Southwest Regional Partnership on Carbon Sequestration (SWP)

DE-FC26-05NT42591

PHASE III DEMONSTRATION: FARNSWORTH UNIT

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Mastering the Subsurface through Technology Innovation & Collaboration:
Carbon Storage & Oil and Natural Gas Technologies Review Meeting
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ACKNOWLEDGMENTS

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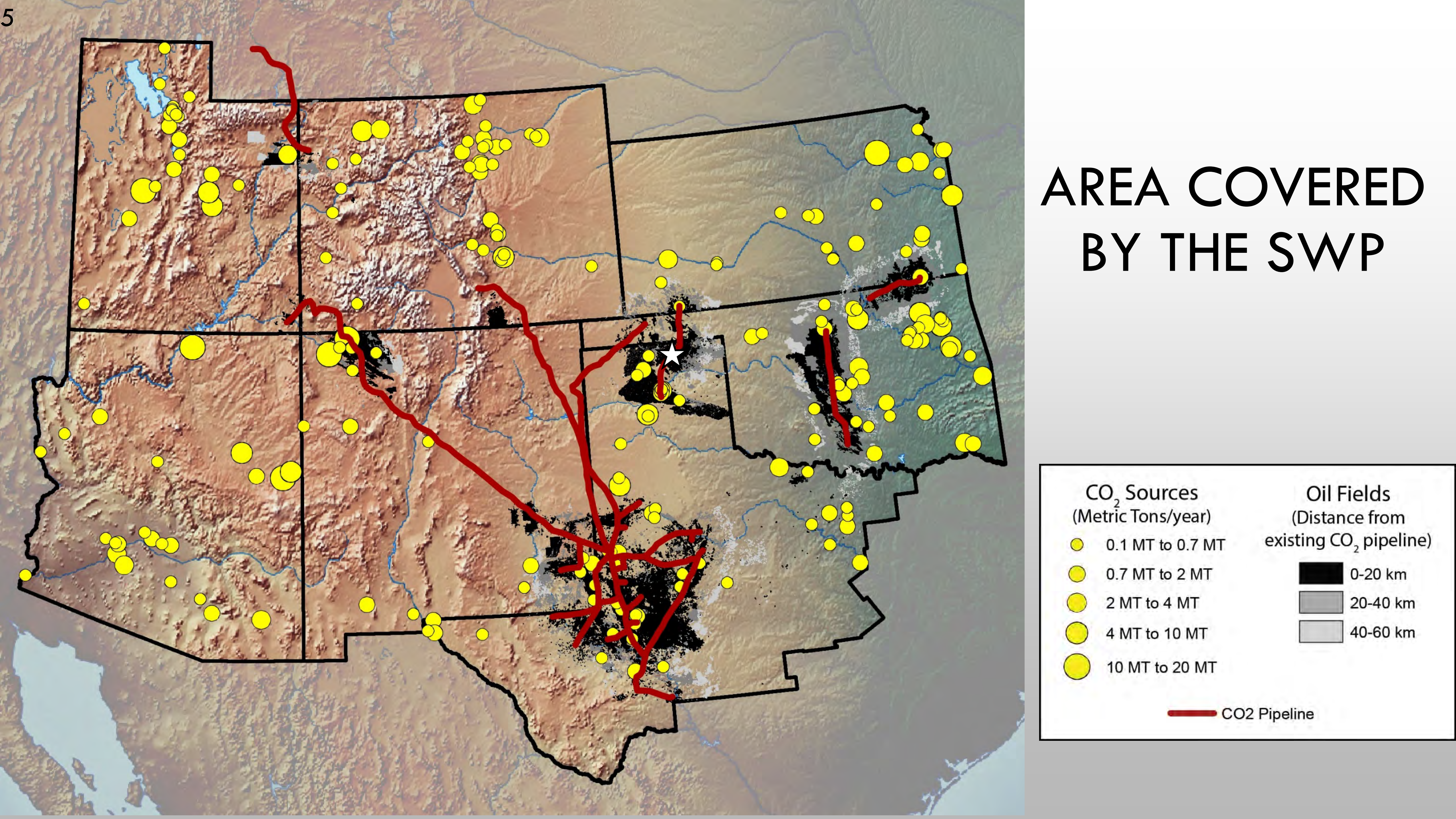
The presenters gratefully acknowledge the contributions of more than 50 SWP scientists and engineers, working at New Mexico Tech, the University of Utah, the University of Missouri, Los Alamos National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories.

OUTLINE

- Introduction to the SWP
- Status of Milestones
- Effort divided into four groups
  - Characterization effort and lessons learned
  - Simulation effort and lessons learned
  - MVA effort and lessons learned
  - Risk Assessment effort and lessons learned
- Post-Injection Period (BP4) priorities
- Post-Injection Period (BP4) workplan components

THE SOUTHWEST PARTNERSHIP AND FARNSWORTH UNIT

AREA COVERED BY THE SWP



Anthropogenic Supply:
500-600,000
Metric tons
CO_2/year supply

Farnsworth Unit

Legend

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

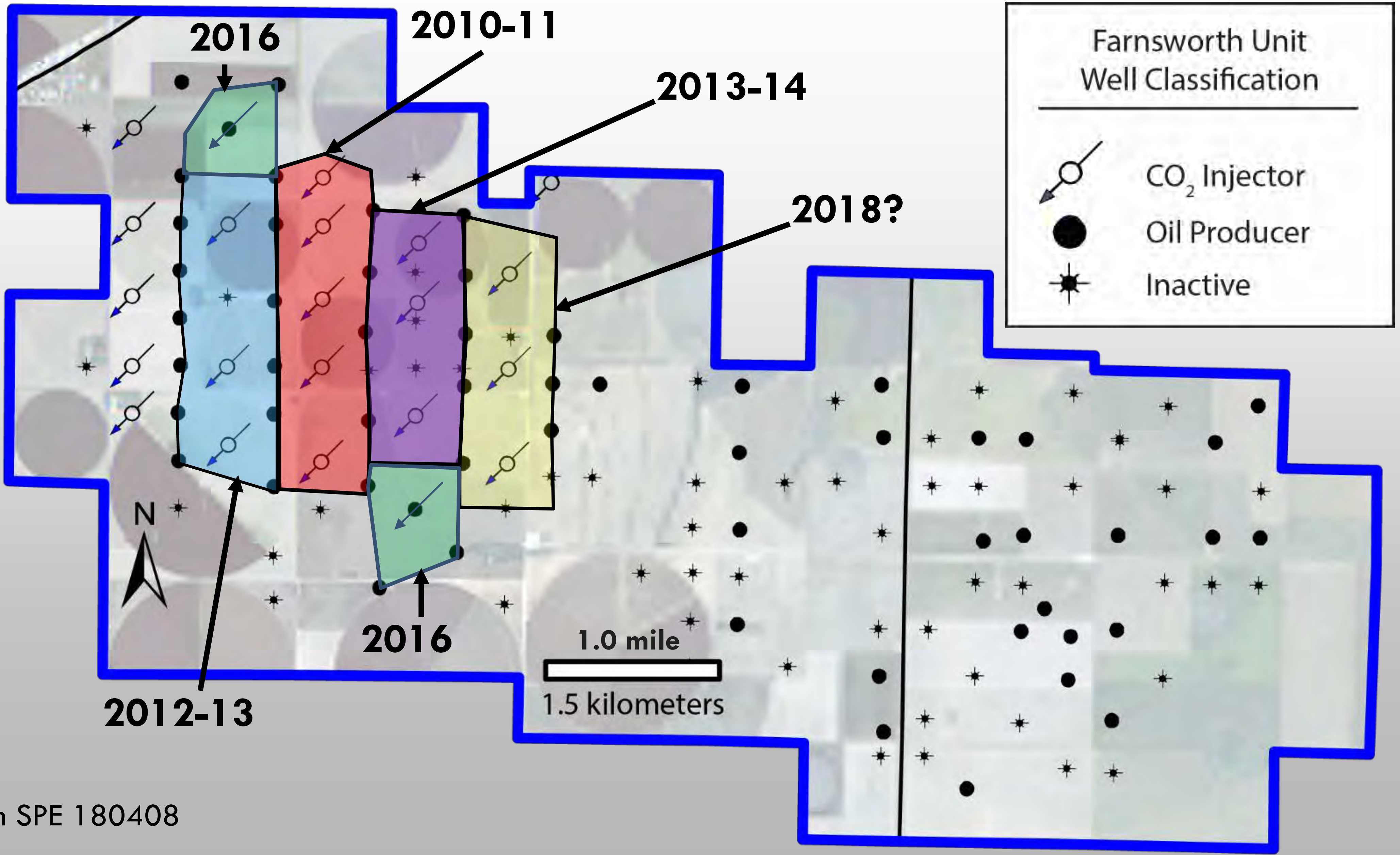
Other CO_2 Sources

- 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

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

www.agrium.com

ACTIVE AND CURRENTLY PLANNED CO_2 PATTERNS



Detailed in SPE 180408

SOUTHWEST PARTNERSHIP: TIMELINE

- Phase I – regional sources and sinks,
  - ID Phase II studies
- Phase II – pilot scale studies
  - ID Phase III study site
- Phase III Budget Period 3 – Large Scale demonstration
  - Pre-injection
  - Injection
- Phase III Budget Period 4 – "Post-Injection"

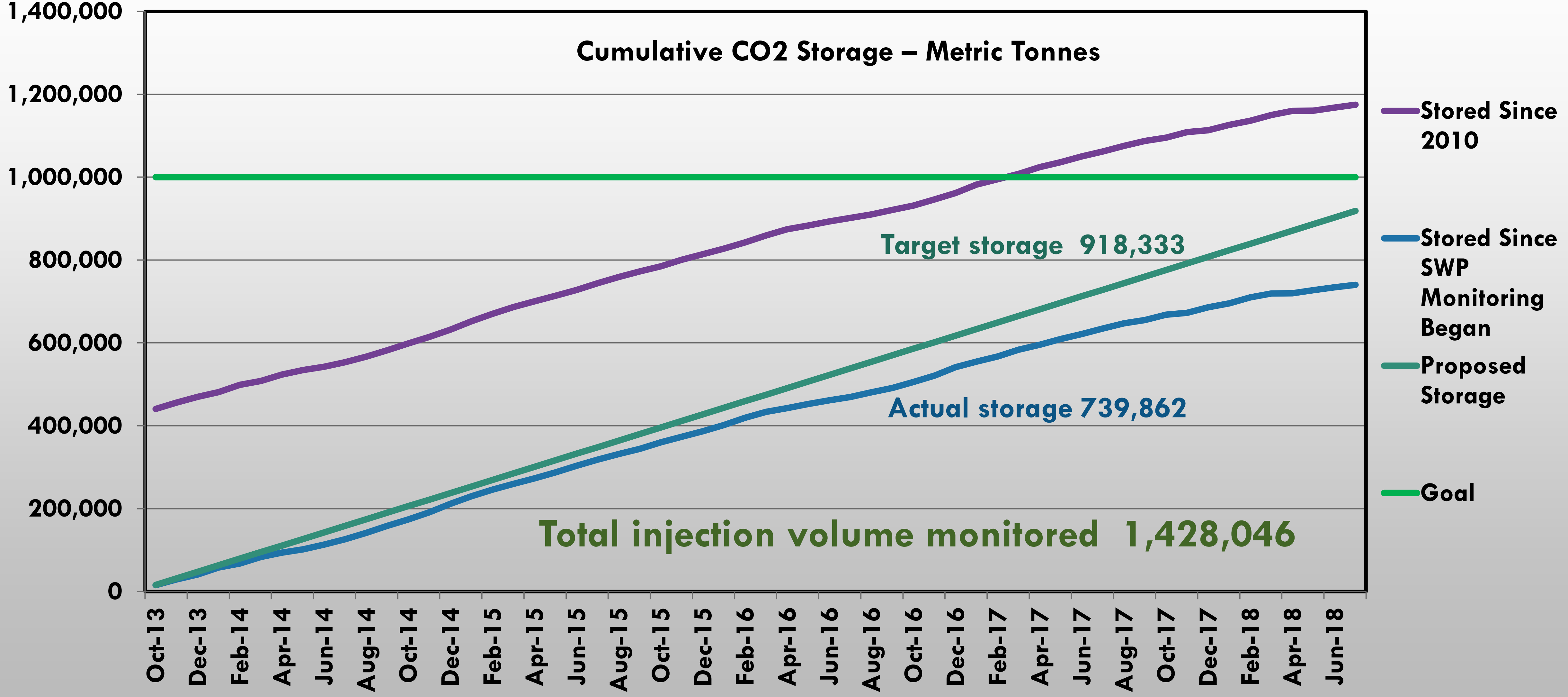
STATUS OF MILESTONES - PHASE III

SOUTHWEST PARTNERSHIP: MILESTONES MET

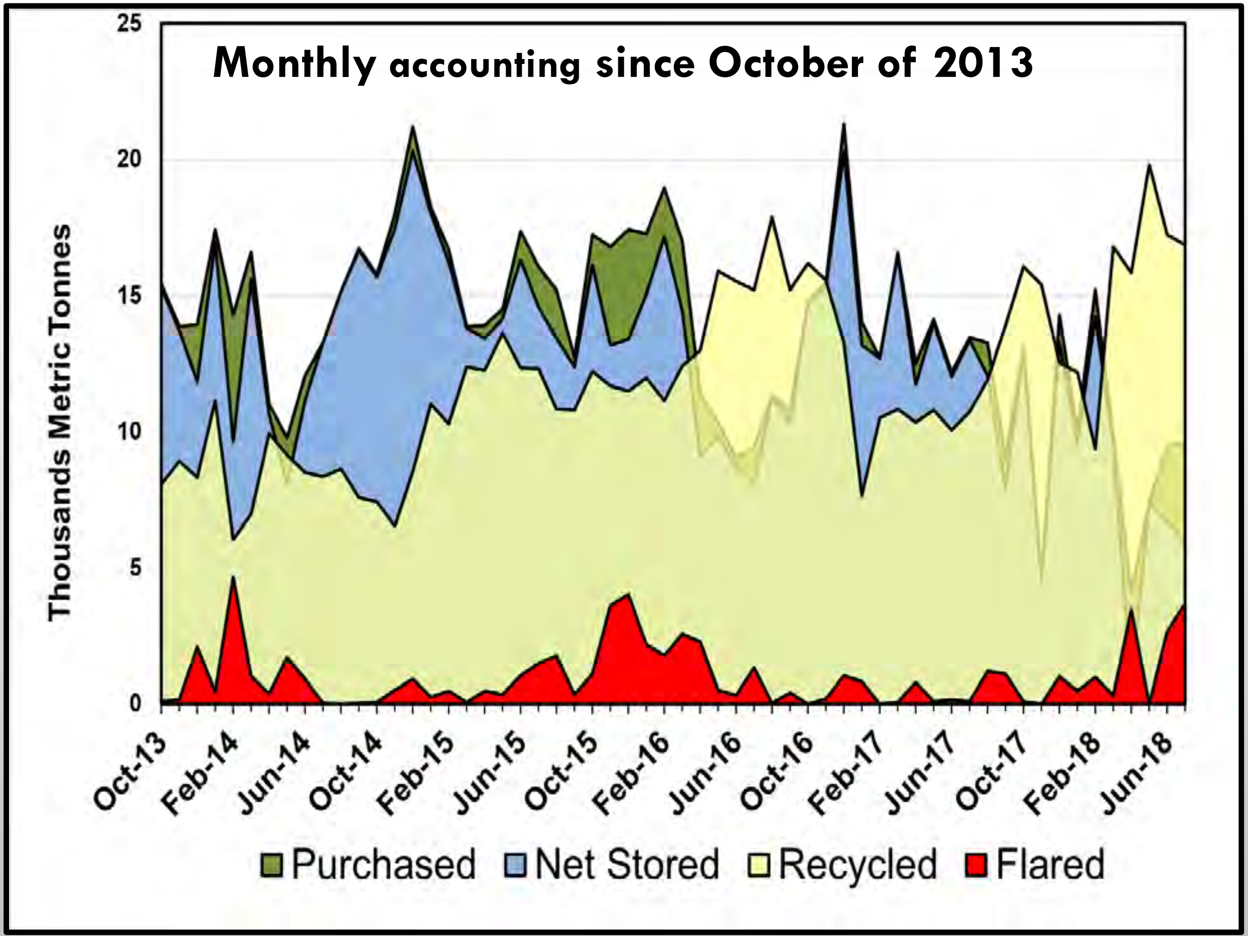
- Critical Milestones – 25
  - 23 completed
  - 2 ongoing
    - Tracer analysis (due Q2-FY17 – initial report delivered Q1-FY18)
    - Final injection period simulation (due Q3 of FY18)
- Technical Milestone – 73
  - 66 completed

  7 ongoing
    - Five tracer-related milestones
    - One risk mitigation plan update
    - One 3-phase reactive transport model

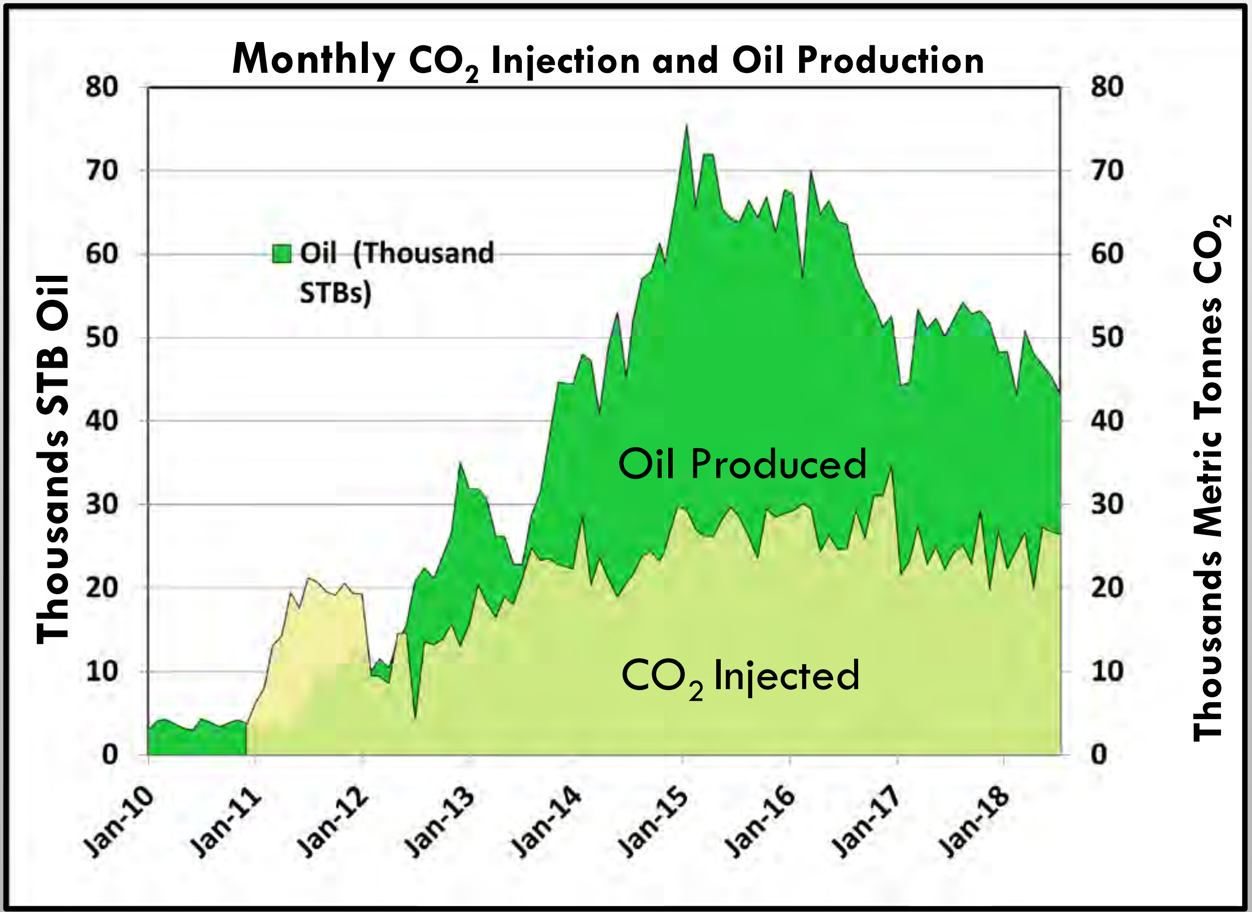
SOUTHWEST PARTNERSHIP: CO_2 STORAGE



ACCOUNTING - CO_2 AND INCREMENTAL PRODUCTION



- Average monthly oil rate increased from ~3,500 to ~65,000 BBL's in first 4 years of CO_2 Flood
- Initial production response within 6 months
- ~3.8 million STB produced during CO2 flood



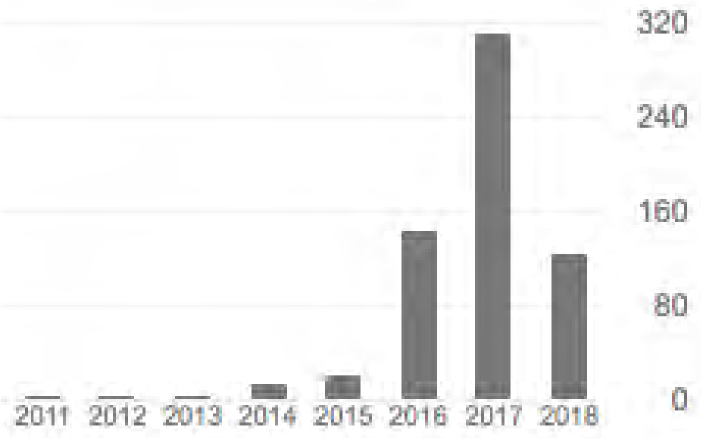
- 739,863 tonnes stored since October 2013
- 688,183 tonnes recycled since October 2013
- 1,180,379 tonnes stored since November 2010
- **92.7% of purchased CO_2 still in the system**

SOUTHWEST PARTNERSHIP: BIBLIOGRAPHY

- >85 publications, major presentations, SPE DL
- Springer Book – 25 Papers covering multiple aspects

Cited by VIEW ALL

	All	Since 2013
Citations	643	616
h-index	14	14
i10-index	16	15



TITLE	CITED BY	YEAR
An integrated framework for optimizing CO2 sequestration and enhanced oil recovery Z Dai, R Middleton, H Viswanathan, J Fessenden-Rahn, J Bauman, ... Environmental Science & Technology Letters 1 (1), 49-54	112	2013
CO2 accounting and risk analysis for CO2 sequestration at enhanced oil recovery sites Z Dai, H Viswanathan, R Middleton, F Pan, W Ampomah, C Yang, W Jia, ... Environmental science & technology 50 (14), 7546-7554	64	2016
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Uncertainty analysis of carbon sequestration in an active CO 2-EOR field F Pan, BJ McPherson, Z Dai, W Jia, SY Lee, W Ampomah, H Viswanathan, ... International Journal of Greenhouse Gas Control 51, 18-28	38	2016
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SWP CHARACTERIZATION EFFORTS AND LESSONS LEARNED

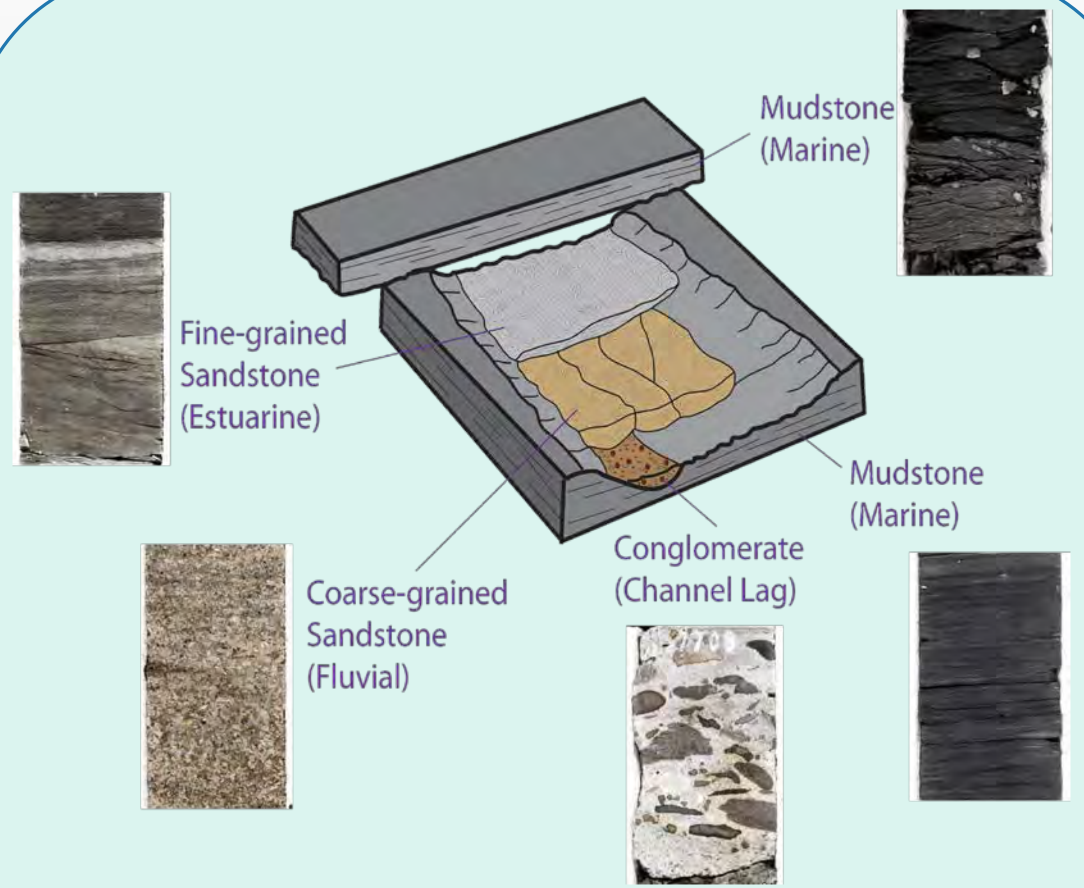
CHARACTERIZATION –GEOLOGICAL UNDERSTANDING

- Goal: Reservoir & caprock description – depositional setting, reservoir architecture, lithologies, fracture potential, geomechanical properties
- Tools: Cores & core analyses, thin section, microprobe, log & seismic data, geomechanical, borehole image logs, CT scanning

CHARACTERIZATION –GEOLOGICAL UNDERSTANDING

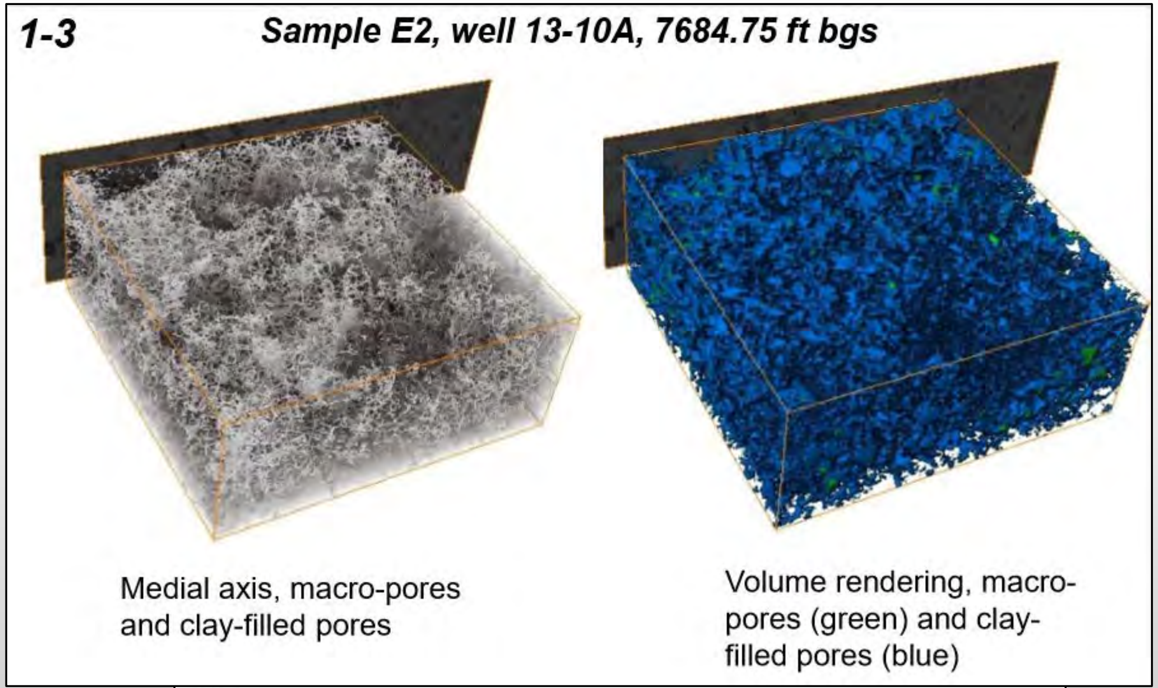
- Findings:
  - Incised valley model fits well, reservoir can be divided into lithofacies based on core descriptions
  - Lithofacies provide a record of marine transgressive/regressive sequences that have effects on reservoir diagenesis
  - Reservoir can also be characterized by Hydraulic Flow Units (HFU) determined from porosity and permeability data using Winland R35 approach, these have different pore structure and interconnectivity
  - Caprock is a sequence of interbedded mudstones/shales and diagenetic limestones
- Better understanding of fluid/rock interactions, relative permeability data

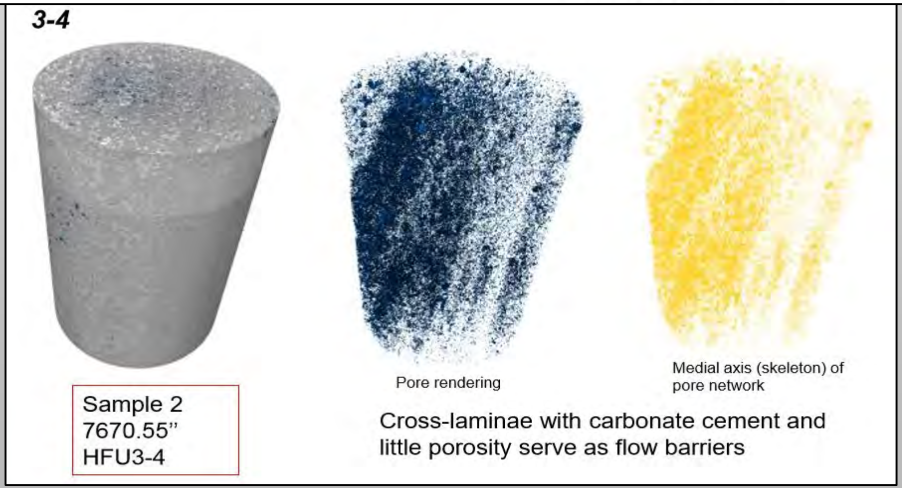
CHARACTERIZATION OF GEOLOGY AT MULTIPLE SCALES



Facies model – reservoir scale

MicroCT Imaging – pore scale, can differentiate between HFUs defined by R35 method

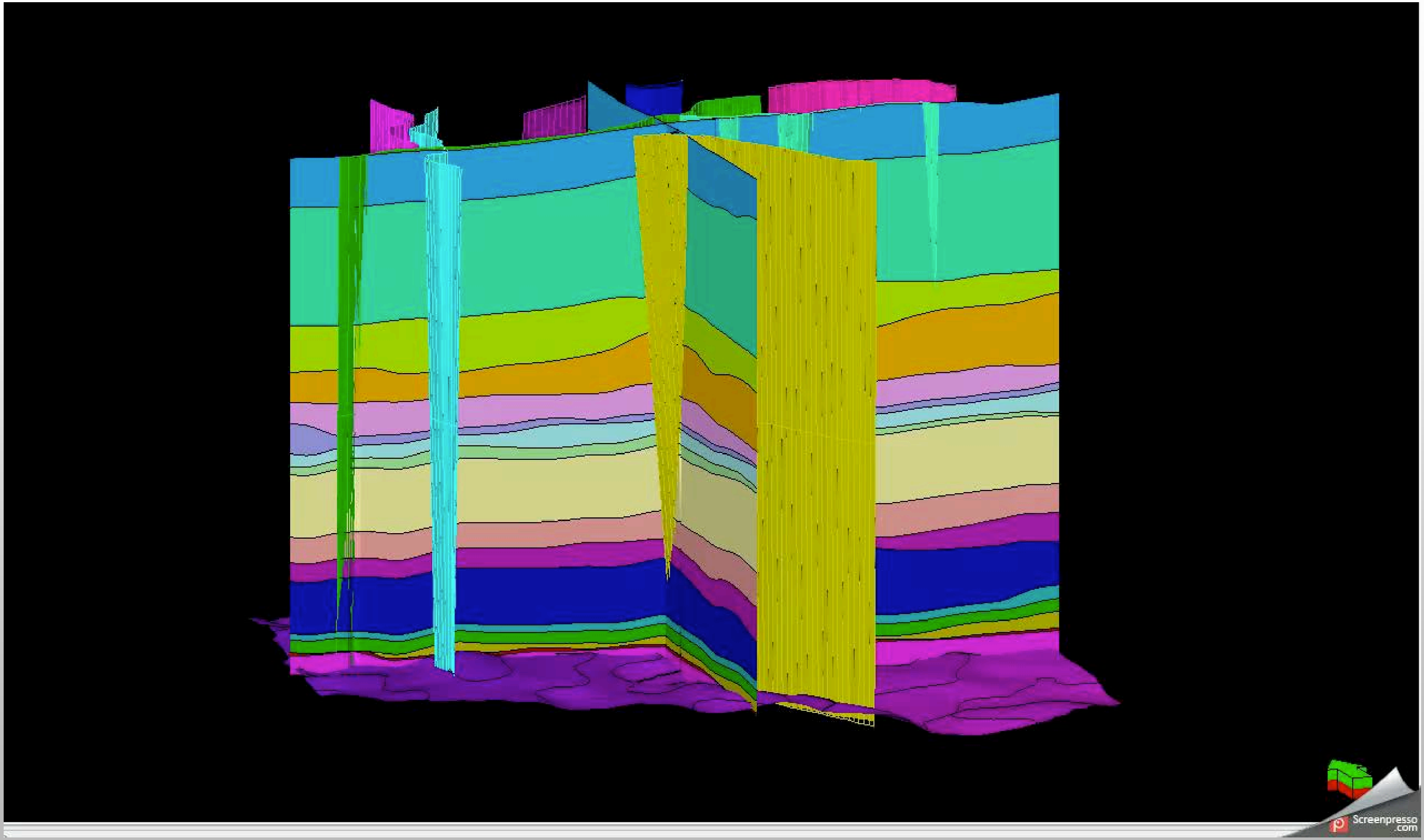




CHARACTERIZATION USING SEISMIC DATA

- Goal - characterizing reservoir architecture & facies distribution, mapping any faults, fractures, or structural features that could influence plume movement or reservoir integrity
- Tools – well logs, 3D surface seismic, 3D VSP's, cross-well tomography
- Findings- A geologic model was generated using all available seismic and well log information available. Geologic information and fault-like features interpreted from 3D seismic were included into this model. (See animation). The reservoir does exhibit heterogeneity. Features that may be faults but are still open to interpretation were noted in seismic data, and there is variation in reservoir thickness and structure across the Farnsworth field
- Geological model updated annually > propagated to simulation model

CHARACTERIZATION: SEISMIC DATA



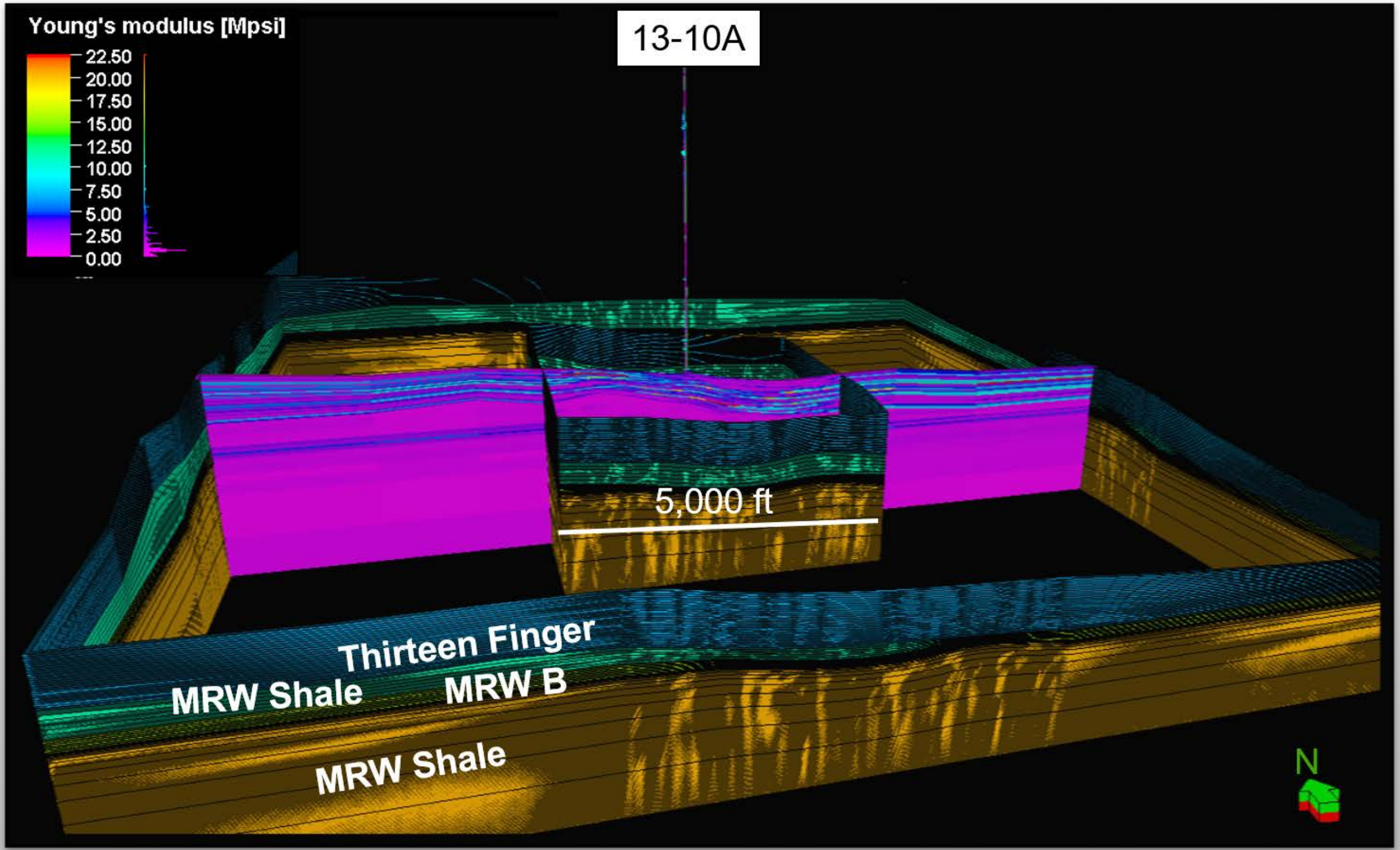
Annually updated Geological model

Planar features may be faults, fractures, and/or facies changes, paleovalley walls – remains to be determined

CHARACTERIZATION: MECHANICAL EARTH MODEL

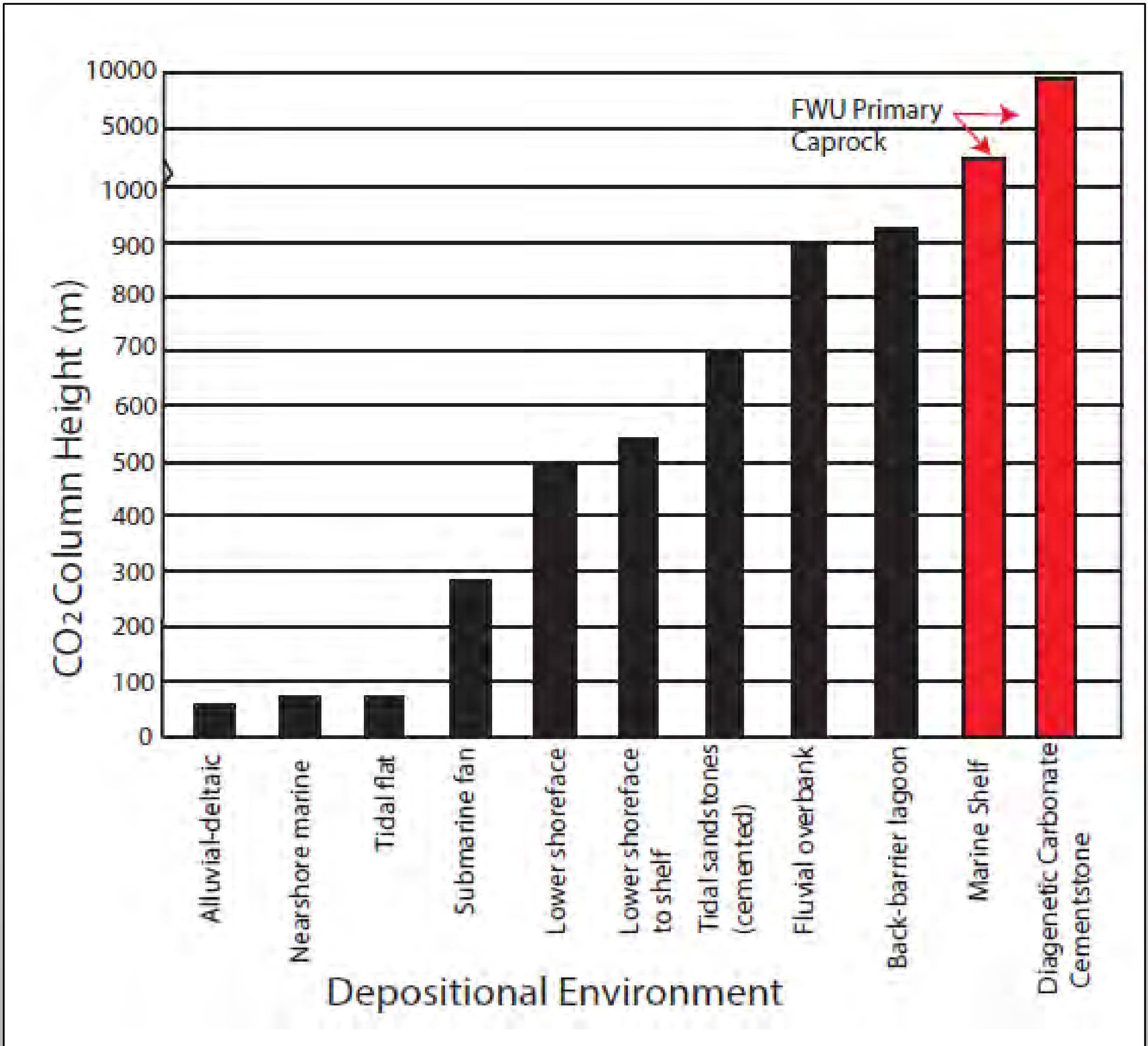
- Goal: Create a mechanical earth model that could be used to model rock behavior under a variety of scenarios
- Tools: Well logs, mechanical tests, geophysical studies
- Results: A small scale (5000 ft. by 5000 ft.) mechanical earth model centered on 13-10A. Utilized 1D geomechanical model generated by Schlumberger at 13-10A from sonic logs and post stack 3D seismic inversion to calculate geomechanical properties

Small-scale MEM Young's modulus



CHARACTERIZATION: CAPROCK INTEGRITY

- Goal: Caprock Integrity – how good is the seal?
- Tools: Core analysis, lithofacies & petrographic studies, mechanical testing, isotope analysis, mercury porosimetry, capillary pressure data
- Findings: Caprock The highest CO_2 column height is in the cementstone lithology at 11000 m (36089 ft). The lowest CO_2 column height for the caprock system is in the mudstone lithology within the upper Morrow Shale at 1100 m (3609 ft).
- Fracture gradients indicate that the Morrow B sandstone reservoir is weaker than the overlying lithologies, so any fractures initiated around the injection zone should be contained



SWP MVA EFFORTS AND LESSONS LEARNED

The MVA technologies deployed by the SWP are targeted to provide the data necessary to track the location of CO_2 in the study area, including migration, type, quantity and degree of CO_2 trapping. Monitoring data is used to facilitate simulation and risk assessment, particularly with respect to USDWs, the shallow subsurface, and atmosphere.

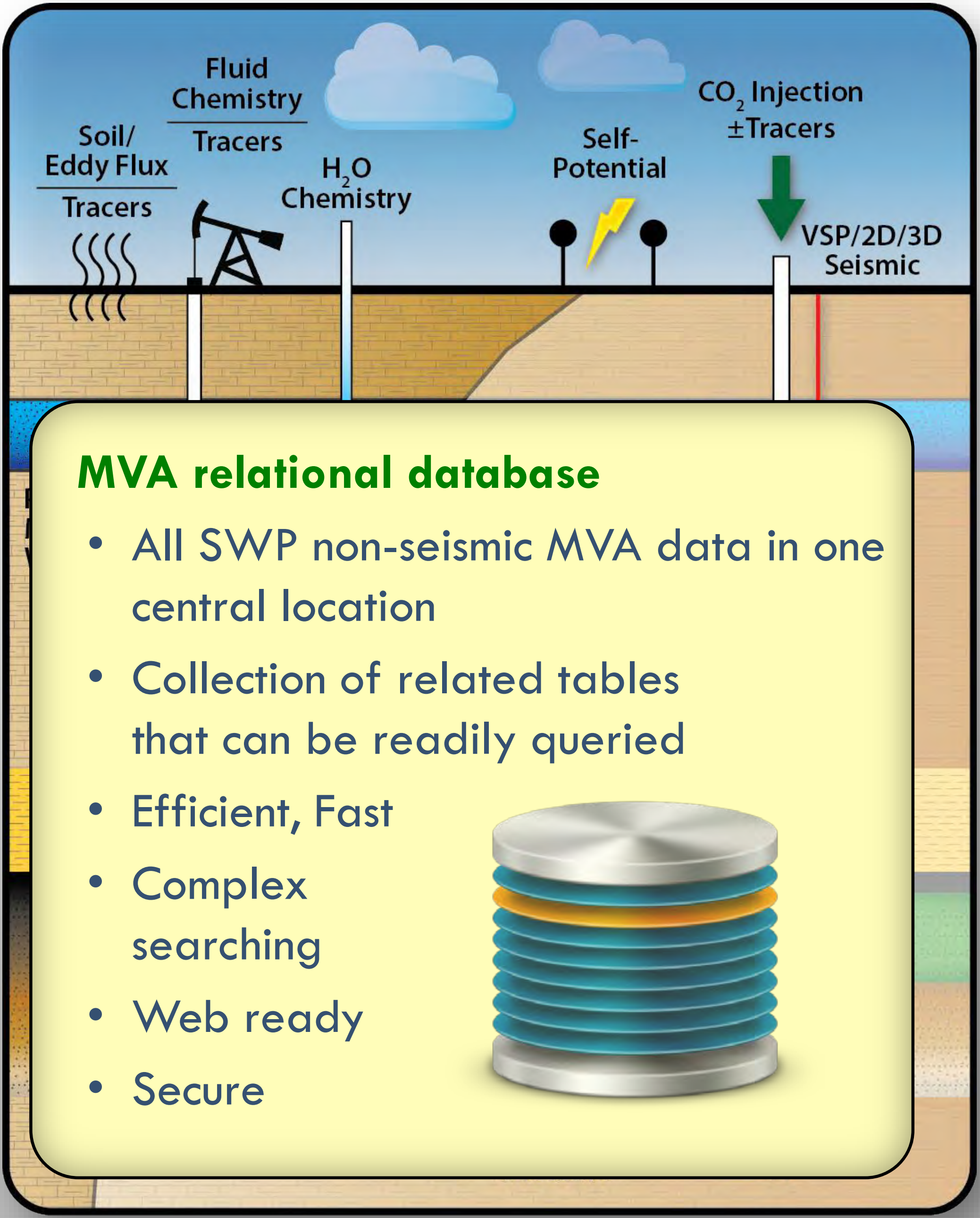
MVA OVERVIEW – TECHNOLOGY

Detecting CO_2 and/or brine outside Reservoir:

- Groundwater chemistry (USDW)
- Soil CO_2 flux
- CO_2 & CH_4 Eddy Covariance
- Aqueous- & Vapor-Phase Tracers
- Self-potential (AIST)
- Distributed Sensor Network (Ok. State)

Tracking CO_2 Migration and Fate:

- *In situ* pressure & temperature
- 2D/3D seismic surveys
- VSP's
- Cross-well seismic
- Passive seismic
- Fluid chemistry (target reservoir)
- Aqueous- & Vapor-Phase Tracers
- Gravity surveys & MagnetoTelluric (AIST)



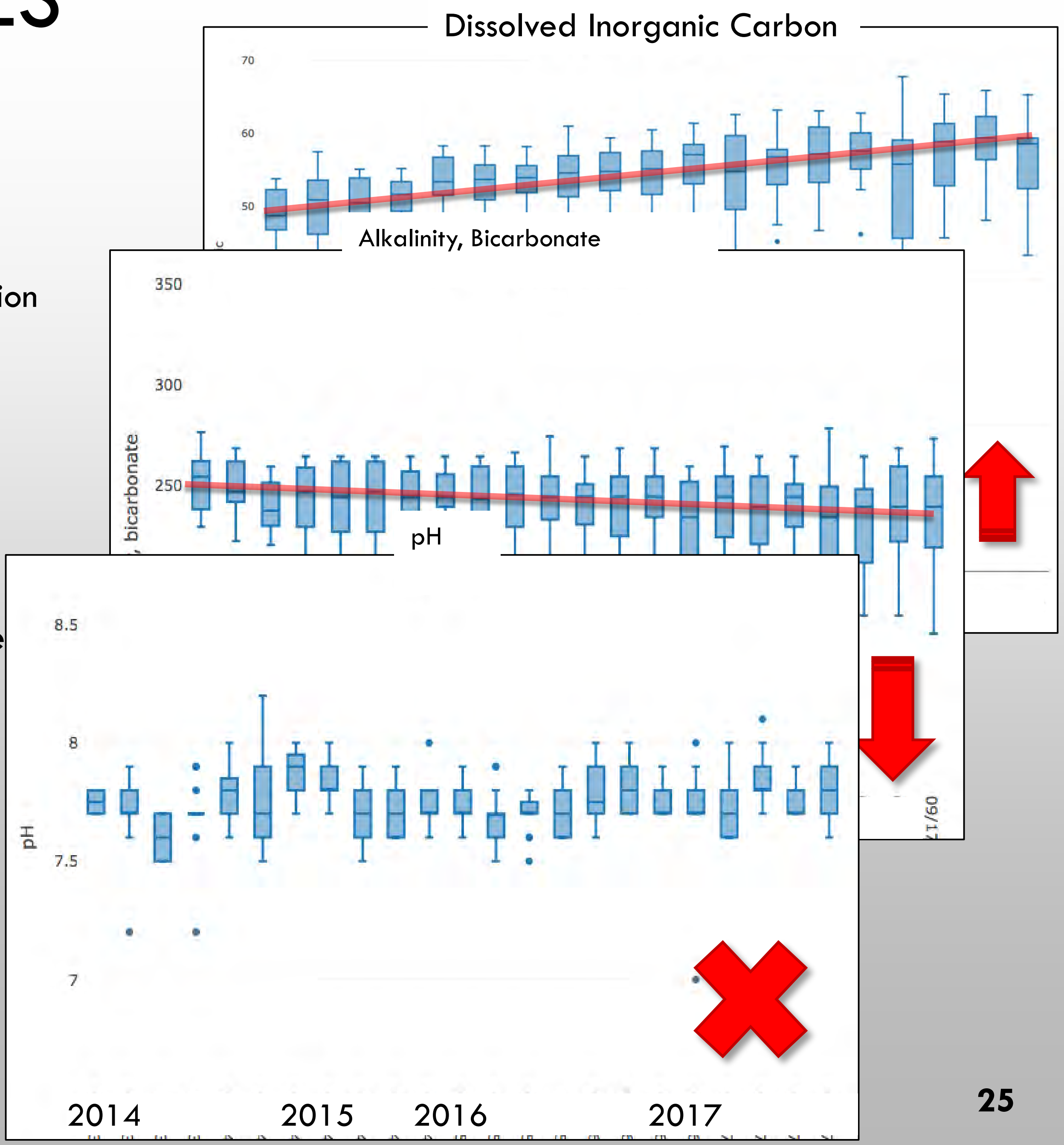
MVA relational database

- All SWP non-seismic MVA data in one central location
- Collection of related tables that can be readily queried
- Efficient, Fast
- Complex searching
- Web ready
- Secure

MVA OVERVIEW – SUCCESSES

USDW Monitoring

- Quarterly sampling of groundwater wells in/around FWU (n≈22) to monitor for brine, hydrocarbon and/or CO_2 leakage from depth.
  - Includes Major Cations/ Anions, pH, Conductivity, Alkalinity, Oxidation and Reduction Potentials (ORP), Inorganic Carbon (IC) and Organic Carbon (OC), Trace Metals and Isotopes (13C,18O, and D).
- Total/Dissolved Inorganic Carbon (DIC) *increasing* “field wide” (>18 USDW wells).
  - DIC (C_T) = $[CO_2] + [HCO_3^-] + [CO_3^{2-}]$
  - **DIC is a measure of CO2 in an aqueous system**
  - **However!** No other indicators of CO_2 leakage yet measure (pH steady, Alkalinity decreasing, ORP increasing)
  - More data needed, but increasing DIC values likely due to regional recharge and/or groundwater contamination from the surface (e.g. fertilizers)
- Technology validates spatial and temporal sampling as a means to monitor USDW for potential leakage

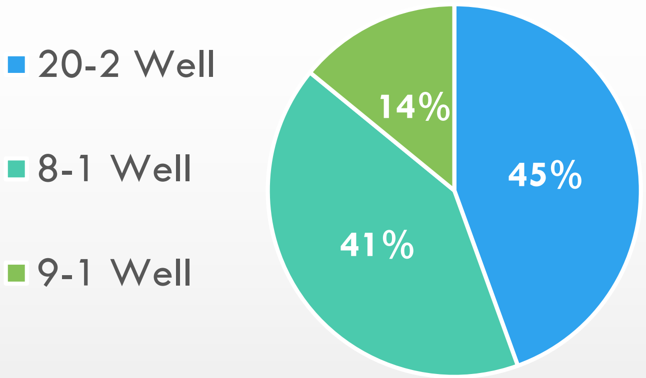


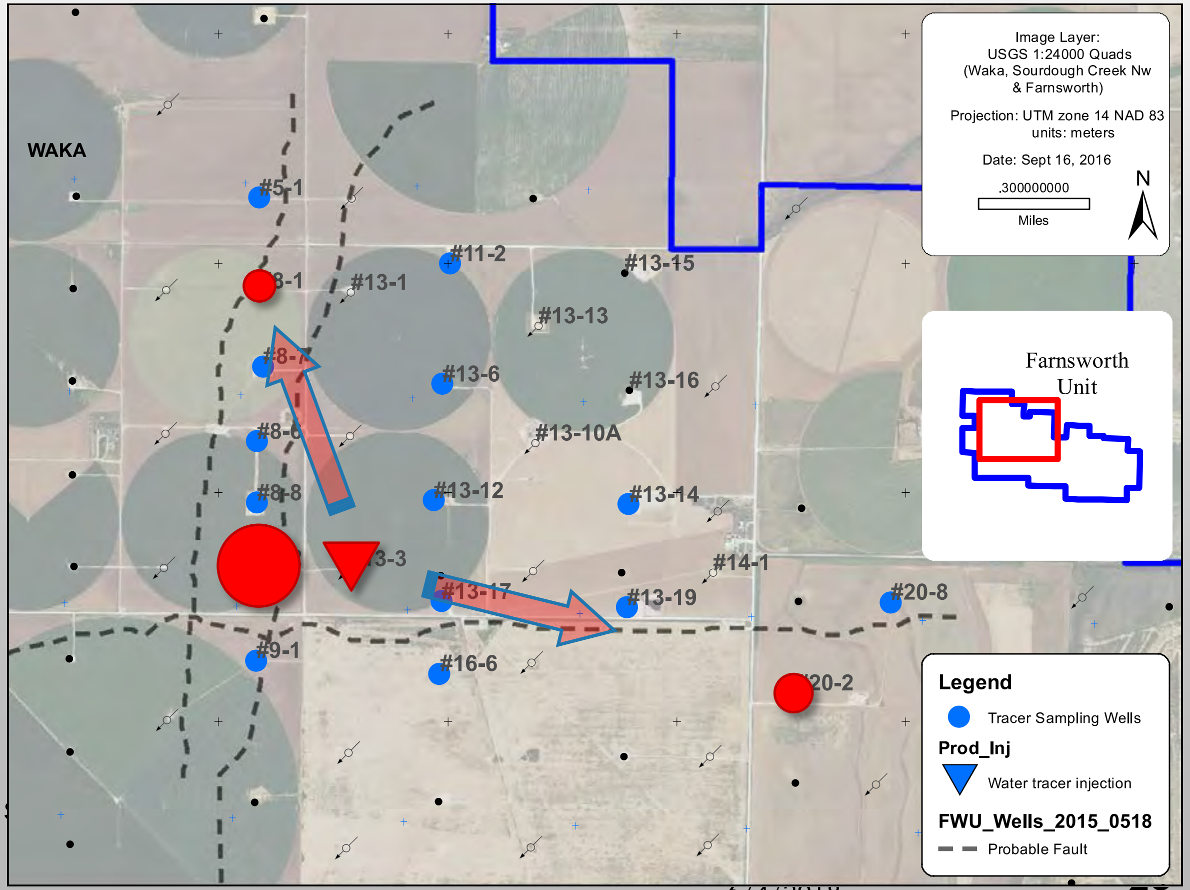
MVA OVERVIEW – SUCCESSES

Reservoir Tracers – Aqueous Phase

- Aqueous-phase tracer slugs (Naphthalene sulfonates) were injected into 5 well patterns to successfully evaluate fluid velocities, interwell connectivity and identify and characterize significant reservoir heterogeneities (faults).
    - The latest injection (FWU #13-3) yielded results indicating significant preferential fluid flow along two adjacent faults <map at right>
    - Relative tracer recovery along (#8-2 and #20-2) and across faults (#9-1) indicate variable transmissive versus sealed characteristics

2-NS Relative recovery between FWU wells #8-1, #9-1 and #20-2

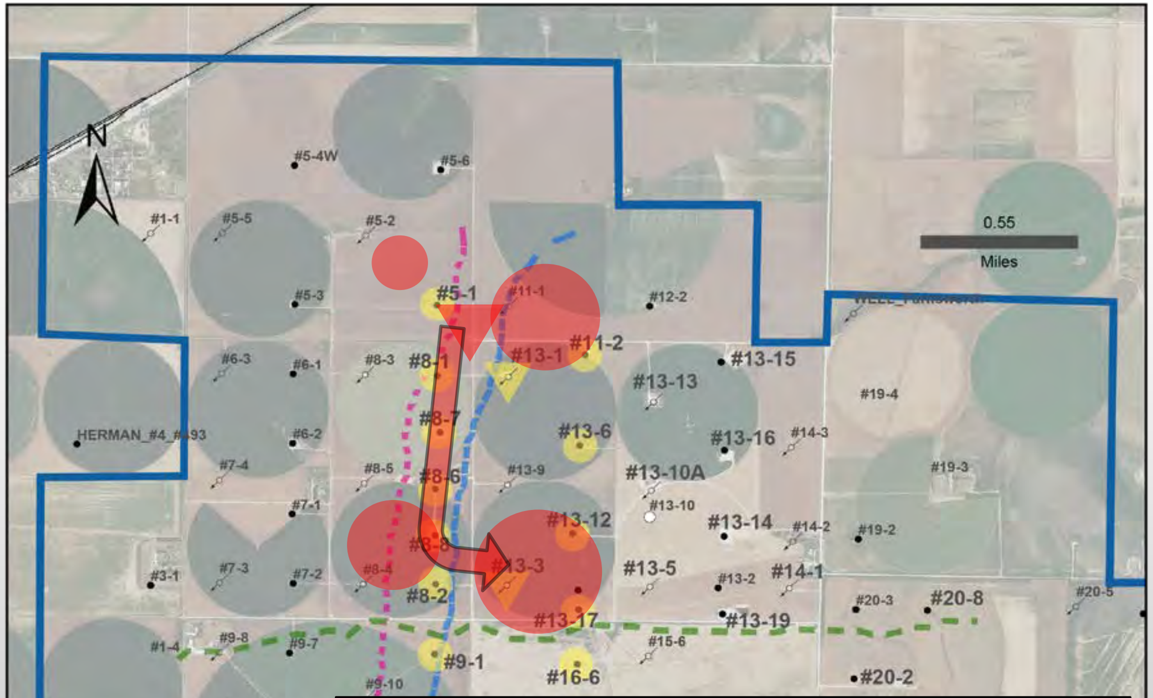


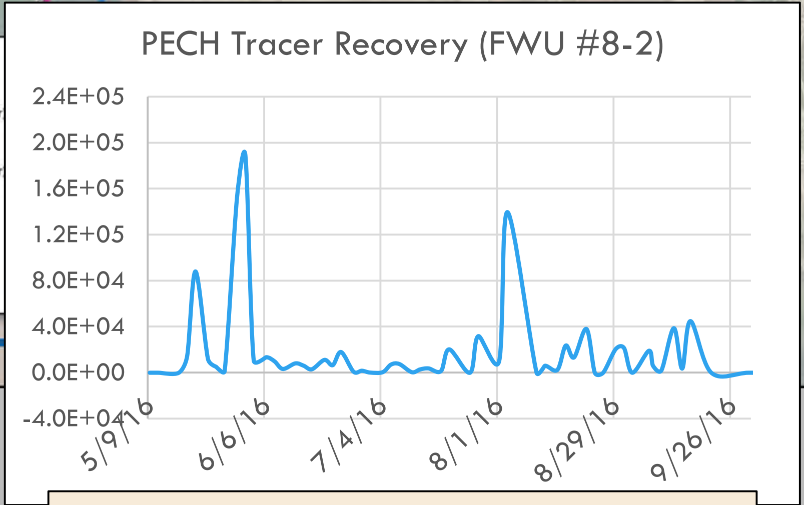


MVA OVERVIEW – MIXED SUCCESSES

Reservoir Tracers – Vapor Phase

- Vapor-phase tracer slugs (Perfluorocarbons) were injected into 4 well patterns in an attempt to assess CO_2 migration in the reservoir.
  - An injection into FWU #13-1 yielded results suggesting preferential fluid flow along two adjacent faults <map at right>
  - However, vapor-phase tracer recovery is not as straightforward (multiple spikes) as the aqueous-phase tracers, leading to uncertainty in analysis.
  - Despite technological advancements made by NMT for the purpose of gas tracer collection, injection and sampling sampling both require specialized equipment and procedures that increase on-site access, effort and costs.





Fluctuating vapor-phase tracer return curve for FWU well #8-2 is indicative of most wells sampled.

GOST: Gas Oil Separation Tank for collection of vapor-phase tracers

MVA MAJOR FINDING: COUPLING OF GEOPHYSICS, MODELING & TRACERS

Geophysical modeling & structural interpretation using 3D reflection seismic

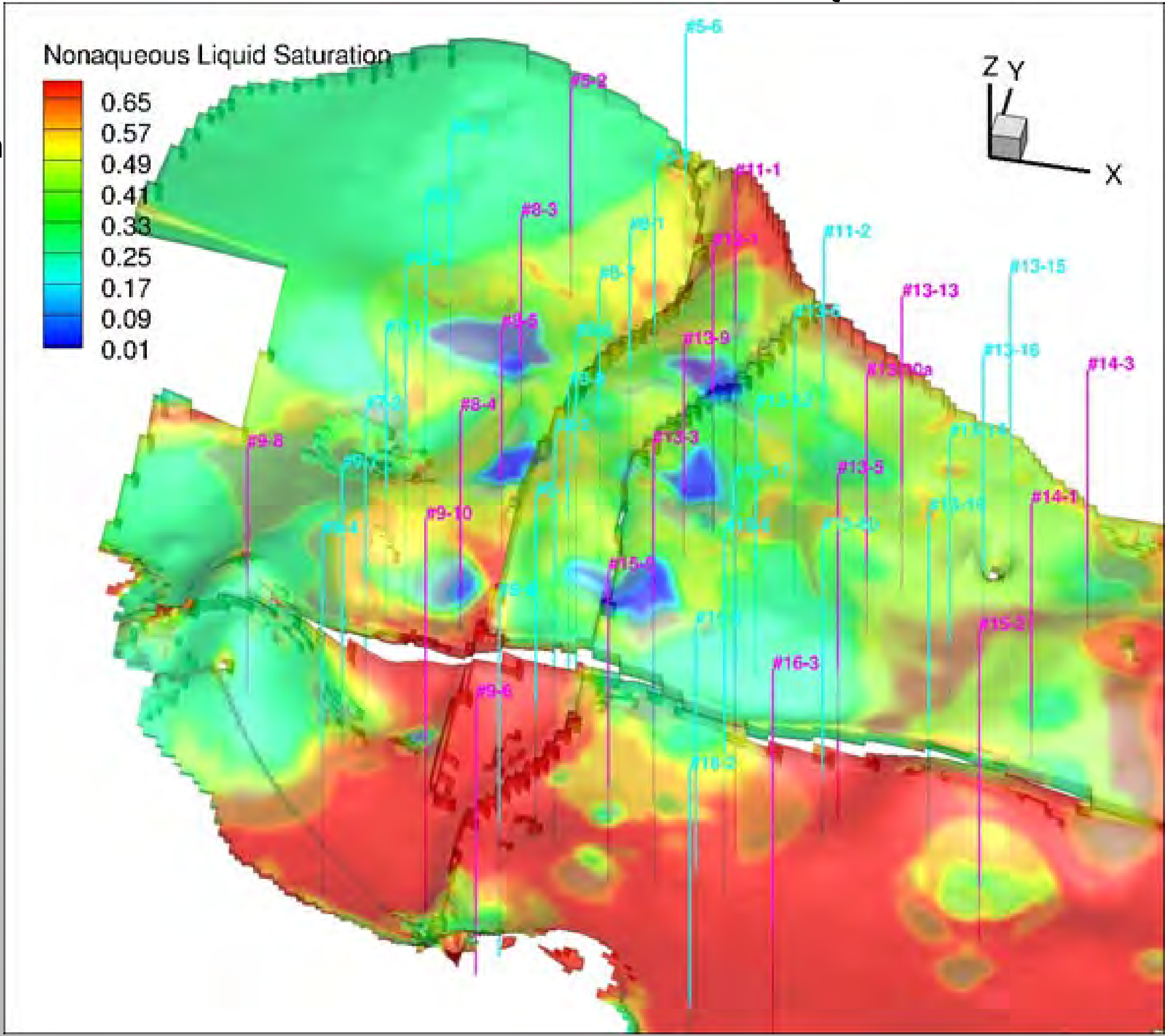
- Seismically resolvable faults/fault-like features interpreted by seismic attributes
- Implies many smaller faults/fractures
- Faults probably act as sealing features rather than seal bypass systems
- Faults affect geologic properties in geomodel

Reservoir Tracers

- Reservoir tracer data yielded useful model development data, including verification of and characterization of faults and transport pathways.

Modeling & Simulation

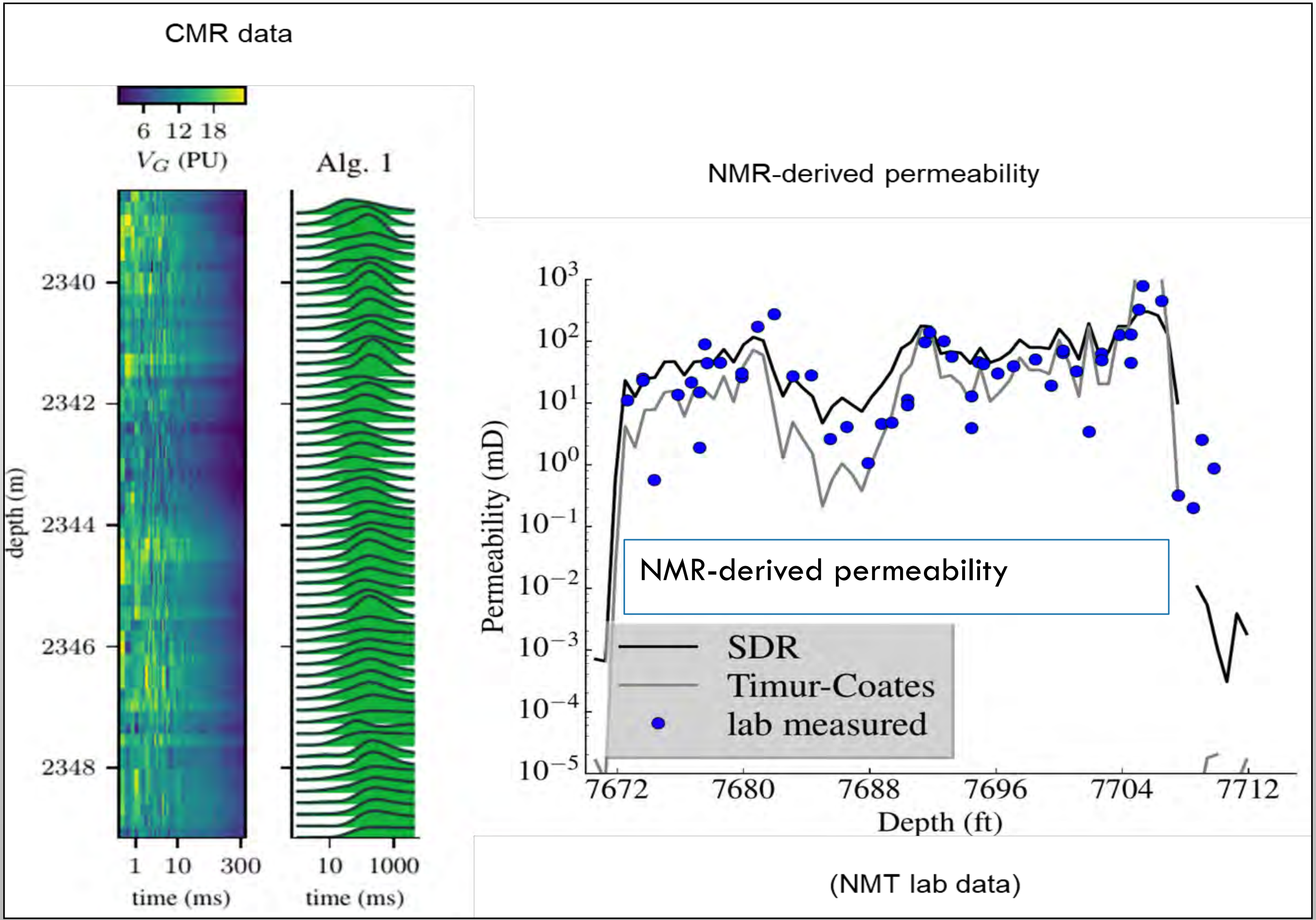
- Numerical simulations of the aqueous-phase tracer injections were able to successfully predict fluid transport in specific well patterns and increased permeabilities along adjacent faults.



SWP SIMULATION EFFORTS AND LESSONS LEARNED

SIMULATION: DATA SOURCES

- Geological Model
- Field Historical data
- Fluid Samples
- SCAL data/Capillary pressure data
- Borehole NMR (CMR)
- Tracer injection/recovery data
- Lab derived data



SIMULATION: TECHNOLOGIES AND APPROACH

SOFTWARE:

- Different software used to satisfy the full range of THMC processes
- STOMP-EOR (PNNL)
- Eclipse/Petrel (Schlumberger)
- Geochemist's Workbench (U. Ill.)
- TOUGHREACT (LBNL)
- Other in-house codes for specialty applications (proxy/ROMs, resource analysis, economics, etc.)

CALIBRATION:

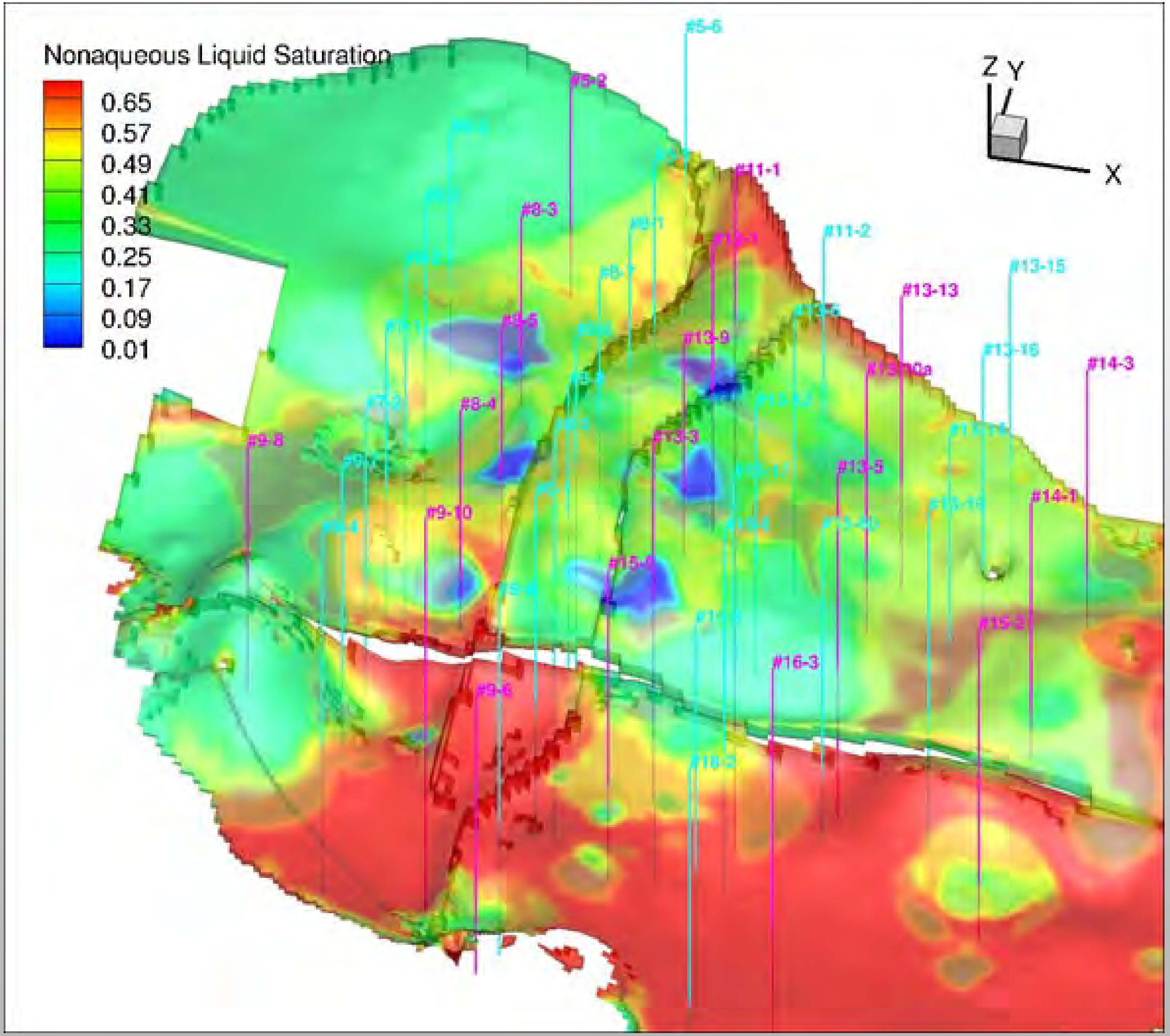
- Porosity & permeability inverted from logs
- Calibration with laboratory tests yields good results, e.g.
  - Slim tube experiment for MMP
  - Relative permeability tests

SOME HIGHLIGHTED GOALS:

- Computer assisted history matching
- Proxy Modeling (ROMs)
- Optimization framework

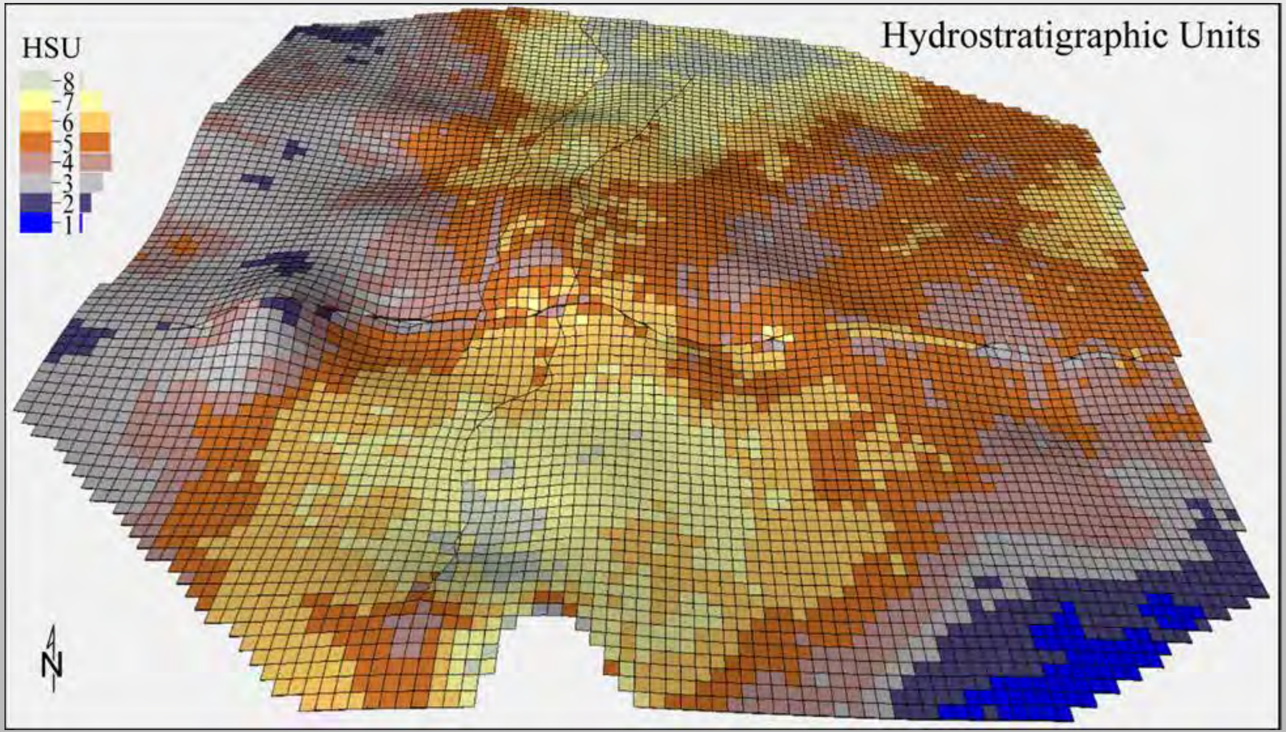
SIMULATION RESULTS: EXAMPLE

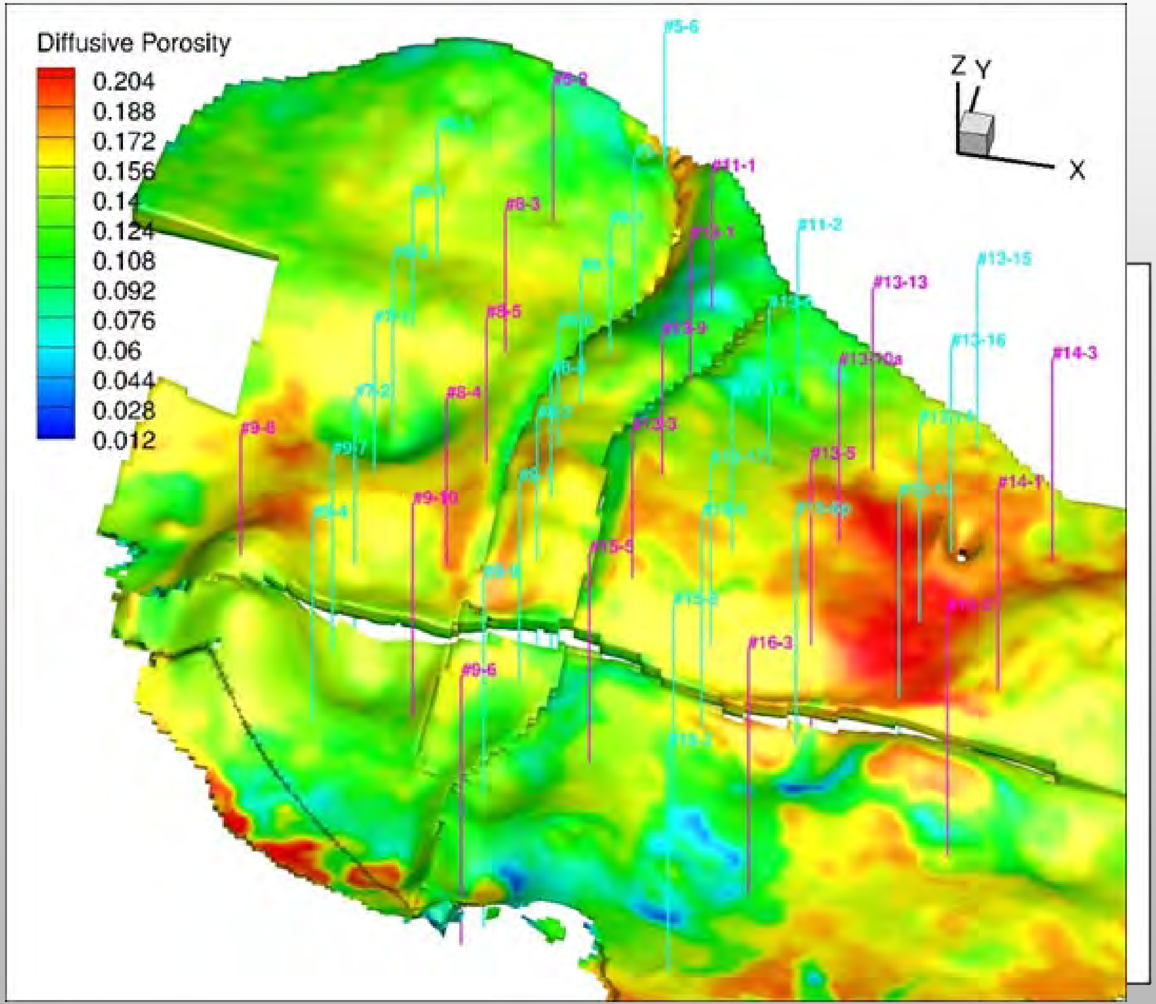
Simulation model showing Non-aqueous Liquid Saturation and impact of planar features on flow



SIMULATION: WHAT WORKED

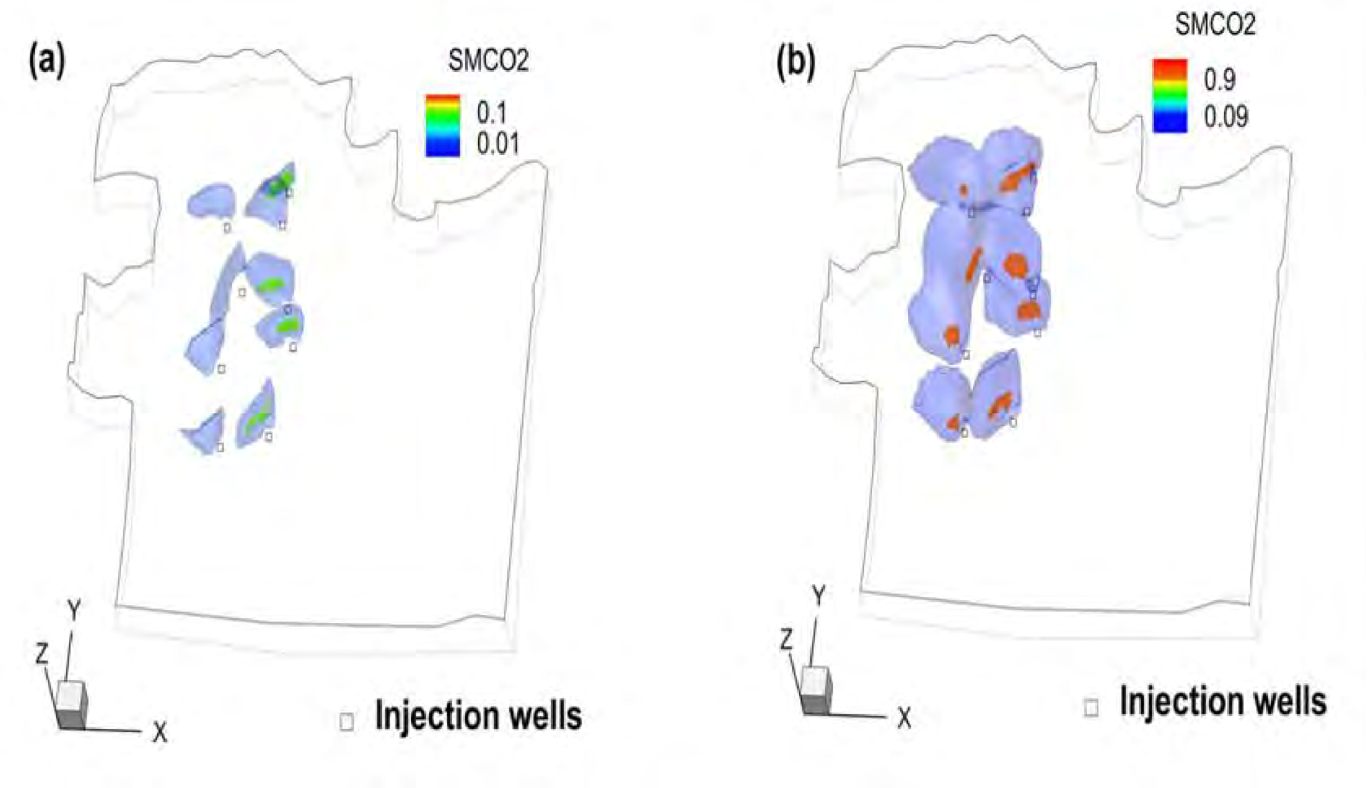
- Incorporation of Geologic models from characterization
- UU's model and NMT's history matched model are in good agreement with historical data
- Used as the basis for relative permeability analysis, fluid substitution analyses, etc.





SIMULATION: WHAT WORKED

Exchange of field data, geologic models, and PVT data between disparate modeling / simulation software (e.g., for different capabilities, including Petrel, Eclipse, STOMP, TOUGHREACT)



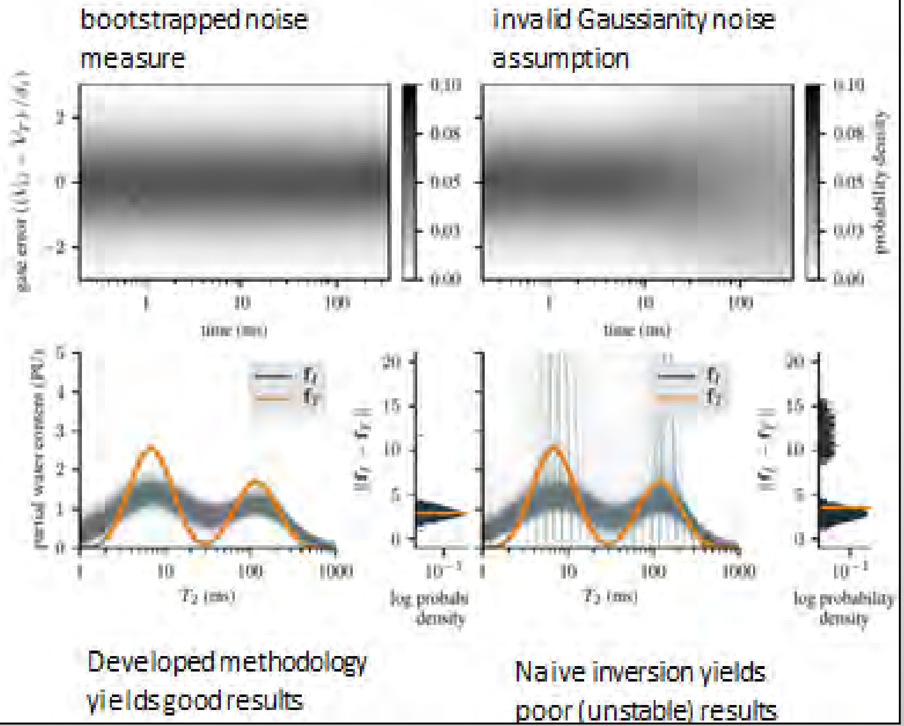
TOUGHREACT simulation plots of the western FWU showing the SMCO2 parameter, i.e. the mass of injected CO_2 sequestered as carbonate minerals in kg/m^3 of porous medium at times of (a) 1 year and (b) 57 years

- CO_2 was injected continuously for the first 10 years of the simulation

SIMULATION: WHAT DIDN'T WORK

Initial inversions with full surface seismic

- geophysical inversion
- ill-posed & non-unique problem
- reliability of inversion (previous slide) depends on careful regularization
- preliminary CMR log analysis may be misleading

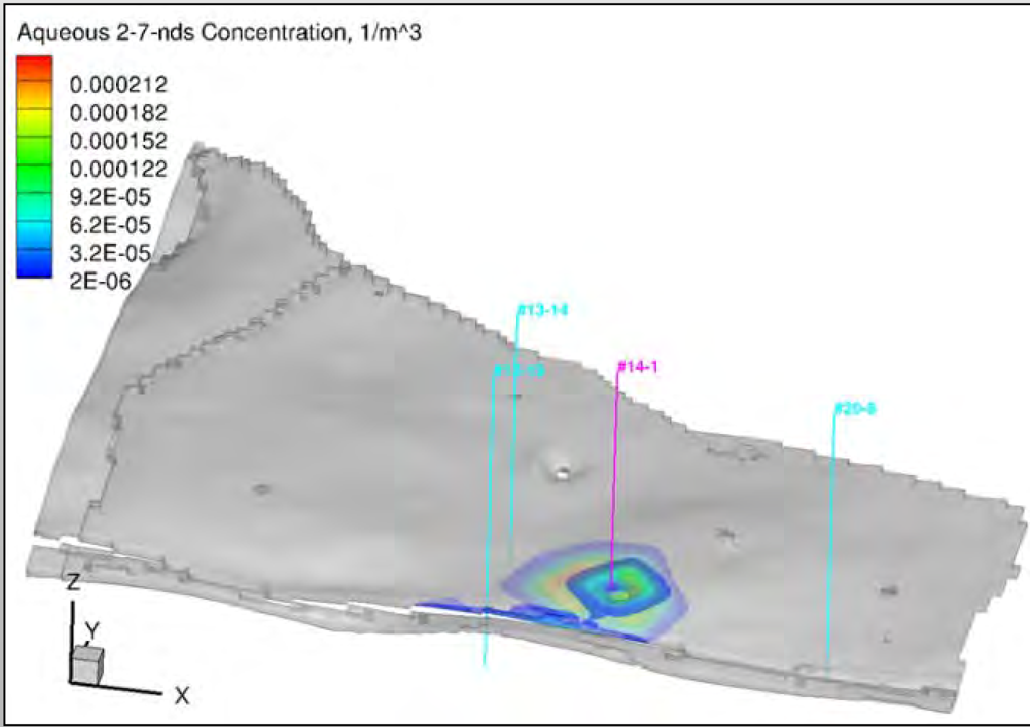


What didn't work and needs further evaluation

- Recover predictions for tracer 2,7-NDS at production well #20-8
- STOMP-EOR simulations require longer execution time than Eclipse, demonstrating difference between production and scientific software (and the need for parallelization)

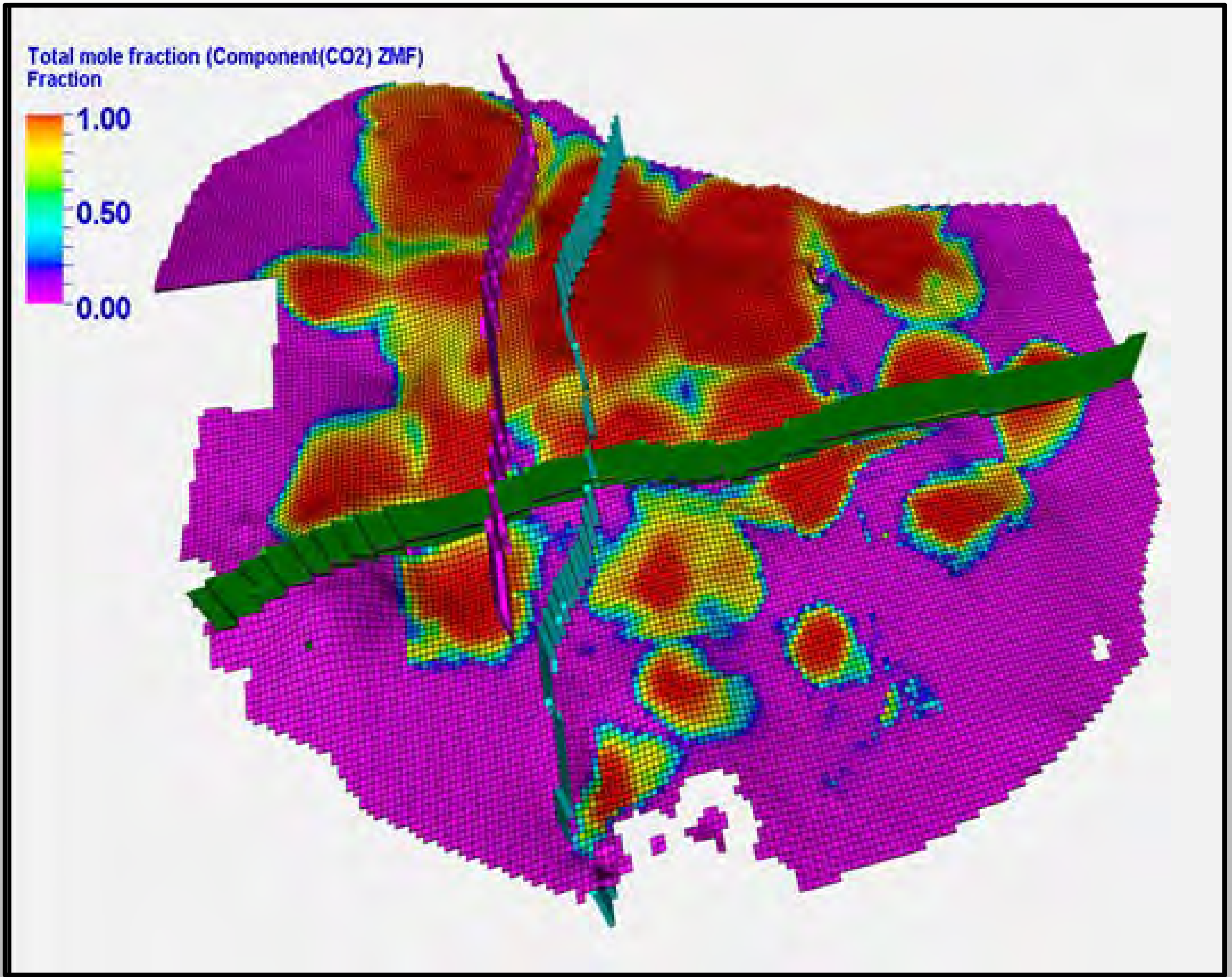
What didn't work and needs further evaluation

- Differences in modeling approaches for faults between Eclipse and STOMP
- Modifications required in STOMP to match fault modeling approach in Eclipse



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_2 storage and oil recovery framework which may be applied to other projects



SIMULATION: RECENT FINDINGS

- For this field, injected CO_2 persists as an immiscible phase for only a few decades after injection ceases
- Calcite was predicted to be the most abundantly precipitated carbonate mineral over the entire study area (model domain)
- In the immediate vicinity of injection wells, dolomite was the most abundantly precipitated carbonate mineral
- Native reservoir minerals, albite, clinochlore, and illite, were predicted to dissolve, whereas quartz, kaolinite, and smectite were predicted to precipitate
- Dissolution and precipitation of minerals in the Morrow B Sandstone induce negligible changes in its porosity

SWP RISK ASSESSMENT EFFORTS
AND
LESSONS LEARNED

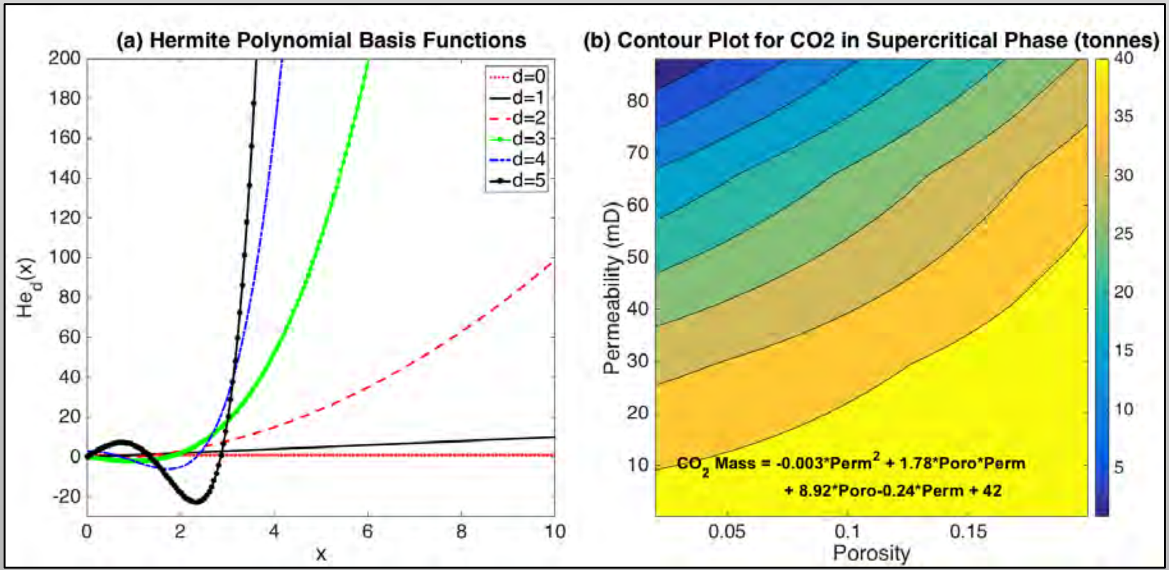
RISK ASSESSMENT: TECHNOLOGIES

- Qualitative Risk Analysis (MOSTLY COMPLETE)
  - Risk Registry via Failure Modes and Effects Analysis (FMEA)
  - Annual Risk Survey (2014-2017)
  - Process Influence Diagram (PID)
- Quantitative Risk Analysis (ONGOING)
  - Probabilistic Assessment
  - Geologic/reservoir models
  - Reduced Order Models (ROMs)
    - Response Surface Method
    - Polynomial Chaos Expansion (PCE)
  - NRAP tools: NRAP-IAM-CS, RROM-GEN

RISK ASSESSMENT: RECENT ACCOMPLISHMENTS

- Updated Risk Rankings in 2018 (much like in 2014, 2015, 2016 and 2017)
- Constructed process influence diagrams (PIDs) for quantitative risk assessment
- Developed apparently-robust ROMs for representing full-reservoir model simulation results, to save computational time and effort.
- Developed workflow from physics-based reservoir simulators to performing leakage calculations using NRAP-IAM-CS
- Developed integrated framework of combined batch experiments and reactive transport simulations to analyze mechanisms of trace metal mobilization.

2017 FEP No.	2016 FEP No.	Rank 2014	Rank 2015	Rank 2016	Rank 2017	**2017 FEP** (* different wording in prior year/s)
F515	F22	6	1	1	1	Price of oil (or other related commodities)
F506	#N/A	#N/A	#N/A	#N/A	2	DOE financial support
F407	F65	35	28	16	3	On-road driving
F501	#N/A	#N/A	#N/A	#N/A	4	Change of field owner and/or operator
F502	F19	2	7	4	5	CO2 supply adequacy
F508	F23	37	2	7	6	EOR oil recovery
F513	F24	7	3	5	7	Operating and maintenance costs
F511	F63	29	18	2	8	Legislation affecting CO2 injection or CO2-EOR*
F306	F40	1	36	23	9	Simulation and modeling - parameters*
F609	#N/A	#N/A	#N/A	#N/A	10	Well component failure (tubing, seals, wellhead, etc.)
F109	F13	16	15	29	11	Reservoir heterogeneity
F401	F66	18	8	3	12	Accidents and unplanned events
F207	#N/A	#N/A	#N/A	#N/A	13	Workovers: Damage to instrumentation
F603	F53	48	16	24	14	Defective hardware*
F310	F36	9	6	25	15	Simulation of geomechanics
F206	F16	12	25	39	16	Seismic method effectiveness*
F608	F41	84	#N/A	10	17	Severe weather
F111	F06	52	#N/A	51	18	Undetected features
F516	F26	21	9	31	19	Project execution strategy (DOE project, not EOR or production)*
F304	F33	10	10	41	20	Over pressuring



RISK ASSESSMENT: MAJOR FINDINGS

Wellbore Leakage:

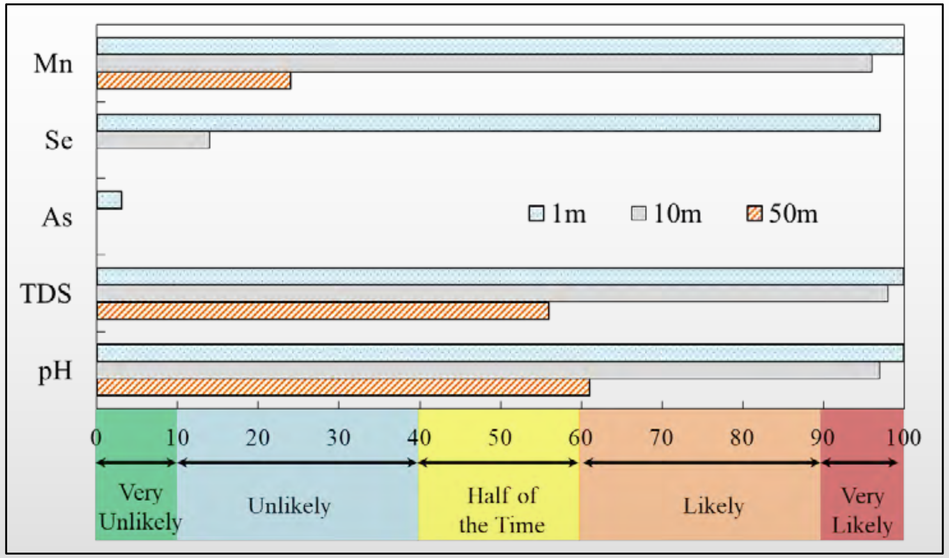
- Wellbore cement at the FWU will likely maintain its structure and integrity within 100 years, and is unlikely to provide leakage pathways.

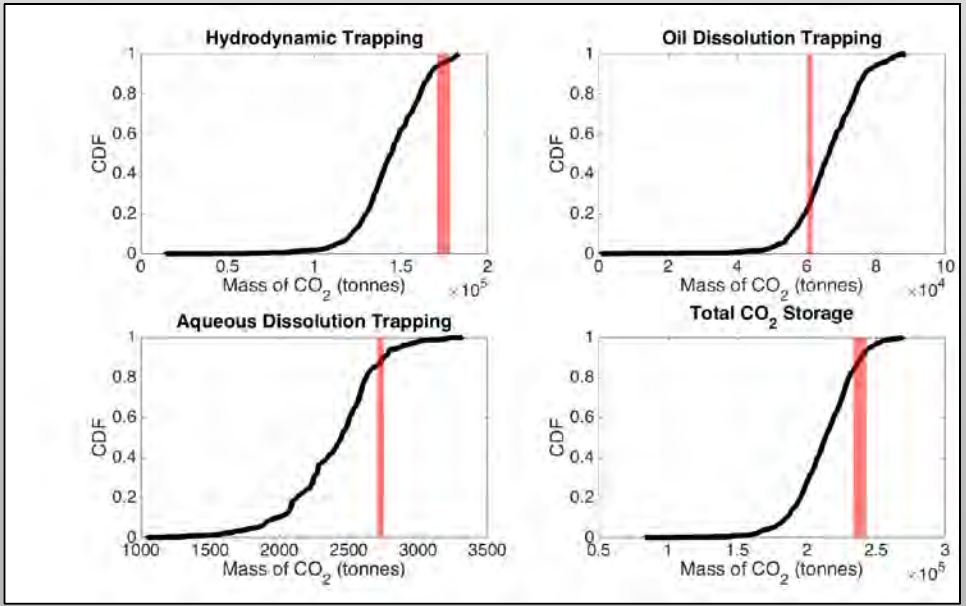
USDW Impact:

- Toxic trace metals may be considered an insignificant long-term concern for the Ogallala formation: simulations indicate that clay adsorption mitigates impact of CO_2 and brine leakage from the reservoir
- Increased salinity of USDW via leaked saline water may likely be a larger concern than associated trace metals release.

CO_2 Storage and Economics:

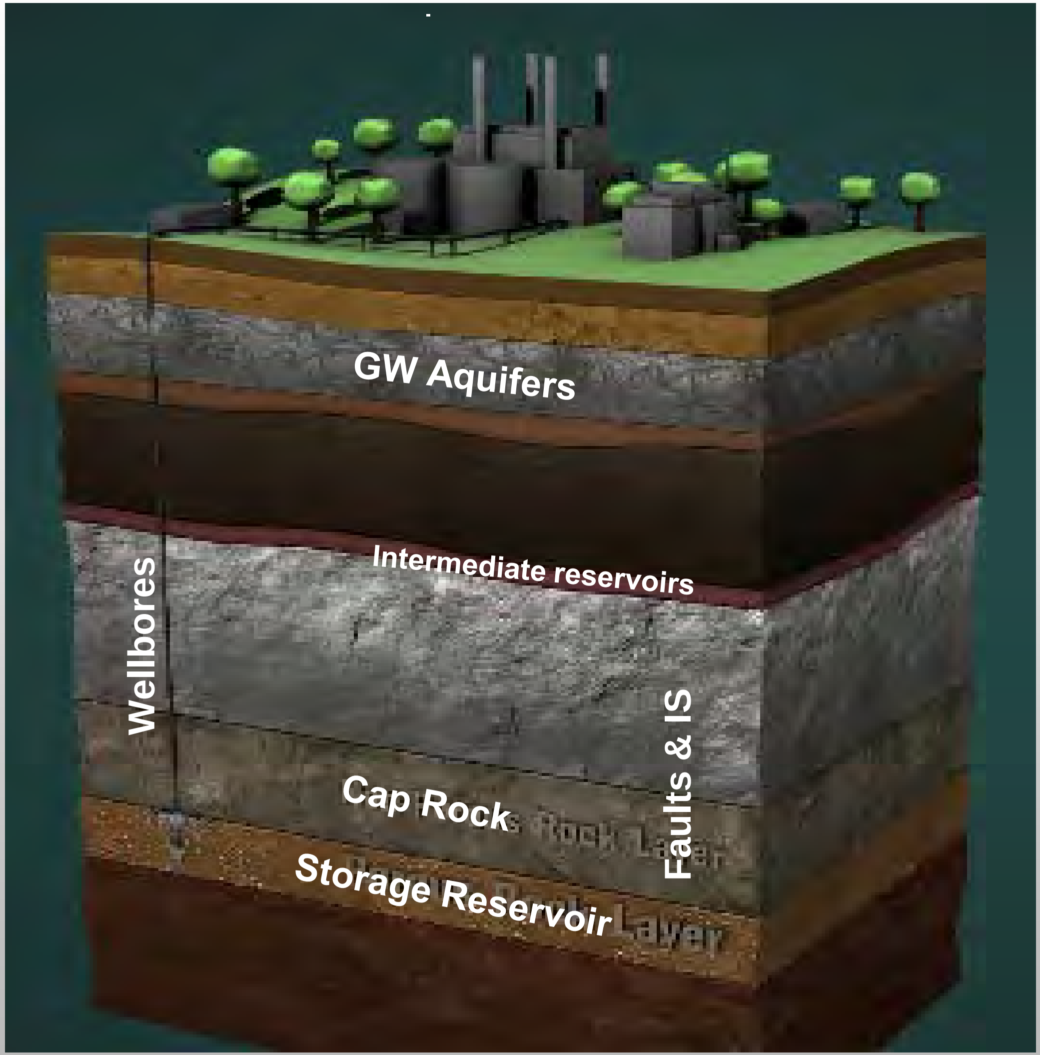
- Hydrodynamic trapping sequesters the most injected CO_2 at the FWU, followed by oil dissolution trapping, and aqueous dissolution trapping.
- ROMs analyses suggest that 31% of the 1000 realizations designed for FWU may be profitable.





RISK ASSESSMENT: NEEDS FURTHER EVALUATION

- Leakage Assessment
  - Compare leakage risk for FWU in current EOR operations to FWU if it had been developed as a greenfield, CO_2-storage-only site
  - Enhance wellbore leakage models to include oil with the CO_2 and brine leakage.
- Uncertainty Reduction
  - Heterogeneity of groundwater (Ogallala) formation/caprock/reservoir could be included in simulations for further site characterization.
  - Further calibration of geochemical reactions/cement degradation of site-specific samples may be utilized to reduce uncertainty of forecasted key parameters.
  - Uncertainty may be reduced with more and/or higher-resolution characterization data.



POST-INJECTION PERIOD (BP4) PLANS

INCOMPLETE AND FINAL WORK ITEMS

Critical work that is incomplete

- Support work
  - Characterization
  - Simulation
  - Monitoring (MVA)
- Passive seismic
- Depleted oilfield storage analysis (post EOR storage)
- Risk assessment (quantitative things)
  - Storage security
  - Leakage pathways
  - Wellbore integrity

Risk relies on much input from prior tasks and thus significant work remains

FOCUS AREA: SUPPORT WORK

- Characterization
  - VSP, Xwell, geobodies, larger scale mechanical earth model
  - Fine scale VSP based models and time-lapse geomodels
  - Better understanding of fault/fault-like features
- Simulation
  - Incorporate all tracer data
  - Contribute to long-term storage and risk assessments
  - Incorporate lab generated data, especially hydraulic flow and facies
- Monitoring (MVA)
  - Continue monitoring efforts until project close
  - Continue to provide support, data, and feedback to model builders, simulators, and risk assessment

FOCUS AREA: PASSIVE SEISMIC

- Test of an inexpensive off the shelf system to monitor if activity existed was successful in that it identified microseismic activity related to injection
- The system ultimately failed due to hardware limitations and damage incurred during emplacement leading to increasing signal to noise ratio
- Utilization of passive seismic not only as a risk assessment but also characterization tool
  - example: Aneth faults for characterization/risk and
  - example: AZMi and BZMi for risk
- New system slated for installation in October 2018

FOCUS AREA: RISK ASSESSMENT

Major work left in:

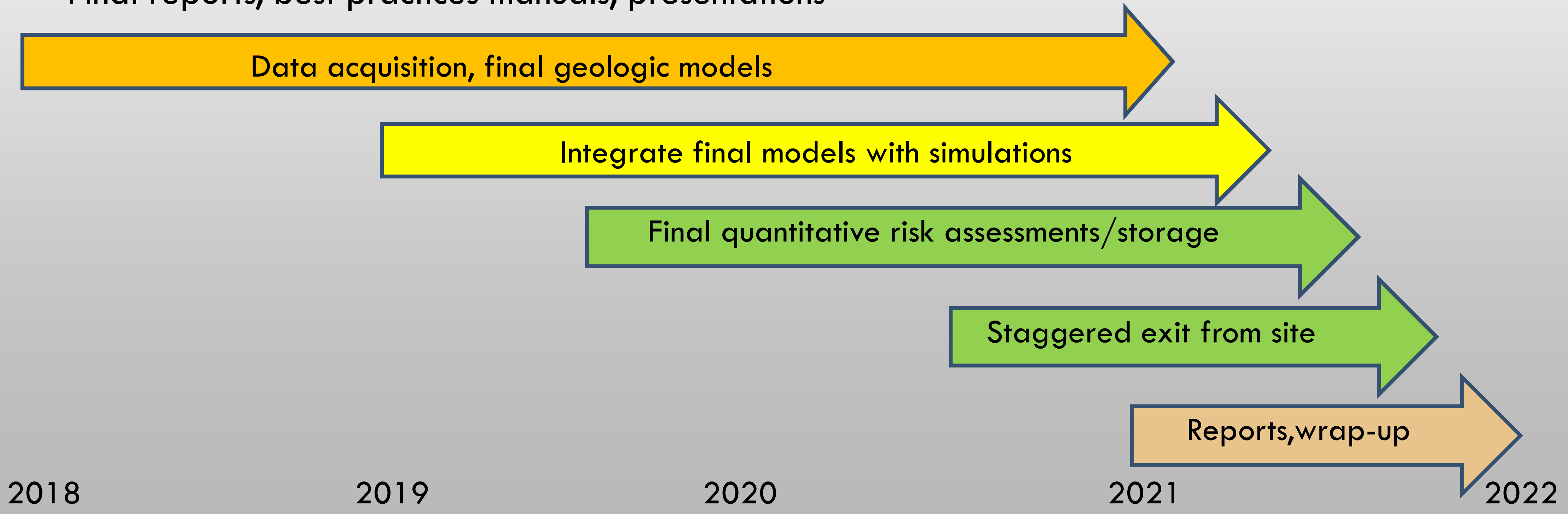
- Storage security
- Leakage pathways – chemomechanical studies of rock/fluid interactions under reservoir PT conditions
- Wellbore integrity – inventory older wells for cement quality, do sidewall coring, study effects of CO_2 on cement and near-wellbore rock
- Take results from reduced order models back into full-scale simulation

FOCUS AREA: DEPLETED OILFIELD (POST-EOR) STORAGE ANALYSIS

- Capacity analysis – quantifying capacity for commercial storage when factoring in post-EOR storage.
- Portability to other Anadarko or SW basins (Morrow reservoirs in particular – screen other fields based on FWU criteria and results).
- Evaluate impacts of credits such as 45Q on future projects
- Provide example and operational procedures for future EOR operations utilizing storage credits

TIMELINE TO COMPLETE PROJECT – 4 YEARS

- 24-36 months data collection: Passive seismic installation, acquisition, processing, and assimilation; Hydrophone Cross-well baseline and repeat; tracer results to be acquired and assimilated
- Integration of new data into geologic, simulation, and risk models
- Quantitative risk estimates using final models
- SWP exits FWU site
- Final reports, best practices manuals, presentations



Southwest Regional Partnership on Carbon Sequestration

Project DE-FC26-05NT42591

http://SWP.rocks