SMART-CS Initiative

Science-informed Machine Learning to Accelerate Real Time (SMART) Decisions in Subsurface Applications

Task 2 : Real Time Visualization of Rock and Fluid Properties

David Alumbaugh (LBL) and Dustin Crandall (NETL)

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U.S. DEPARTMENT OF ENERGY

Task 2 : Rock Property Visualization

Task 2 Mission: Evaluate existing and state of the art technologies for incorporating multiple types of disparate scale data to assess rock properties (CO_2 saturation for Phase 1) in a 'real time' sense, and identify/apply/test machine learning strategies that can aid in this endeavor.

Task 2: Rock Property Visualization Project Leadership
David Alumbaugh (LBNL, Lead)
Dustin Crandall (NETL, Co-Lead)

Sub-Target Resolution Scale Team

Dustin Crandall, Paul Holcomb, Foad Haeri, Tom Paronish (**NETL**)

Zuleima Karpyn, Russ Johns, Sanjay Srinivasan, Zihan Ren, Prakash Purswani, Fangya Niu, Parisa Shokouhi (**PSU**)

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Manika Prasad, Mathias Pohl, Savini Samarasinghe, Similoluwa Oduwole (**CSM**)

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Supra-Target Resolution Scale Team

David Alumbaugh, Michael Commer, Erika Gasperikova, Evan Um (**LBNL**)

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Xianjin Yang (**LLNL**)

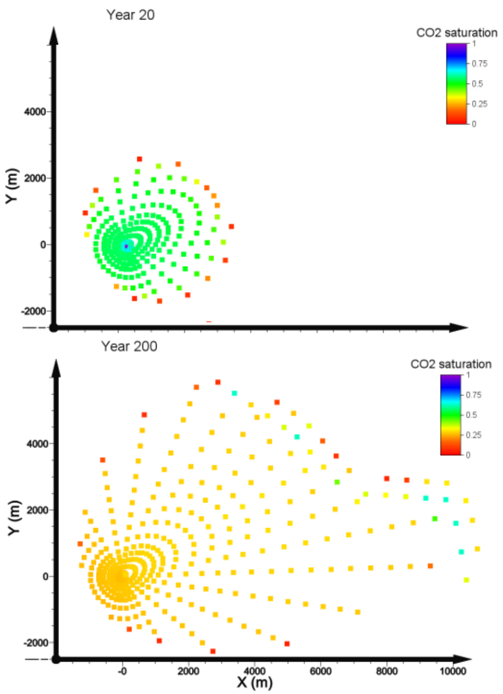
William Harbert (**NETL**)

Task 2 : Rock Property Visualization

- **Task 2 Goal For Phase 1 : Proof of concept for applying Physics-Based Machine Learning for providing estimates of CO_2 saturation at depth, along with uncertainties in those estimates, at 1 to 10m resolution.**
- **Specific Sub-Tasks**
    1. Determine data that we will be using for testing, and how that data will be used for estimating CO_2 saturation
        a. Core-to-Well scale: What data measured in lab provides value to estimating CO_2 saturation at target resolution?
        b. Well-to-field scale: What multi-physics data should we use, and how to use it to estimate CO_2 saturation?
    2. Implement and test physics-based approaches for estimating CO_2 saturation from various data types
    3. Implement and test ML approaches for
        1. Estimating CO_2 saturation from the various scales and types of data
            a. Upscaling from the Core-to-Well scale to the target resolution
            b. Downscaling from the Well-to-Field scale to target resolution, and provide images of CO_2 saturation rather than geophysical properties
        2. Provide estimates of uncertainty of CO_2 saturation at different scales

Task 2 Data : Kimberlina 1.2 Model/Data Creation

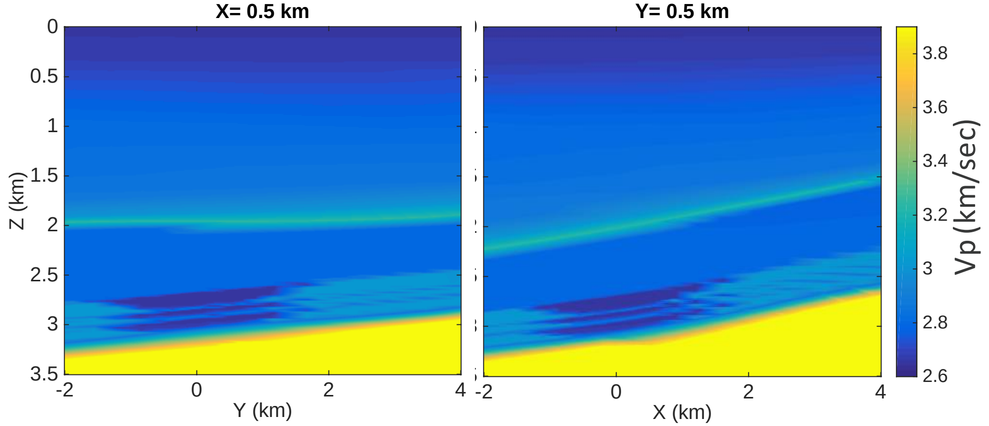
Unstructured TOUGH2 Mesh

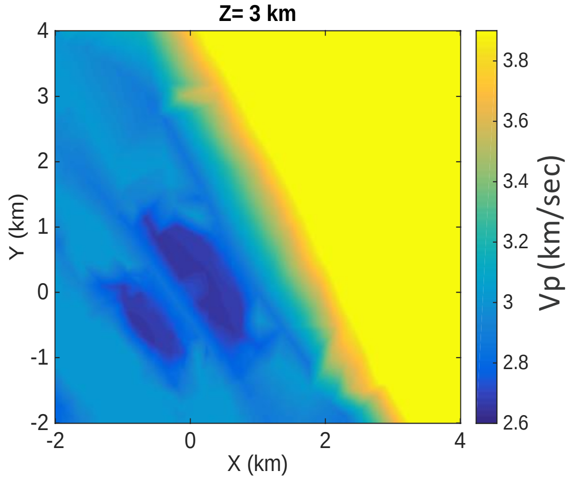


Interpolation/Extrapolation

Regular fine mesh
CO_2 Saturation
Vp and Vs
Density
Resistivity

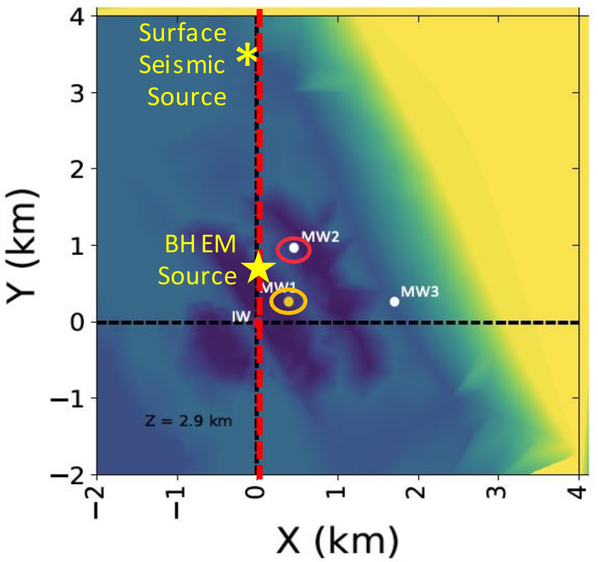
Vp at 20 Years on Regular (10m x 10m x 10m) grid

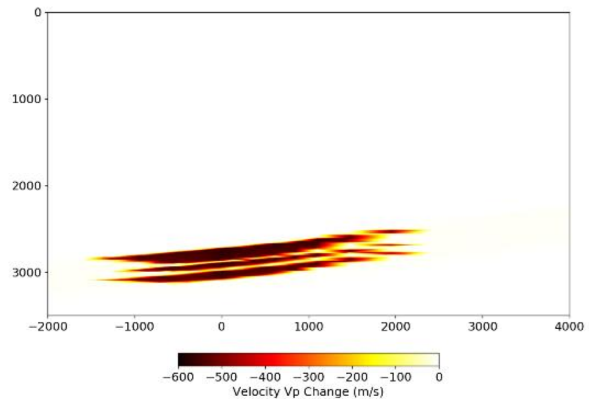




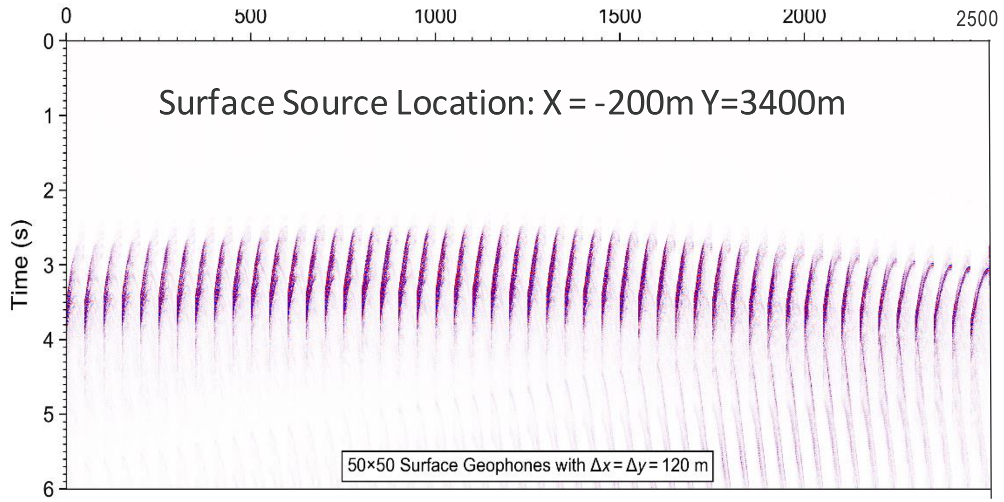
- **Using 100 different realizations / TOUGH2 runs of the Kimberlina 1.2 Model**
  - Each realization has 35 different time steps
  - Interpolation/extrapolation to regular grid more difficult than expected
- **Test Data sets computed for Year 0 and Year 20 from Sim001**
- **2D Testing**
  - Test data computed along Y direction at X=0 in Year 0 and Year 20
  - Training data computed along Y-Lines from X=-2 to X=3km for all 35 time steps in Sim001
    - 2D surface seismic at X=100m intervals
    - Borehole-to-surface EM with 2 sources at X=200m
    - Gravity in 2 boreholes per line and surf at X=200m
- **3D Testing**
  - Use all 100 Sims and 35 Time steps
  - For EM and Gravity use 3 monitoring wells shown to left for borehole sources/data
- **All models/data to be uploaded to EDX**

Task 2 Data : Kimberlina 1.2 Model/Data Creation
Time Lapse Calc. Geophysical Data (Year 20- Year 0)





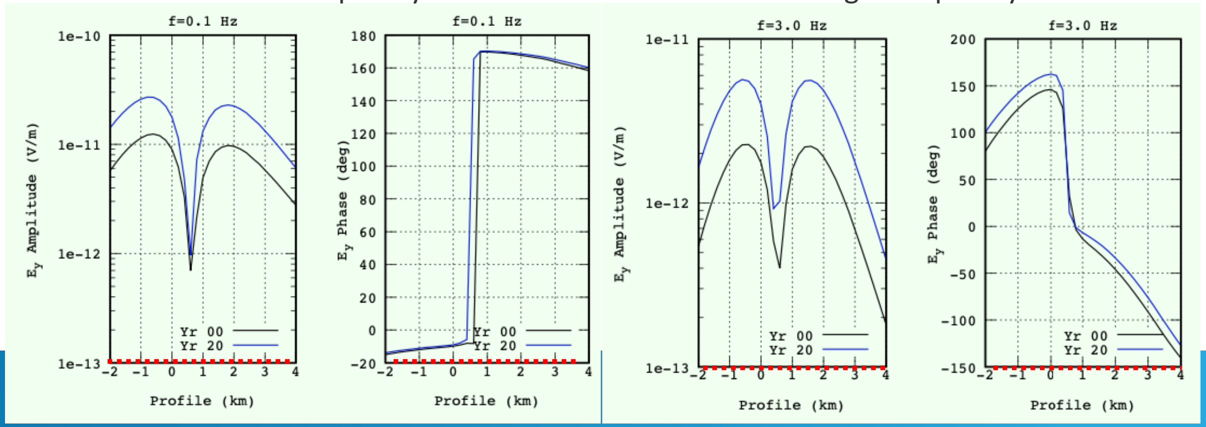
Time Lapse Surface Seismic



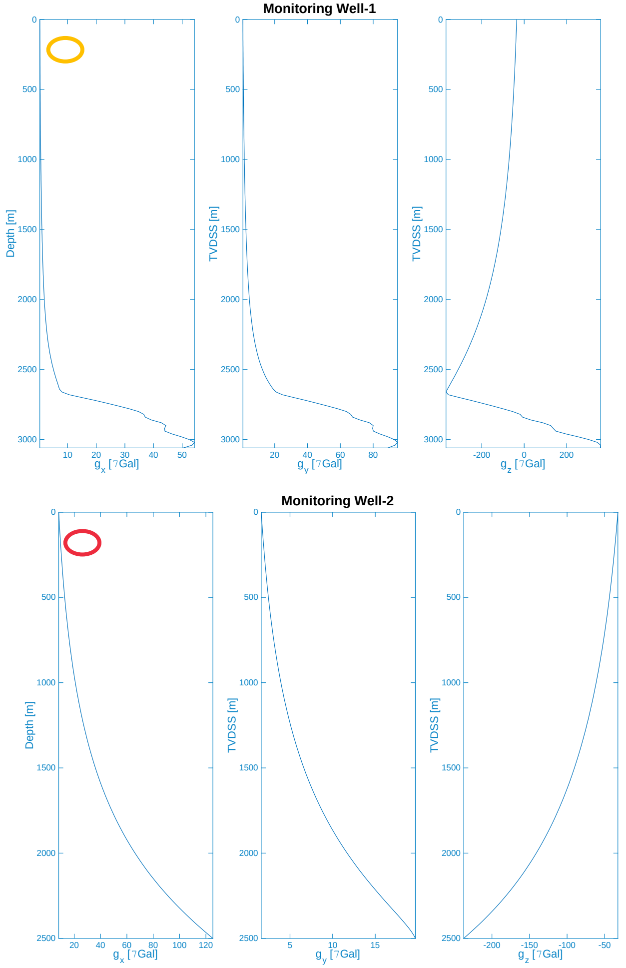
Time Lapse Borehole-to-Surface EM

Low Frequency

High Frequency



Time Lapse Borehole Gravity

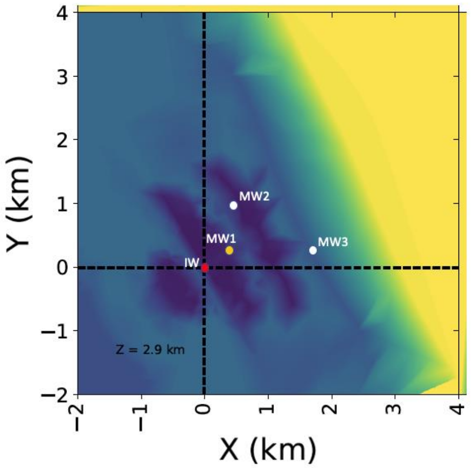


Task 2 Data : Kimberlina 1.2 Model/Data Creation

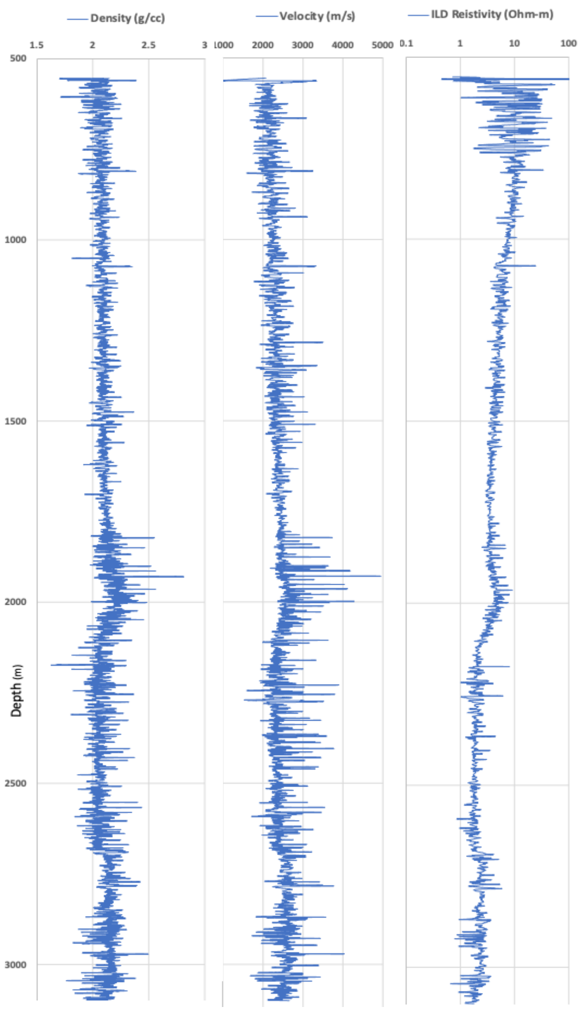
Creation of Kimberlina 1.2 Synthetic Well logs

- Synthetic logs created in 4 hypothetical well locations
- Density, velocity and resistivity logs created in 3 monitoring wells at 0, 1,2, 5, 10, 15 and 20 years after injection start
- Time lapse CO_2 saturation logs created in all wells at times after injection
- Geophysical logs created by taking high frequency content present in real Kimberlina 1 well log and adding to model property values at well locations. CO2 saturation created by multiplying model CO2 values by scaled porosity logs

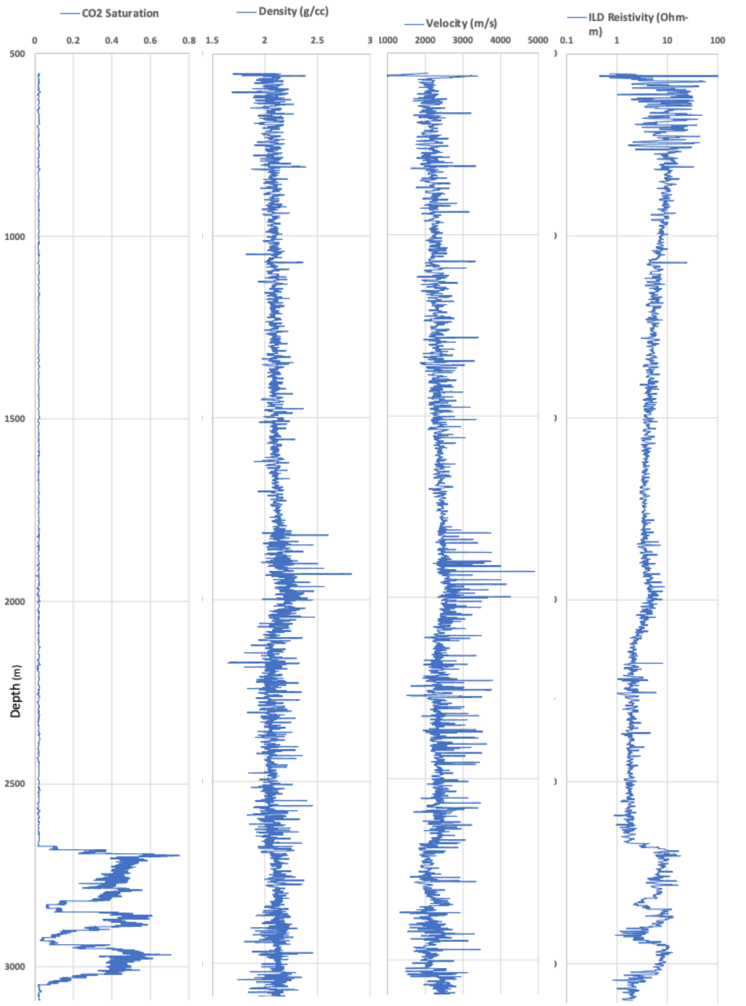
Map view with well locations



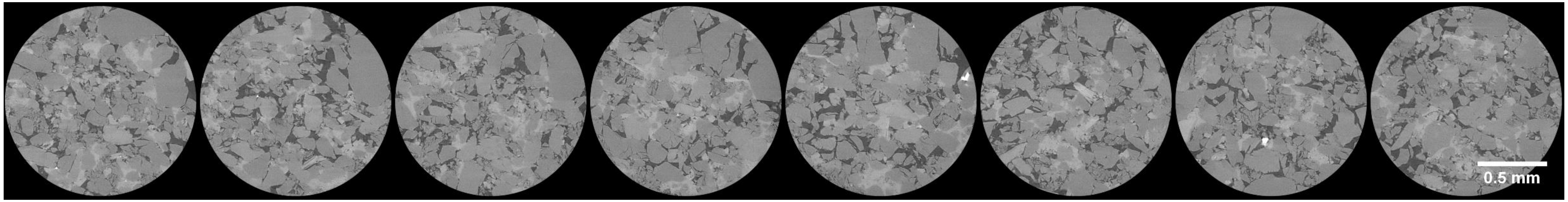
MW1 Pre-Injection Logs



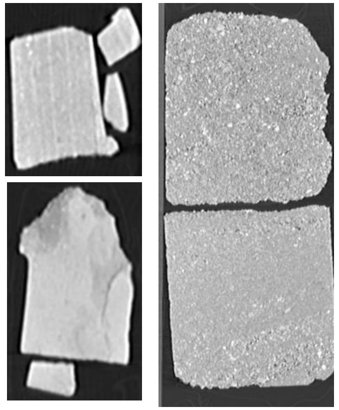
MW1 Logs after 20 Years of Injection



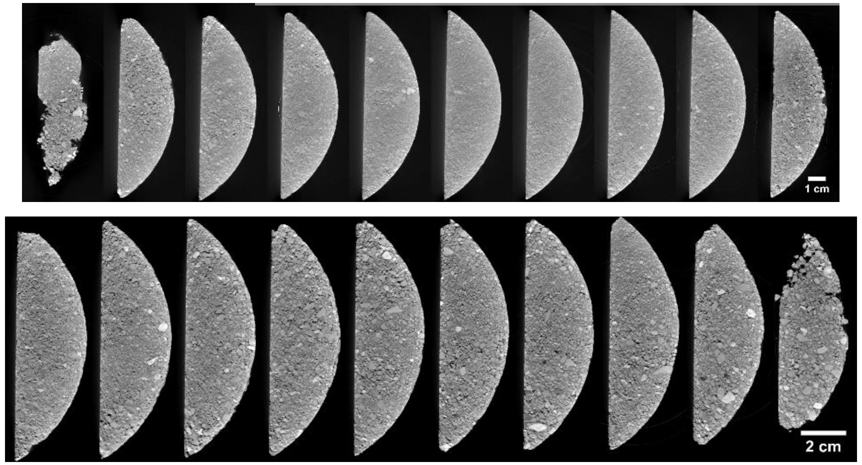
Task 2 Data : Kimberlina 1.2 Model/Data Creation



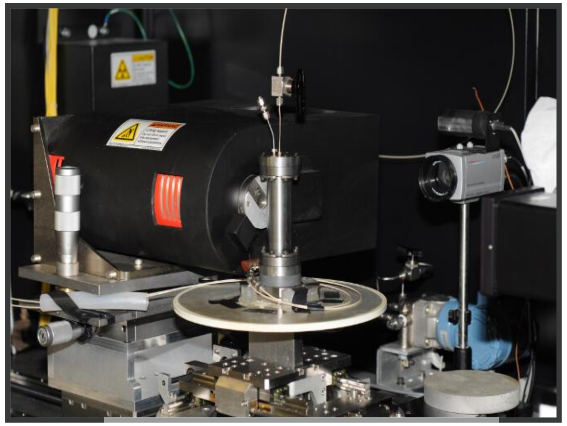
High-resolution micro-CT images (1 voxel = 1.4 microns)



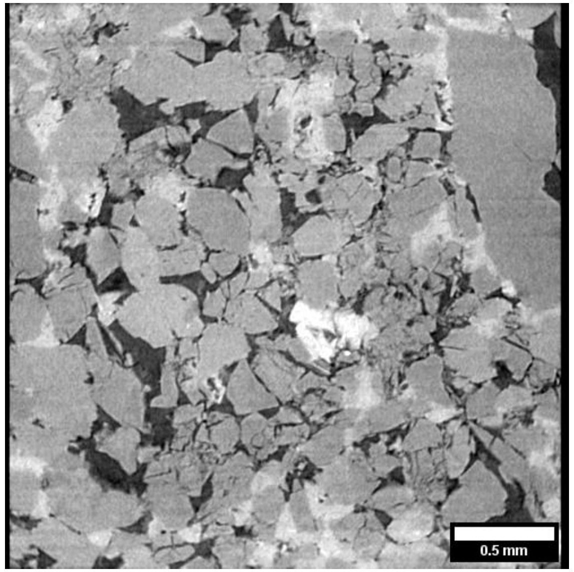
Low resolution medical CT images



High resolution industrial CT images



Micro-CT scanner with core holder



- Core to pore scale characterization underway of Round Mountain Well #1 (3500-3900')
  - $scCO_2$ saturation tests in micro-CT scanner Completed
  - Two zones initially tested too low permeability to perform $scCO_2$ injection

Task 2 Data : Status of 'Bell Creek' Data Sharing Agreement

- **Three iterations so far….**
  - Initial concept was to allow access to anyone who clicked a button acknowledging that they agree to the terms and conditions associated with use of the data. The EERC compiled an initial draft of this language and shared it with Denbury for review.
  - Denbury requested a more in-depth agreement requiring that each party sign the agreement prior to accessing the data. The EERC worked with Denbury to prepare a new agreement.
  - Due to concerns raised by NETL and several universities (primarily over the indemnification language in the document), NETL prepared a new agreement based on their standard NDA which would cover any entities subcontracted by NETL (i.e. – universities). Denbury has agreed to this agreement; however, there was no language covering other national labs.
- **Currently, NETL is reaching out to the other national labs to determine how to best incorporate them into the agreement. Once that language is incorporated, the agreement will be provided to Denbury for review.**

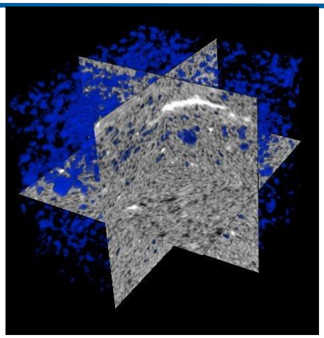
Pore-to-Well Scale Efforts

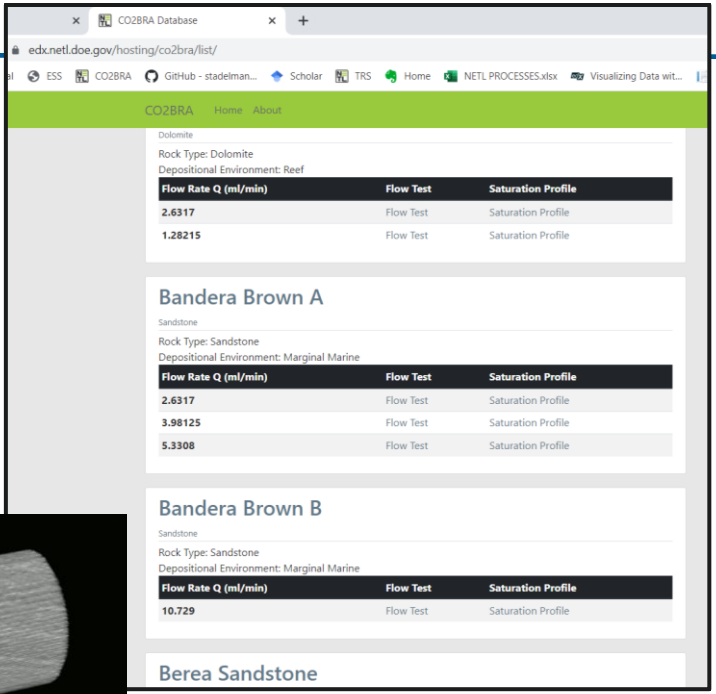
- **Four pore to core scale experimental data sets (CT to k_r, CT plus acoustic, NMR measurements of saturation, and thin section/2D image analyses) to create a robust set of data to upscale to well-scale properties.**
- **Two methods being evaluated to go from centimeters to meters**
- **Leveraging unique laboratory facilities to capture data that would not typically be available. ML to understand what features of pore to core scale properties could be further utilized to constrain and improve models of saturation evolution in injection reservoirs**
  - Efforts for site core characterization distilled down to a porosity, permeability, and maybe some heterogeneity.

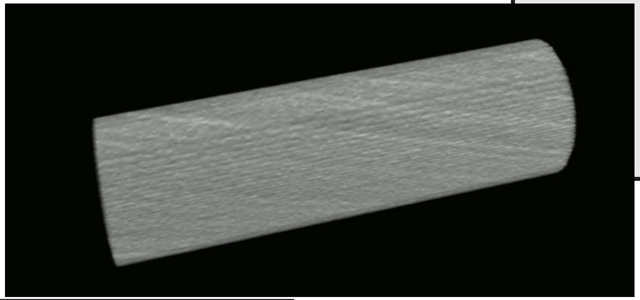
Pore Scale Isolation & Core Flow

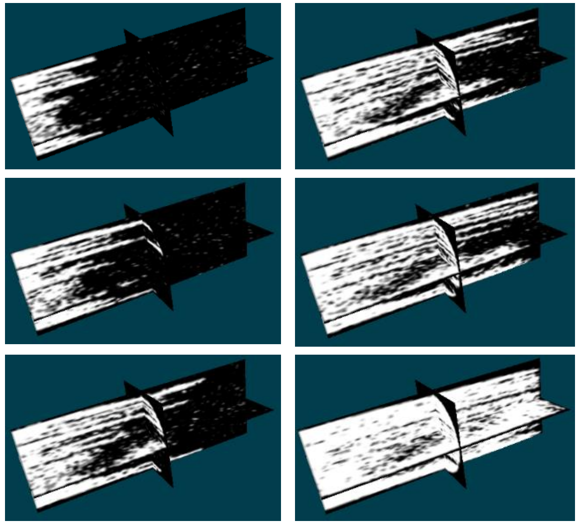
With Medical CT scanner

- $scCO_2$/brine relative permeability measurements through the samples that have had pore scale imaging performed on sub-cores.
- And porting to core scale simulations









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Rapid determination of supercritical CO_2 and brine relative permeability using an unsteady-state flow method

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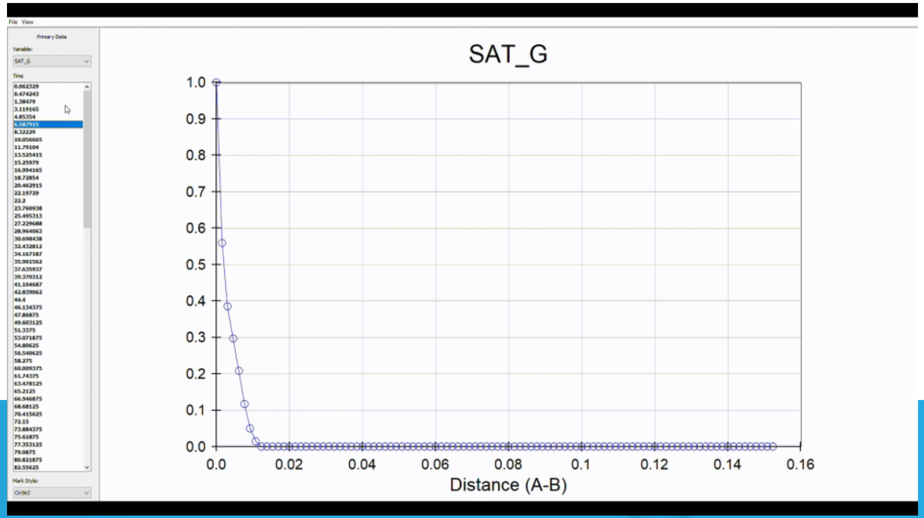
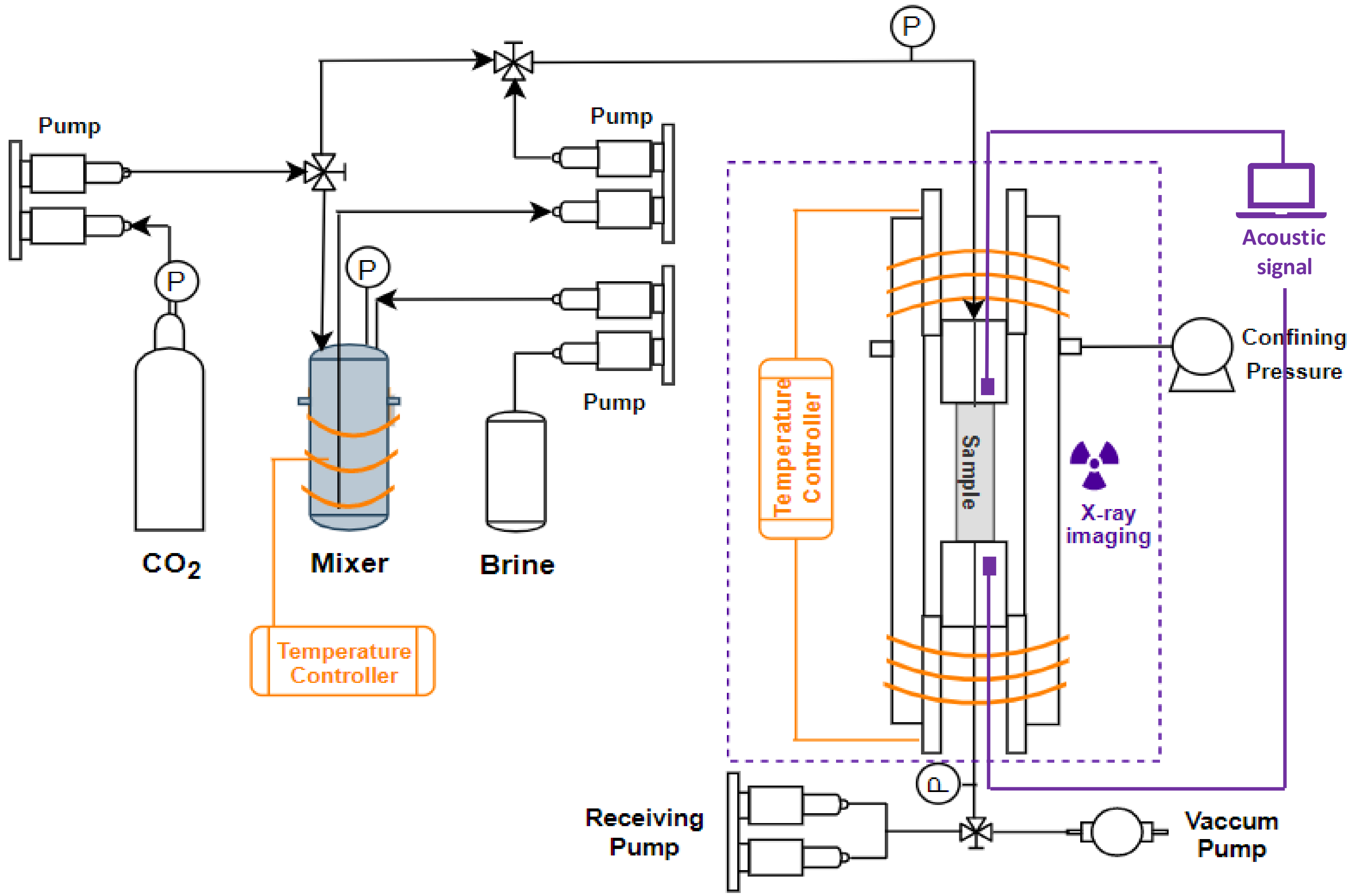
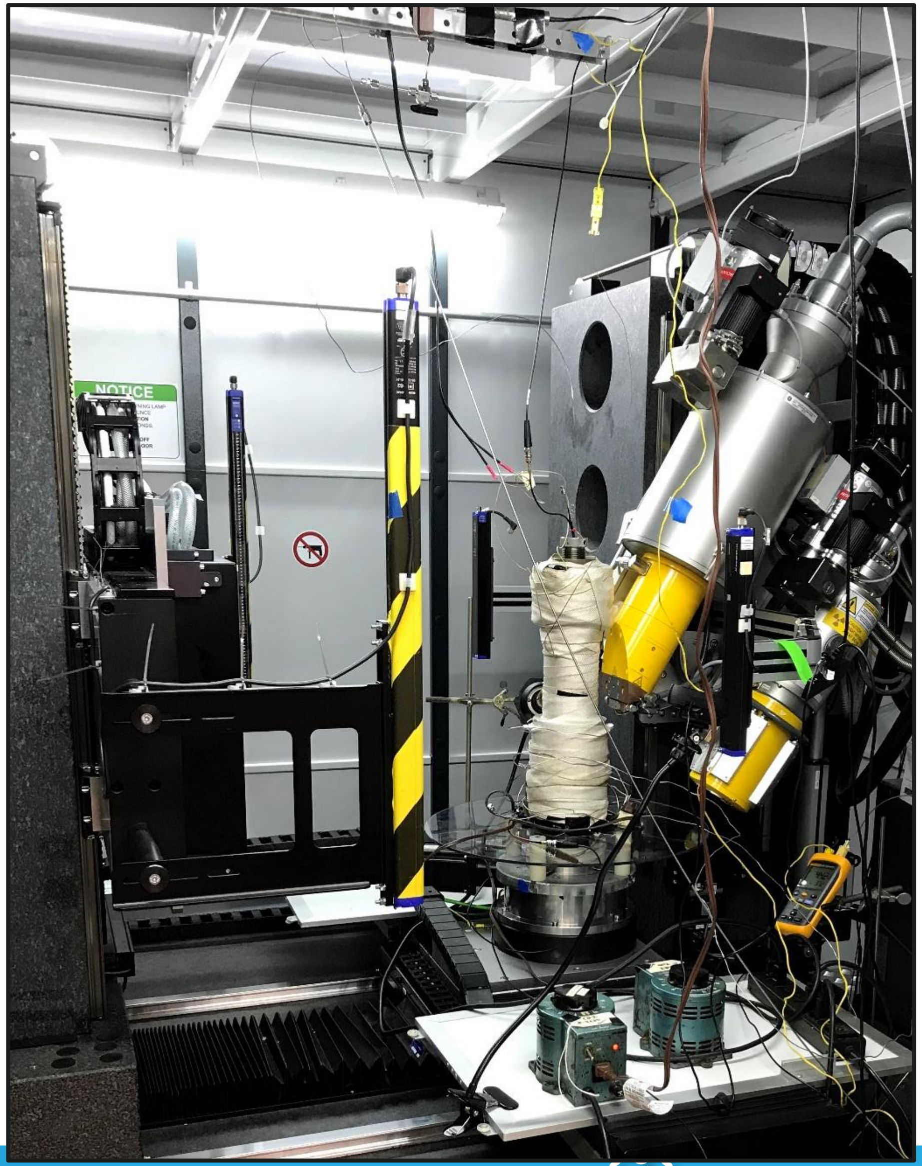


Pore-scale Imaging Experimental Setup

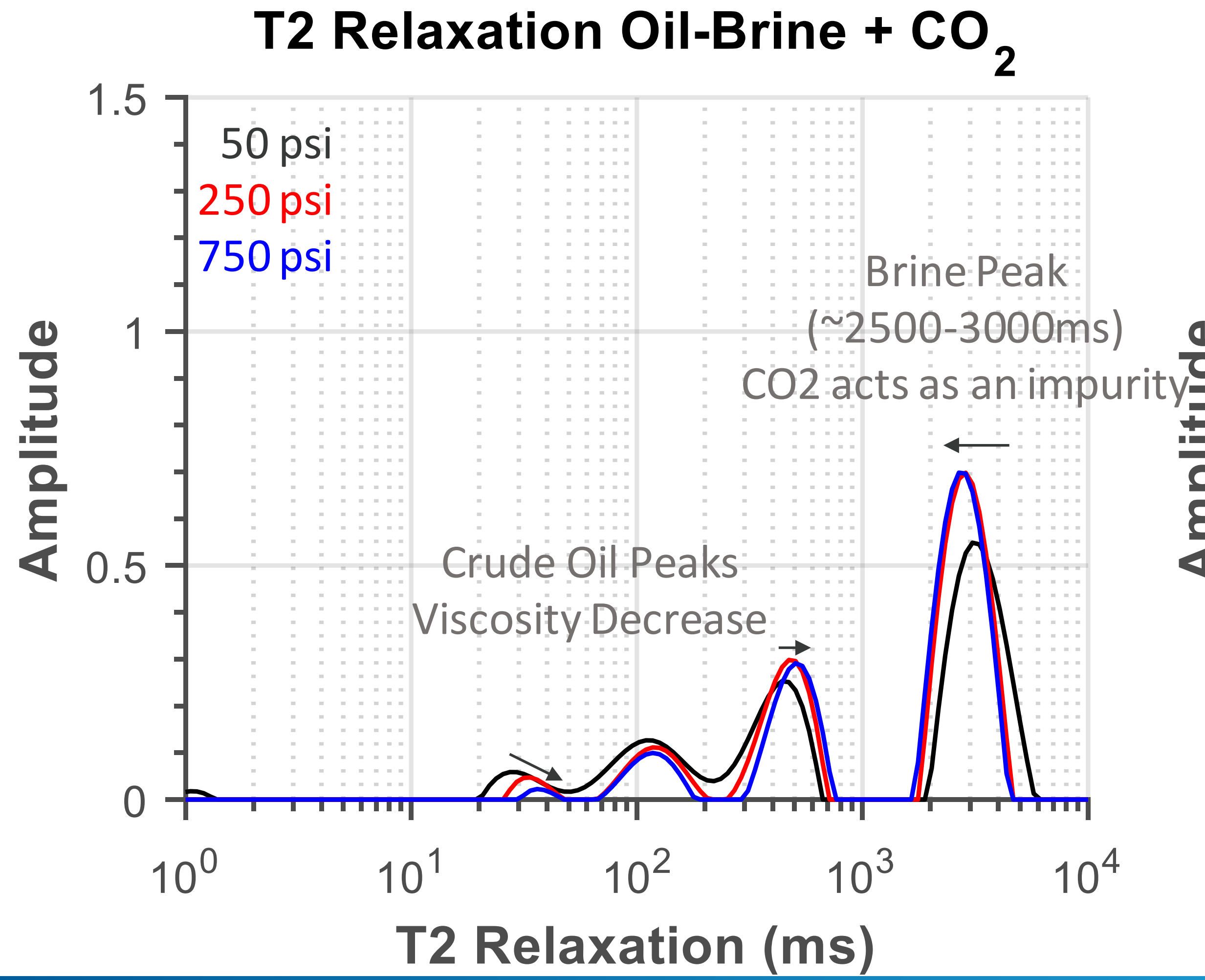
PSU Core Imaging Scale

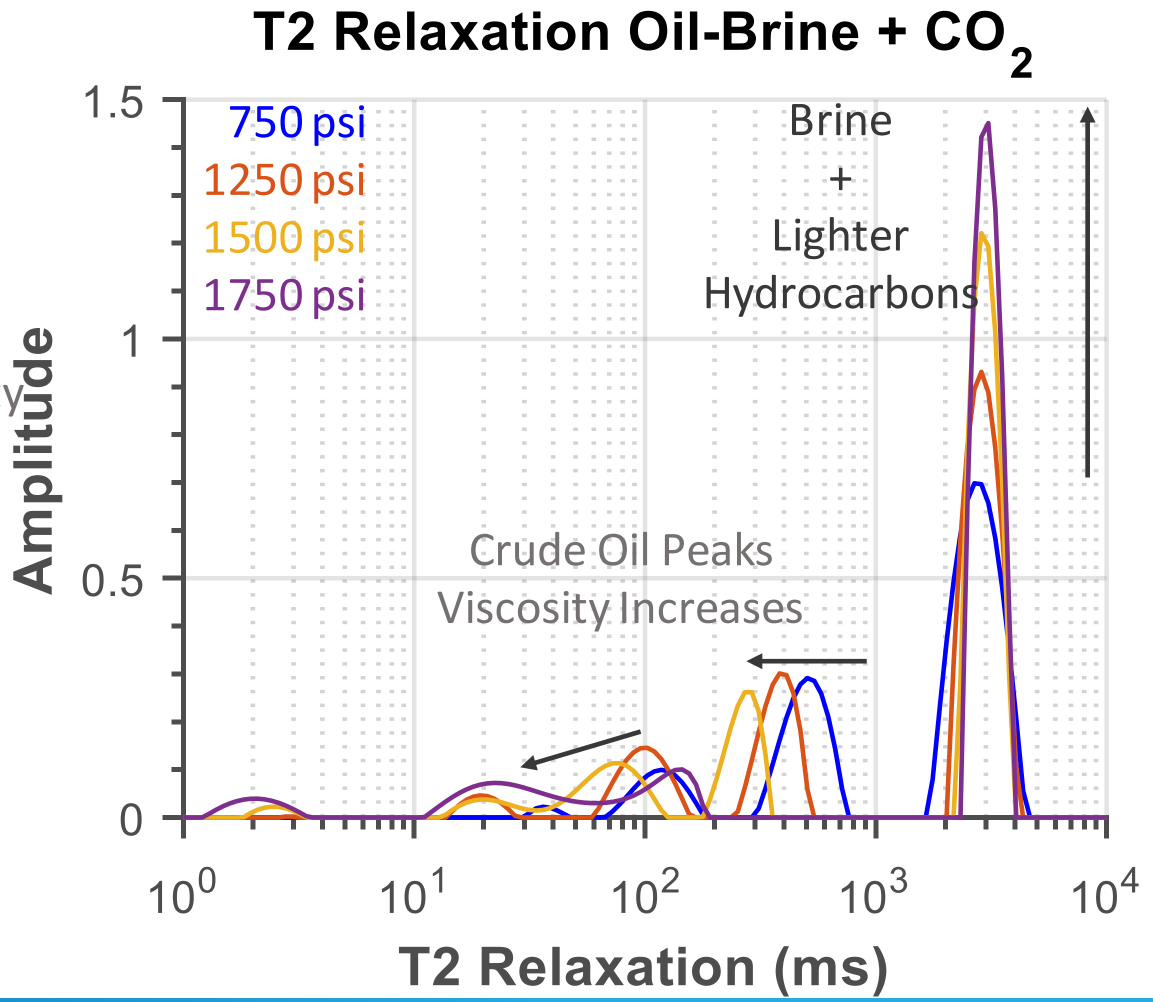
Schematic and photograph of the CT + ultrasonic measurement setup at PSU





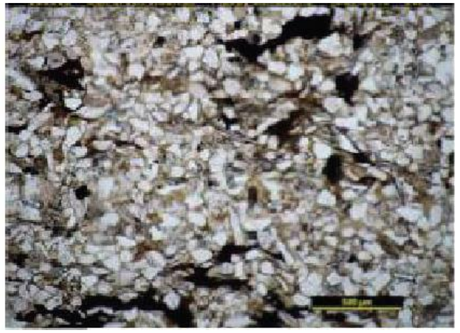
Nuclear Magnetic Resonance Results: Oil-Brine + CO2

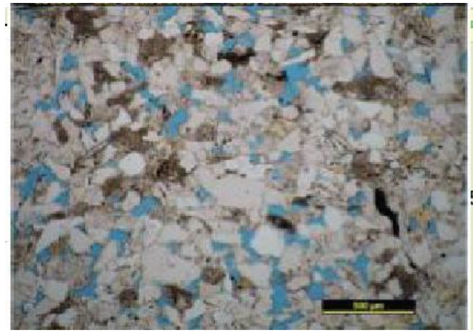




Upscaling Pore Features to Well Scale

CORES

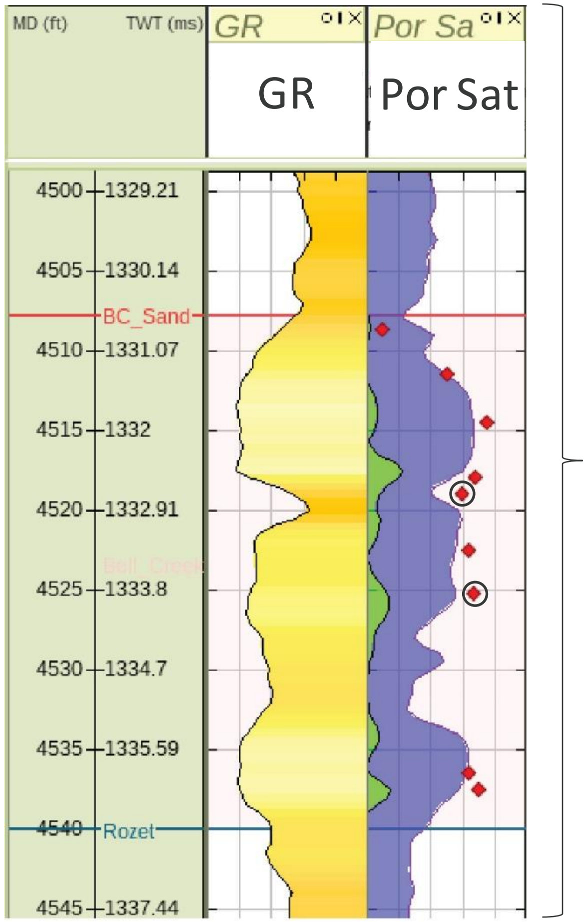




UPSCALE

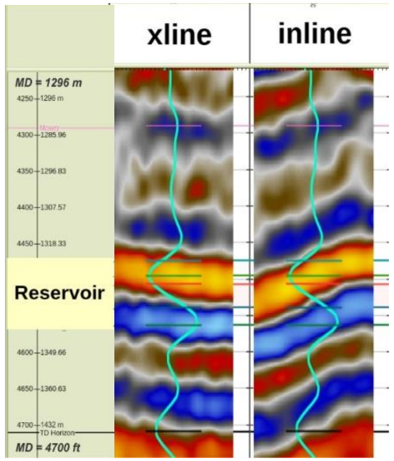
2D and 3D machine learning-driven image analysis coupled with fractal theory to estimate rock properties

WELL LOGS



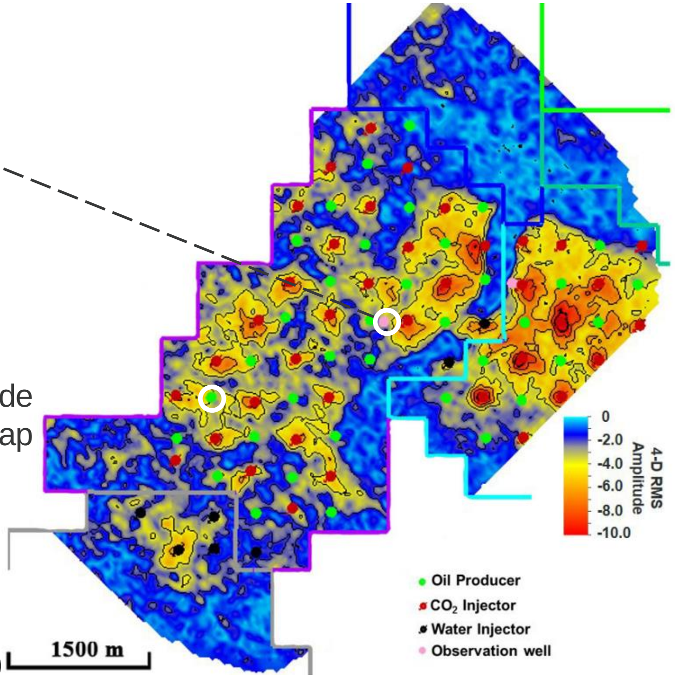
BELL CREEK DATA

SEISMIC DATA



DOWNSCALE

RMS Amplitude Difference map (2014-2012)

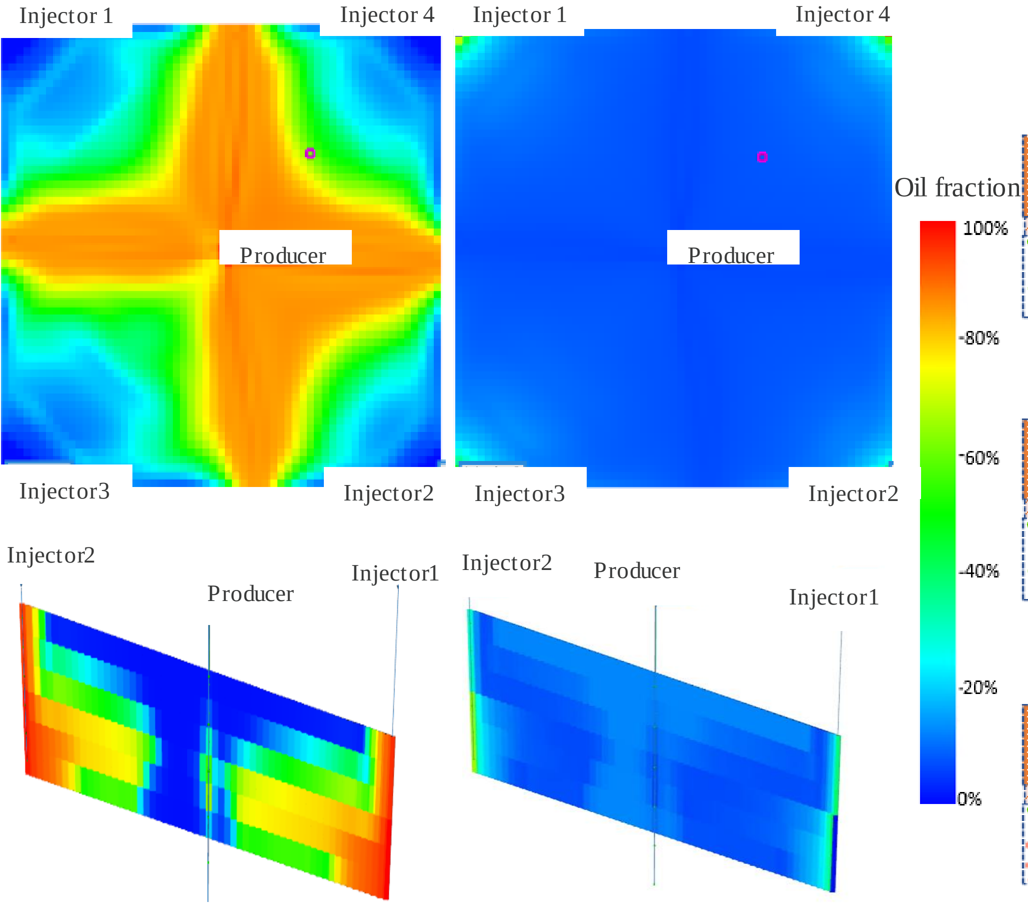


(Salako et al., 2017)

Reservoir Simulation

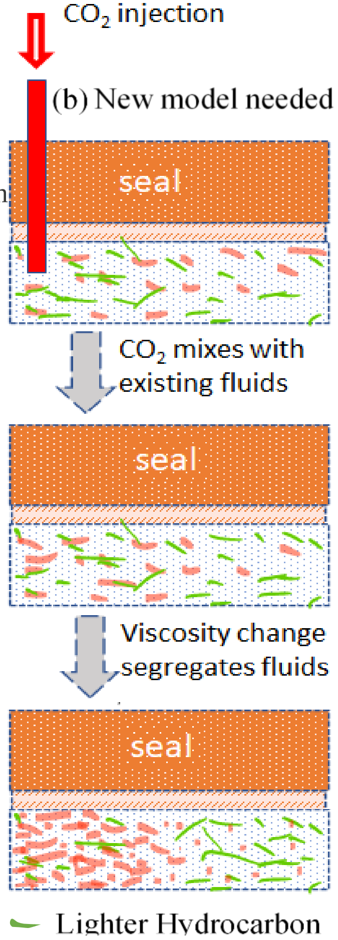
Reservoir Fluid Analysis

Light fraction Heavy fraction

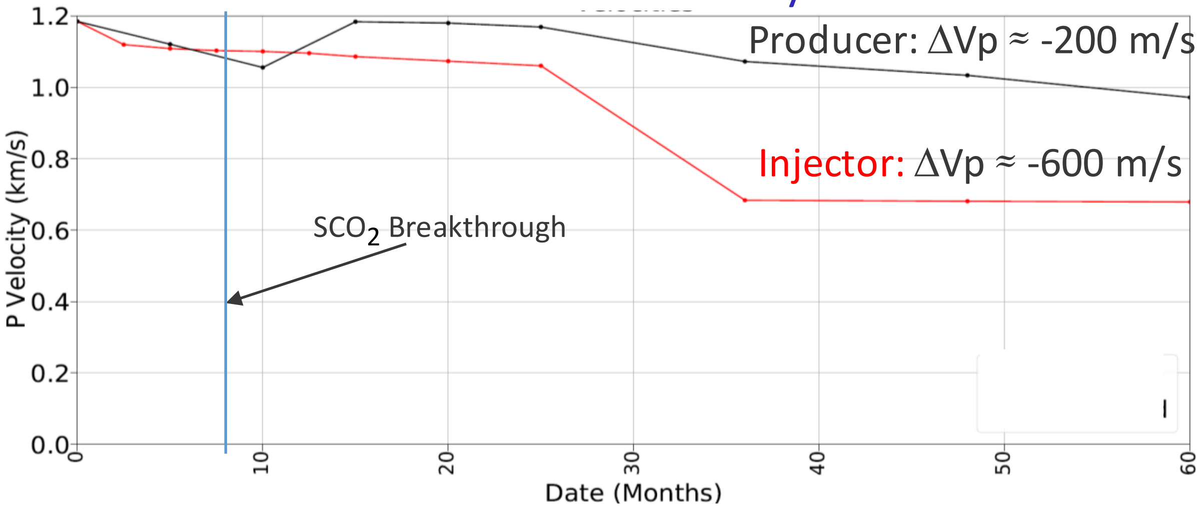


Fluid segregation (1 year)

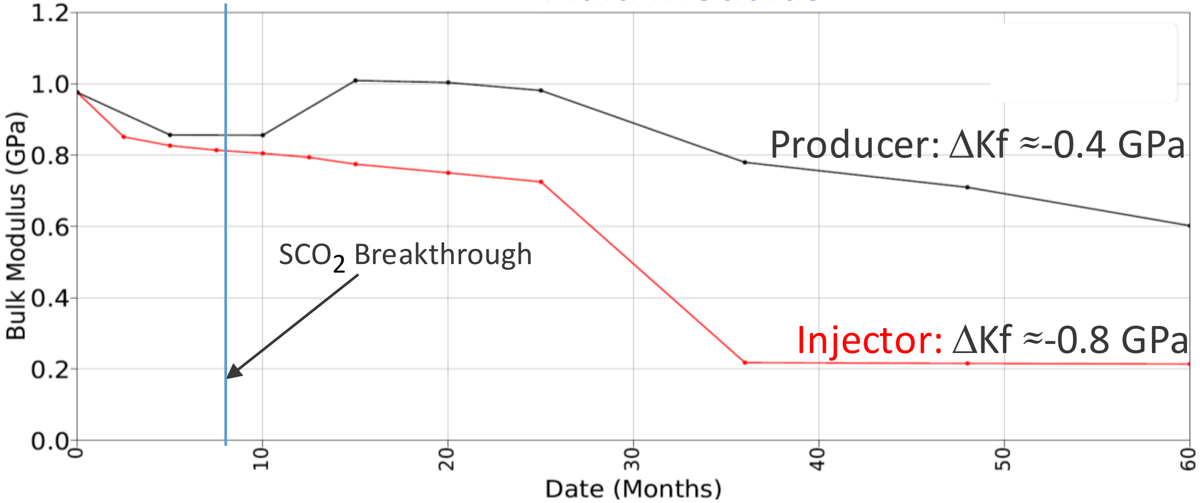
Flow Concept



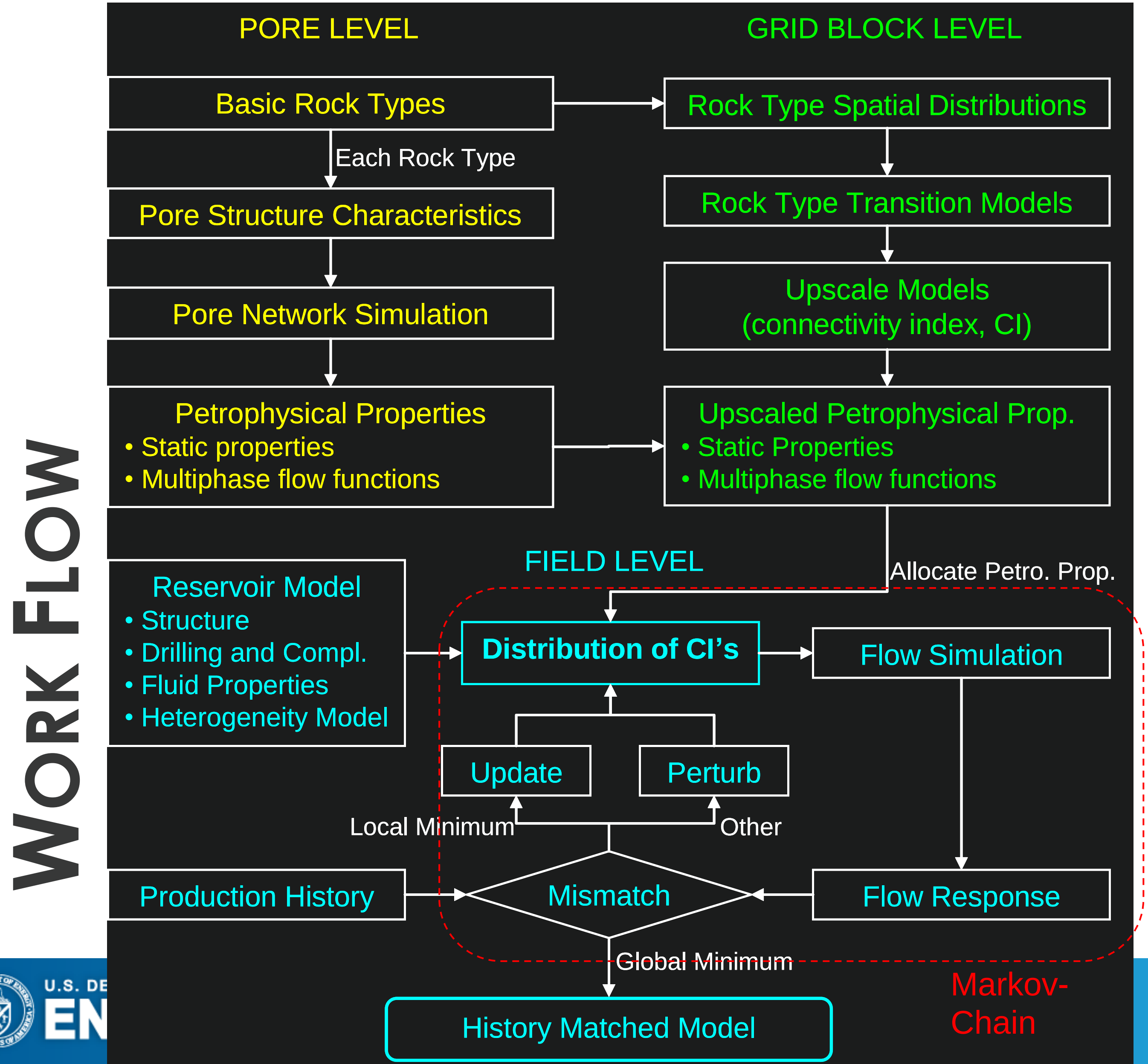
Fluid Velocity



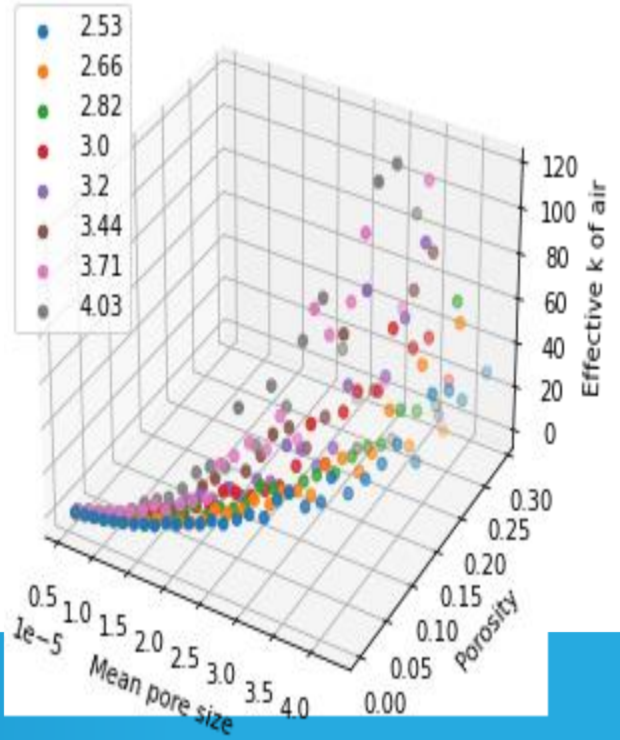
Fluid Modulus



Rock Typing to Upscale Flow Properties

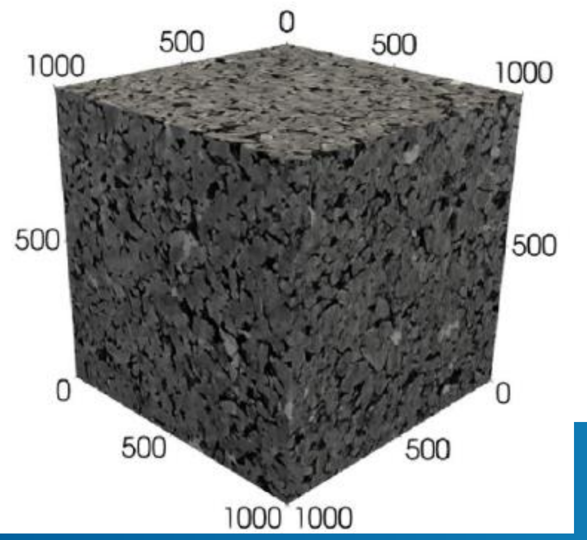


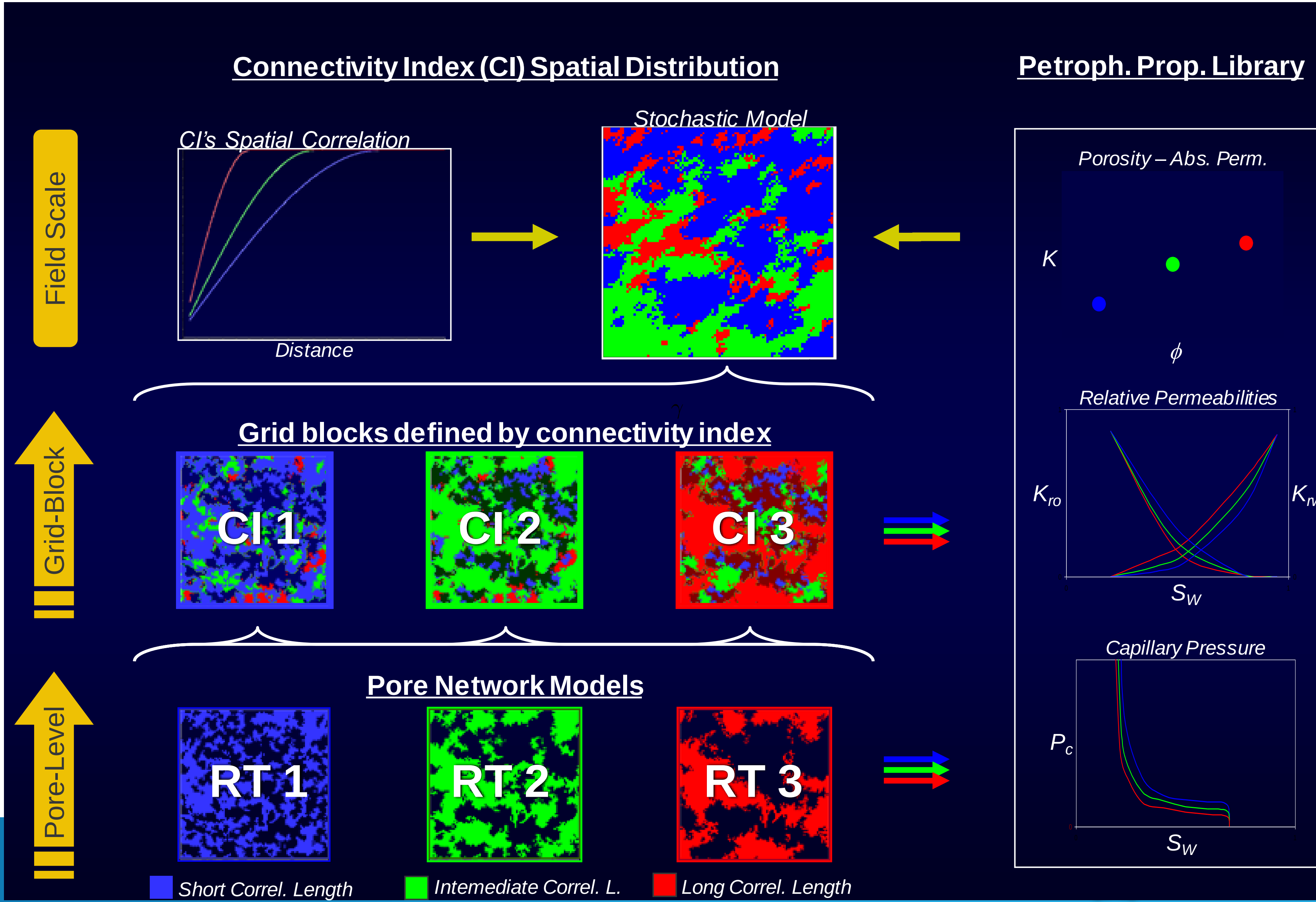
- Upscaling saturation functions via multiscale geologic models
- Random forest to train data set. Feature space: saturation, mean pore size, mean throat size, porosity, permeability and coordination number. Target: permeability.



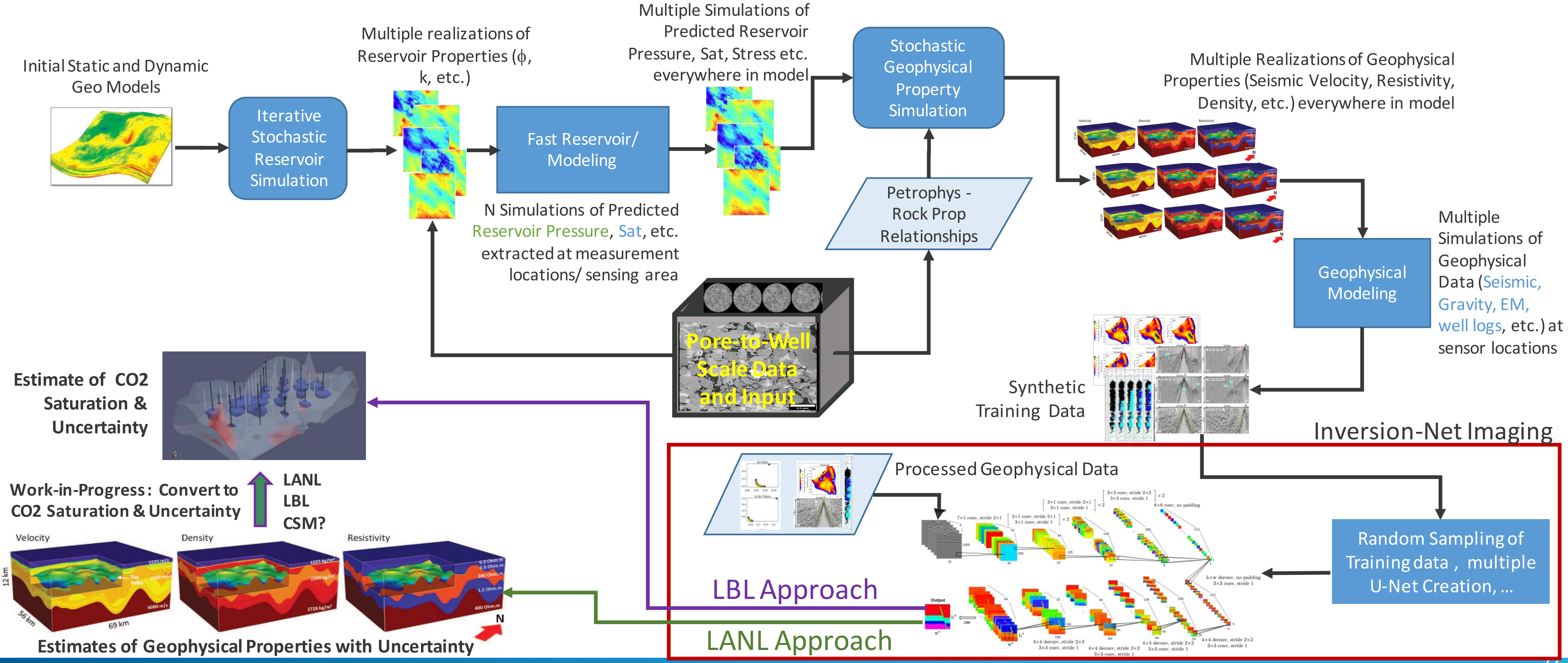
Upscaling Saturation Functions from to Meter Scale

- Connectivity index, pore/throat features, and bulk properties being used to create near-well models of representative flow



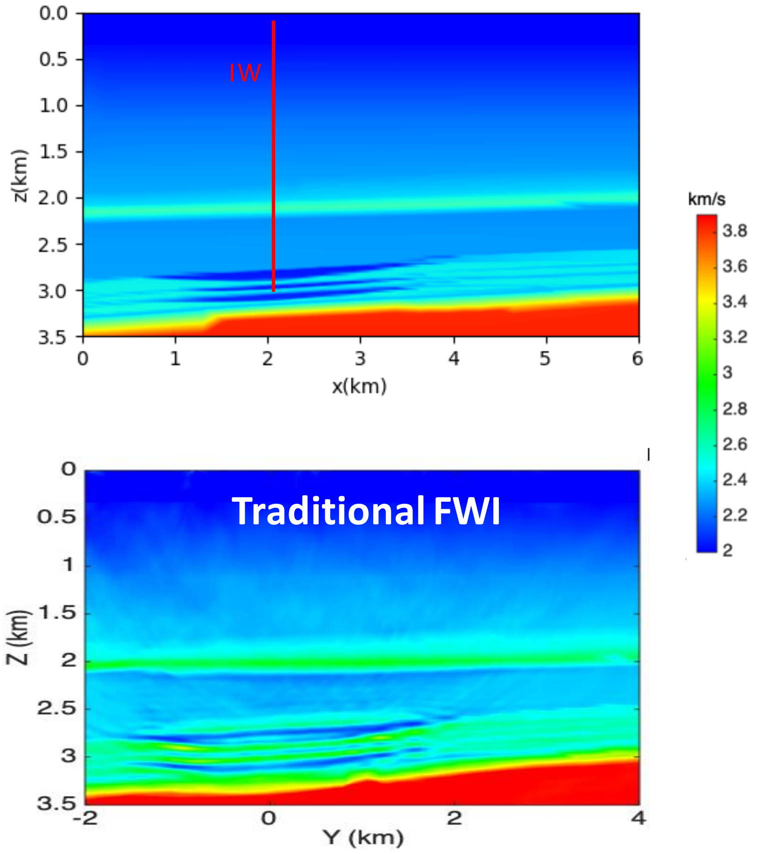


Task 2 Well–to–Field Scale Imaging / Visualization
Stochastic Neural-Net Workflow

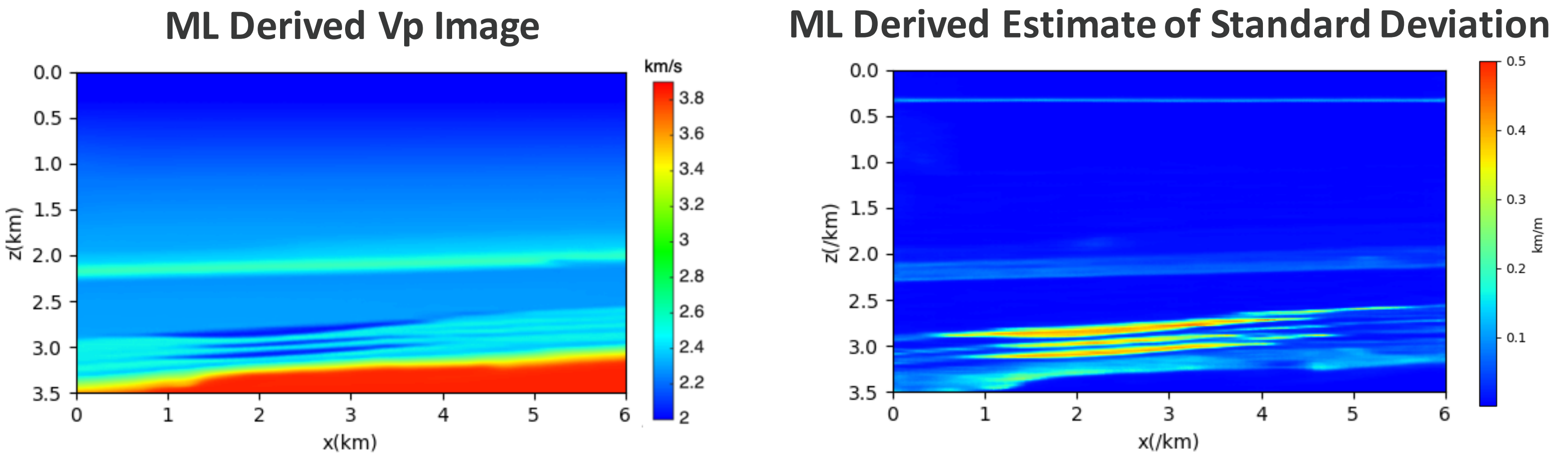


Task 2 Well–to–Field Scale Imaging / Visualization
2D Inversion-Net Example (LANL Approach)

Kimberlina GCS Model



Deep Learning Seismic Imaging with Uncertainty



- Improved resolution and fewer artifacts compared to traditional seismic full waveform inversion (see image to left)
- ML derived estimates of uncertainty in conjunction with Vp image

Task 2 Well–to–Field Scale Imaging / Visualization

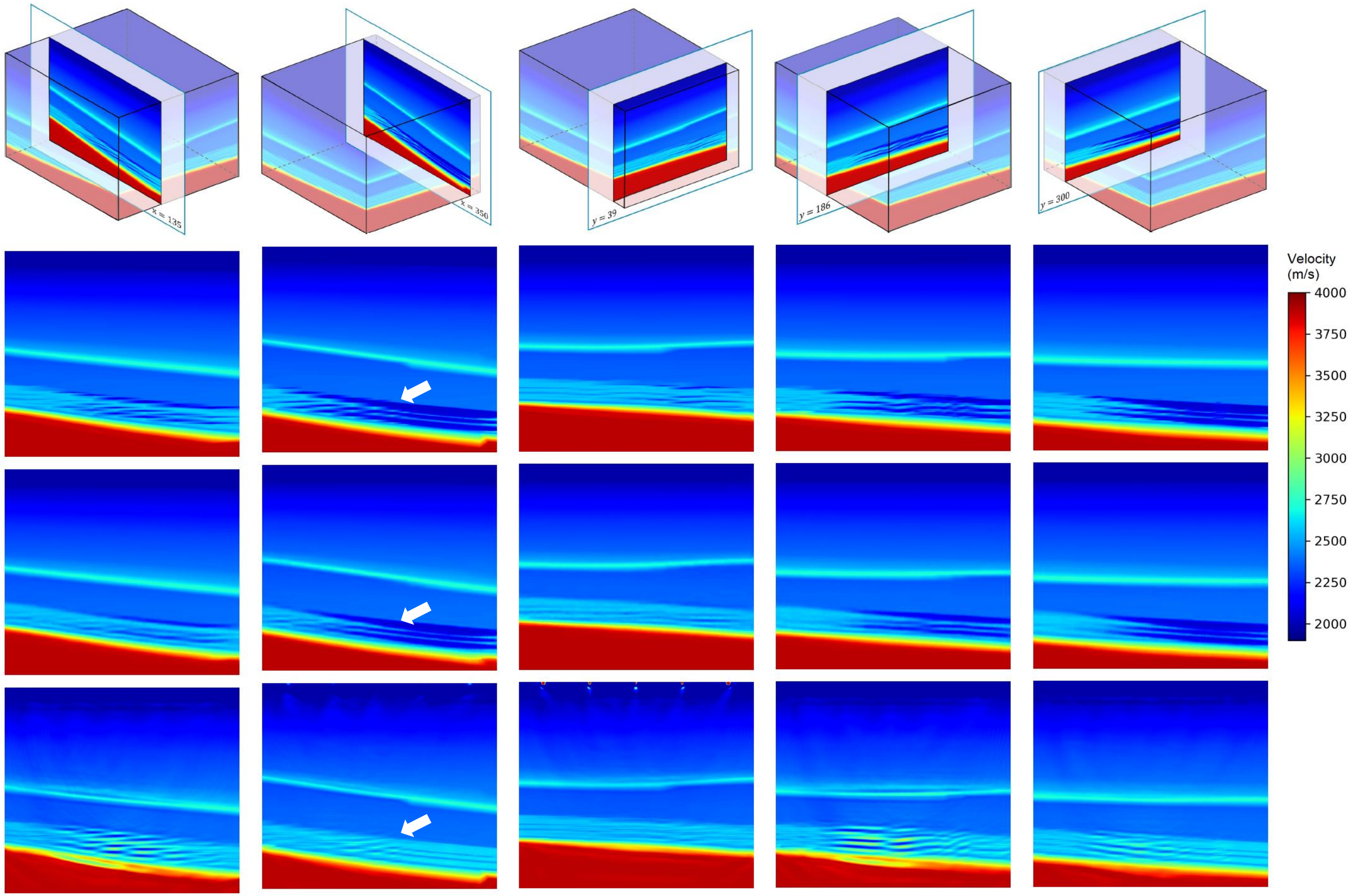
2D Inversion-Net Example (LANL Approach)

Kimberlina GCS Model (3D)

Kimberlina GCS Model (2D)

InversionNet3D

Physics-based Inversion

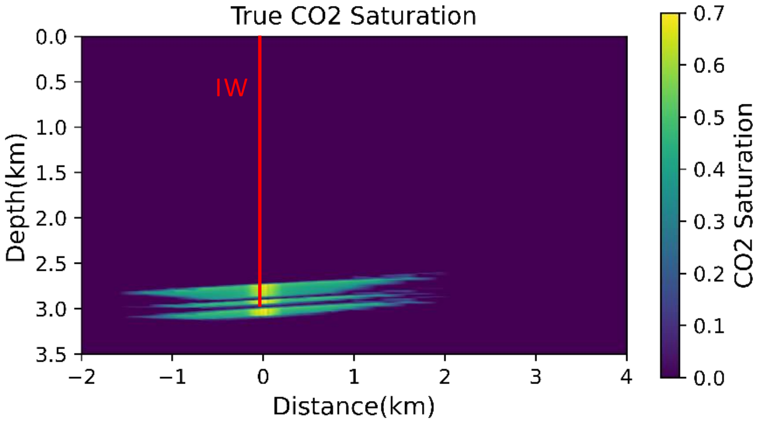


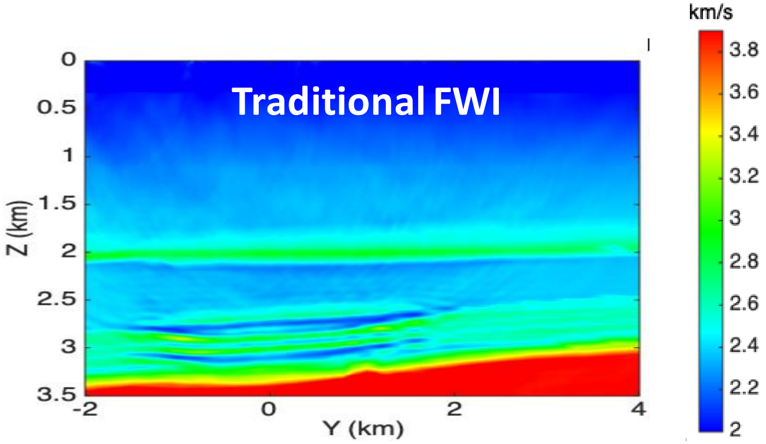
Test Results on Kimberlina Data

Qili Zeng, Shihang Feng, Brendt Wohlberg, and Youzuo Lin, "**InversionNet3D: Efficient and Scalable Learning for 3D Full Waveform Inversion**," pre-print available in arXiv, 2021 (also Under Review in IEEE Transactions on Geoscience and Remote Sensing).

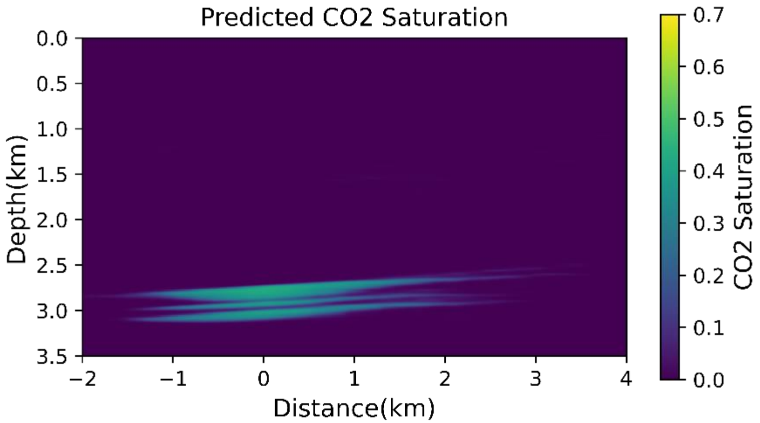
Task 2 Well–to–Field Scale Imaging / Visualization
2D Stochastic U-Net Example (LBL Approach)

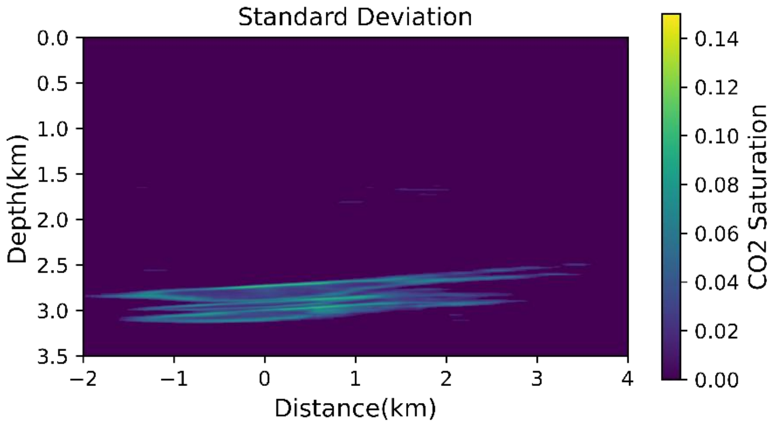
Kimberlina GCS Model





Deep Learning Stochastic CO2 Imaging/ Visualization

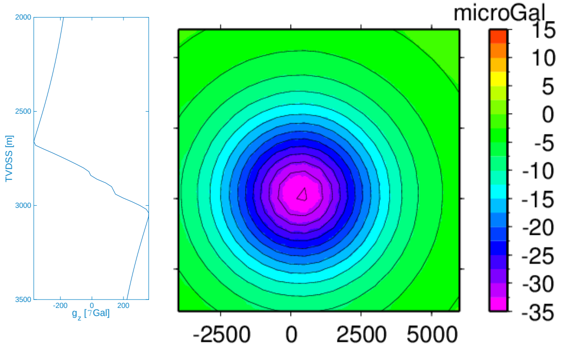




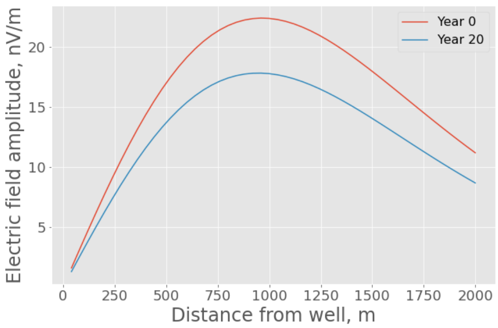
- Providing CO_2 saturation images and uncertainty estimates in real time.
- Improved resolution and fewer artifacts compared to traditional seismic full waveform inversion (see image to left).
- Direct estimates of CO_2 saturation rather than proxy geophysical properties.

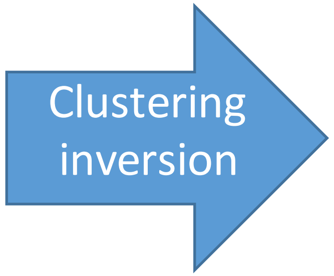
Task 2 Well–to–Field Scale Imaging / Visualization
3D Statistical Physics Based Inversion (CSM)

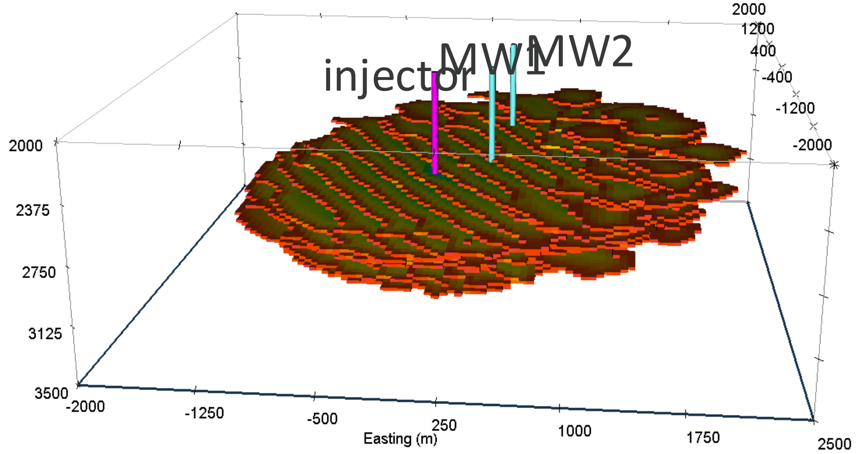
Time-lapse gravity data

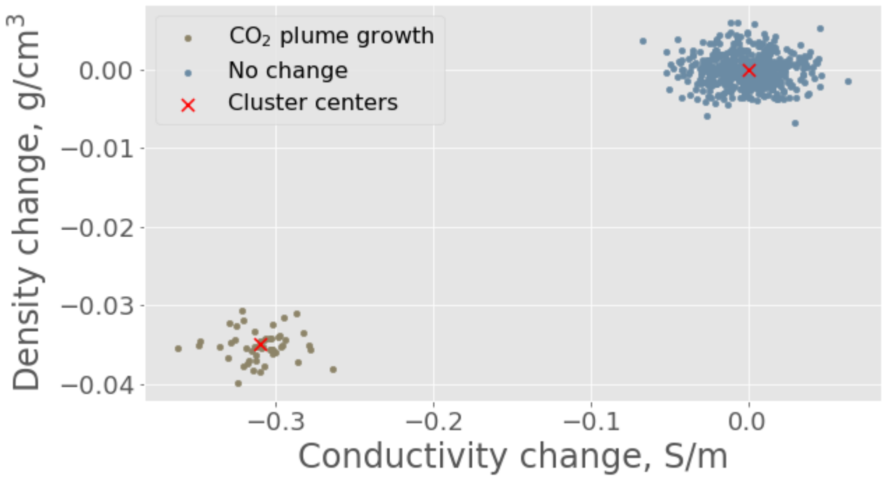


Time-lapse CSEM data









- Jointly invert time-lapse geophysical survey data
  - Controlled-source electromagnetic data
  - Surface/borehole gravity data
- Clustering identifies regions of change in conductivity and density
- Combine with petrophysical model to convert to CO_2 saturation changes

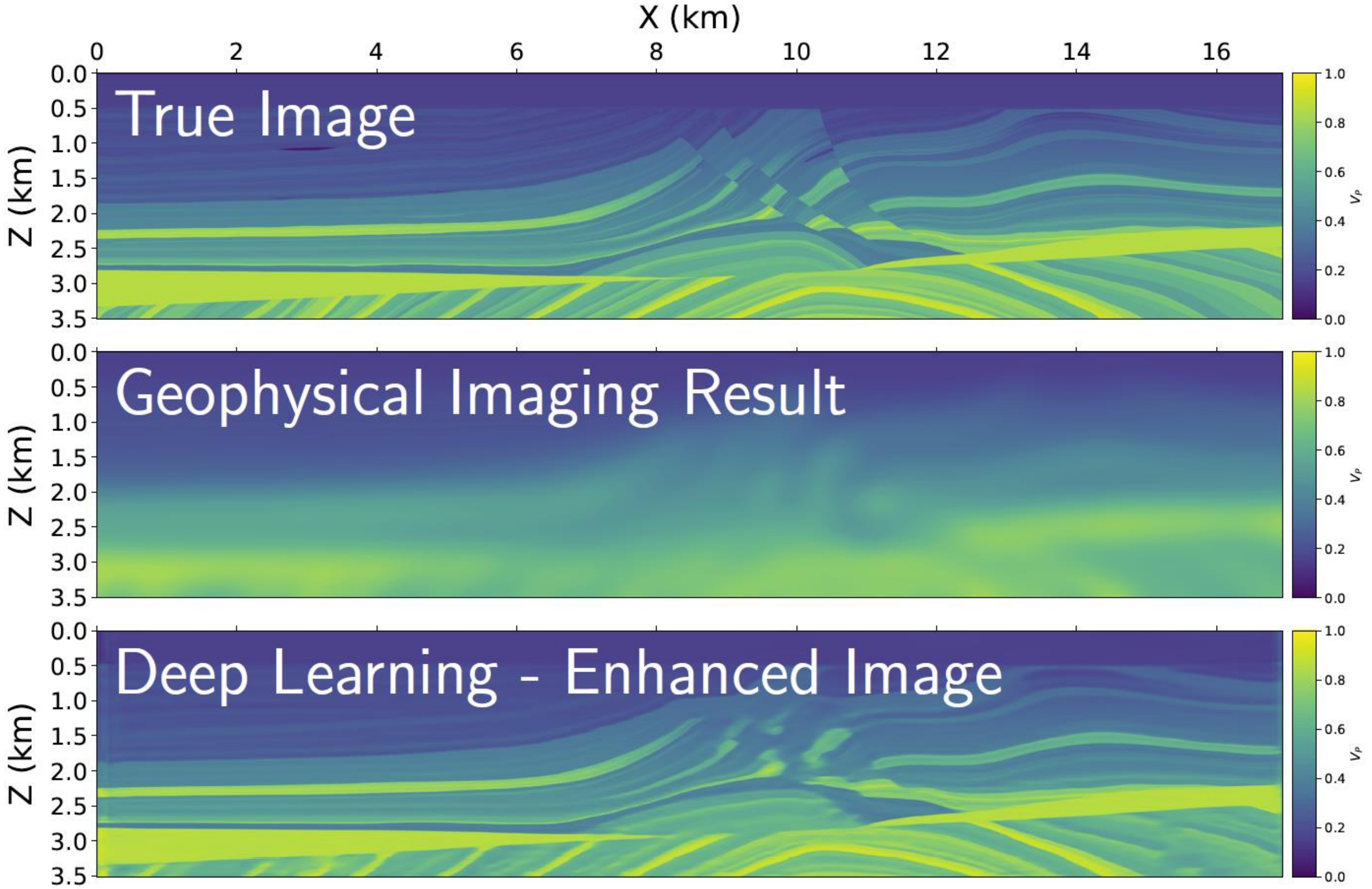
Sun, J., & Li, Y. (2015). Multidomain petrophysically constrained inversion and geology differentiation using guided fuzzy c-means clustering. *Geophysics*, *80*(4), ID1-ID18.

Task 2 Well–to–Field Scale Imaging / Visualization
Resolution Enhancement by Supervised Learning (CSM)

Behura & Prasad, CSM

Concept

- Well-log resolution result
- Applicable to other attributes
- Apply to any field with wells
- Works with wells of any geometry
- Hi-resolution poro-perm fields



Note: Testing of a ‘CGAINS’ ML algorithm for downscaling was shown by CSM researchers not to perform.

Questions?

Thank you!

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