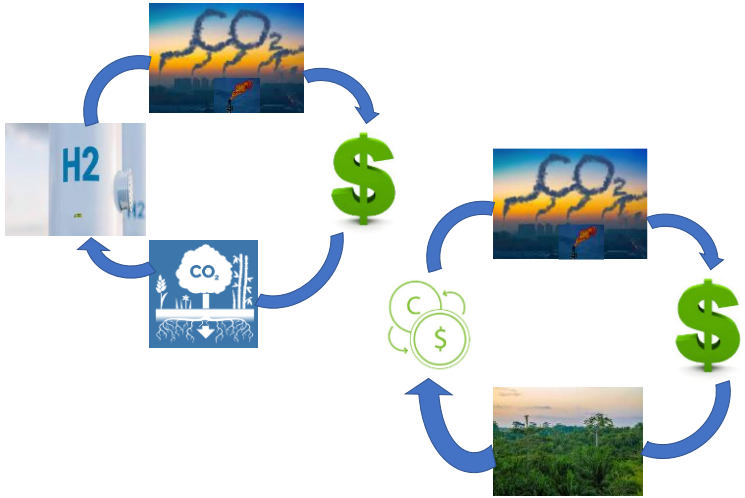
Stanford Center for Carbon Storage

2021 Research Highlights

Carbon-free fossil fuel-based alternatives to oil and gas: a Nigeria transition planning study

Scientific Achievement

Detailed technoeconomic assessment of export blue hydrogen production from oil and gas, and emissions offset market potential.



Significance and Impact

To inform low-carbon transition planning for oil-dependent countries like Nigeria with alternatives that meet environmental and development goals without compromising economic stability.

Research Details

- Geospatial assessment of optimal sites for blue hydrogen production, using flared natural gas as ”low-hanging fruit”.
- Analysis of potential for market-based approach to oil and gas commodity decarbonization.

Fola Olanrewaju Ayoola, Sally Benson

Optimizing Hydrogen Infrastructure Build-Out in California

Scientific Achievement

Conducting geo-spatial and techno-economic analysis to determine optimal locations in California to build blue and green hydrogen production facilities to minimize total project cost.

Significance and Impact

This research can help guide investment in hydrogen infrastructure into the future in California and can be expanded upon to guide hydrogen investments on a global scale.

Research Details

- Hydrogen infrastructure buildout is likely for the transportation sector with the issuance of Executive Order N79-20 and the Low Carbon Fuel Standard (LCFS).
- To make blue hydrogen cost optimal, locate the facility above CO_2 storage locations, near existing natural gas pipelines, where natural gas prices are low, and where a high H_2 demand is expected
- To make green hydrogen cost optimal, locate the facility in high solar irradiance regions, near existing electricity transmission lines, and where electricity prices are low

Geological Carbon Storage Opportunities in Kern County

Scientific Achievement

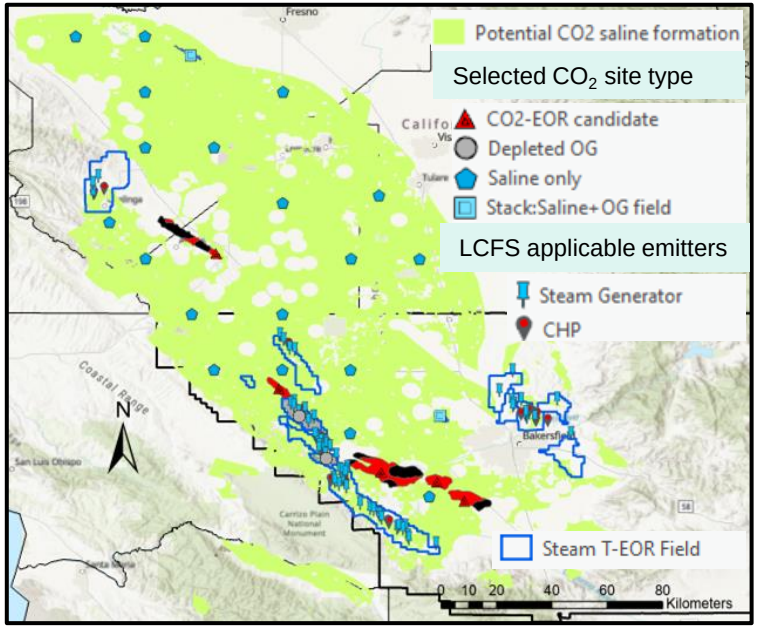
- **Potential CO_2 storage sites in the target area were assessed with screening criteria, exclusion zones, and scoring system.**
- **The emissions of oil & gas production facilities were quantified in each thermal EOR field.**

Significance and Impact

- **Assessed oil & gas production facilities and potential CO_2 storage sites. Laid groundwork for techno-economic analysis.**

Research Details

- The potential CO_2 storage resource was estimated
  - Saline formationd:16.6 - 52 $GtCO_2$, - Oil & gas fields: 0.45 – 1.16 $GtCO_2$
- The 28 high & moderate priority storage sites (3.1 – 8.9 $GtCO_2$) in the target region were selected with scoring system.
- Identified ~ 12 $MtCO_2$/y capturable CO_2 from oil & gas production facilities.



Priority CO_2 storage (OG fields/saline) sites and CO_2 emitters (oil/gas production facilities).

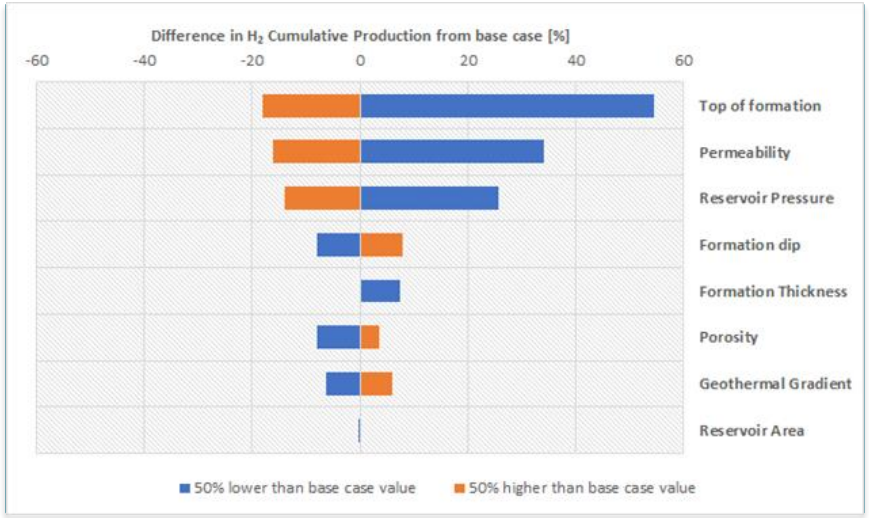
Hydrogen Storage in Porous Media: Preliminary Site Selection Criteria

Scientific Achievement

Preliminary development of site selection criteria for hydrogen in depleted gas fields.

Significance and Impact

UHS in porous media has the potential to support large-scale hydrogen storage, which will complement renewable energy generation and help with GHG emission reduction initiatives.



Research Details

- A multistage screening and site selection process is being developed for optimal selection of potential UHS reservoirs.
- The geoscience approach is complemented by numerical simulation
- Shallow reservoir depth, low permeability and low reservoir pressures are key factors to consider in maximizing hydrogen storage and extraction from porous media.

Rita E. Okoroafor Ph.D., Prof. Anthony Kovscek, Sarah Saltzer, Ph.D.

Development of gas power plants with carbon capture and storage in California's electricity sector

Scientific Achievement

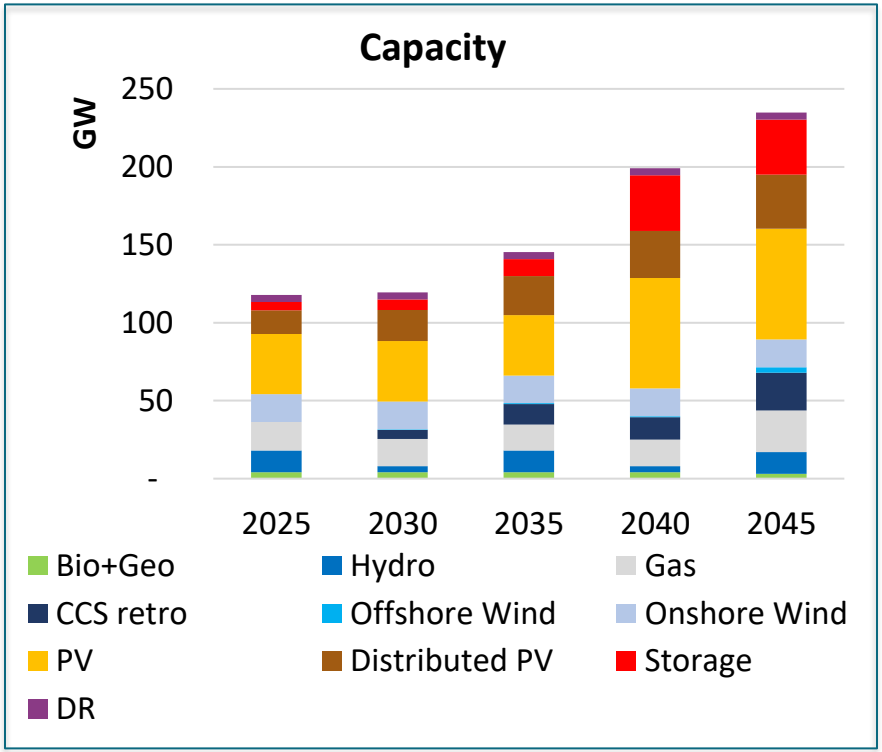
Retrofitting gas power plants with carbon capture and storage (gas-CCS) can be cost-effective within California's decarbonized electricity systems as early as 2030

Significance and Impact

Developing Gas-CCS in California's electricity grid can help California achieve its decarbonization goals faster

Research Details

- Growth rate of gas-CCS is in line with historic growth rates of natural gas power plants in California
- Gas-CCS generation will likely exceed current natural gas generation in California due to large growth in load



Ejeong Baik and Sally M. Benson, Department of Energy Resources Engineering

Distributional Health Impact of Electricity Imports in the US

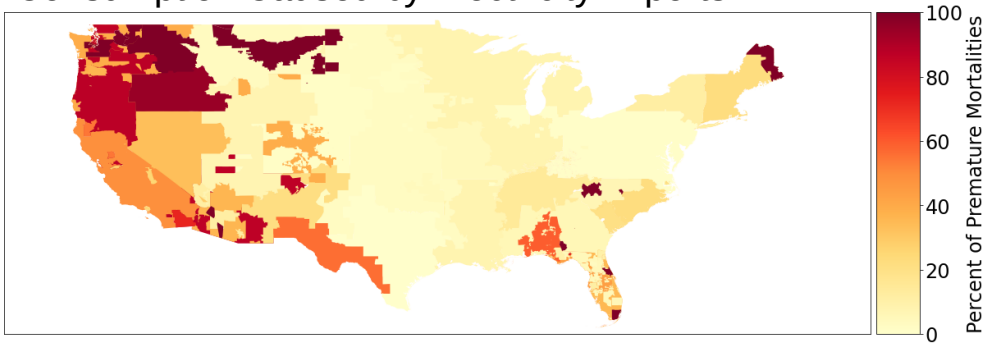
Scientific Achievement

Demonstrate that electricity imports in the Western US cause significant health damages and CO_2 emissions in distant communities

Significance and Impact

Energy policy must account for the heterogeneity in the effects of electricity imports

Percent of Health Damages from Electricity Consumption Caused by Electricity Imports



Research Details

- We use consumption-based accounting and flow tracing to track the emissions and health damages associated with electricity imports
- We determine the magnitude of damages caused be each balancing area, and the distribution of the effects.

Eleanor Hennessy, Jacques de Chalendar, Sally Benson, and Inês Azevedo

The impact of small-scale lamination on CO_2 plume migration

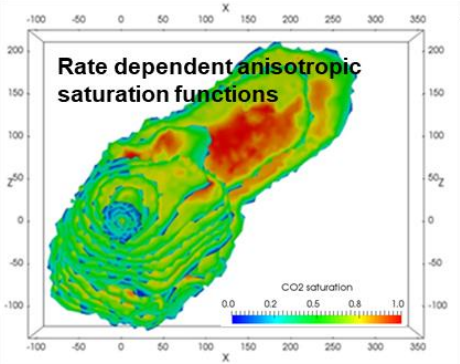
As part of the GeoCquest Project – funded by BHP

Scientific Achievement

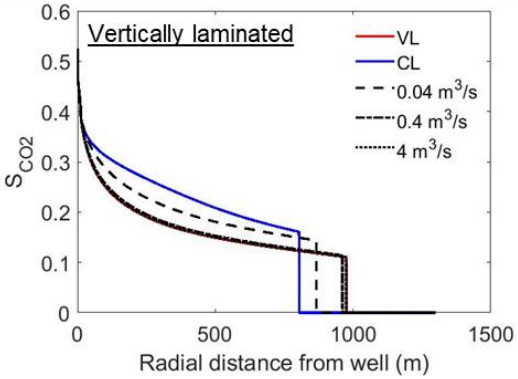
Semi-analytical and numerical models have been developed that can incorporate the impact of small-scale heterogeneity on CO_2 plume migration into field-scale models.

Significance and Impact

Small-scale heterogeneity has a significant impact on CO_2 plume migration. To incorporate this impact into field-scale models requires the use of flow-rate dependent saturation functions which is not supported by most reservoir simulators. Our models provide a way to investigate the impact of small-scale laminations on field-scale plume migration.



Qi Shao, et al. Under review in IJGGC



Research Details

- Semi-analytical models that include the effects of capillary and viscous forces are used to obtain effective saturation functions over a wide range of capillary numbers for horizontally and vertically layered systems. The new models can be implemented into an extended Buckley-Leverett solution.
- Anisotropic flow-rate dependent saturation functions were derived for the 15 rocktypes of the Paraatte Fm at the Otway site and used to investigate the implications of feedbacks between the regional flow regime and the local saturation distributions with a compositional reservoir simulator.

Maartje Boon, Stephan K. Matthai, Qi Shao, AbdAllah Youssef, Kuncho Kurtev & Sally M. Benson

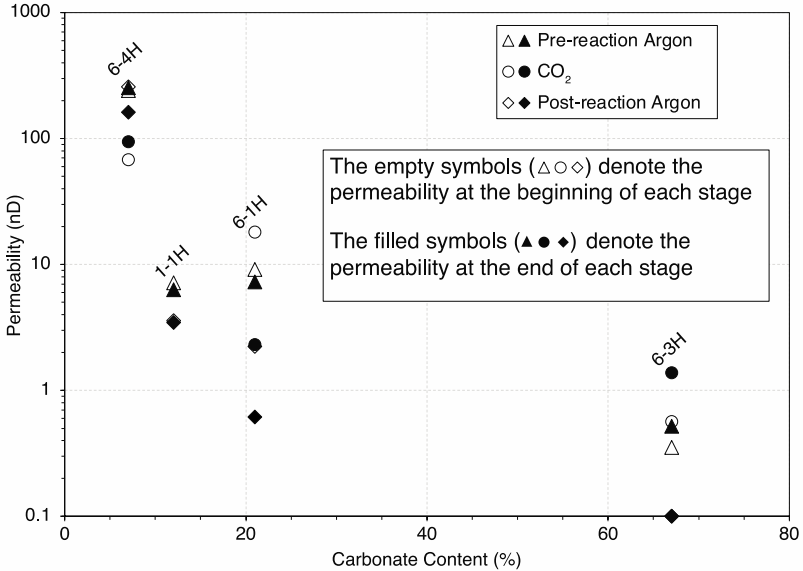
Long-term permeability evolution of shale rocks with argon and $scCO_2$

Scientific Achievement

We found that carbonate dissolution might lead to increase or decrease in matrix permeability by either introducing new porosity and/or matrix weakening. Viscoelastic deformation, swelling-induced microcracks, and salt precipitation were among other processes involved with long-term evolution of permeability in shale rocks.

Significance and Impact

The initial permeability of the samples was a more important parameter than permeability evolution.



Research Details

- Matrix weakening found to be present in samples with moderate/high amounts of carbonate.
- Enhanced permeability decay rate after long-term interaction with $scCO_2$.
- Salt precipitation occurred in high-clay sample, leading to reduction of permeability but overshadowed by increase in permeability due to creation of swelling-induced micro-cracks.

Arash Kamali-Asl; Anthony Kovscek; Mark Zoback

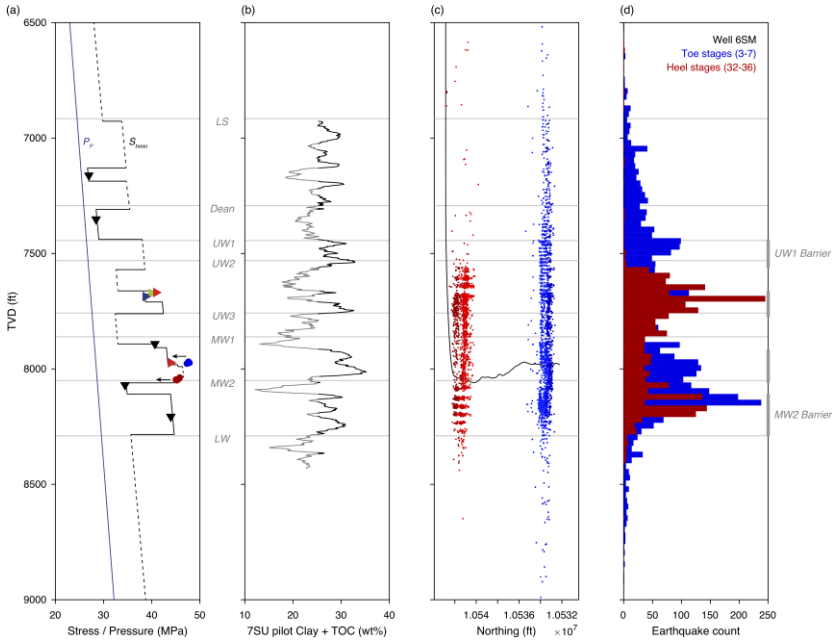
Stratigraphic stress variations control vertical hydraulic fracture growth and injection-induced seismicity

Scientific Achievement

We studied stress, microseismicity and hydraulic fracturing growth at the Hydraulic Fracture Test Site-1. We found that stratigraphically-controlled stress variations strongly impact hydraulic fracture growth and the characteristics of induced microseismicity.

Significance and Impact

Our study represents a general approach for incorporating stress measurements, logs, and core data to predict variations in the stimulation. This approach is directly relevant to CO_2 storage in depleted oil and gas reservoirs.



Research Details

- Clay + TOC-rich layers show significant stress relaxation and act as frac barriers
- Stress variations between stages result in different patterns of stimulation in space and time
- Applications to CCS
  - Calculate fracture network area to determine injectivity and model injection
  - Accounting for stress variations in determining conditions for fault reactivation

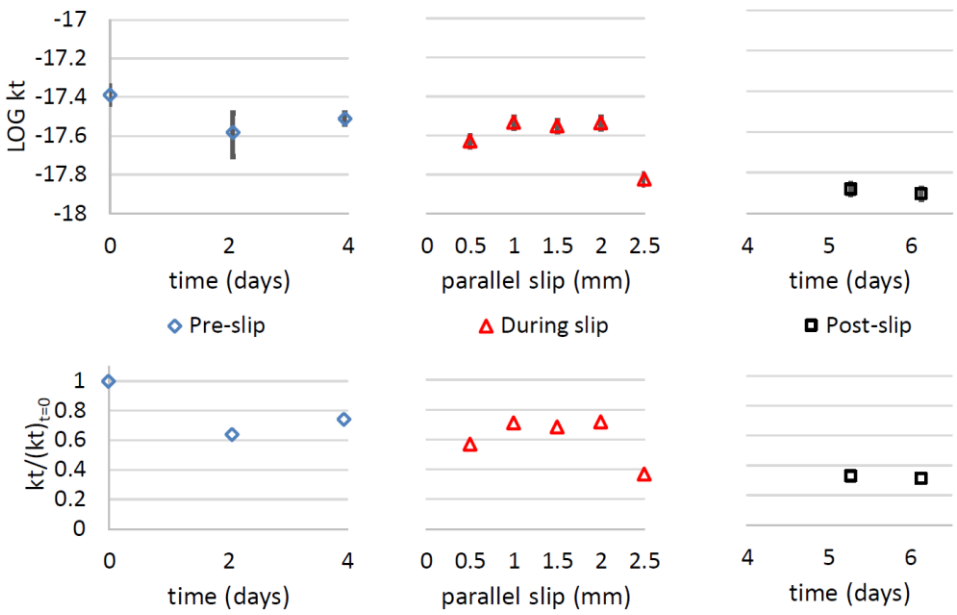
Investigating Transport and Structural Changes of Faults Slipping under sc-CO_2 Conditions in Shale

Scientific Achievement

We investigated the evolution of fault permeability as a result of sc-CO_2 saturation and slipping. We found these two factors to negatively affect fault permeability.

Significance and Impact

Our study provides insights of CO_2 behavior in the vicinity of faults. These insights help understanding CO_2 transport in the CO_2 storage process.



Research Details

- Faults were successfully slipped with both pore pressure and incremental axial loading.
- Saturating with high adsorption capacity fluids reduces fracture permeability.
- Slipping a smooth fault considerably reduced fault permeability.
- CT imaging helped visualizing diffusion of fluids and quantifying porosity.

Talal Al Shafloot, Tae Wook Kim, Arjun Kohli, Anthony Kovscek

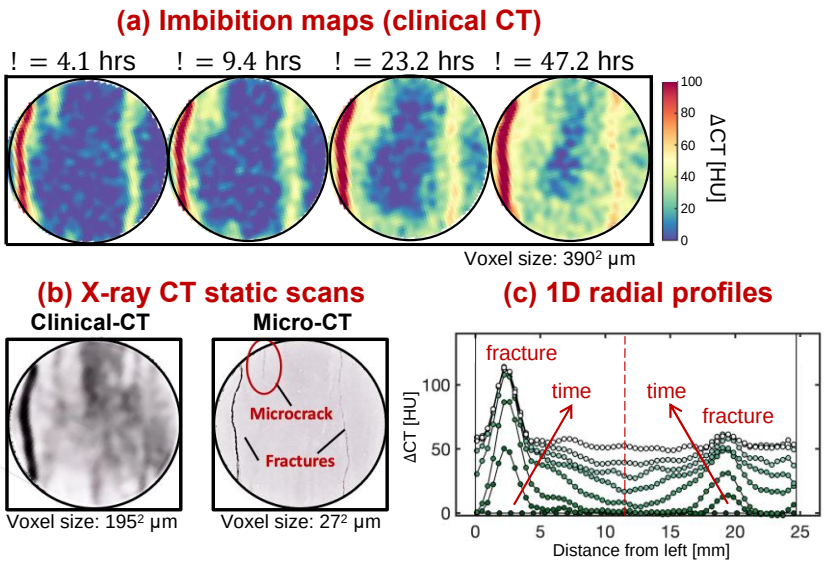
Visualizing fracture-matrix interactions during single- and multi-phase flows using imaging techniques

Scientific Achievement

We deployed X-ray CT to uncover the dynamic interactions between brine, CO_2, fractures and the host matrix of geological rock cores in three-dimensions

Significance and Impact

Our experiments provide a direct understanding into the effects of fractures (ranging from nm to *μ*m) during imbibition process in subsurface rocks and are among the most useful tools for characterizing transport properties in micro-fractured geologic rocks



Research Details

- We show the paramount role of sub-micron fractures on the spatial extent of imbibition
- Regardless of the aperture size, spontaneous imbibition proceeds uniformly away from the fractures, thereby significantly accelerating the speed of imbibition
- We demonstrate that spontaneous imbibition perpendicular to the fractures is the dominant process controlling the location and rate of imbibition.

T. Kurotori, M.P. Murugesu, C. Zahasky, B. Vega, H.J. Khan, J. L. Druhan, A.R. Kovscek, S. M. Benson

Long-term Redistribution of Residually Trapped Gas due to Non-convective Transport

Yaxin Li and Prof. Sally M Benson

Scientific Achievement

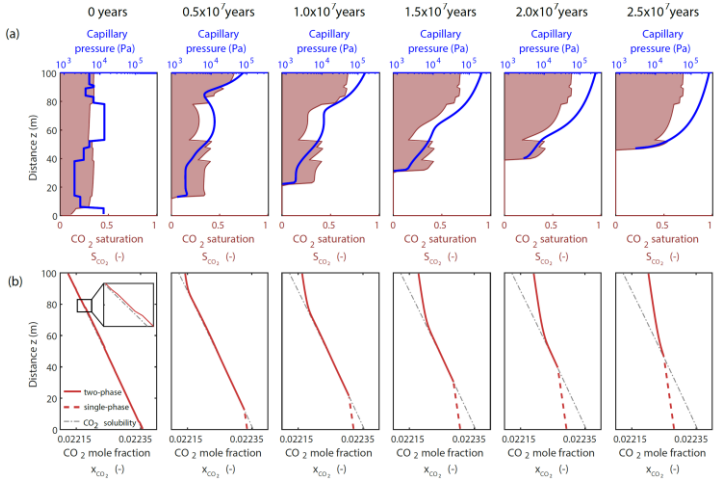
We show that residually trapped CO_2 is thermodynamically unstable and thus can be redistributed by diffusion while remaining trapped.

Significance and Impact

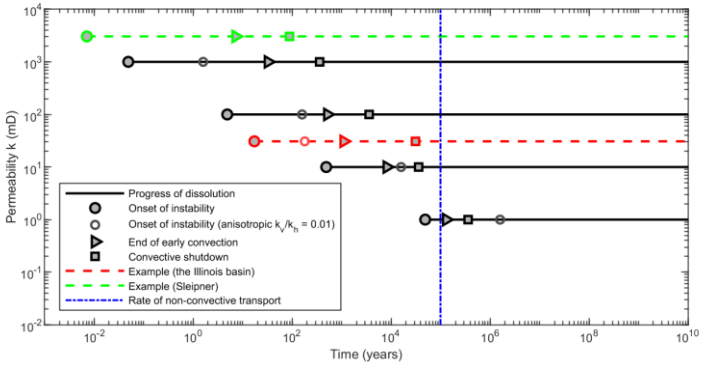
We develop a comprehensive theory to evaluate the long-term stability of residually trapped CO_2, paving the path for systematically evaluating the long-term reliability of CO_2 entrapment in CCS projects.

Research Details

- Hydrostatic pressure, geothermal gradients and capillary heterogen can create energy gradient to cause residual CO_2 thermodynamical unstable
- Thermodynamic potential gradients can induce diffusion to redistrib residual gas across the system while the gas phase remains trappe
- Timescales for gas redistribution (10^5 years/m) show that residual g can remain stable over periods relevant for CO_2 storage



Comparison between timelines of convective mixing and non-convective mixing



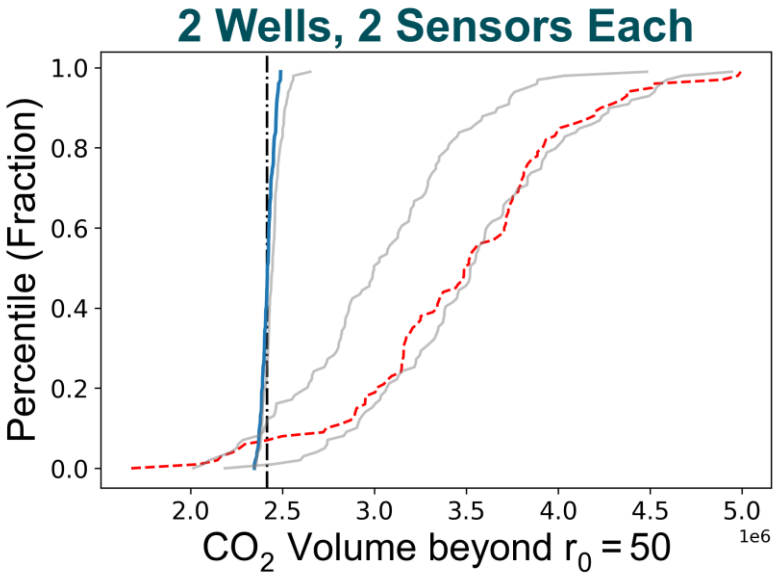
Optimal Monitoring for CO_2 Storage Projects

Scientific Achievement

We have developed a general workflow for optimizing pressure monitoring well locations used in CO_2 tracking.

Significance and Impact

This framework will contribute to permitting wells in the Illinois Storage Corridor for real CCUS projects.



Research Details

- Developed workflow to optimally place monitoring wells
- Current implementation utilizes a surrogate flow model (Gege Wen et al. 2020), but the framework is compatible with any simulator
- Demonstrated significant uncertainty reduction with CarbonSAFE base-case model using overall workflow

Dylan Crain, Sarah Saltzer, Sally Benson and Louis Durlofsky

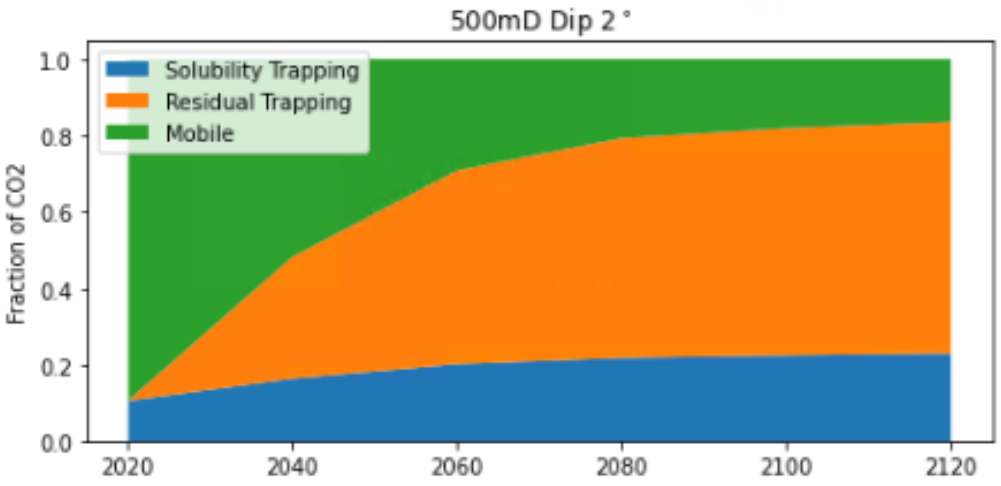
The Impact of Dip Angle on CO2 Storage in Saline Reservoirs

Scientific Achievement

Investigated the tradeoff between plume migration and secondary trapping for dipping saline reservoirs in particular the impact of dip angle and permeability

Significance and Impact

In homogeneous dipping saline reservoirs, a permeability of 500mD and a dip angle of greater than 1° will immobilize 20% after 100 years post-injection of the plume with less up-dip migration than higher permeabilities



Research Details

- A 3D model in CMG GEM with varying dip angle and permeability was used to investigate secondary trapping and plume migration in dipping saline reservoirs
- Capillary pressure and relative permeability hysteresis was included using the Land Trapping model and Brooks Corey relations to calculate the amount of residual and solubility trapping

Catherine Callas, Sally Benson, Tony Kovscek

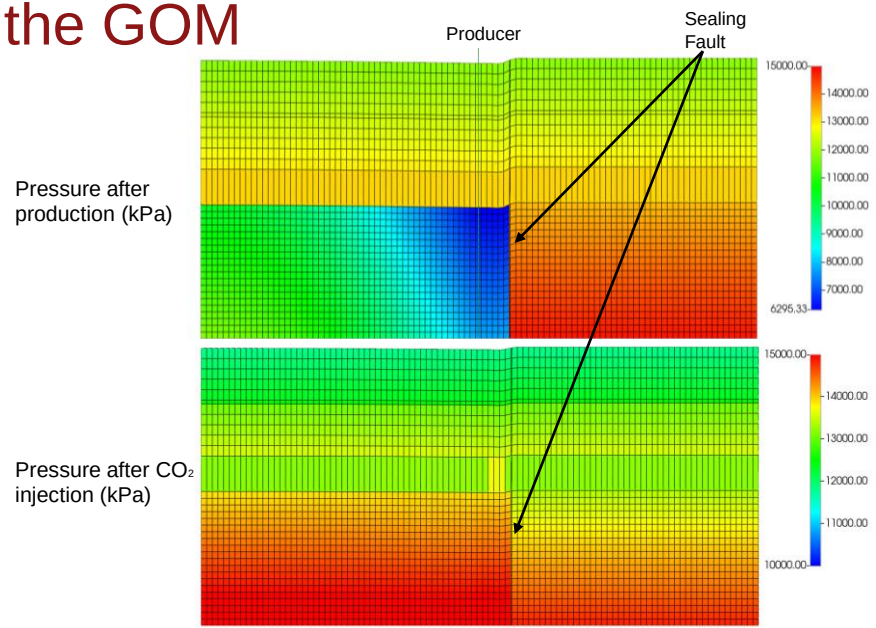
Numerical Investigation of Geomechanical Effects of Past Reservoir Depletion and Future CO_2 Injection in the GOM

Scientific Achievement

The process of reservoir depletion and CO_2 injection is being simulated to investigate the changes in geomechanical properties and assess the suitability of both depleted reservoirs and saline aquifers for CO_2 injection from a geomechanical perspective

Significance and Impact

Based on the stress, pore pressure and porosity changes during production, the numerical model helps to identify how stress and pore pressure change will occur during CO_2 injection in reservoirs



Research Details

- We evaluate potential storage scenarios in the Gulf of Mexico and develop coupled reservoir and geomechanics simulations to identify CO_2 storage potential and help defining the optimal injection strategy
- The Cam-Clay and Mohr-Coulomb failure criteria are used to investigate the reservoir compaction and dilation during production and CO_2 injection
- We have carried out several simulations in typical depleted reservoirs and saline aquifers and evaluated the pore pressure and stress changes adjacent to a fault due to production and CO_2 injection
- The distribution of CO_2 plume and pressure build-up near the caprock are identified and Barton-Bandis model is used to assess the possibility of CO_2 leakage in the caprock

Sam Hashemi, Mark Zoback

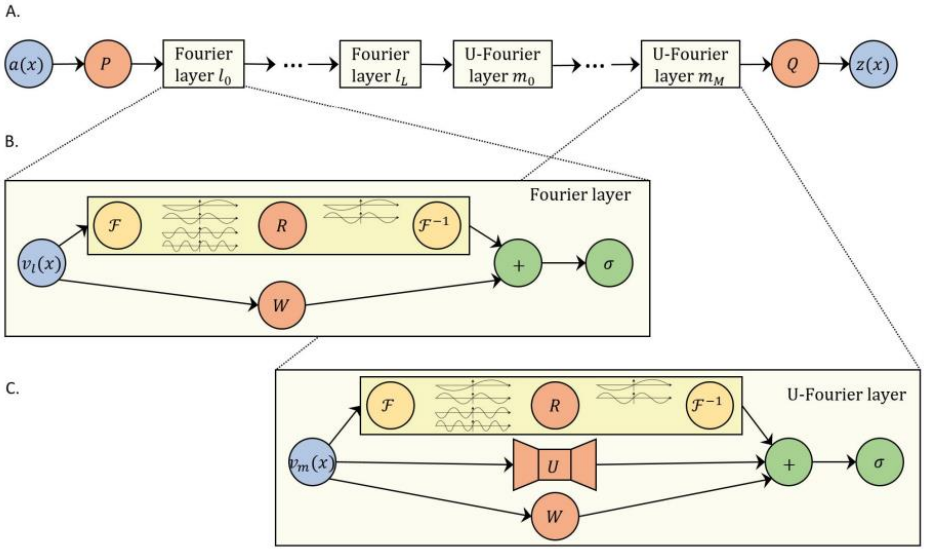
U-FNO - an enhanced Fourier neural operator based-deep learning model for multiphase flow

Scientific Achievement

Developed a Fourier neural operator based model of gas saturation and pressure buildup prediction for CO_2 storage.

Significance and Impact

The trained models can handle heterogeneous permeability, anisotropy, heterogeneous porosity, and many other reservoir conditions and parameters.



Research Details

- The U-FNO model is significantly more accurate in gas saturation predictions comparing to state-of-the-art CNN models
- The U-FNO model can handle high dimensional input-output mappings with a manageable amount of data since they are is less prone to overfitting
- The trained models can support CCSNet.ai with anisotropy and heterogeneous porosity.

Gege Wen, Zongyi Li, Kamyar Azizzadenesheli, Anima Anandkumar, Sally M. Benson