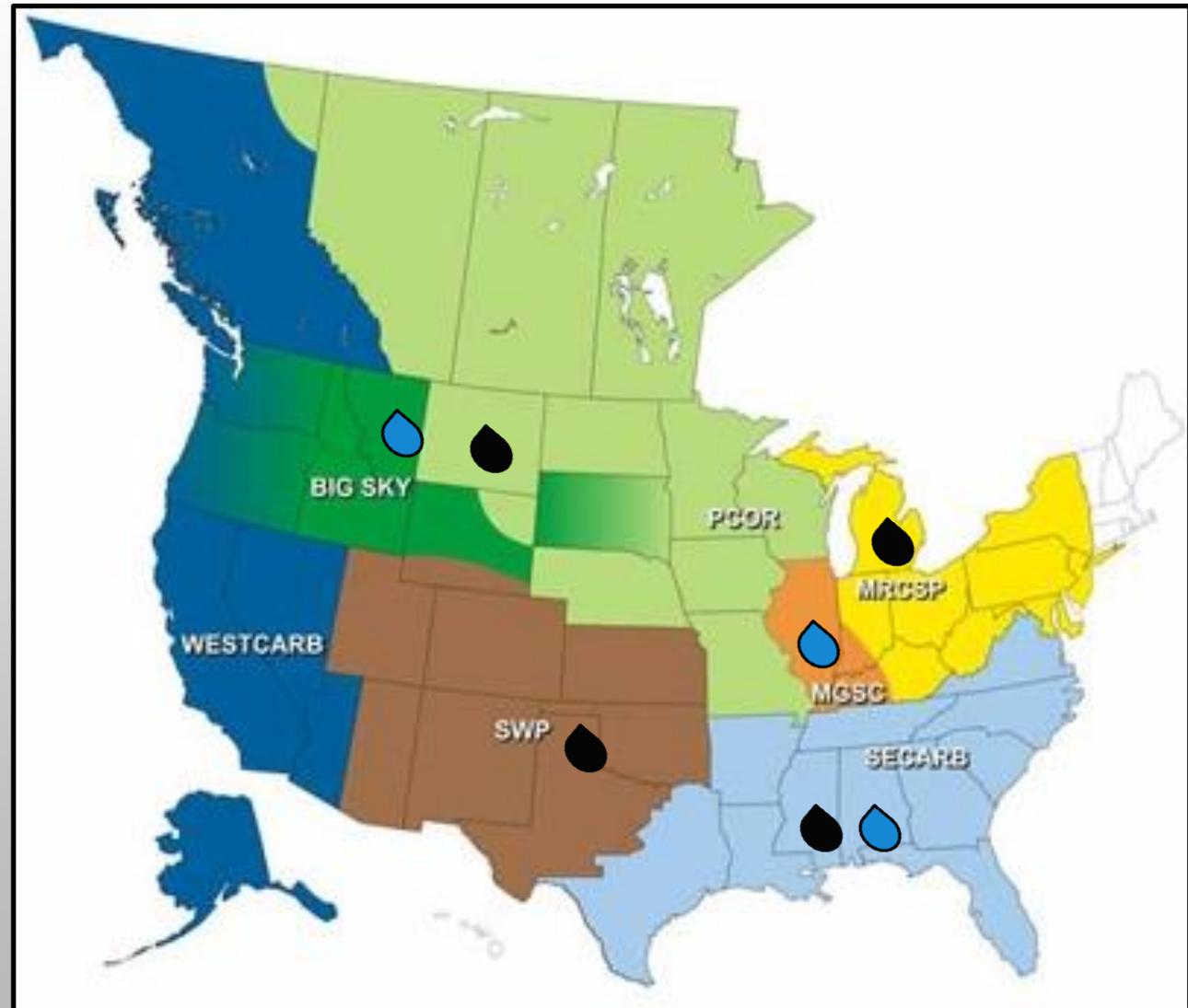


# IMPLICATIONS OF ANTHROPOGENIC CO<sub>2</sub> FOR EOR

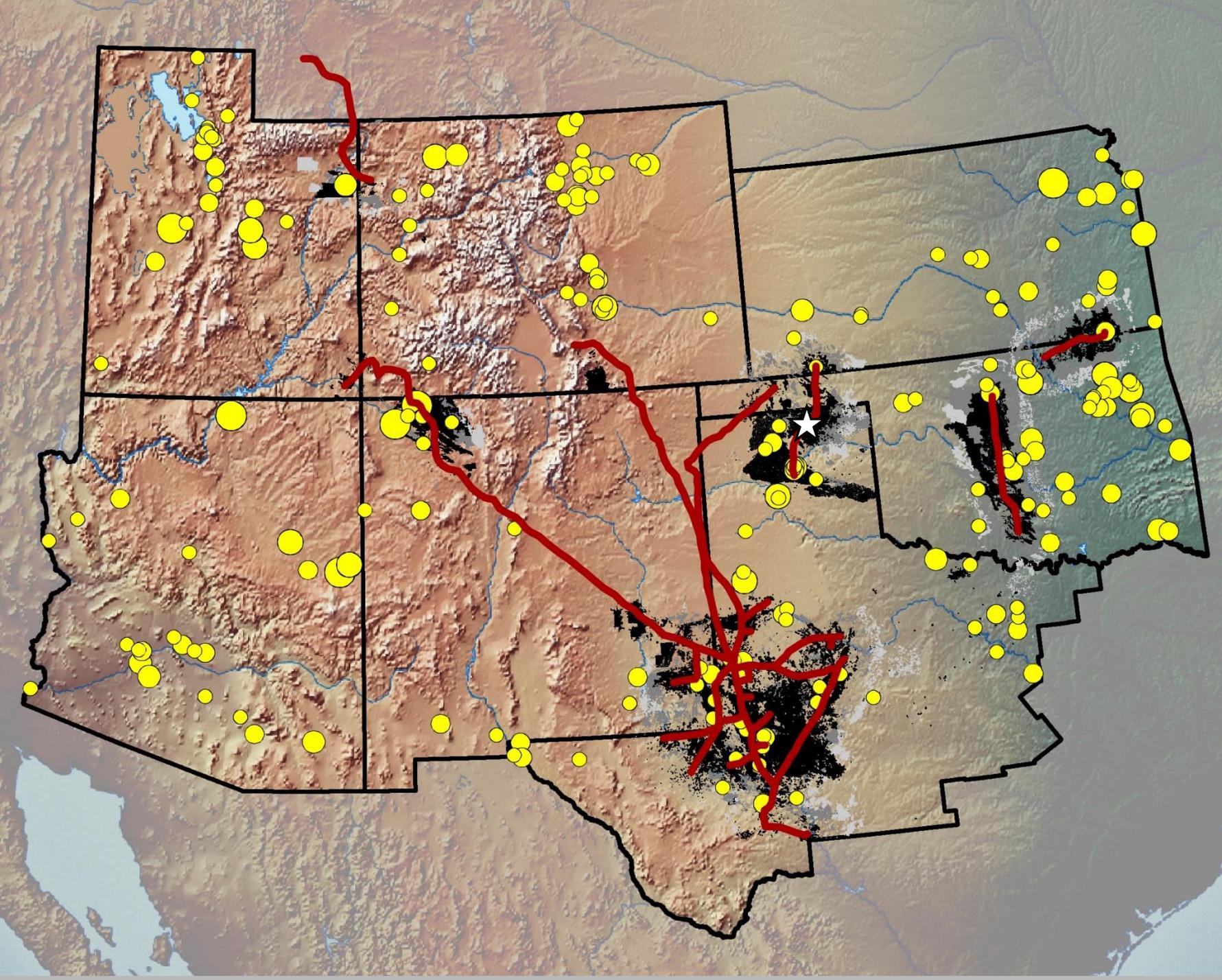
- Governmental Impacts
  - Tax credits/carbon credits
  - Faster path to sequestration due to profit potential
- Impacts for Producing Companies:
  - Local supply: Sources near every oil field
  - Increased recovery:  $\sim 2/3$  of all oil world-wide is stranded
  - Mitigate regulatory impacts
  - Market advantages
  - Public perception

# USA CASE STUDIES FOR CCS

- US Department of Energy  
Regional Carbon Sequestration  
Partnerships
  - Seven regional partnerships
- Each demonstrating injection of at least 1,000,000 metric tons of CO<sub>2</sub>
- Four projects are demonstrating storage in conjunction with EOR
- Developing “best practices” for utilizing captured CO<sub>2</sub>



# AREA COVERED BY THE SWP



CO<sub>2</sub> Sources  
(Metric Tons/year)

- 0.1 MT to 0.7 MT
- 0.7 MT to 2 MT
- 2 MT to 4 MT
- 4 MT to 10 MT
- 10 MT to 20 MT

Oil Fields  
(Distance from  
existing CO<sub>2</sub> pipeline)

- 0-20 km
- 20-40 km
- 40-60 km

— CO2 Pipeline

# FARNSWORTH UNIT

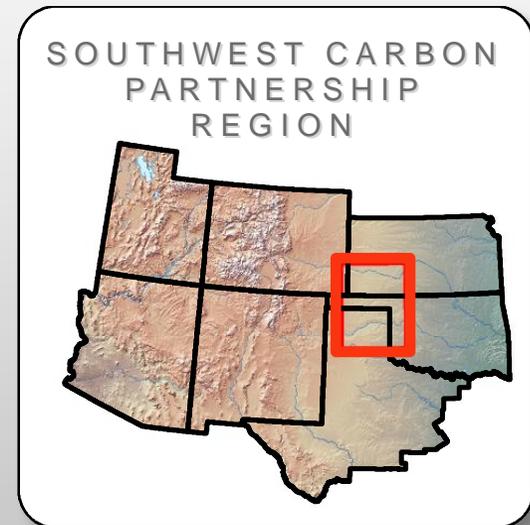
- Farnsworth field was discovered in 1955.
- Over 100 wells were completed by the year 1960.
  - Water injection for secondary recovery started in 1964.

Property	Value
Initial water saturation	31.4%
Initial reservoir pressure	2218 PSIA ( $P_{\text{bubble}}$ 2059)
API	36.7°
Original Oil in Place (OOIP)	120 MMSTB (60 MMSTB west-side)
Drive Mechanism	Solution Gas
Primary Recovery	11.2 MMSTB (9.3%)
Secondary Recovery	25.6 MMSTB (21.3%)

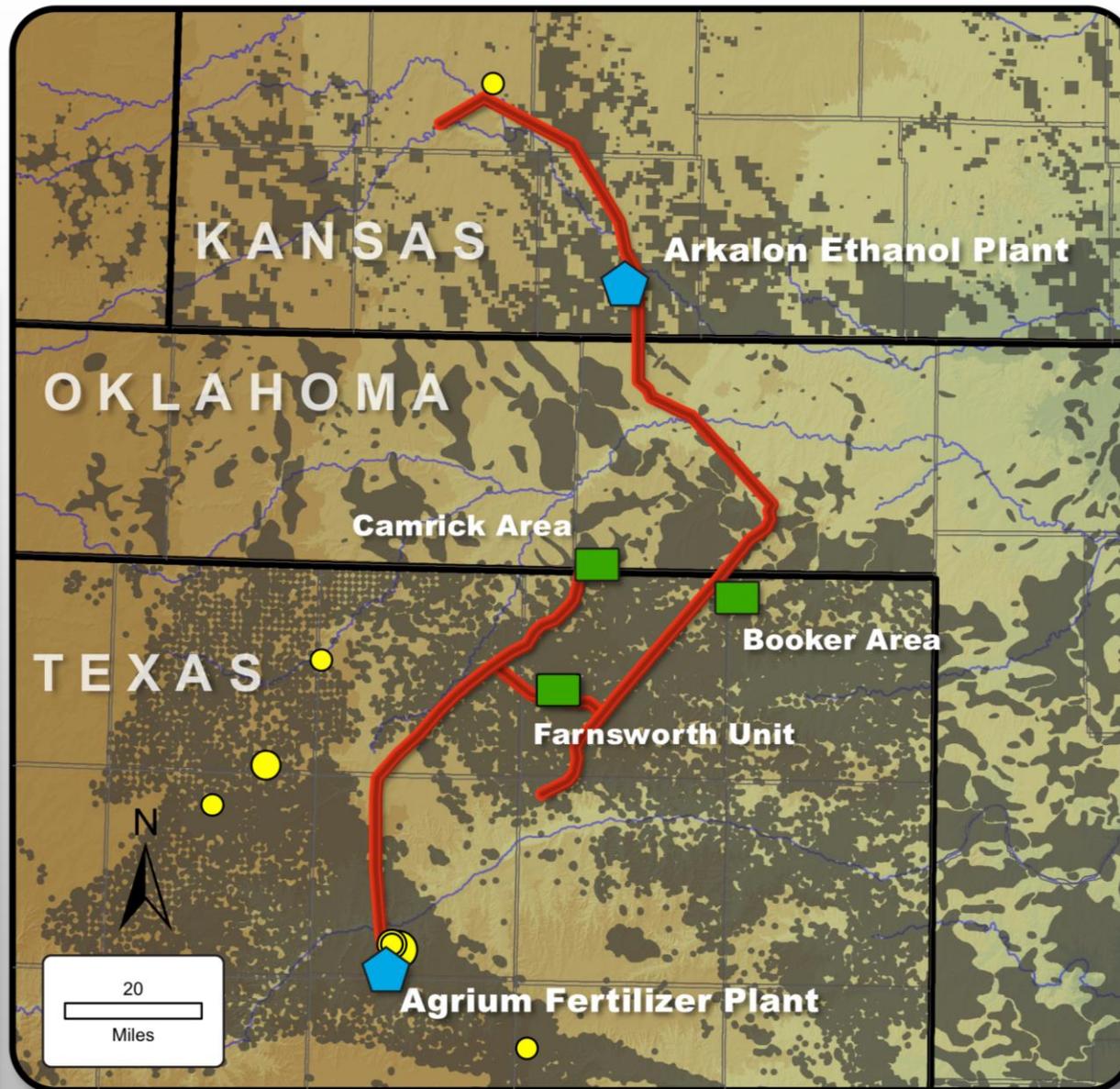
Anthropogenic Supply:  
500-600,000  
Metric tons  
CO<sub>2</sub>/year supply



<http://www.conestogaenergy.com/arkalon-ethanol>



[www.agrium.com](http://www.agrium.com)



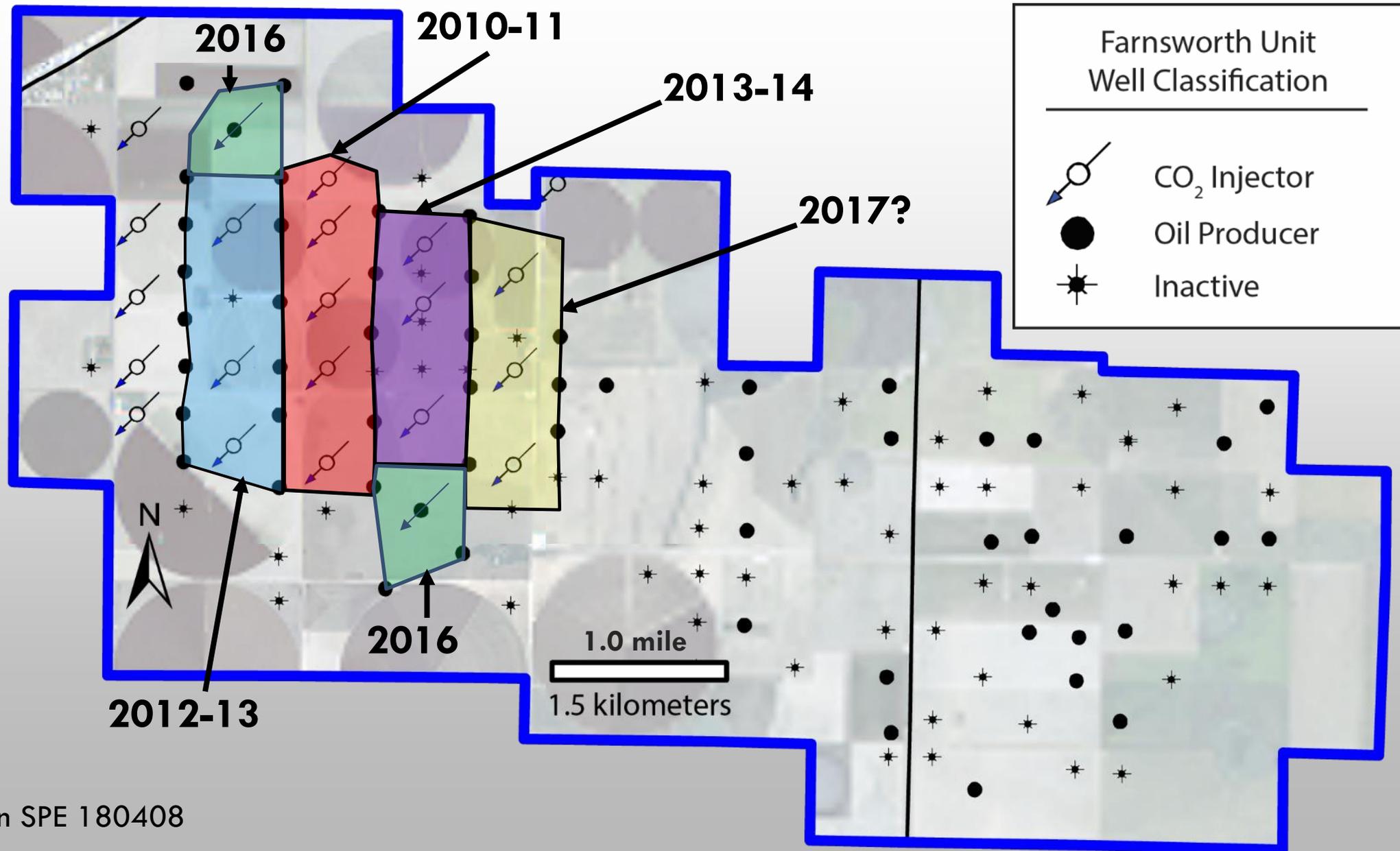
**Legend**

-  Utilization & Storage
-  Carbon Capture
-  Transportation
-  Oil Fields

**Other CO<sub>2</sub> Sources**

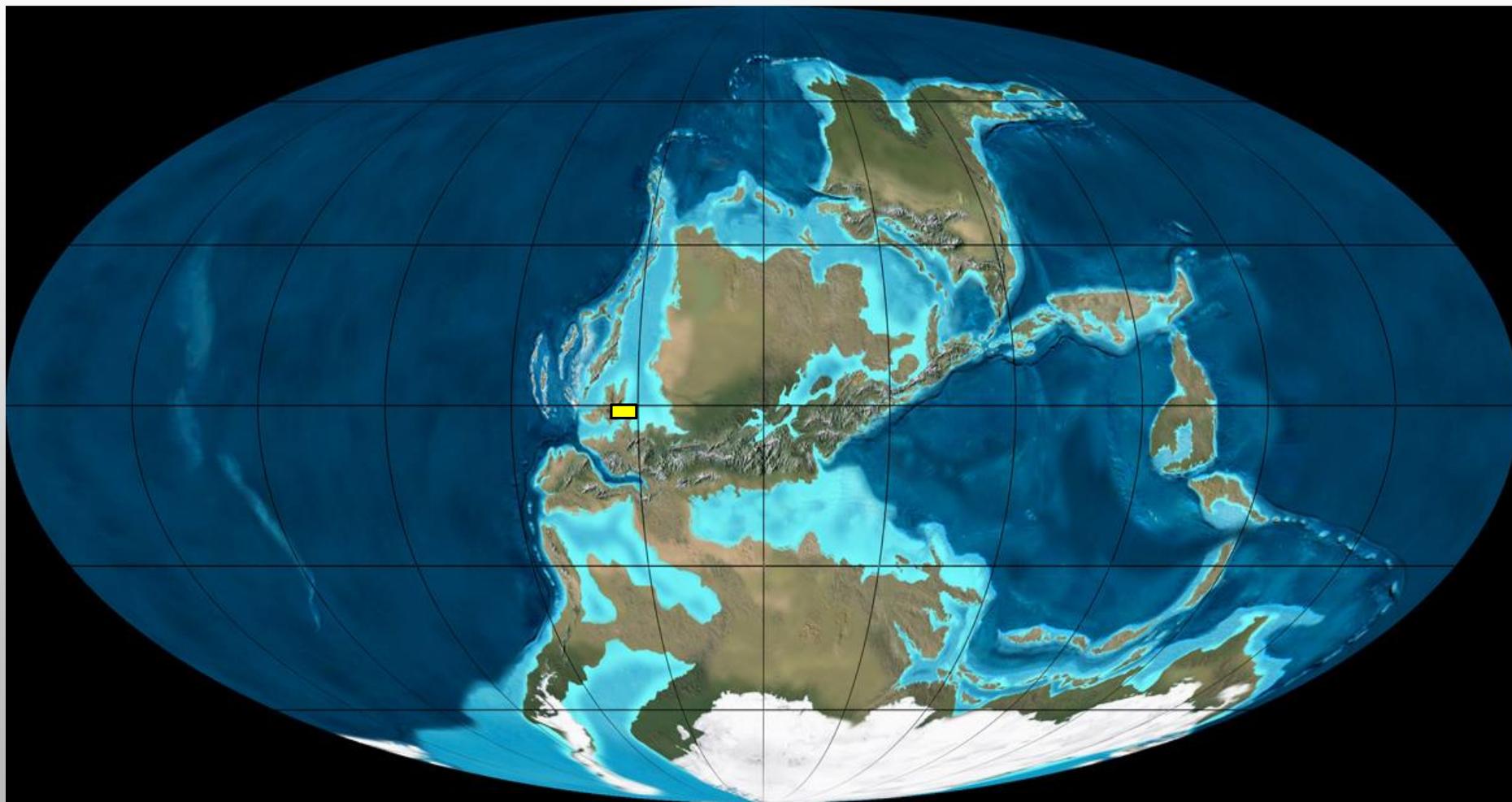
-  0.1 to 0.7 MT/yr
-  0.7 to 1.8 MT/yr
-  1.8 to 4 MT/yr
-  4 to 10 MT/yr
-  10 to 20 MT/yr

# ACTIVE AND CURRENTLY PLANNED CO<sub>2</sub> PATTERNS



# CHARACTERIZATION

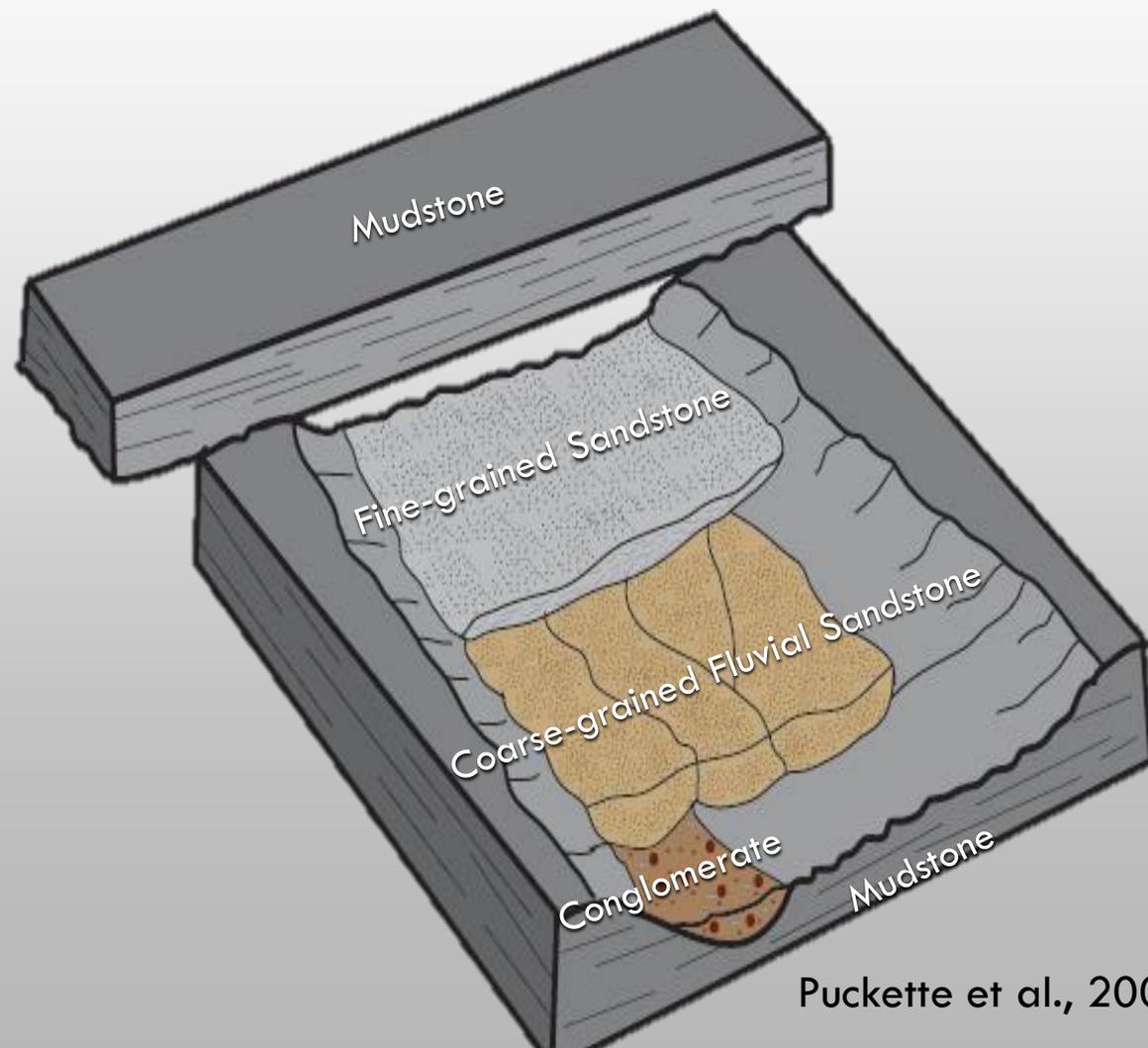
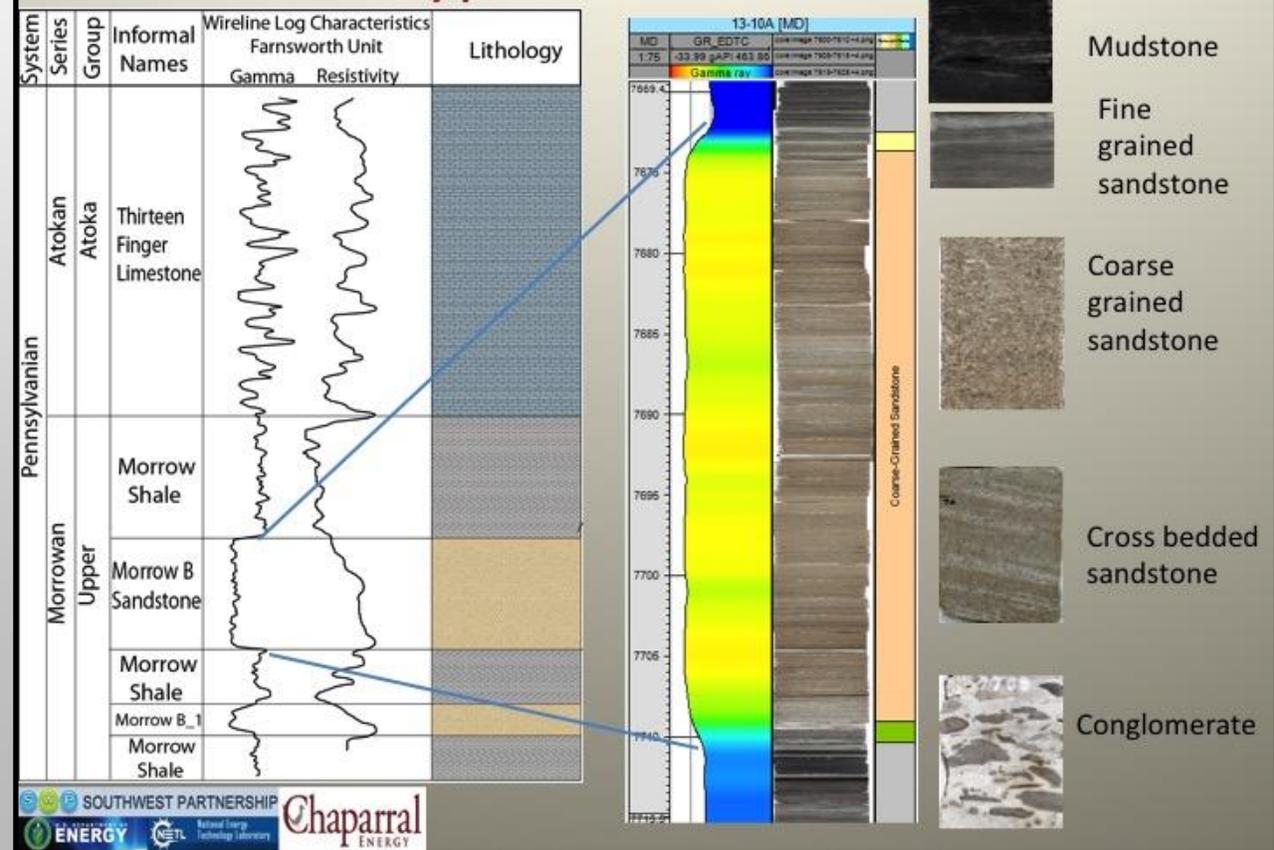
- Goals are to better understand geology of storage system
- Deliver fine scale facies based models including hydraulic flow units to improve flow simulation

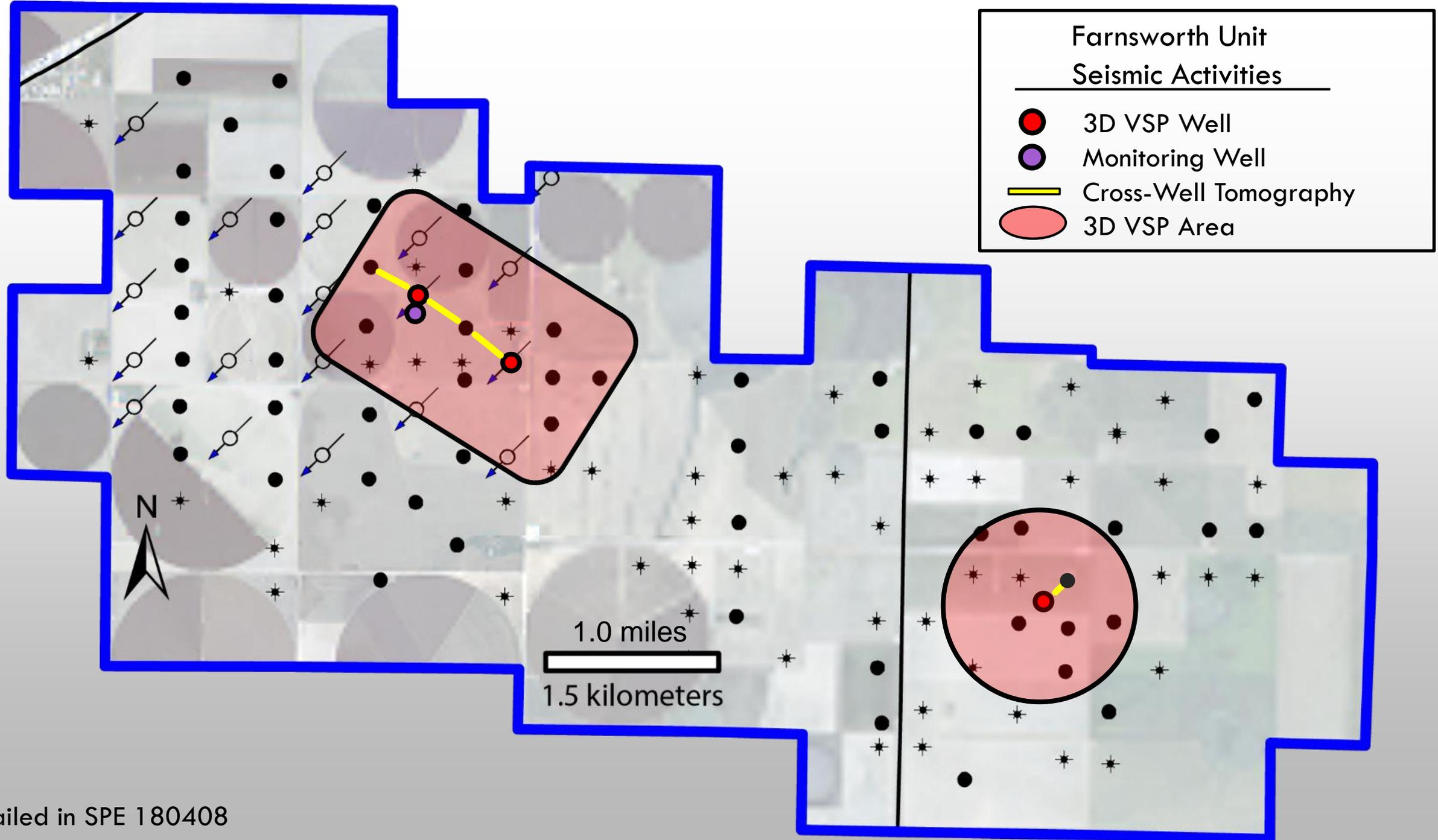


# CONCEPTUAL GEOLOGIC MODEL

## Incised Valley Depositional System

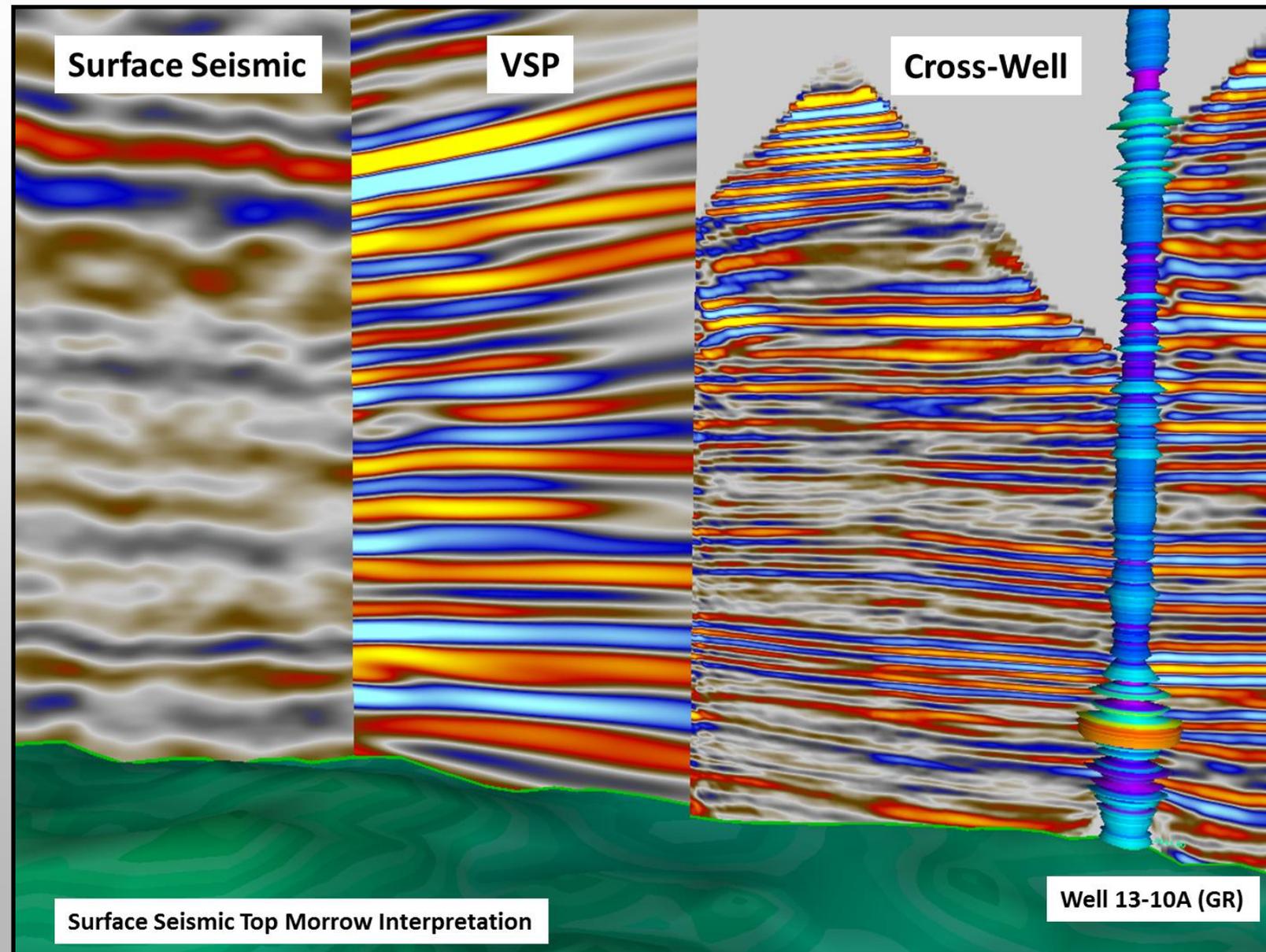
### Farnsworth Type Section



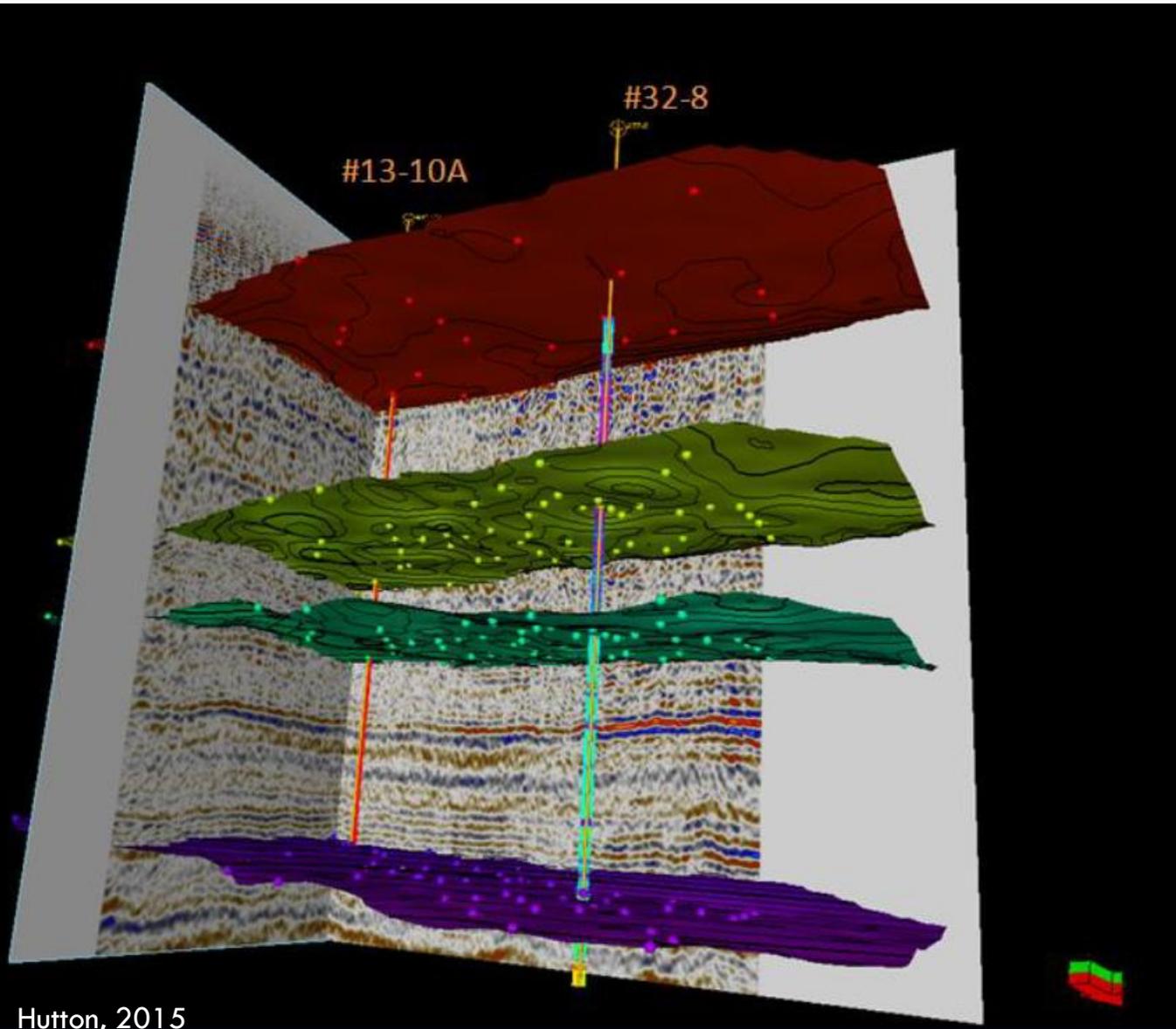


# SEISMIC INTERPRETATION

- Multiple scales of seismic data allow for leveraging of information
- Core and log-scale data at the well-bore can be interpreted out to increasingly lower resolution data sources



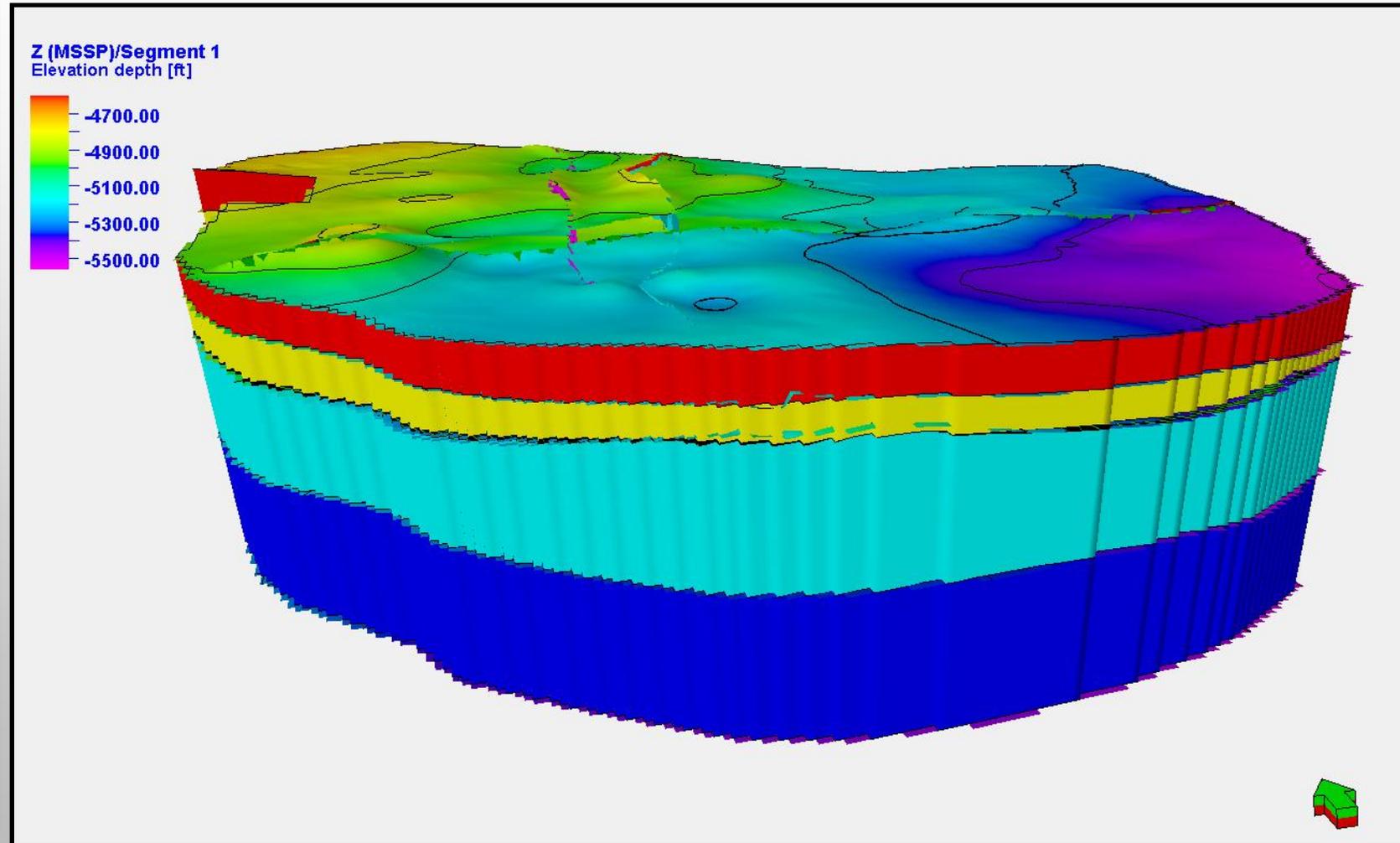
# SEISMIC INTERPRETATION



- Interpreted 16 horizons down to the target *Morrow* reservoir (purple)
- Seismic horizons picks allowed a well-tie between time domain seismic and depth-domain well logs
- Allows for direct relationships between log/core and seismic features

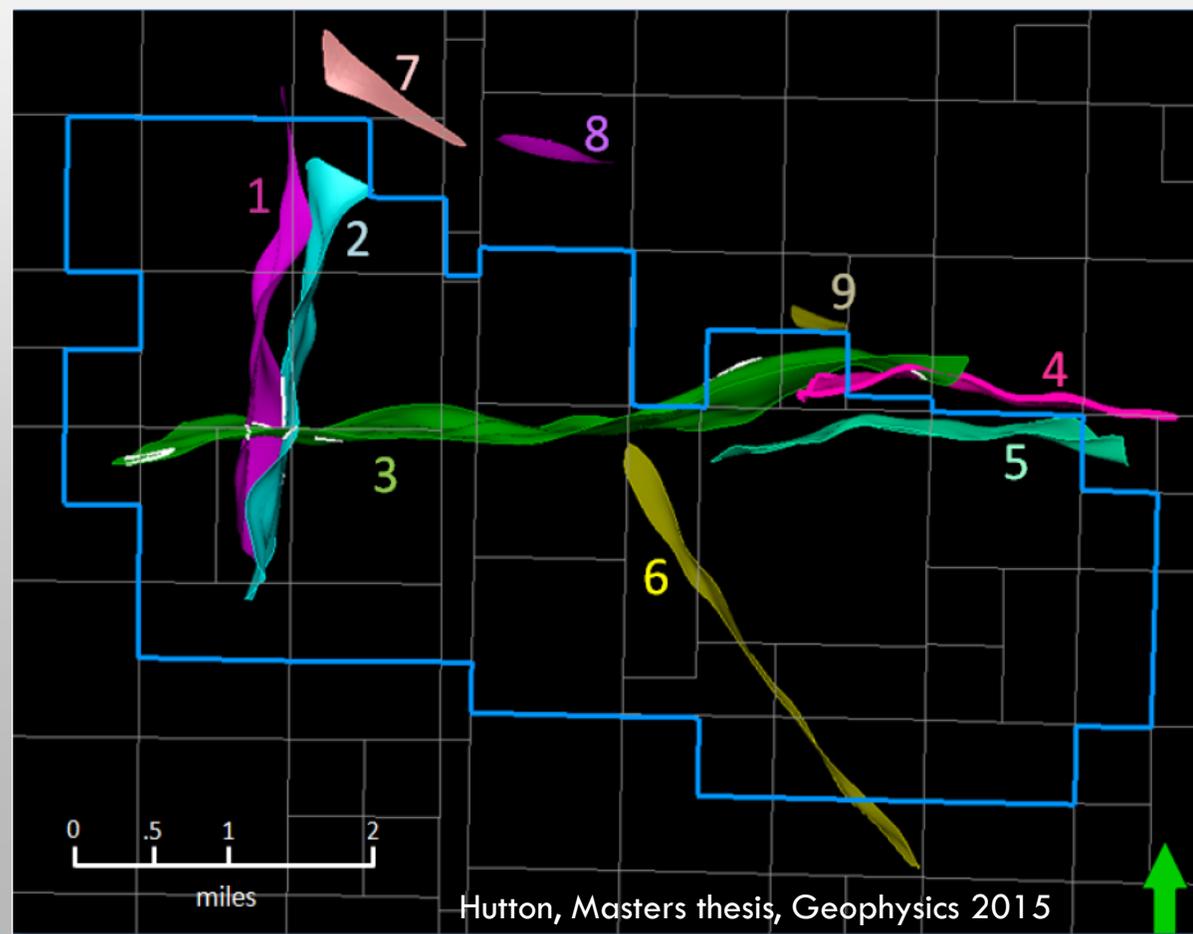
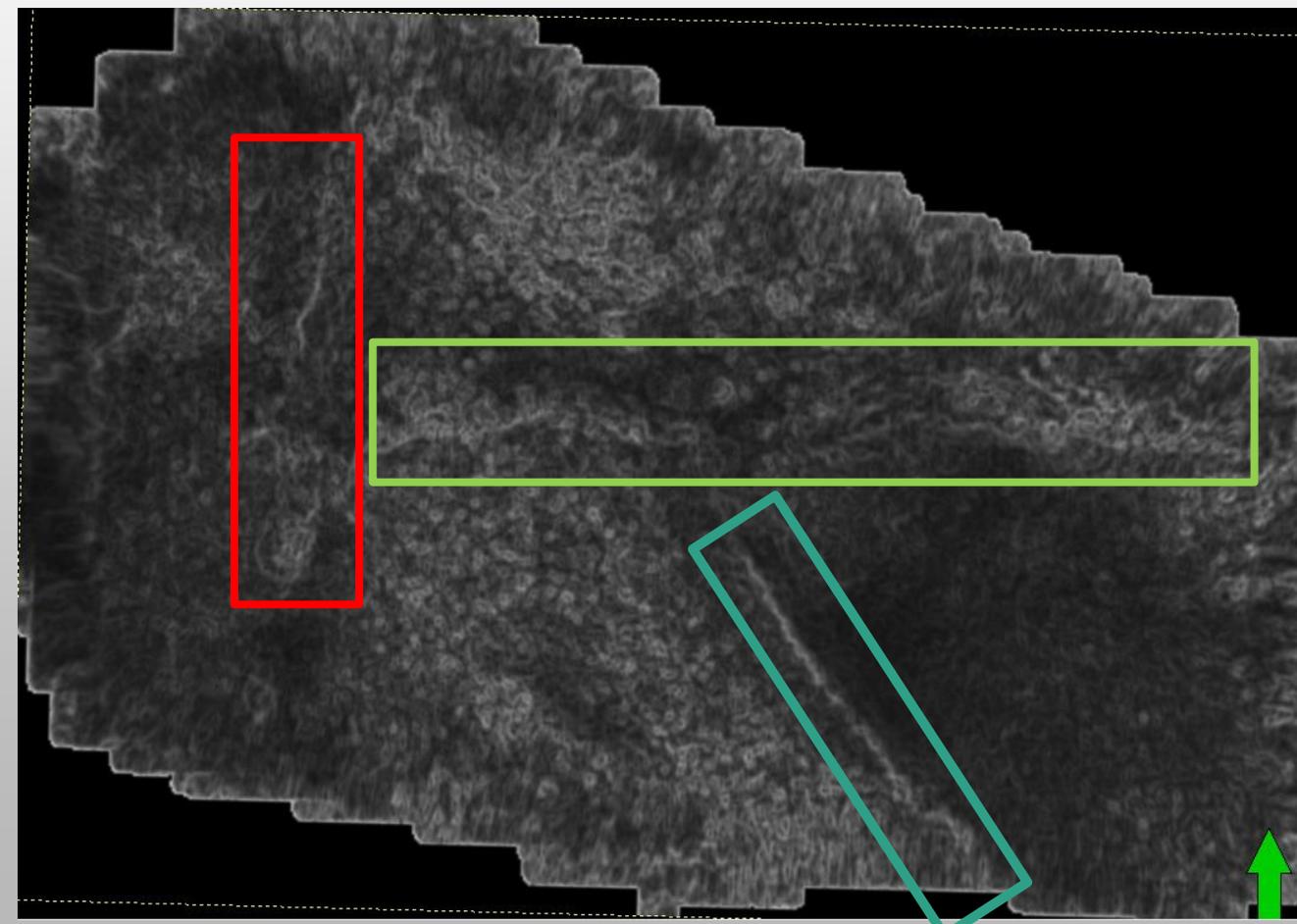
# Model Horizons

System	Series	Group	Informal Names	Wireline Log Characteristics		Lithology	
				Farnsworth Unit Gamma	Resistivity		
Pennsylvanian	Atokan	Atoka	Thirteen Finger Limestone				
Morrowan	Upper		Morrow Shale				
			Morrow B Sandstone				
			Morrow Shale				
			Morrow B_1				
			Morrow Shale				



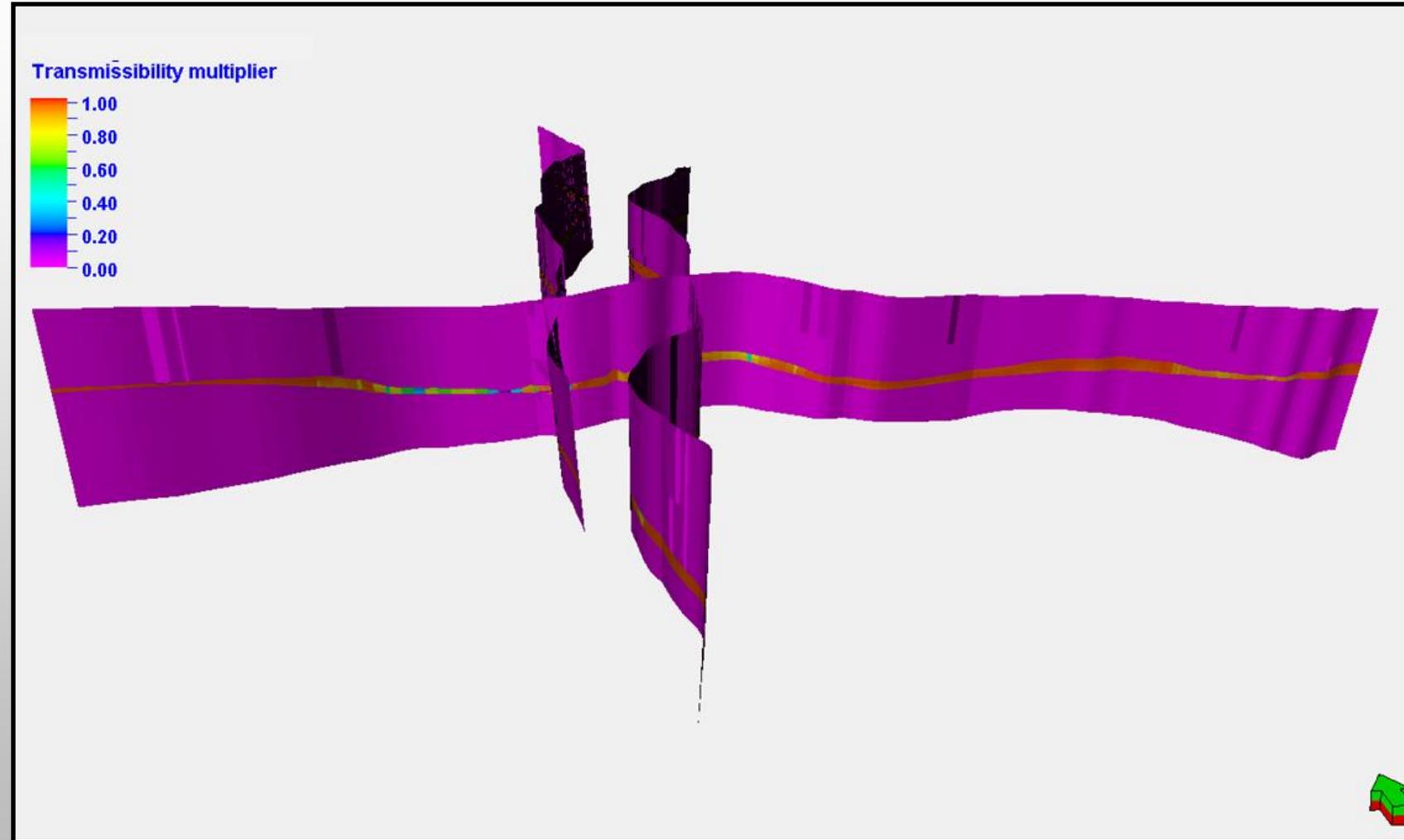
# LARGE SCALE FAULTS AND CHANNELS

Nine faults and fault-like features were interpreted using a variety of seismic attributes and mapping observed features in the 3D seismic volume.

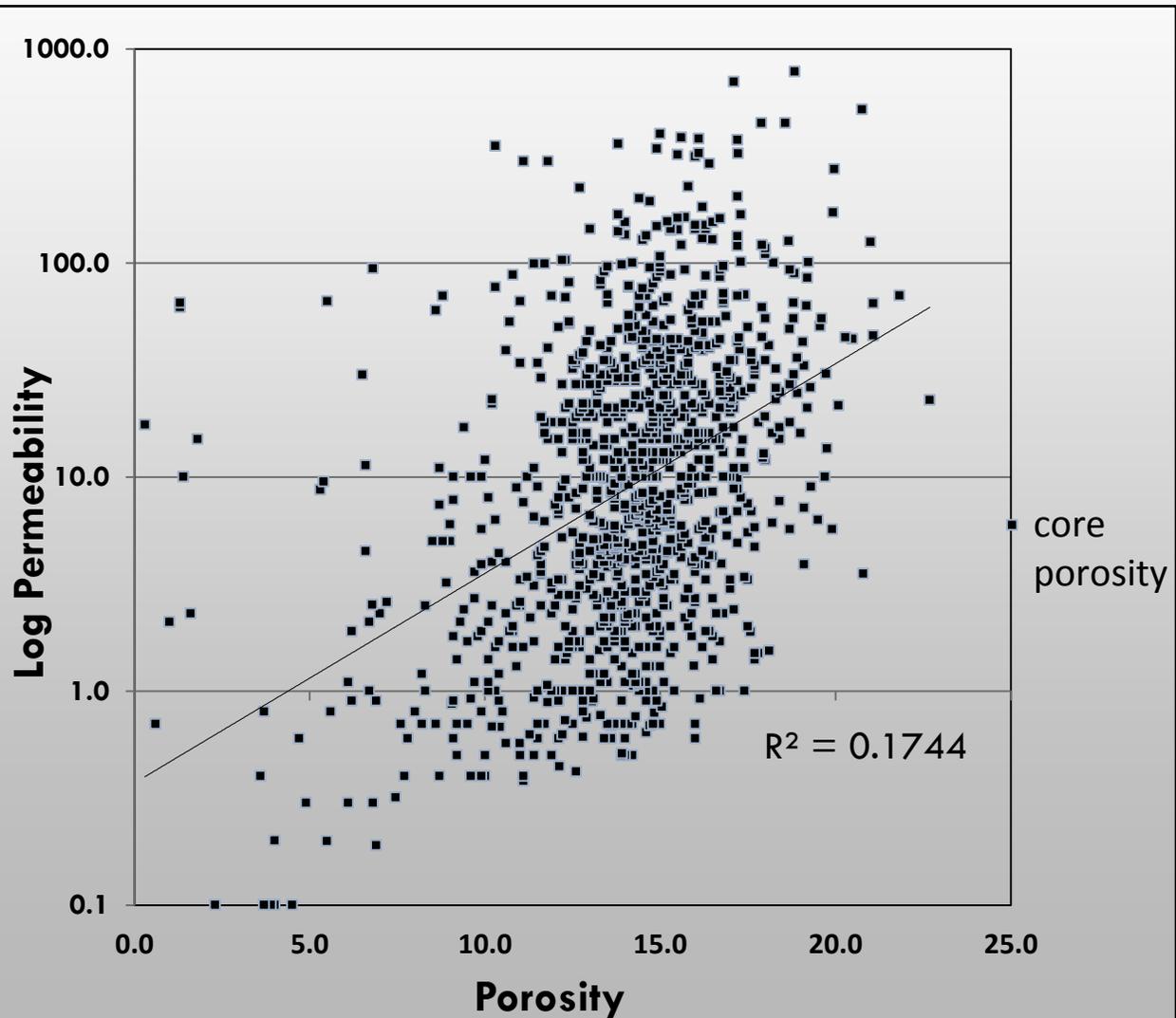


# FAULT MODELING

- Model : Sperrivick
- Use Vsh, NGR, Permeability to compute SGR
- High SGR means completely seal fault
- Maximum burial depth: ~3300m
- Maximum depth at time of deformation: 1300m
- Minimum depth at time of deformation: 300m



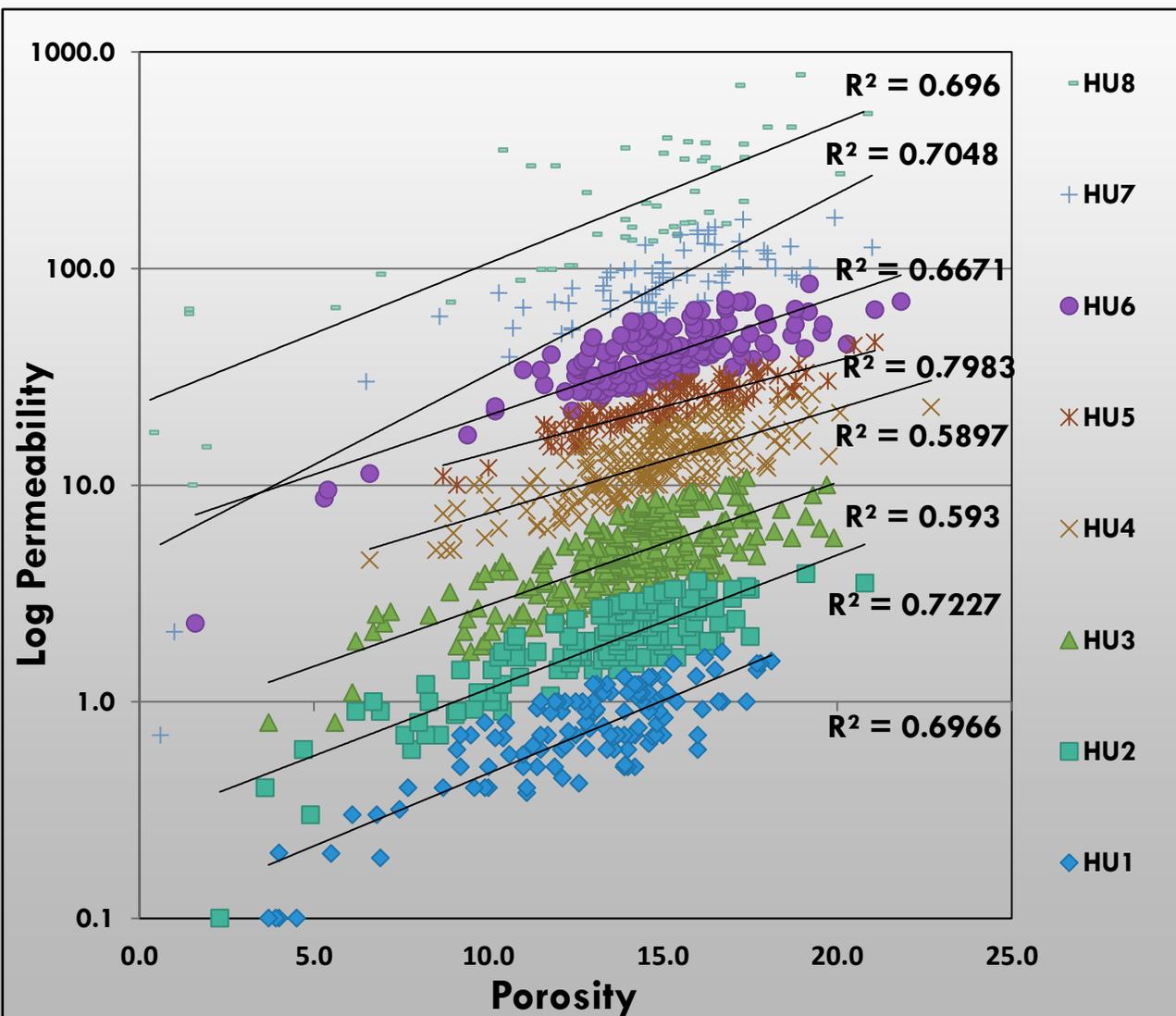
# PETROPHYSICAL MODELING



## Core porosity vs log permeability was computed for 51 cored wells

- Over 750 feet of core were collected in three SWP drilled characterization wells
- Extensive logs from near surface through the reservoir were collected
- The data was inconclusive in relating porosity to permeability

# IMPROVED HYDRAULIC FLOW UNITS

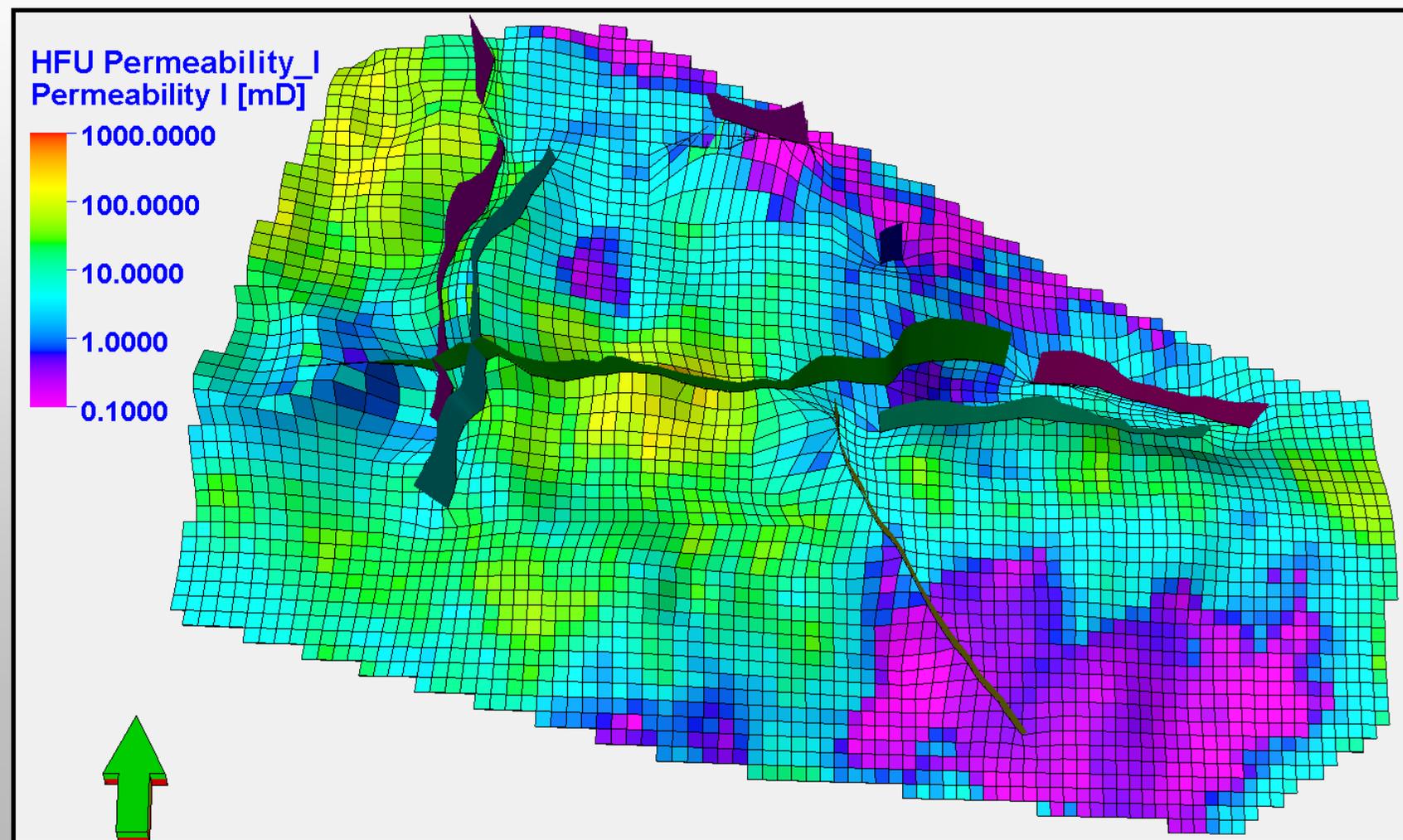


**The Winland equation relates porosity to permeability using variables that impact hydraulic flow (Kolodzie, 1980):**

- $\log R35 = 0.732 + 0.588 \log K_{air} - 0.864 \log \phi_{core}$
- Hydraulic units were grouped into porosity/permeability categories based on similar pore throat sizes

# GEOLOGIC MODELS ARE USED FOR SIMULATION

- SWP evaluates and updates fine-scale geologic models yearly
  - Goal is to integrate, and honor, seismic and well data
- Includes fault planes picked from seismic
  - Faults impact reservoir properties

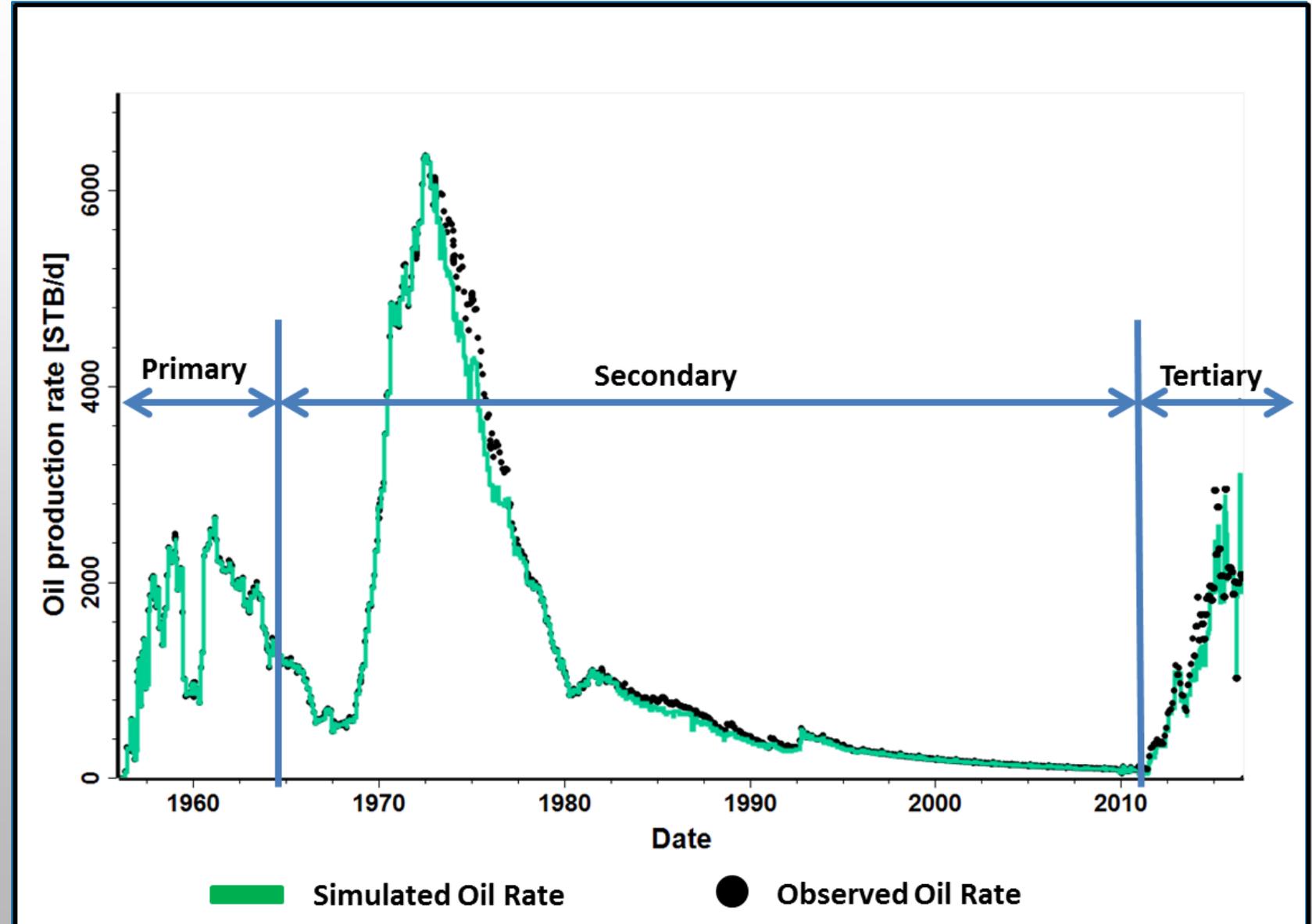


# SIMULATION STUDIES

- Reservoir production history matching through primary, secondary, and tertiary recovery.
- Carbon dioxide interactions with reservoir minerals and fluids.
- Predictions of future production and carbon dioxide storage in the reservoir.
- Enhanced oil recovery and carbon dioxide storage with coupled geochemistry and geomechanics.
- Reduced order models for risk assessment and optimization.

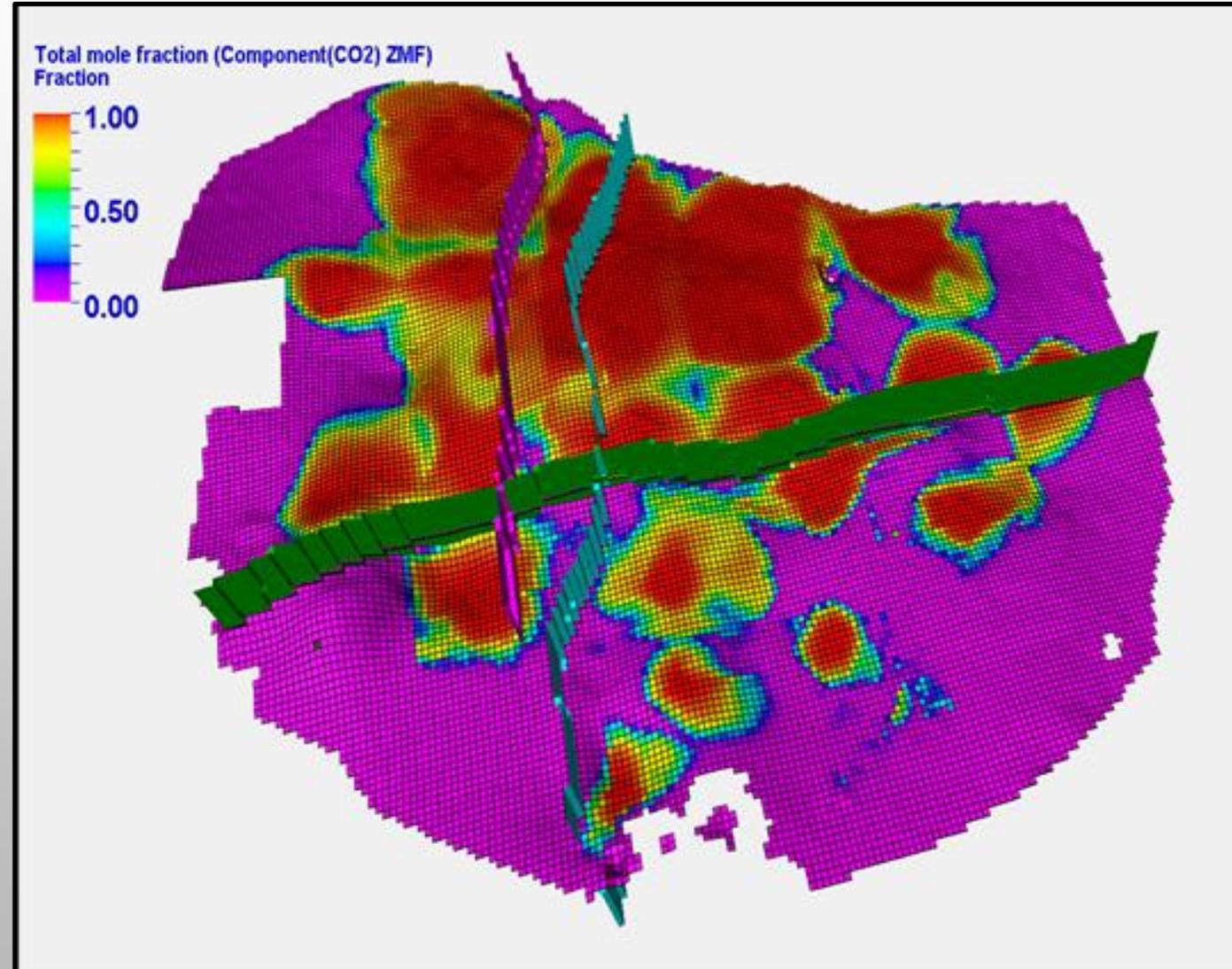
# HISTORY MATCH

- Primary:
  - 1956 – 1964
  - 11.2 MMStb
  - 9.3% of OOIP
- Secondary:
  - 1964 – 2010
  - 25.6 MMSTB
  - 21.3% of OOIP
- Tertiary CO<sub>2</sub>:
  - 2010-2016
  - 2.6 MMSTB



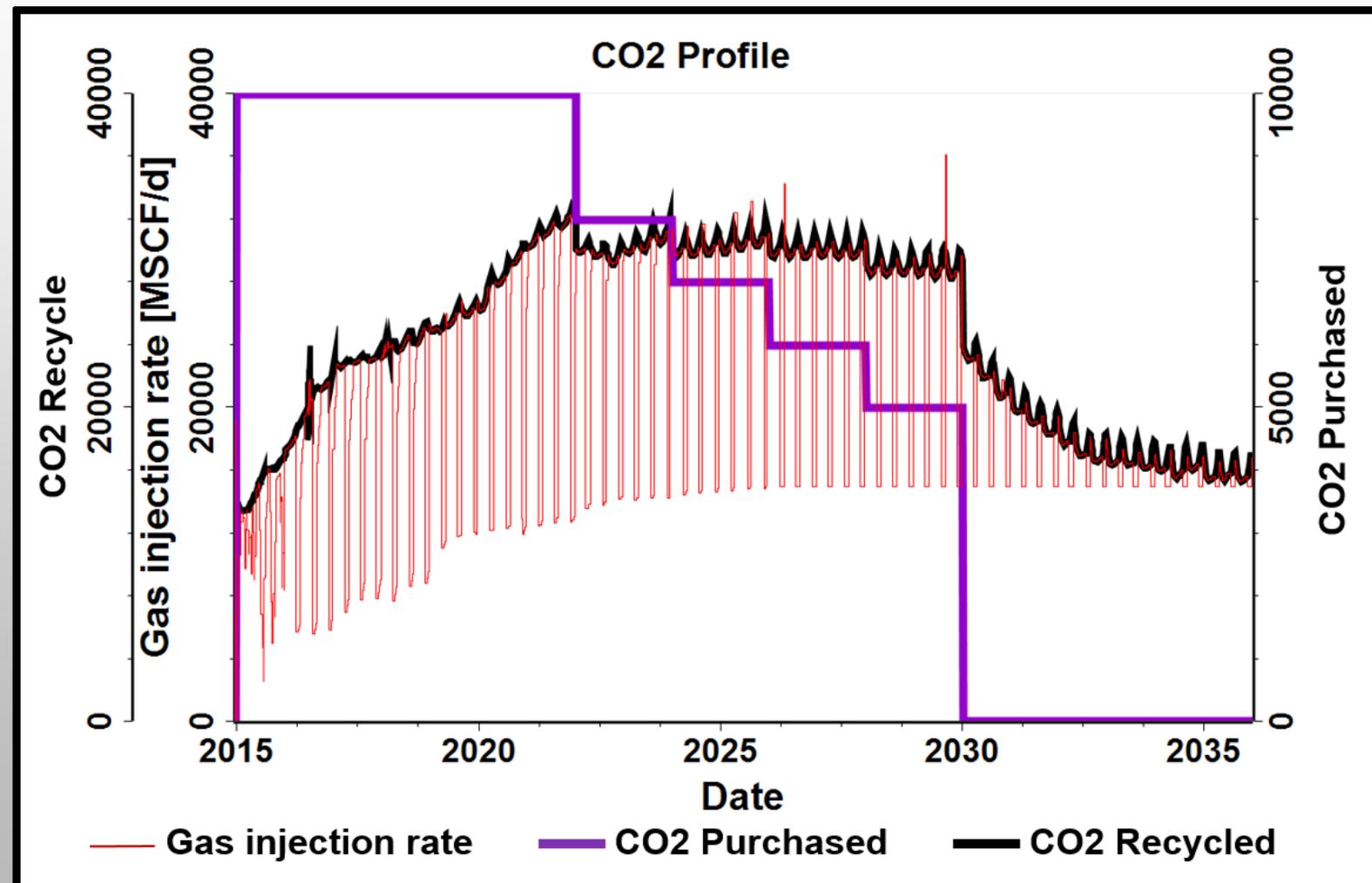
# SIMULATION: MAJOR FINDINGS

- Successfully history matched several generations of geomodels provided by the Characterization group
- Successfully implemented proxy modeling technique to reduce computational time without compromising accuracy
- Successfully developed co-optimization of CO<sub>2</sub> storage and oil recovery framework which may be applied to other projects



# OPTIMIZATION OF WAG CYCLES

- Water Alternating Gas (WAG) Cycles optimized for using proxy models
- Predictions for 25 patterns in West Farnsworth with recycle
- Goal is to co-optimize production and minimize CO<sub>2</sub> waste (flaring)



# OPTIMIZATION OF WAG CYCLES WITH PROXY MODELS (25 PATTERNS – WEST SIDE)

<b>Results</b>	<b>Unit</b>	<b>Base case</b>	<b>Optimized</b>
CO <sub>2</sub> Purchased	BScf	61	61
CO <sub>2</sub> Production Cumulative	BScf	73	100
Recycle	BScf	56	97
CO <sub>2</sub> Injection Cumulative	BScf	118	158
Total Storage*	BScf	45	58
% Storage	%	74	<b>94</b>
Incremental Oil Production	MMstb	15	<b>18</b>
% of OOIP (60 MMSTB)	%	25%	<b>30%</b>

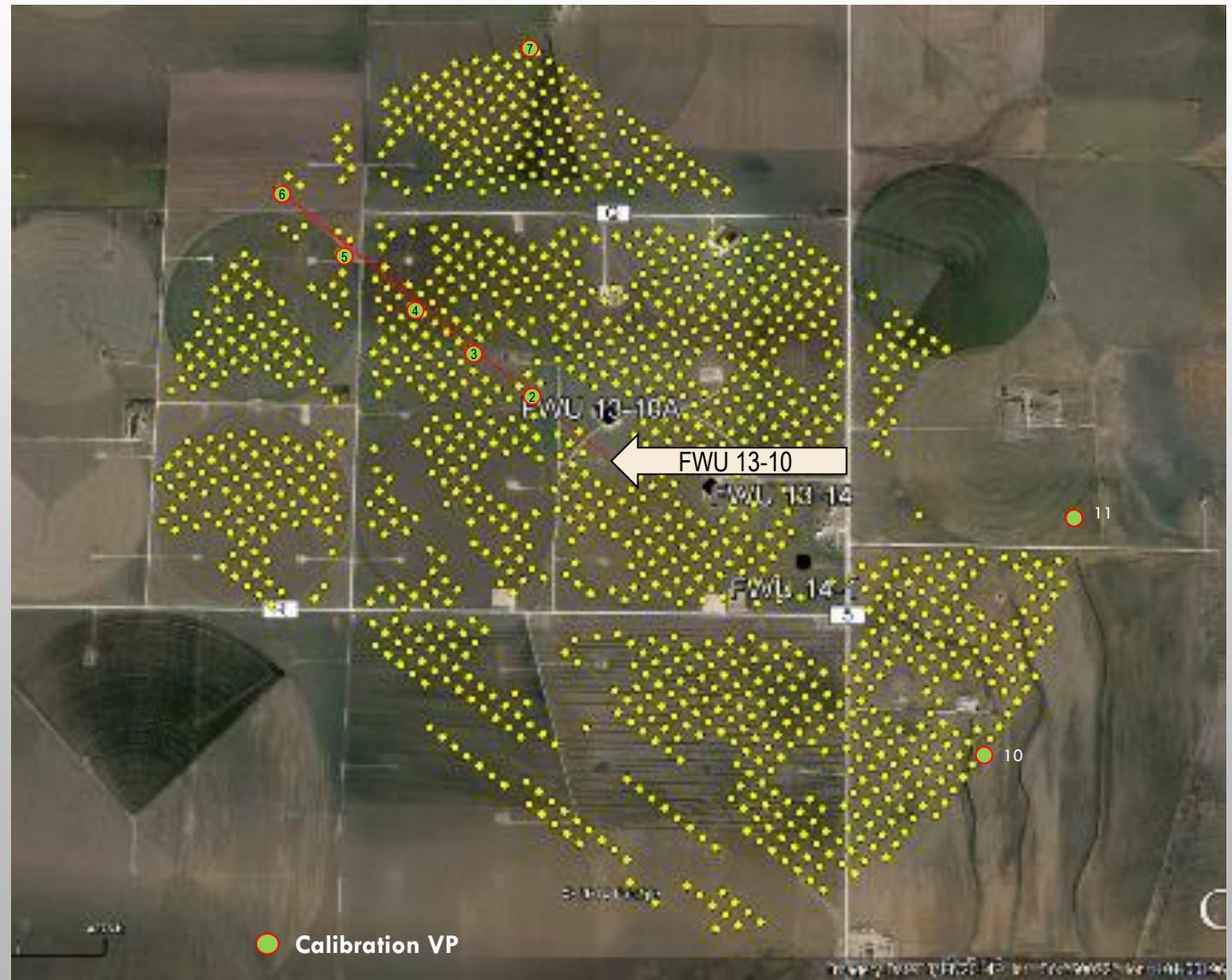
# MONITORING (MVA)

- As a demonstration project a comprehensive monitoring strategy is in place.
- **Monitoring** – understand CO<sub>2</sub> plume movement over short and long time periods
  - **Direct monitoring** - tests repeat air and water samples for seeps, leaks, and well-bore failures
  - **Seismic MVA** - utilizes time lapse seismic data at a variety of scales to image the CO<sub>2</sub> plume over time
- **Verification** – assurance that CO<sub>2</sub> stays in target reservoir, doesn't make it back to atmosphere
- **Accounting** – Accurately measure amount of stored carbon including storage mechanisms

# TIME-LAPSE 3D VSP SURVEYS

**Data Acquired February 2014,  
January 2015,  
December 2016  
December 2017**

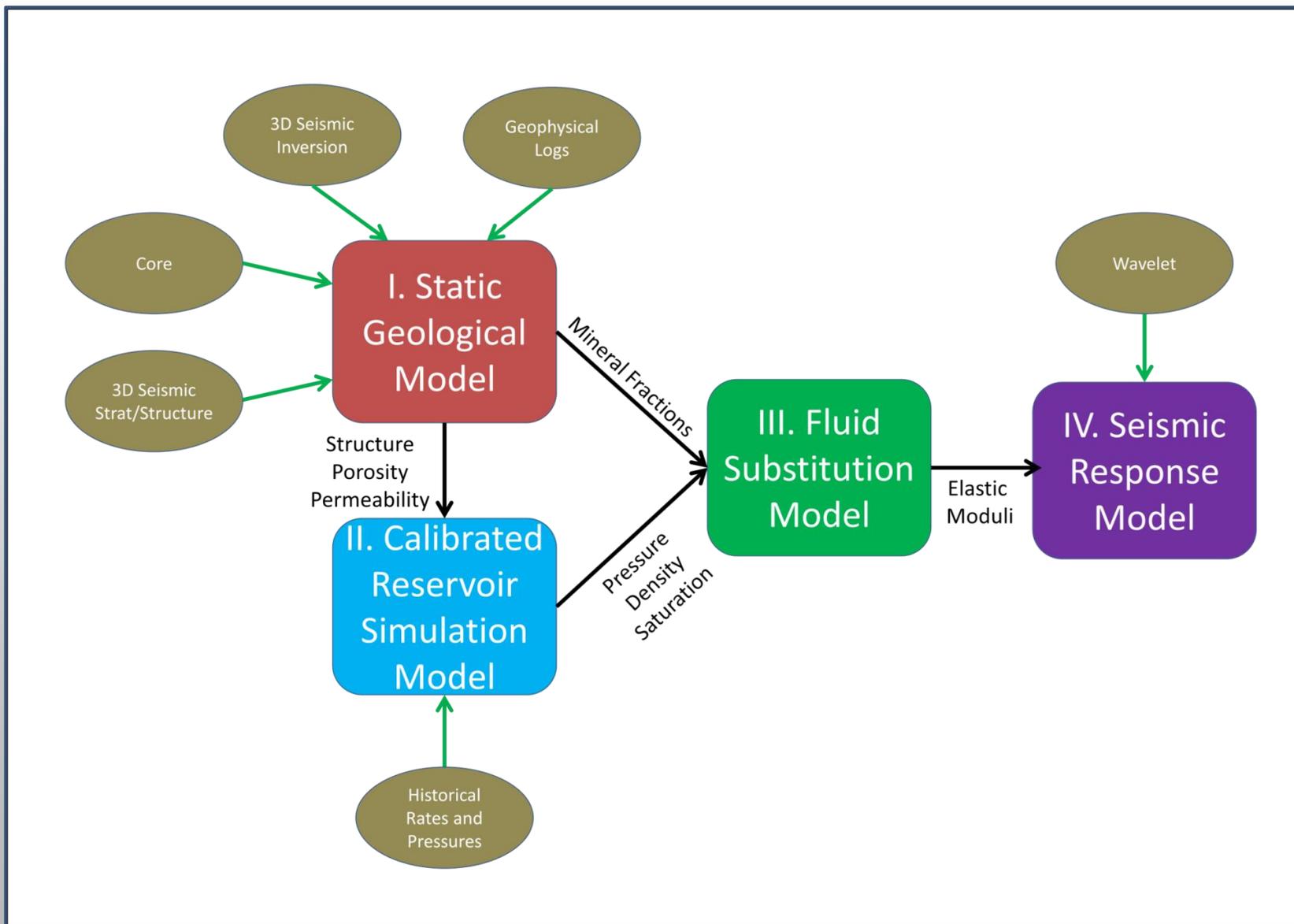
- Processed by WesternGeco
- Excellent repeatability
- Acquired calibration VSP data for micro-seismic array
- Cursory differencing inconclusive



# FLUID SUBSTITUTION MODELING

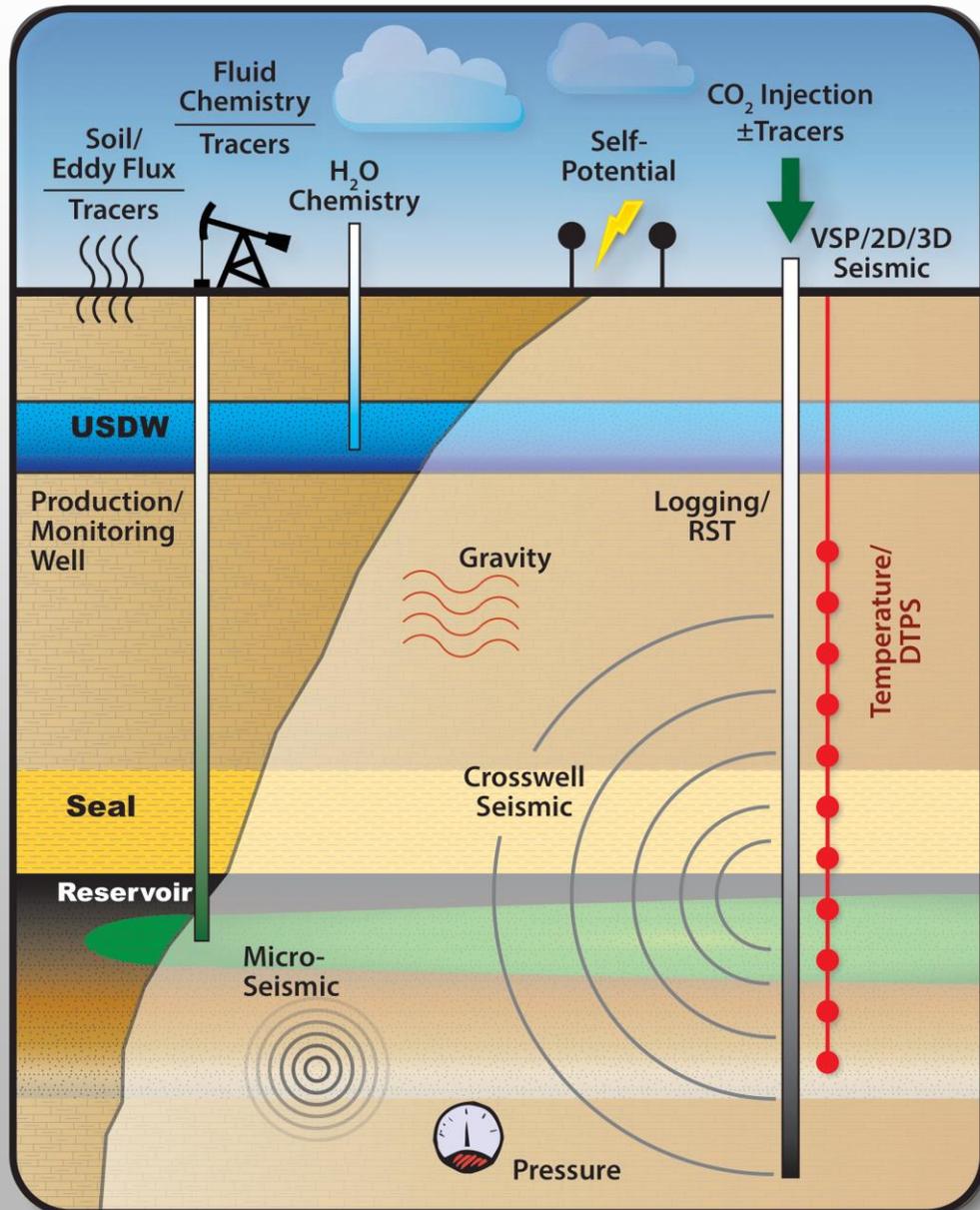
- **Model can be populated with fluids for multiple cases**
  - **Post waterflood**
  - Post 30,000 tonnes injection, etc.
- **Fluid filled models can have synthetic seismic generated from them**
  - Can difference to find expected response at varying CO<sub>2</sub> injection levels
  - Useful for determining detection thresholds
  - Help determine timing of future VSP repeats

# FLUID SUBSTITUTION MODELING – WORK FLOW



- I. Modeling begins by development of a static geologic model using all available data such as logs, core, inversion, and seismic stratigraphy and structure
- II. The fine scale geologic model is history matched, and then used to predict the fluid state of the reservoir at various times corresponding to different CO<sub>2</sub> injection volumes
- III. The fluid substitutions can change the elastic properties of the rock, which can then impact the seismic response

# DIRECT MONITORING STRATEGY



## Detecting CO<sub>2</sub> at Surface:

- Surface soil CO<sub>2</sub> flux
- Atmospheric CO<sub>2</sub>/CH<sub>4</sub> eddy flux
- Gas phase tracers

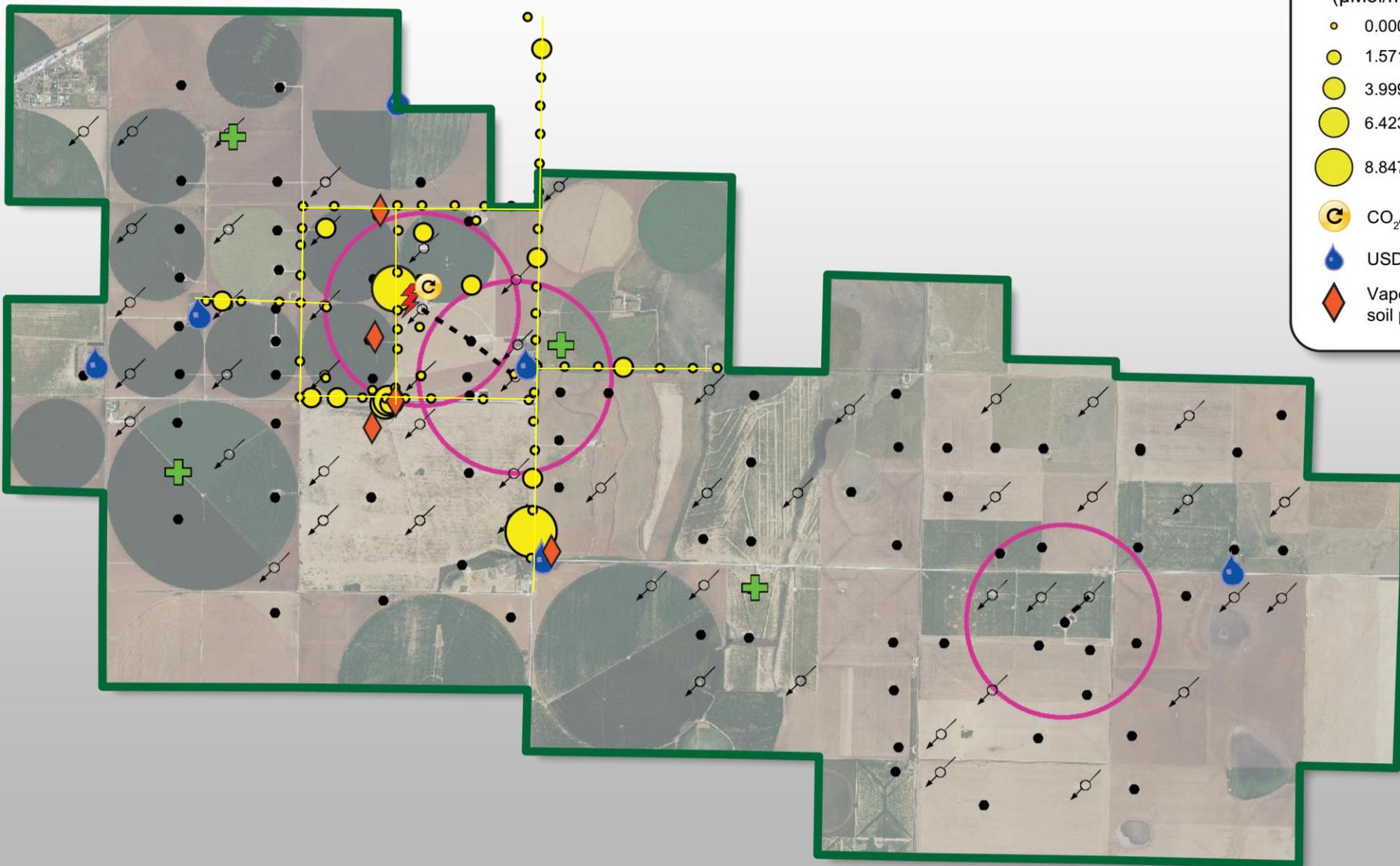
## Detecting CO<sub>2</sub> and/or other fluid migration in Target/Non-Target Reservoirs:

- Groundwater chemistry (USDWs)
- Water/gas phase tracers

## Tracking CO<sub>2</sub> Migration and Fate:

- *In situ* pressure & temperature
- 2D/3D seismic reflection surveys
- VSP and Cross-well seismic
- Passive seismic

# MVA OVERVIEW



## CO<sub>2</sub> Soil Flux ( $\mu\text{Mol/m}^2/\text{sec}$ )

- 0.000 - 1.570
- 1.571 - 3.998
- 3.999 - 6.422
- 6.423 - 8.846
- 8.847 - 11.270

CO<sub>2</sub>/CH<sub>4</sub> Eddy Flux Tower

USDW Sampling wells

Vapor-phase atmospheric/  
soil probes

Cross-well Seismic

Passive Seismometers

Repeat VSP Surveys

Self-potential

Gravimeter

Oil Production Well (with  
accompanying water/CO<sub>2</sub>/  
tracer)

CO<sub>2</sub>/Water/Tracer  
Injection Well

Image Layer:  
USGS 1:24000 Quads  
(Waka, Sourdough Creek Nw  
& Farnsworth)

Projection: UTM zone 14 NAD 83  
units: meters

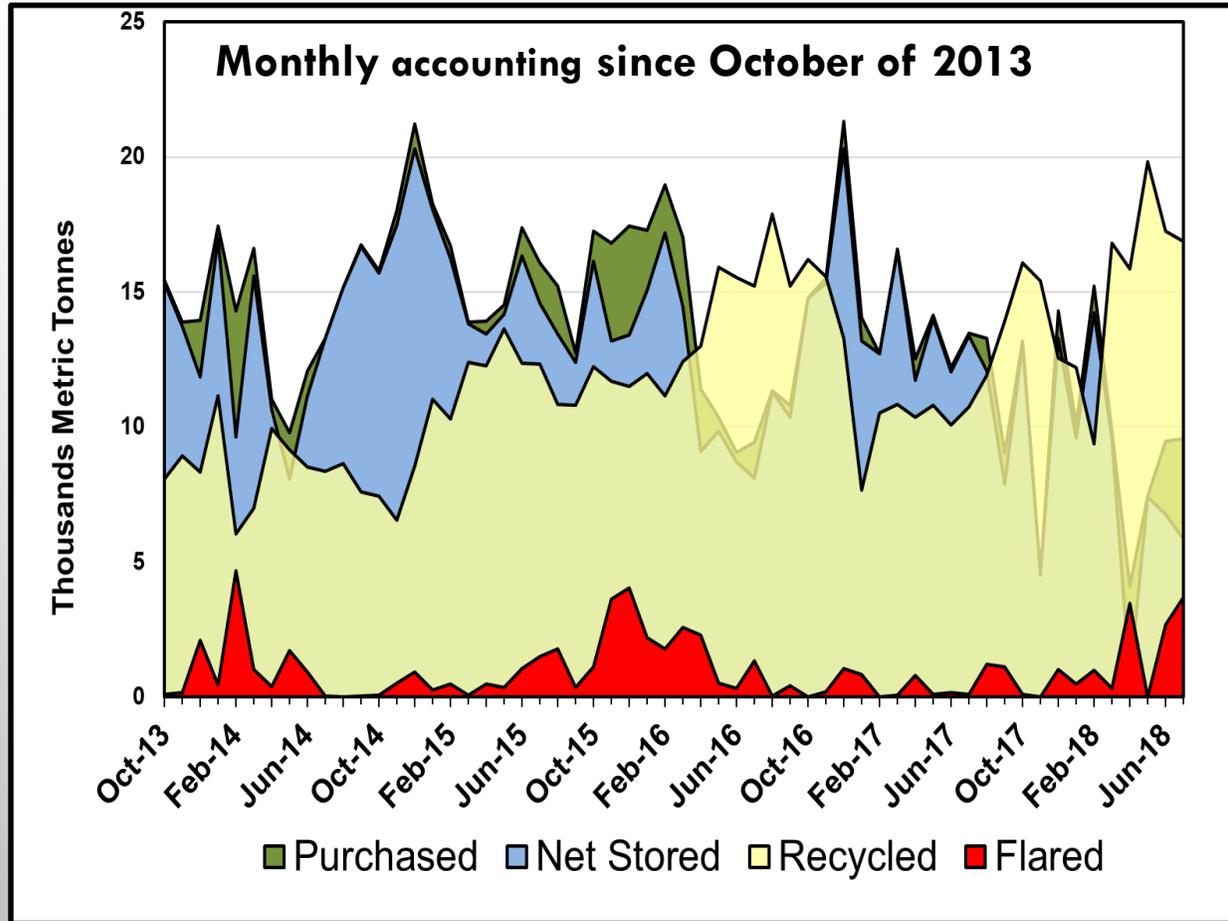
Date: Aug 12, 2015

0.8

Miles

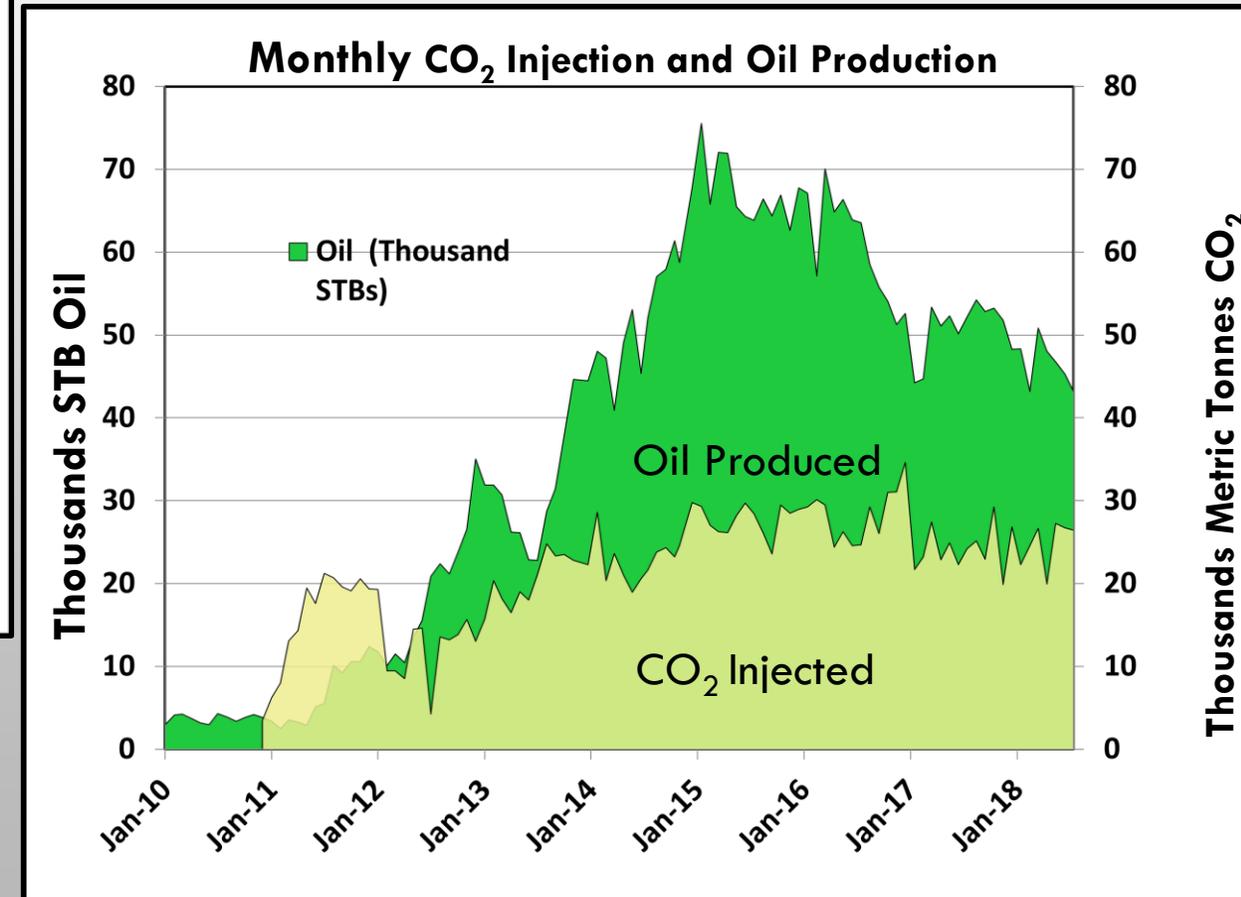


# ACCOUNTING - CO<sub>2</sub> AND INCREMENTAL PRODUCTION



- 739,863 tonnes stored since October 2013
- 688,183 tonnes recycled since October 2013
- 1,180,379 tonnes stored since November 2010
- **92.7% of purchased CO<sub>2</sub> still in the system**

- Average monthly oil rate increased from ~3,500 to ~65,000 BBL's in first 4 years of CO<sub>2</sub> Flood
- Initial production response within 6 months
- ~3.8 million STB produced during CO<sub>2</sub> flood



# CONCLUSIONS

- Demand for CO<sub>2</sub> for EOR projects has outpaced natural supplies
- Carbon Capture can mitigate CO<sub>2</sub> emissions using geologic storage and is responsive to government interests in reducing carbon emissions, worldwide
- Costs for using anthropogenic CO<sub>2</sub> for EOR purposes is mitigated by existing oilfield infrastructure and increased oil production
- Case studies can provide “best practices” and demonstrate viability of the use of local anthropogenic sources
- The Farnsworth project highlights enhanced recovery with ~92% carbon storage
- Extensive characterization, modeling, simulation, and monitoring studies have demonstrated long term storage security

# **Southwest Regional Partnership on Carbon Sequestration**

DOE Project DE-FC26-05NT42591

<http://SWP.rocks>