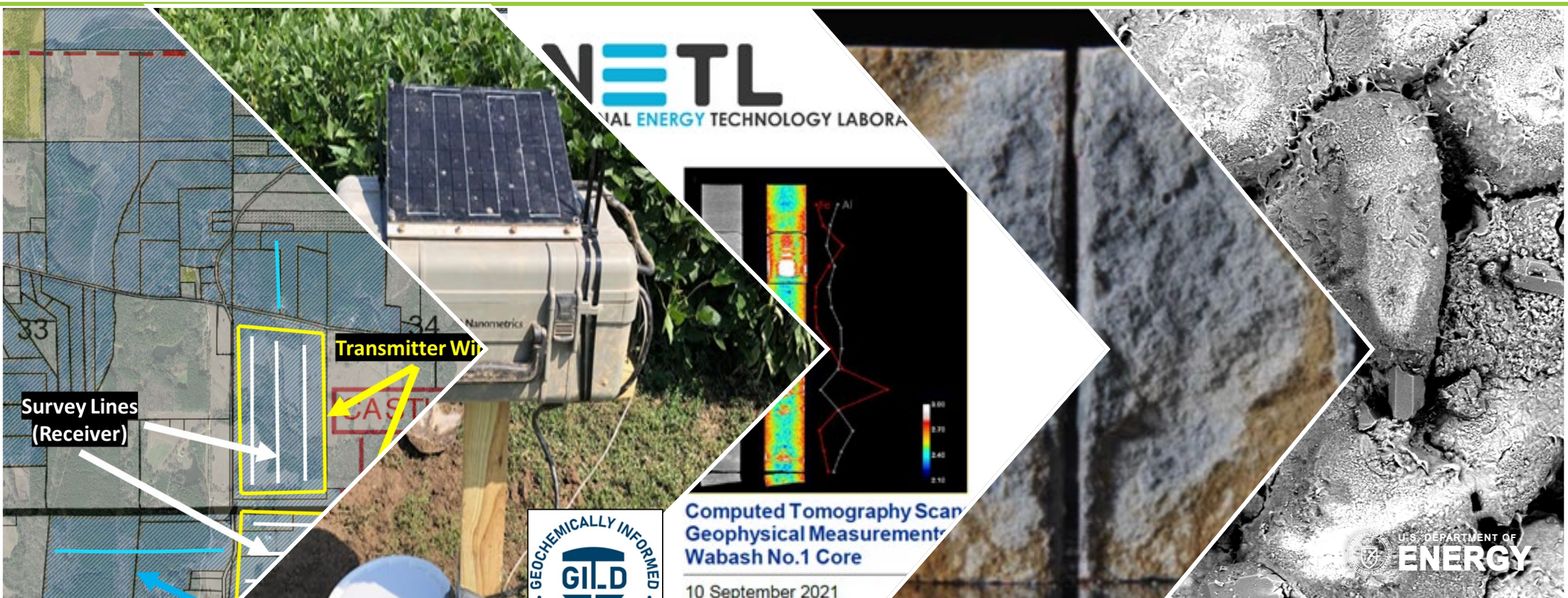
NETL RIC Efforts Supporting CarbonSAFE Projects (FWP-1022403)

Dustin Crandall, NETL RIC Dustin.Crandall@netl.doe.gov

8/30/2023



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NETL RIC CarbonSAFE Assistance

OK, so let's talk about this task

- **The NETL Research and Innovation Center (RIC) cannot directly work on many of the projects that DOE Fossil Energy & Carbon Management put out in funding opportunity announcements.**
  - Conflict of interest, GOGO lab status, and so forth.
  - And this is fine! The grass is green.
- **But … we have world class research facilities, a research staff that has spent decades thinking about CO_2 Storage, and we want DOE FECM field labs to succeed.**
  - This task is an effort to square that circle and make NETL RIC Advanced R&D Storage resources available to assist with field scale labs funded by DOE FECM.

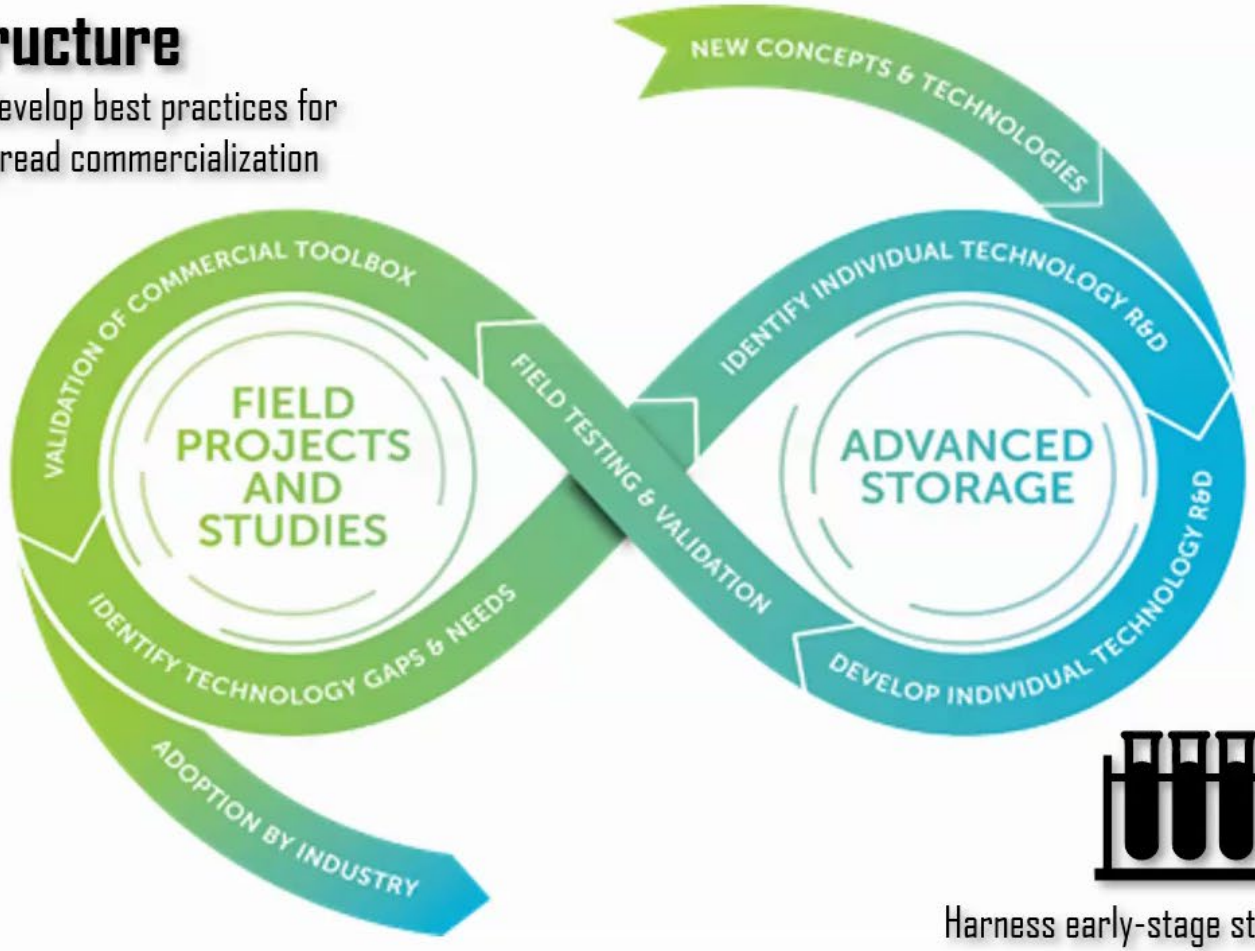
To Infinity and Beyond

Storage Infrastructure

Large-scale field projects to develop best practices for industry and facilitate wide-spread commercialization

Storage Infrastructure Focus

- CarbonSAFE
- Regional Initiatives
- Offshore Storage
- Brine Extraction Strategy Test (BEST)
- Associated Storage (CO_2 EOR)



Advanced Storage Focus

- Well Integrity and mitigation
- Monitoring, verification, and accounting
- Storage complex efficiency and security
- SMART: **S**cience-Informed **M**achine Learning for **A**ccelerating **R**eal **T**ime Decisions
- NRAP: National Risk Assessment Partnership

Advanced Storage

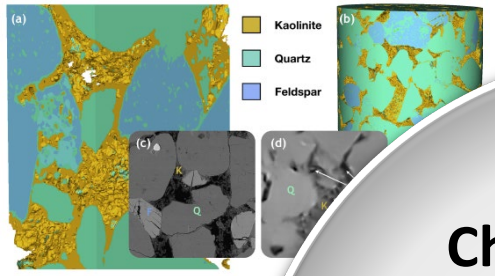
Harness early-stage storage concepts to technology demonstration

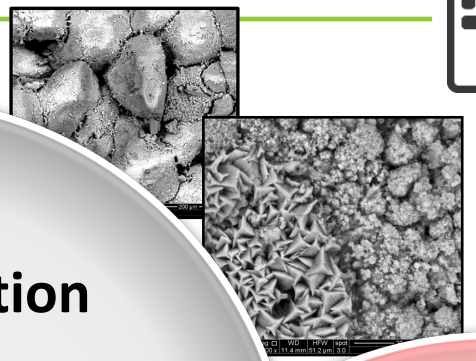
RIC's Carbon Storage Advanced R&D

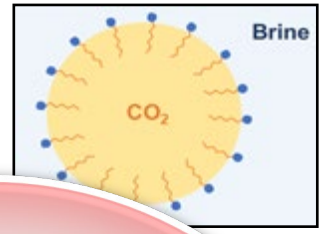
NATIONAL ENERGY TECHNOLOGY LABORATORY

Research to understand Geologic Carbon Storage

- Where can we store CO_2?
- How can we track CO_2?
- Can we store more CO_2?







Characterization

- Field Assessments
- Wells
- Core
- Fluid Interactions

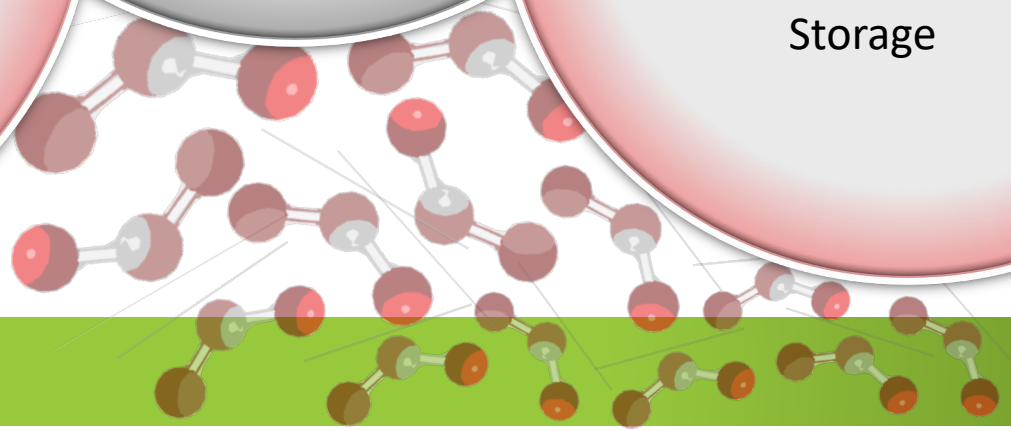
Monitoring

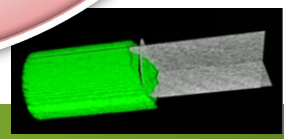
- Field Monitoring
- Machine Learning Assessments of Infrastructure
- Geochemical Fluid Monitoring

Develop Novel Storage Methods

- Co-Injection of CO_2
- Additive Enhanced CO_2 Storage

GEOCHEMICALLY INFORMED • GILD • LEAK DETECTION





NETL RIC CarbonSAFE Assistance

- **2021 was a first-year trial run of officially carving out this 'assist field projects space'**
  - Unclear at outset what specific efforts would be, so main deliverable was to engage, see where alignment occurred naturally, and report on successes and challenges.
  - During Phase III kickoff in Oct 2020 were able to introduce capabilities to CarbonSAFE projects.
  - Numerous follow up meetings with groups interested in exploring the places where NETL RIC capabilities and research interests align with the projects.
- **To be 100% clear here, we are <u>NOT</u> willing or able to take research tasks away from the deliverables pledged by the CarbonSAFE projects**
  - We can't. Complexity of deliverables, our own resource constraints, etc.

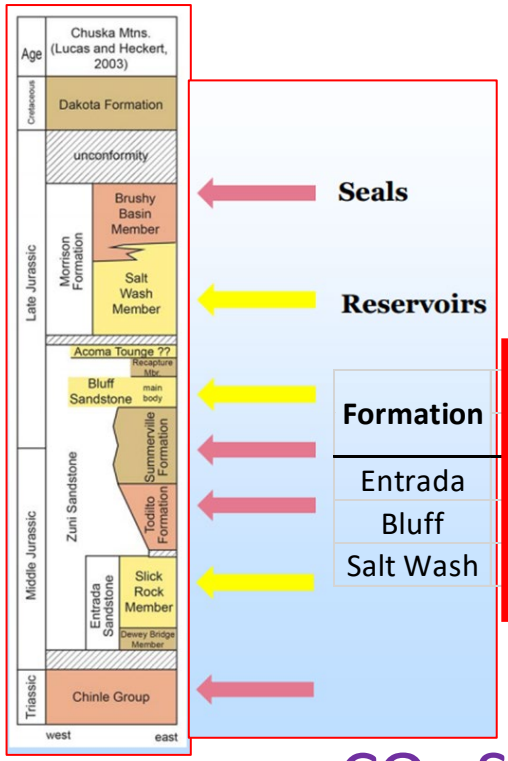
NETL RIC CarbonSAFE Assistance

- **Here's what we are looking to partner on**
  - Assist in the utilization of tools developed by NETL RIC
    - CO_2SCREEN
  - Examine problems encountered beyond the scope of Class VI permits and project scope
    - Changes in mechanical and flow properties due to CO_2 interactions
    - Wettability alteration
  - Acquire baseline properties and disseminate knowledge
    - Seismic surveys
    - Technical reports on core characterization
  - Testing of new monitoring techniques/ideas
    - Geochemically Informed Leakage Detection

Resource Assessment of Field-Scale CO_2 Sites

PI: Angela Goodman

- **Project Summary:**
  - Broaden the applicability of the SCREEN tool to calculate field-specific CO_2 storage estimates
- **Accomplishments**
  - Completed focused analyses on refinement of microscopic displacement (E_d) and volumetric sweep (E_v) efficiency factors based on laboratory measurements.
  - Results showed the storage efficiency factor terms E_vE_d varied from 10.5% in the south to 21.7% in the north of proposed injection locations.
  - Coupled refined efficiency factors with field scale geologic properties in tandem with SJB CarbonSAFE researchers to estimate overall efficiencies of the proposed sites.



San Juan Basin: Physical Parameter Data

Formation	Area (km2)		Gross Thickness (m)		Total Porosity (%)	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Entrada	841.75	42.09	148.47	18.26	23.00	1.15
Bluff	841.75	42.09	63.94	4.94	14.89	0.85
Salt Wash	841.75	42.09	69.52	7.21	14.89	0.85

CO_2-SCREEN Results

Formation	Storage Resource (Mt)			Storage Efficiency (%)		
	P_{10}	P_{50}	P_{90}	P_{10}	P_{50}	P_{90}
Entrada	140.37	560.77	1718.31	0.68	2.72	8.30
Bluff	39.14	154.66	479.04	0.67	2.68	8.17
Salt Wash	41.54	168.93	519.43	0.67	2.68	8.14

Resource Assessment of Field-Scale CO_2 Sites (2)

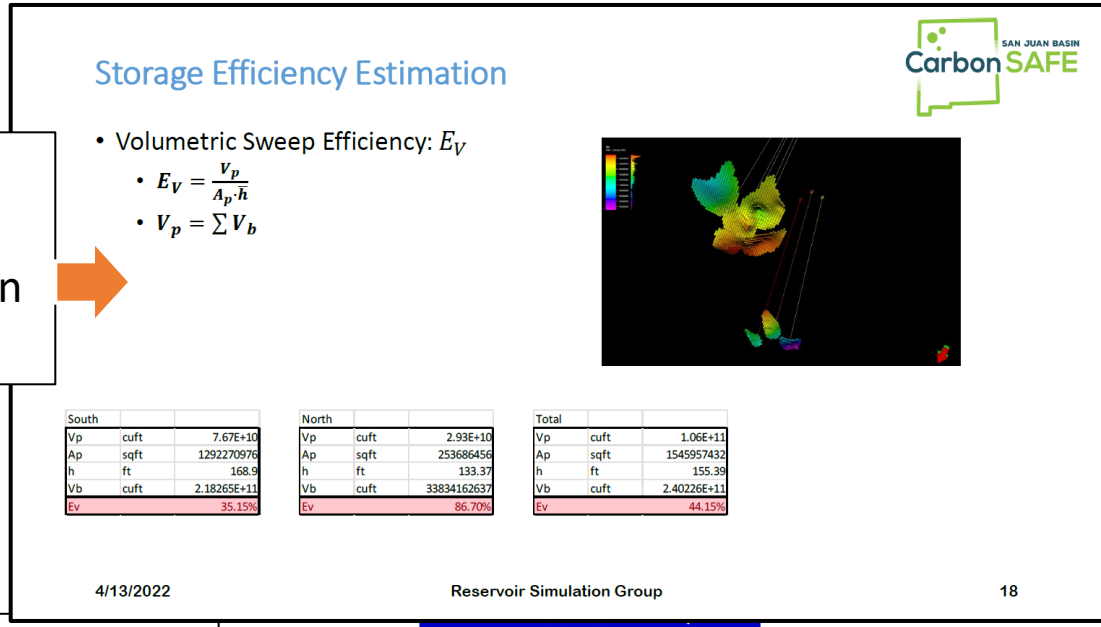
PI: Angela Goodman

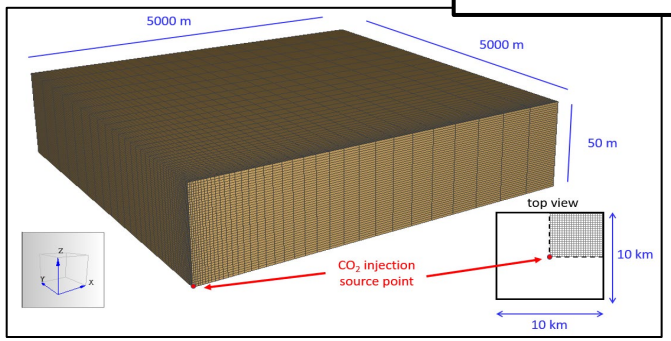
$$G = A^d h^s \phi^s \rho^s {E_{saline}}^s$$

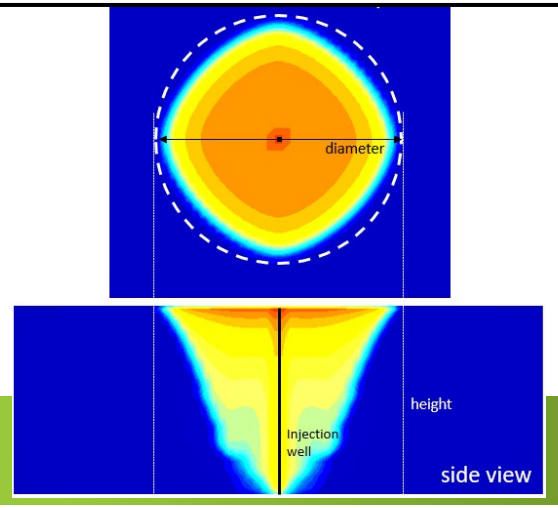
$${E_{saline}}^s = {E_A}^s {E_h}^s {E_\phi}^s {E_V}^s {E_d}^s$$

- **Project Summary:**
  - Broaden the applicability of the SCREEN tool to calculate field-specific CO_2 storage estimates
- **Accomplishments (2)**
  - Converted SJB's 3D geologic input model of the Entrada formation into a TOUGH3 format suitable for simulations that can aid in estimating and comparing storage efficiencies performed by SJB.
  - Reached an agreement with the Illinois group to share the data for various depositional environments and lithologies, for further development of storage efficiencies associated with the Mt. Simon Formation.

Modelling by SJB CarbonSAFE Reservoir Simulation Group







Chemical & Mechanical Alteration

PIs: Angela Goodman and Barbara Kutchko

- **Project Summary:** Measurement of core properties under simulated subsurface conditions to determine the impact of CO_2-saturated brine exposure on the integrity of well, reservoir, and seal materials.
- **Accomplishments:**
  - Examined core from the Integrated Mid-Continent Stacked Carbon Storage Hub core from the Sleepy Hollow fields in Red Willow County Nebraska
  - SEM analyses of SJB cores as well
    - Bluff and Entrada outcrop cores

Experimental Plan:

- Static autoclave (1-week exposures)
  - Brine (SJB recipe)
- Fluid analysis
  - ICP, pH, and TDS
- SEM
  - Feature relocation before and after reaction
- Contact angle
- Mechanical measurements
  - Compressive strength, porosity, permeability, Young's Modulus, Poisson's Ratio, Bulk Modulus, Shear Modulus

Chemical & Mechanical Alteration

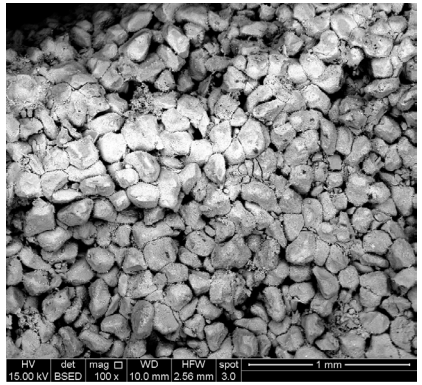
- **Mechanical Property Testing**
  - New England Research Autolab 1500
    - Young's Modulus & Poisson's ratio
  - Autolab Test conditions
    - P_{EFF} = 5-15 Mpa, ~ 40° C
    - Velocity measurements taken at 5, 10, 15 MPa for 2 full cycles
- **Helium porosimeter measurements and permeability with pulse decay or flow through tests**

MSCS-HUB SHRU 86A well

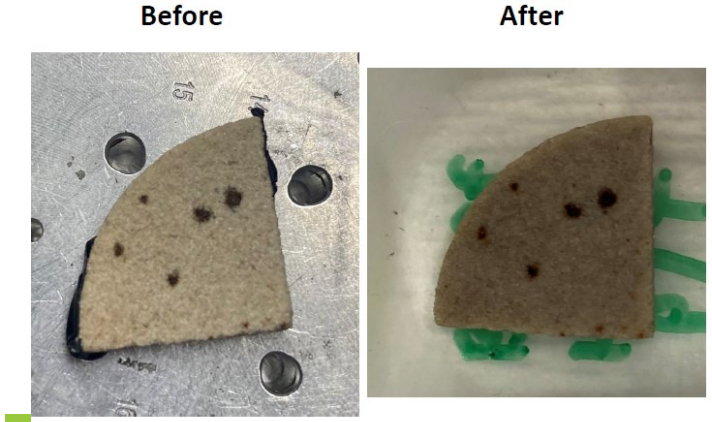
Sample Depth (ft)	Length (mm)	Diameter (mm)	Mass (g)	Dry Bulk Density (g/cc)	Pore Volume (cc)	Porosity (%)	Permeability (mD)
2903-2906	64.69	25.03	73.97	2.32	2.38	7.46	0.3400
2903-2906 (p)	41.53	24.99	45.42	2.23	1.81	8.90	0.6200
2906-2909	57.92	25.03	72.72	2.55	1.60	5.63	0.0030
2924-2927	No sample integrity						
3024-3027	50.10	25.03	63.39	2.57	0.84	3.40	0.0009
3036-3039	64.86	24.83	61.85	1.97	8.16	25.99	21.2600
3179-3182	66.82	25.04	83.64	2.54	1.60	4.86	0.0010
3179-3182 (p)	75.78	25.02	94.20	2.53	1.98	5.30	0.0002
3188-3191	51.78	24.81	48.67	1.94	6.70	26.78	22.7100
3491-3494	58.27	24.99	75.05	2.63	0.59	2.08	0.0003

Mechanical Property Alteration

- Permeability of core under confining pressure was shown to vary over 6 orders of magnitude, where sub micro-Darcy permeability of zones was observed and is expected to create vertical baffles during injection.
- Porosity of core in select intervals was measured above 25%, indicating that storage potential in zones is quite high.
- Mechanical properties (Young's modulus and Poisson's ratio) analyses continue
- Pre/post static exposure via SEM on SJB samples showed little change



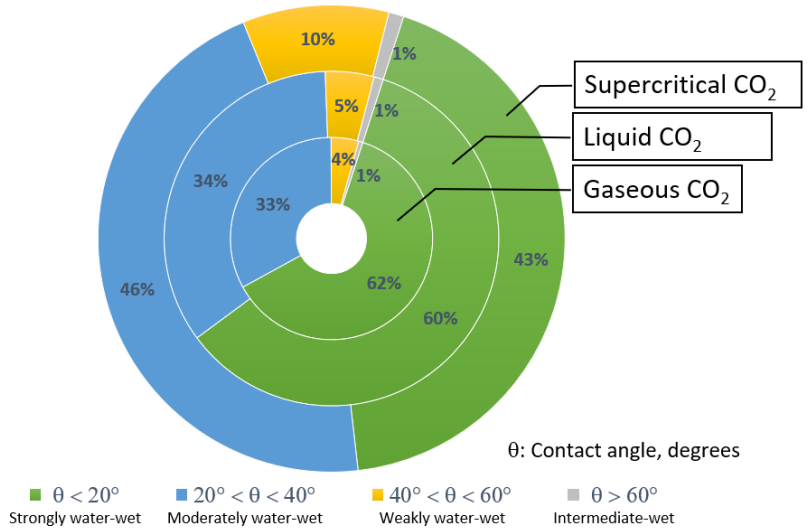
Unexposed_Bluff_Para2



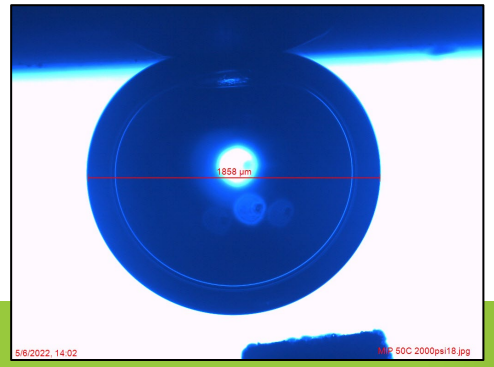
Contact Angle Measurements of Reservoir Core

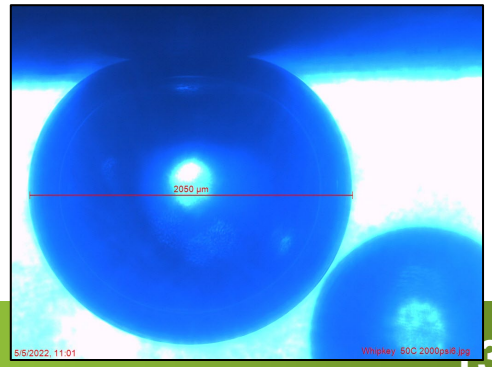
PI: Angela Goodman

- **Project Summary:** Contact angle and interfacial tension will be measured in situ at geologic pressures and temperatures.
- **Accomplishments:**
  - Obtained outcrop core from SJB CarbonSAFE cores in early 2022, and performed analysis of $scCO_2$/brine contact angles
  - Completed contact angle measurements for two Entrada samples at 90°C and 120°C at 3300, 7500, and 9950 psig.
  - -Measured 75 contact angles that ranged between 10° and 85°. This data set indicates that the Entrada samples are strongly to weakly water wet.



Haeri, F., Tapriyal, D., Sanguinito, S., Shi, F., Fuchs, S.J., Dalton, L.E., Baltrus, J., Howard, B., Matranga, C., Crandall, D., Goodman, A. (2020) **CO_2-Brine Contact Angle Measurement on Navajo, Nugget, Bentheimer, Bandera Brown, Berea, and Mt. Simon Sandstones**, Energy & Fuels 34(5), 6085 - 6100 https://doi.org/10.1021/acs.energyfuels.0c00436





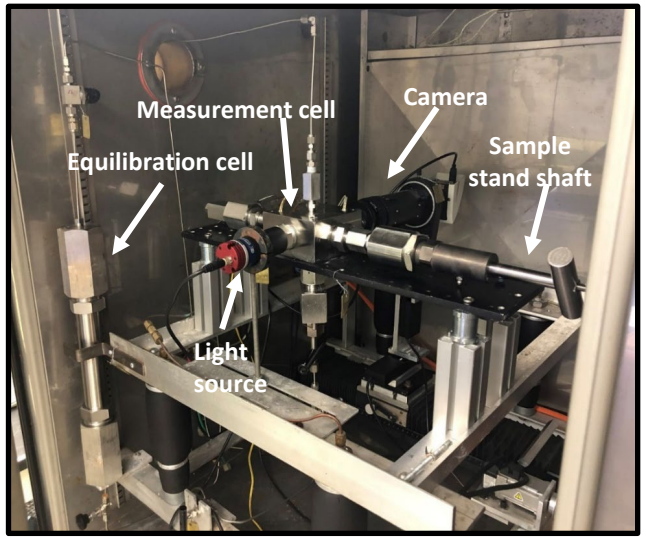
CO_2 Fundamental Interaction & Reaction Experimental (FIRE) Lab

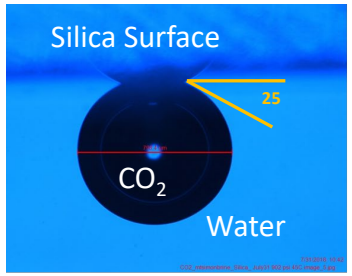
POCs: Angela.Goodman@netl.doe.gov & Deepak.Tapriyal@netl.doe.gov

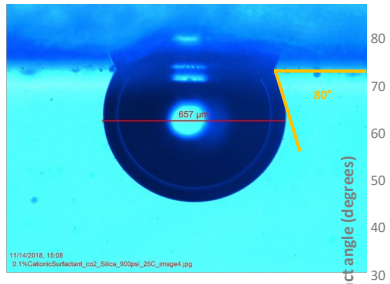
NATIONAL ENERGY TECHNOLOGY LABORATORY

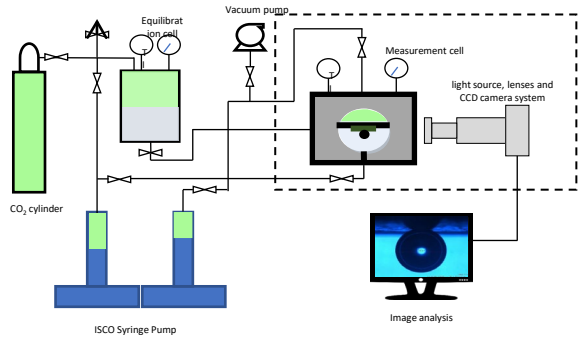
Unique Capabilities: Contact angle measurement system rated to 150°C and 10,000 psi. High resolution Leica camera and apocramatic lens is used to capture images/movies of CO_2 bubbles: size range of 500 μm to 2500 μm. Interfacial measurement system up to 150C and 10,000 psi. Phase behavior and cloud point measurement up to 10,000 psi (could be extended to 40,000 psi). Kruss scientific and Rame-hart contact angle systems.

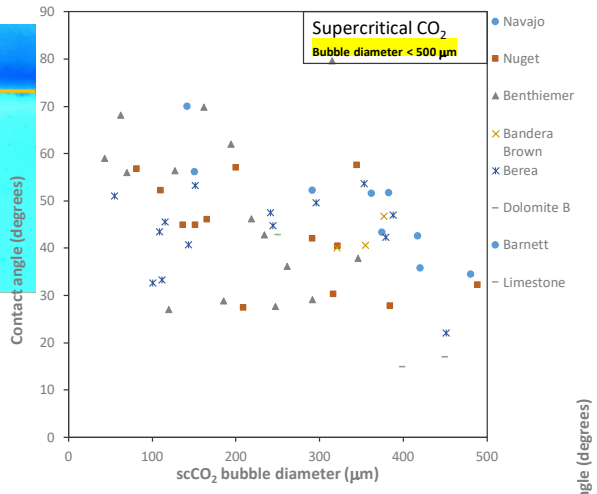
Opportunities: Contact angle measurement of geological samples under *in-situ* conditions with supercritical CO_2. CO_2 bubbles can be generated at the bottom of sample or brine, or other fluid drop can be generated at the top of sample. Samples can be held vertically to create a semi channel of different width or shape to study CO_2 interactions.

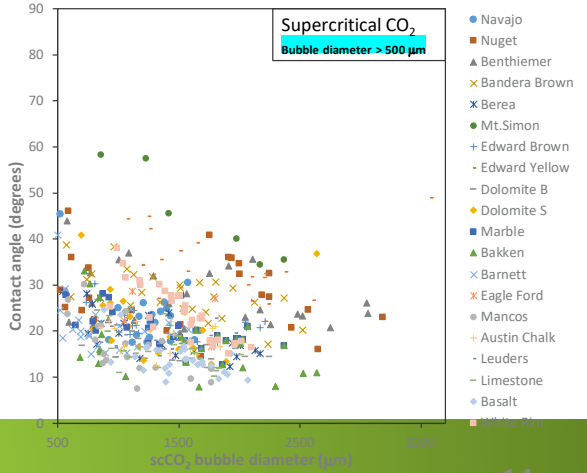












Relative Permeability Measurements of Reservoir Core

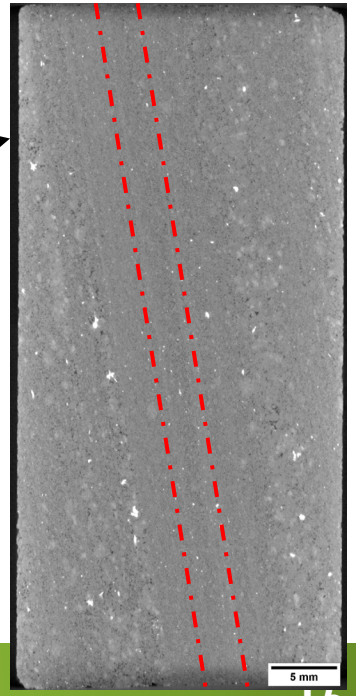
PI: Dustin Crandall

- **Project Summary:**
  - Measure $scCO_2$/brine k_r curves in CarbonSAFE cores and publish data
- **Accomplishments**
  - Outcrop core of relevant formations from San Juan Basin CarbonSAFE.
  - Analyses of Entrada sandstone outcrop cores from the SJB CarbonSAFE site revealed that flow through high permeability bedding controlled fluid migration.
  - Analyses of Bluff sandstone outcrop core from the SJB CarbonSAFE site revealed a matrix with high permeability and moderate homogeneity. This enabled a relatively high sweep efficiency (~70%) of $scCO_2$ during primary drainage.

Bluff Perp 4

Entrada Perp 1

Entrada Para 2



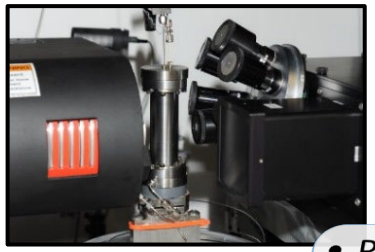
Multi-Scale CT and Core Flow Facility

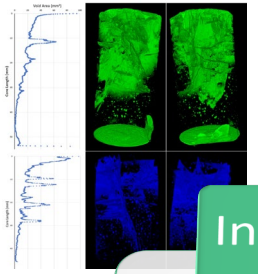
POC: Dustin.Crandall@netl.doe.gov

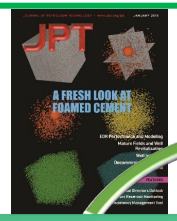
NATIONAL ENERGY TECHNOLOGY LABORATORY

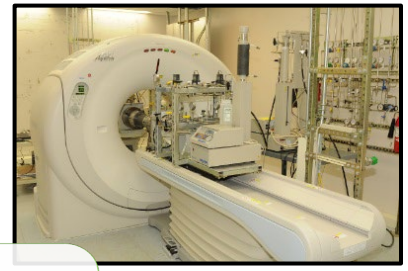
Unique Capabilities: Four computed tomography scanners with 3D resolution from microns to millimeters, all with ancillary core flow capabilities. Able to performed controlled multiphase flow in cores from 0.25” to 2” in diameter at conditions up to 10,000 psi and 200 ˚C. Full time technical staff to assist with rock preparation, experimentation design, setup, execution, and analysis. Plus, controlled flow systems for long term tests, and GeoTek multi-sensor core logger.

Opportunities: Direct examination of rocks from carbon storage sites under *in-situ* conditions with supercritical CO_2. Stressing of samples to understand mechanical behaviors. Examination of relationships between rock properties, geochemical alteration, and permeability (or structural properties). Scanning to complement other experiments, or to digitally and non-destructively preserve core from relevant locations.









- *Pore Scale*
- *Small Samples*
- *Dynamic Flooding*

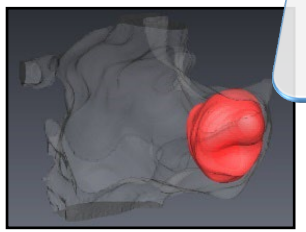
Micro-CT

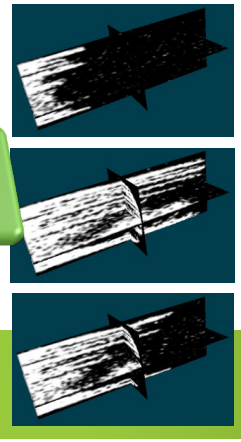
Industrial CT

- Pore & Core scale
- 1” Diameter plus Samples
- Highest Pressures

- Core Scale
- Large Samples
- Dynamic Flooding

Medical CT



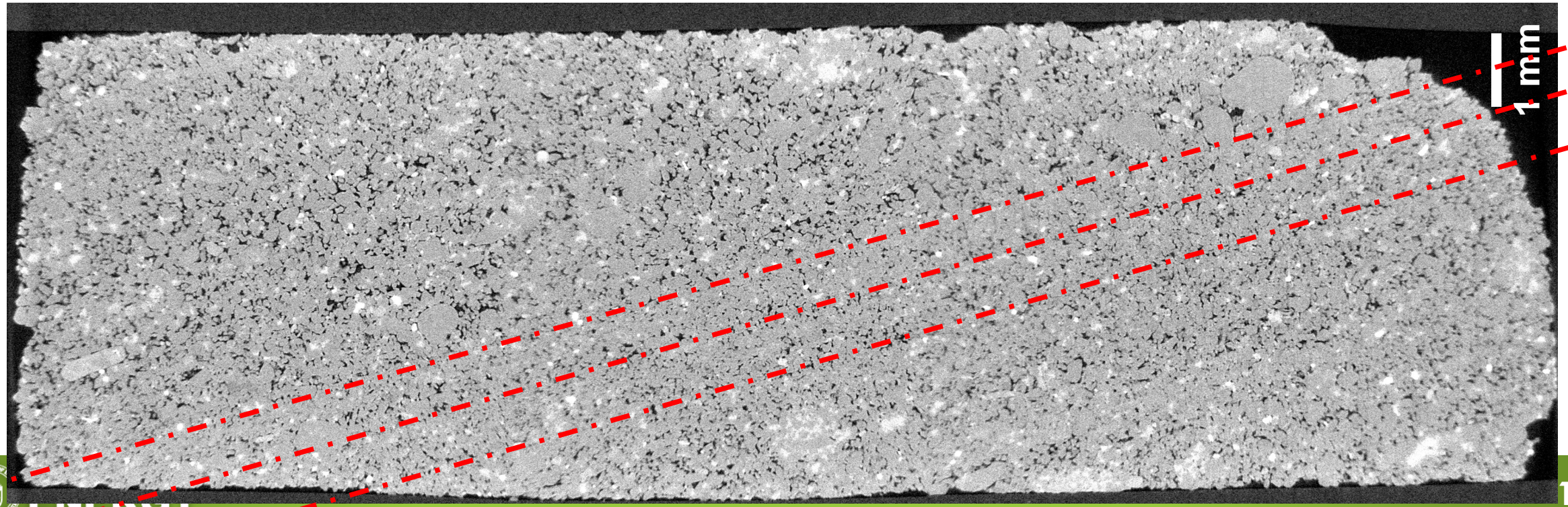


For More Information:

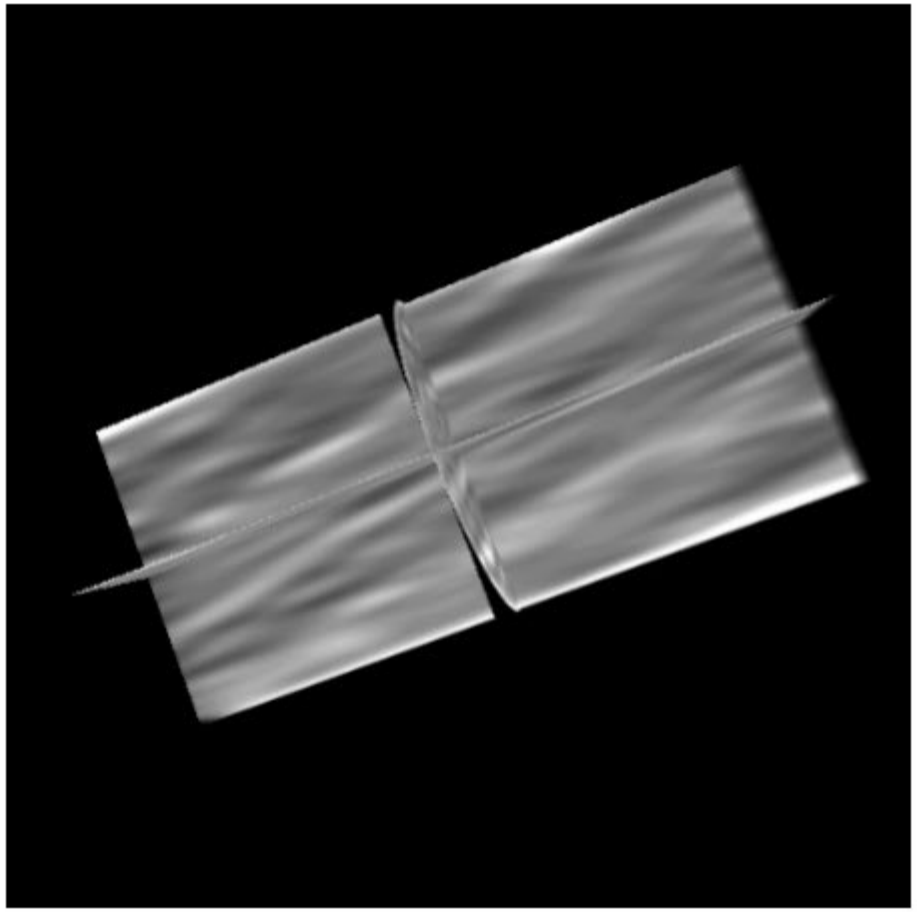
- Equipment/Lab Factsheet (link)
- Core characterization EDX Data Group (link)
- Core characterization YouTube Video (link)
- CO_2 Brine Relative Permeability Accessible Database (link)

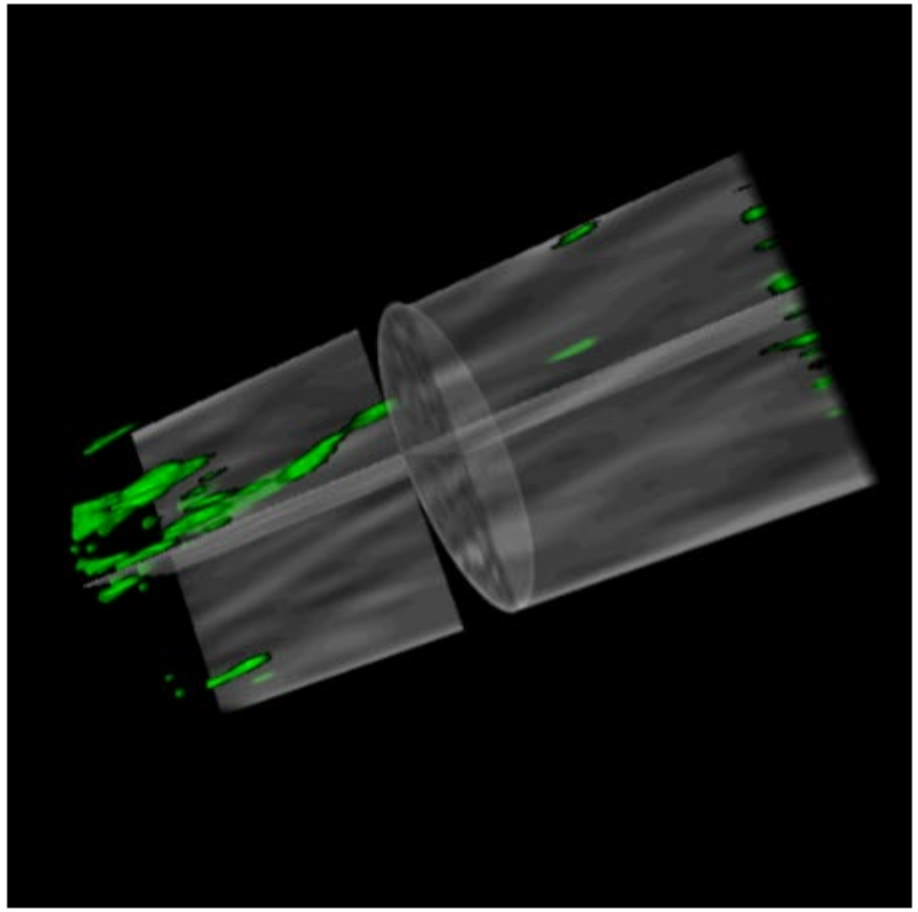
Relative Permeability Measurements of Reservoir Core

- High resolution micro-CT scans in addition to lower resolution dynamic CT scans of CO_2 injection
- Bedding plane orientation of core drastically influenced migration of some cores



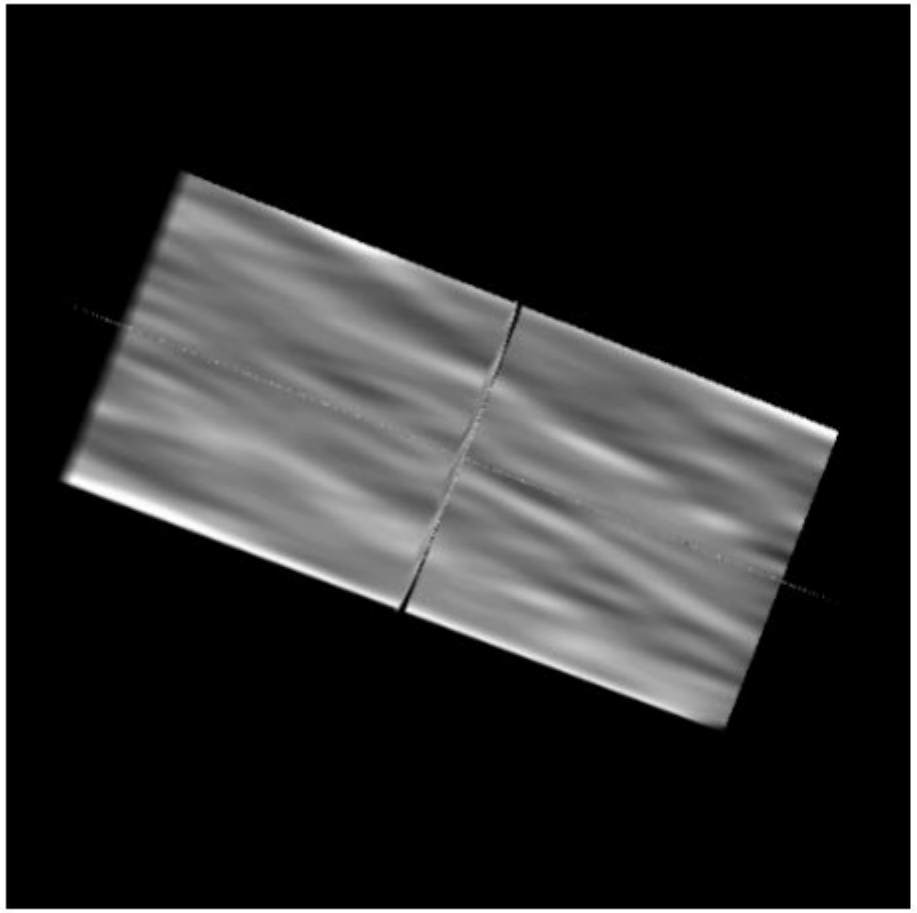
Entrada Para 1 – Flow Images

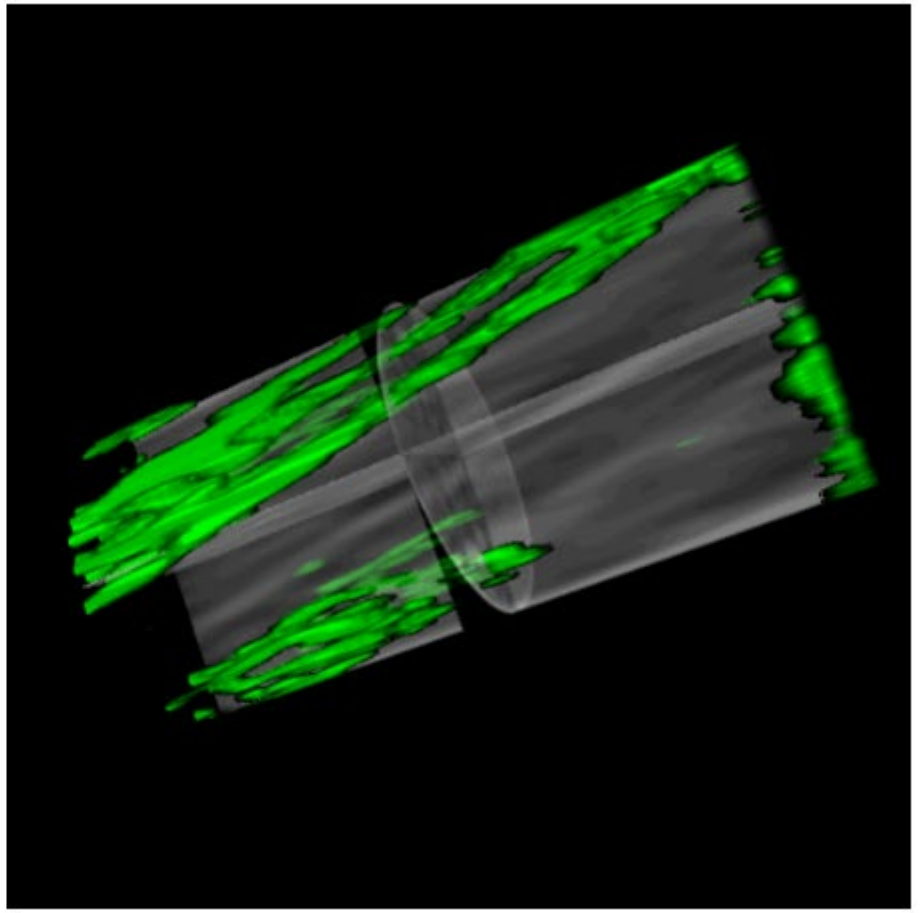




- 16 seconds between scans
- Breakthrough through between 32-80 seconds.
- Short circuited along primary bedding, but backfilled prior to breakthrough

Entrada Para 1 – Flow Images

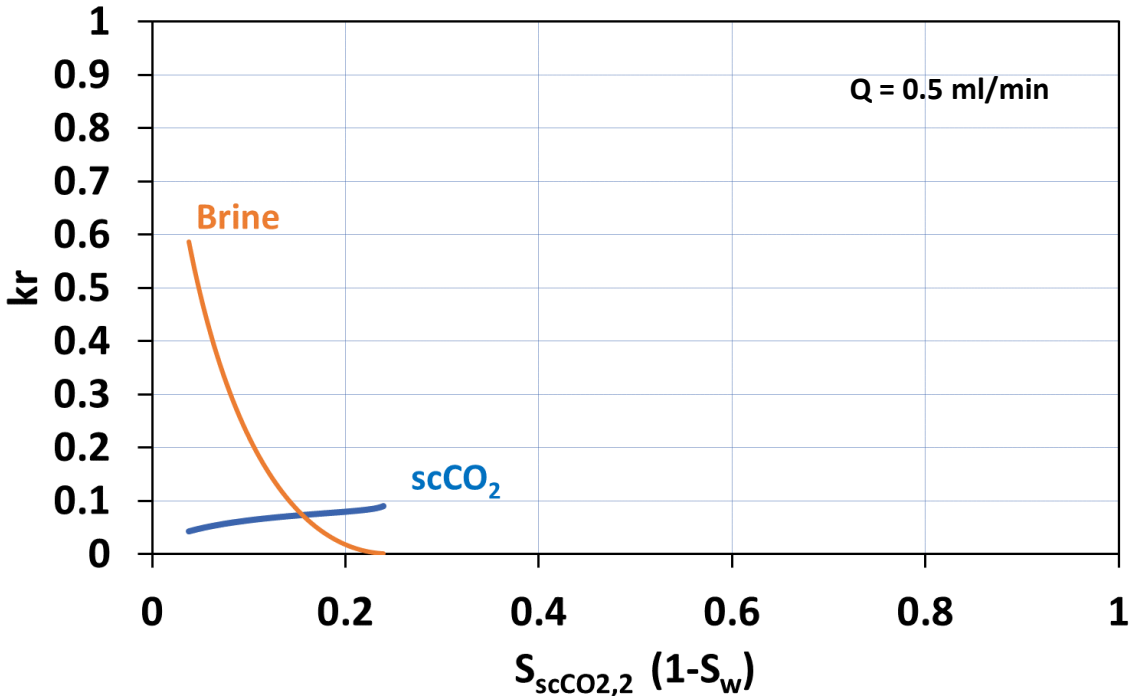


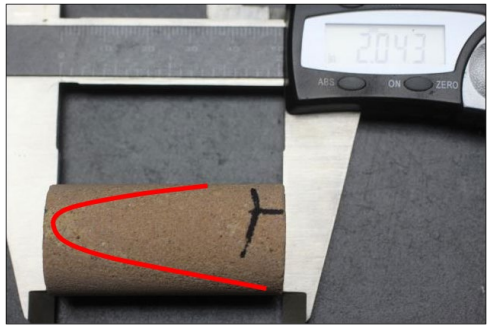


- 16 seconds between scans
- Breakthrough through between 32-80 seconds.
- Short circuited along primary bedding, but backfilled prior to breakthrough

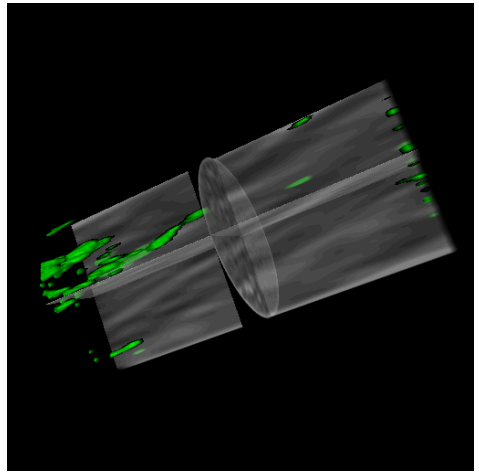
Entrada 1 Results

Parameter	Value	Unit
Specimen length, l:	0.05	(m)
Specimen radius, r:	0.01	(m)
Specimen volume, Vs:	25.08	(ml)
Pore volume, Vp:	4.31	(ml)
Porosity,ϕ :	17.20	(%)
Permeability	21.09	(mD)





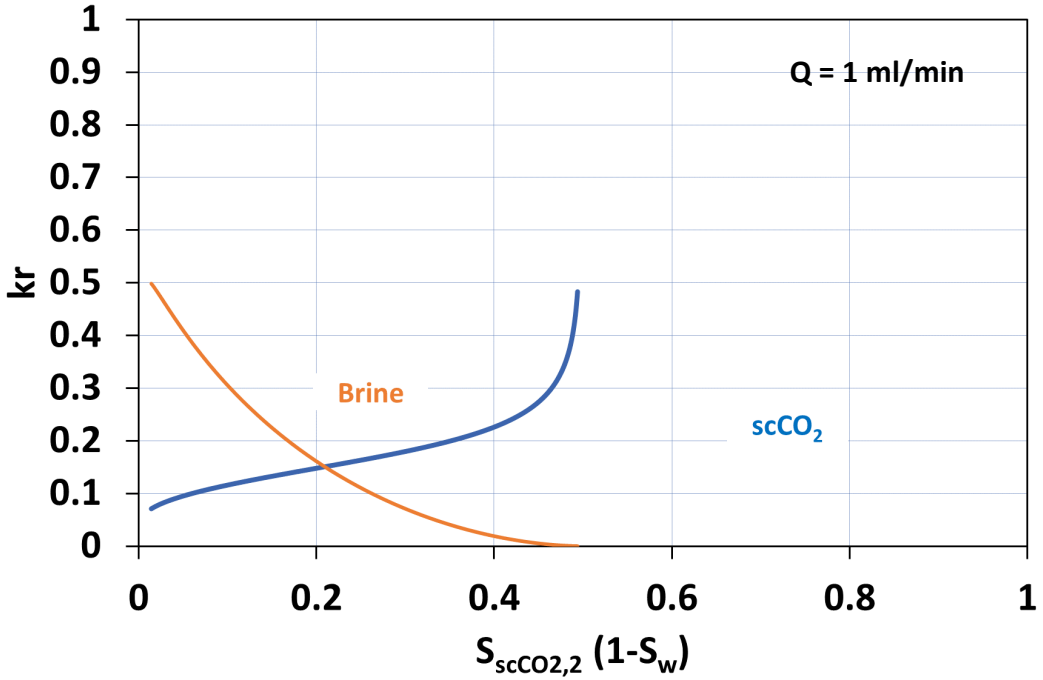
CO_2 in green

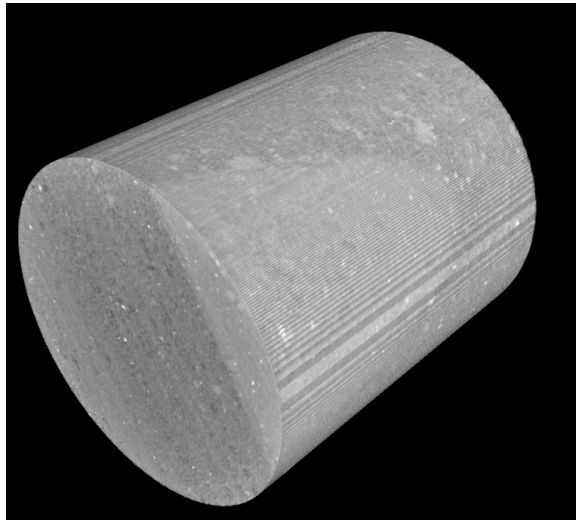


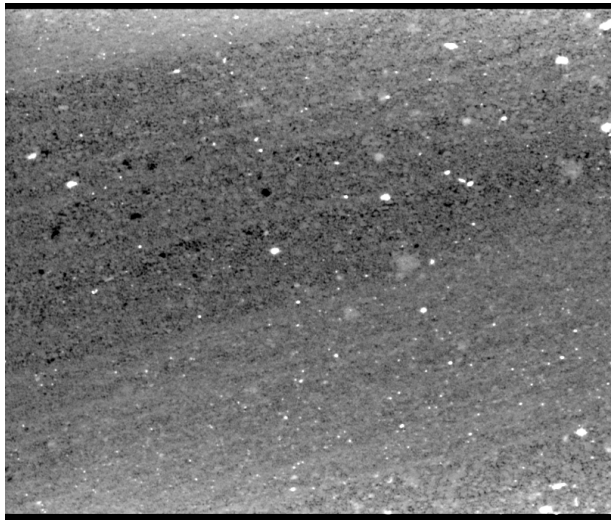
Bedding plane dominated flow that resulted in short circuiting of fluid. Results in overall low cross-over saturation and end point saturation.

Entrada 4 Results

Parameter	Value	Unit
Specimen length, l:	0.05	(m)
Specimen radius, r:	0.01	(m)
Specimen volume, Vs:	23.31	(ml)
Pore volume, Vp:	4.0	(ml)
Porosity,ϕ :	17.1	(%)
Permeability	5.97	(mD)



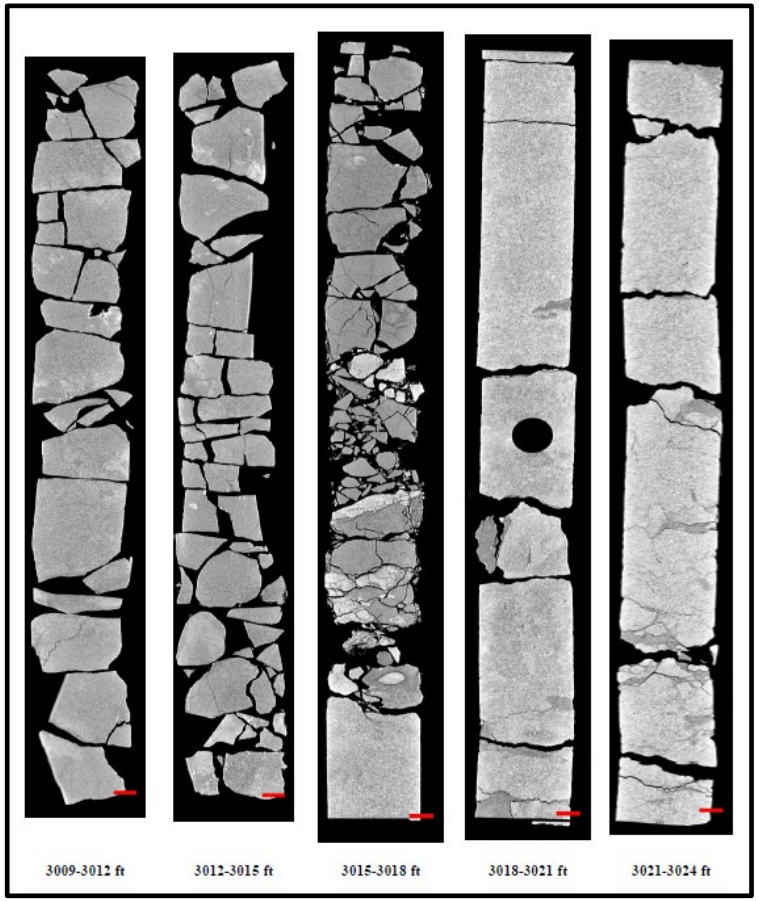




CCS Core Characterization and Digital Distribution

PI: Dustin Crandall

- **Project Summary:** Obtain relevant CCS core, scan, and make data digitally available.
- **Accomplishments:**
  - ISGS Wabash CarbonSAFE and Kansas Geologic Survey, Wellington 2–32 core reports published
  - Prairie State, One Earth and Illinois Seals core reports published.
  - IMSCS-HUB core from Sleepy Hollow Reagan core report to be published



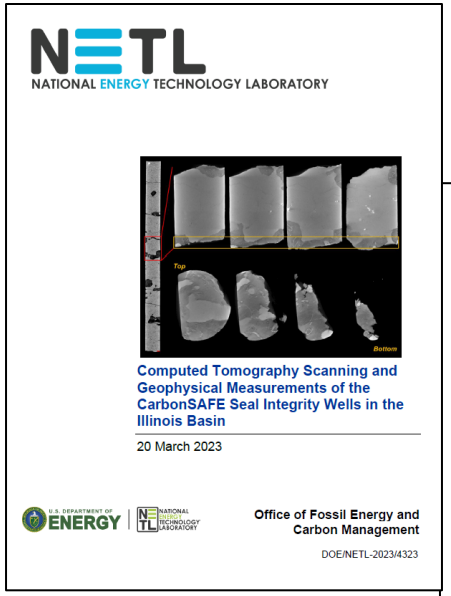
CT images of core from the draft report on IMSCS-HUB Sleepy Hollow Reagan Unit 86A characterization.

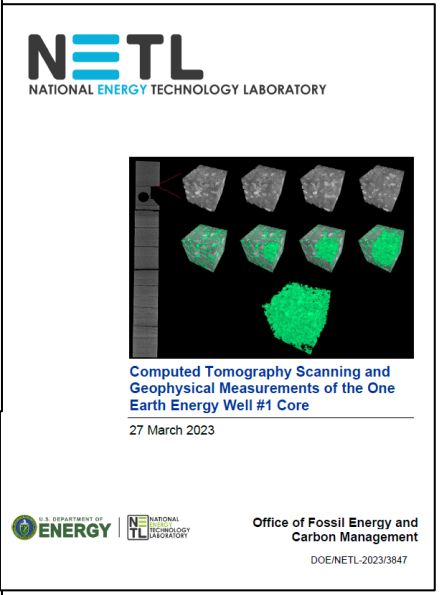
CCS Core Characterization and Digital Distribution

PI: Dustin Crandall

Core reports available on EDX 'Core Characterization' Group (https://edx.netl.doe.gov/group/core-characterization)

- Paronish, T.; Mitchell, N.; Brown, S.; Pohl, M.; Crandall, D.; Blakley, C.; Korose, C.; Okwen, R. **Computed Tomography Scanning and Geophysical Measurements of the CarbonSAFE Seal Integrity Wells in the Illinois Basin**; DOE/NETL-2023/4323; NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2023; p 68. DOI: https://doi.org/10.2172/1962306
- Crandall, D.; Paronish, T.; Mitchell, N.; Jarvis, K.; Brown, S.; Moore, J.; Gill, M.; Blakley, C.; Okwen, R.; Korose, C.; Carman, C. **Computed Tomography Scanning and Petrophysical Measurements of the Lively Grove #1 Well Core**; DOE/NETL-2023/3877; NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2023; p 60. https://doi.org/10.2172/1989188
- Crandall, D.; Gill, M.; Paronish, T.; Brown, S.; Mitchell, N.; Jarvis, K.; Moore, J.; Blakley, C.; Okwen, R.; Korose, C.; Carman, C. C**omputed Tomography Scanning and Geophysical Measurements of the One Earth Energy Well #1 Core**; DOE.NETL-2023.3847; NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Morgantown, WV, 2023; p 60. https://doi.org/10.2172/1963265



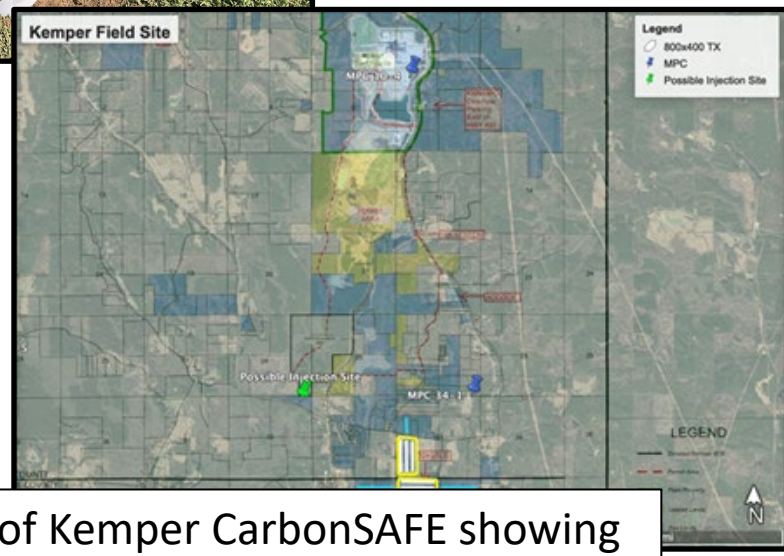


Geophysical Monitoring of Carbon Storage Reservoirs

Task PI: Rick Hammack

- **Project Summary:** Passive seismic monitoring of CO_2 EOR sites in prior years and currently acquiring baseline seismic at Prairie State CarbonSAFE site.
- **Accomplishments:**
  - Approximately three months of baseline seismic data have been collected from seismometers deployed at the Prairie State CarbonSAFE site in Washington County, Illinois.
  - Initial seismic data from the Prairie States site recorded local seismicity with 17 events having a magnitude of 2.
  - Kohnke, C., Li, Y., Hammack, R., 2021, **The Feasibility of MT Tipper Data to Monitor CO_2 Storage Sites**, *2021 SEG Annual Meeting*, Denver, CO, Sept 26-Oct 1, 2021.
    - Actual deployment at Kemper has been delayed due to COVID and subcontract issues

NETL seismometer at Prairie State CarbonSAFE Site, Washington County, IL



Map of Kemper CarbonSAFE showing approximate location of proposed electromagnetic surveys

Geophysical Monitoring of Carbon Storage Reservoirs

Task PI: Rick Hammack

- **Project Summary:** Passive seismic monitoring of CO_2 EOR sites in prior years and currently acquiring baseline seismic at Prairie State CarbonSAFE site.
- **Ongoing work:**
  - Planning to deploy a monitoring network of 8 broadband seismometers around the class VI injection well at Red Trail site in North Dakota. This will complement the dense surface network of vertical geophones. The project is aimed at performing long term (tentatively 24-36 months time window) monitoring of CO_2 injection activity and tracking seismic activity related to CO_2 plume movement in the subsurface.

NETL seismometer at Prairie State CarbonSAFE Site, Washington County, IL

Geophysical Monitoring of Carbon Storage Reservoirs

Task PI: Rick Hammack

- **For an update on monitoring efforts in the last year:**

11:50 AM Tomorrow – Ballroom B
Rick Hammack

Update on Semi-Airborne, Controlled Source Electromagnetic Survey at a Potential Carbon Storage Site in Kemper County, Mississippi

NETL seismometer at Prairie State CarbonSAFE Site, Washington County, IL

Assorted Efforts Ongoing

- **It took time to setup, meet projects where they were, and get analyses underway**

- **This time to develop working relationships, make sure that complementary work could be done, and then develop specific work plans was the biggest challenge**
  - The CarbonSAFE projects have such phenomenal lifts they are undertaking, with so many moving parts already integrated into the official project, this is not a big surprise.
  - Where previous connections existed, time to start much shorter.

Final Thoughts

- **Not working with all CarbonSAFE projects**
  - No point in 'assisting' where not needed …
  - This isn't Pokémon, we're not trying to 'collect them all'
  - Realistically, impractical from NETL RIC resource stance as well
- **There will likely be a need for this type of effort at a larger scale as field projects ramp up over the next years**
  - Having this expand beyond NETL RIC would be great. GOGO nature with Trade Secrets Act restrictions on data sharing beneficial for initial pilot
  - "Dial-A-Lab" sort of "hotline" for nascent projects to get support for unexpected or unusual occurrences?

Thank you!

- Thank you to the field labs for letting us work with you!

- Thank you to all the PIs and RIC Researchers for prioritizing this work with them!