The possibility of causing felt seismic events because of CO$_2$ injection could be a “showstopper” to deploying large-scale CO$_2$ storage. A 2013 National Academy of Sciences report, *Induced Seismicity in Energy Technologies*, stated that “Given that the potential magnitude of an induced seismic event correlates strongly with the fault rupture area, which in turn relates to the magnitude of pore pressure change and the rock volume in which it exists, large-scale CCS may have the potential for causing significant induced seismicity.”

Based on the DOE Midterm Review and the GSCO2 Annual Review Meeting, the GSCO2 recognized its unique position to conduct research that will lead to better understanding of the mechanical and seismic properties of geologic formations that influence the occurrence of microseismicity.

This research consists of measuring and predicting mechanical properties of rocks and modeling (computational and laboratory) the transmission of energy through geologic formations as it relates to microseismicity induced by CO$_2$ injection and storage. The Center has a single overarching research question:

*What are the mechanisms of injection-induced microseismicity, and can we control and predict its occurrence?*

To effectively answer this question, the Executive Committee, identified five research themes (see insert) named Microseismicity, Geomechanical Measurements, Reservoir-scale Geology, Geochemical Reactions, and Pore-scale Pressure Transmission. In addition, researchers were added with expertise in measurements of mechanical properties of rocks at the pore and core scale and computational modeling of energy transmission through pore space and surrounding solid rock fabric (grains and cementation).

This research is based on the collective experience of the research team, including experience from the Illinois Basin–Decatur Project, the GSCO2’s deep subsurface observatory. Data and results from this observatory are used to test hypotheses and validate models. Because the measured and located microseismic events at the deep subsurface observatory are proximate to the injection well and perforated interval, the research plans are focused on the Lower Mt. Simon Sandstone (the injection interval), Argenta Formation (below the Mt. Simon), and Precambrian crystalline basement (below the Argenta). The Argenta and Precambrian are both believed to have joints present and possibly faults with modest offset.
Directing the Center for Geologic Storage of CO$_2$ within the guidelines and expectations of the Energy Frontier Research Center program is a unique experience. The program, which is sponsored by the US Department of Energy, Office of Science, Basic Energy Science division (DOE OS BES), has no explicit deliverables, unlike many other contracts. At a very high level, we are expected to collaborate, produce, and educate.

Collaborative research begins at the grass-root level. There is a keen distinction between “working together” and collaborating. The EFRC program expects collaboration to be a symbiotic relationship between researchers—that is, researchers must be involved with all aspects of each other’s work, from designing experiments to interpreting results. “Working together” is described when researchers work autonomously but their results are shared with each other and are integral to each other’s research. This has been described as “handing off” to each other, which is much less desirable to the EFRC program compared to collaboration.

Doctoral students and postdoctoral scholars are integral to the research plan. We educate the next generation of scientists by providing unique and meaningful experiences for these students and scholars. They are able to contribute to the scientific community through publications, build skills and knowledge in their respective disciplines, and network with fellow researchers from other institutes. We track our alumni’s post-GSCO2 accomplishments in academia, government, and industry.

Publications with multi-institute co-authors are the ultimate product of collaborative research. The EFRC program gauges productivity by quantity and quality of high-impact, peer-reviewed journal publications. Research that results in single-institute publications should be minimized under the auspices of the EFRC program.

The Center’s organizational structure is designed to meet the program’s expectations. We have five themes that consist of 16 principal investigators, 11 PhD students, and six postdoctoral scholars. Three to five institutes are represented in each theme. The members of each theme collaborated in developing their research plans so that the subsequent research completed collaboratively leads to multi-institute publications.

Because the EFRC program focuses on basic research, GSCO2 research must not be applied; however, use-inspired basic research is intended to lead to a solution to a specific observed problem. Observations during the injection of CO$_2$ at the Illinois Basin–Decatur Project were instrumental in identifying the new areas of research: microseismicity and mechanical properties of rocks. Nevertheless, the GSCO2’s basic research contributes to the DOE OS BES Grand Challenge: How do we characterize and control matter away—especially very far away—from equilibrium?

Results from our external review identified and subsequently recommended that mechanical properties of rocks and the associated microseismicity as our sole research focus. The possibility of seismic events occurring as a consequence of large-scale CO$_2$ injection is finite. Recent seismic activity due to water injection in basal sands makes this a potential show-stopper for CO$_2$ storage. Basic research that leads to technologies that can characterize mechanical properties of the geological subsurface and control and predict the occurrence of injection-induced seismicity can address one of the commercial challenges to CO$_2$ storage.

Scott


**New Researchers**

*Dr. Ange-Therese Akono* is an assistant professor in the Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign (UIUC). Dr. Akono is also an affiliate faculty in the Department of Mechanical Science and Engineering and a faculty fellow at the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign. Dr. Akono’s research investigates fracture and failure mechanisms in complex materials systems from the molecular level up to the macroscopic scale.

*Dr. Alexey Bezryadin* is a professor in the Department of Physics at the UIUC. His current research is in three critical and related areas of the physics of low-dimensional nanoscale systems: quantum superconductor-insulator transitions in one-dimensional superconductors; electronic properties of DNA molecules; and Aharonov-Bohm effects in carbon nanotubes.

*Dr. Jennifer Druhan* is an assistant professor in the Department of Geology at the UIUC. She is a long-time associate of the Lawrence Berkeley National Laboratory and collaborates with Earth Science Division scientists in development and application of reactive transport software. Her research focuses on the relationship between physical structure and chemical reactivity in aquifers.

*Dr. Ahmed Elbanna* is an assistant professor in the Department of Civil and Environmental Engineering at the UIUC. His research focuses on developing computational and analytical models for complex material behavior such as friction, adhesion, fracture, and viscoplasticity, and elucidating the implications of these phenomena, in lieu of other microstructural geometric features, on fracture toughness and optimality in multiscale systems.

*Dr. Roman Makhnenko* is a postdoctoral researcher and lecturer at the Swiss Federal Institute of Technology in Lausanne (EPFL, Switzerland) from 2013–2016, who will be joining the UIUC in the fall of 2016. His current research is related to assessing geological storage of CO$_2$, including thermo-hydro-mechanical and petrophysical characterization of possible host rock (sandstones and limestones) and caprock (shales) in contact with high-pressure CO$_2$.

*Dr. John S. Popovics* is a professor in the Department of Civil and Environmental Engineering (CEE) at the UIUC and also holds the title of CEE Excellence Scholar. He has been recognized as a Fellow of the American Concrete Institute and the American Society for Nondestructive Testing. His research investigates testing, analysis, and novel measurements for infrastructure and geologic materials.

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**Image of the Issue: Micro-CT scans of core samples after triaxial loading**

Reconstruction from micro-CT scans of a Castlegate outcrop plug (left) and a Mt. Simon Sandstone core plug (right), after testing in a triaxial load frame. During testing, a weak fracture plane was created intentionally by increasing differential applied stress past the shear strength of each plug, and then the axial stress was reduced and pore fluid pressure was increased. Though the pressure reduction in the last step was larger compared to the initial stress increase, it still caused large shear deformation accompanied by intense acoustic emission events. The red dots highlight areas with significantly higher porosity as measured by X-ray absorption. After segmenting the absorption data, background porosity was removed to leave only the areas with porosity or void volumes above the threshold value. The ensemble of red dots shows the obtained shear failure plane, confirming localization by acoustic emissions. The interbedded layers in the core on the right have either high porosity or contrasting mineral content. The green zone within the Mt. Simon plug indicates a second fracture plane at a different angle. The plugs are 1.5 in. in diameter and 3 in. long.

Image credit: Dr. Pierre Cerasi, SINTEF.
The new GSCO2 organizational structure consists of groups of researchers that collaborated to draft the technical responses that form the teams for each theme. These small multi-institute teams will ensure that this focused, collaborative research leads to multi-institute publications.

The Director recruited leaders for each question and new GSCO2 researchers. These leaders held 1-hour kickoff meetings to develop ideas for a technical response to their respective question, and all new and existing GSCO2 researchers were invited to the meetings. Smaller groups of researchers who had interest in a specific question collaborated through follow-up meetings and email exchanges to draft their technical response, which was submitted to the Director.

In addition, the Center added the position of Associate Director, who will assist the Director with issues and challenges related to the functionality of the Center, such as staff effectiveness and reallocating resources to pursue new, promising research directions. The Associate Director is a member of the Executive Committee, which includes the Director and theme leaders.

Dr. Edward Mehnert, a geohydrologist at the Illinois State Geological Survey, served as the first Associate Director. Dr. Mehnert was the Multiphysics Flow and Transport Theme Coordinator and member of the Executive Committee for the past two years. He retired at the end of December 2016. The GSCO2 staff thanks him for the time, commitment, and knowledge he gave to the Center. Dr. Steve Whittaker, Director of Energy Research and Development at the Illinois State Geological Survey, assumed the role of GSCO2 Associate Director on January 1.

The GSCO2 also added four doctoral students and two postdoctoral researchers. These new students and post-docs bring the total number of students, post-docs, and early career professionals in the Center to 25.

### GSCO2 by the Numbers
- 29 senior/key personnel
- 16 principal investigators
- 20 post-docs and students
- 5 early career professionals
- 11 partner institutions

![Organizational Structure Diagram]

Dr. Edward Mehnert, the first Associate Director, who retired at the end of 2016. Photo credit: Joel Dexter, ISGS.
Research Themes

Geomechanical Measurements
How can measurements of geomechanical properties at pore and core scales be improved?
Completing coordinated but distinct laboratory-scale experiments focusing on characterization of thermo-hydro-mechanical properties of rock will provide improved measurement capability and further enable the linkage of important reservoir material behavior processes, specifically injection-induced microseismicity, across the pore and core scales. New (X-ray CT scanning, advanced ultrasonics) and conventional (electrical resistivity) experimental measurement methods will be used.

Microseismicity
How can the links between injection-induced microseismicity and the stress field be unravelled?
Small, critically stressed fractures that are distributed in clusters with variable orientation are triggered to slip as a response to small changes in the in-situ stress field, associated with minor increases in pore pressure. By injecting fluids at low pressures, artificial fractures will be tested for slip. Computational experiments will be conducted to understand the effect of pressure propagation at the continuum scale to cause microseismicity in small clusters as a consequence of very low pore pressure increases.

Geochemical Reactions
In the presence of specific geologic attributes/features, how do CO$_2$ and brine mixtures affect the geomechanical and seismic properties of rocks?
Geochemical reactions promoted by CO$_2$ alter the stress field and reduce mineral strength along grain boundaries, thus promoting fracture propagation. Similar cores will be characterized, exposed to CO$_2$-saturated brine, and then evaluated for changes in mineralogy, rock mechanical properties, and fracturing. Nanoindentation, sliding friction, and scratch tests will be used on rock samples with pre- and post-exposure to CO$_2$-saturated brine.

Reservoir-scale Geology
How do reservoir-scale geologic features relate to geomechanical and seismic properties of rocks?
A nexus of new research on geologic architecture, new approaches for relating geomechanical properties and seismic velocities to geologic facies, and new research on depositional-based approaches to simulating geologic facies will lead to significant advances in modeling three-dimensional spatial variation in geomechanical properties and seismic velocities. The contact between the basal sedimentary rocks and underlying crystalline basement (igneous, metamorphic, or both) will be studied.

Pore-scale Pressure Transmission
How do pore fluid pressure fluctuations transmit in, and affect the state of, porous and fractured media?
Modeling coupled stress, strain, and multiphase flow processes that induce microseismicity must have pore-scale geologic heterogeneity represented. Realistic geologic heterogeneity of flow paths and solid skeleton can lead to localized increase in pore pressure, leading to localized failure of the solid skeleton or slippage of pre-existing cracks across all scales, thus inducing microseismic events. Models of pore-scale heterogeneity will be developed based on high-resolution CT scans of rock core.

Xiao Ma, MS
PhD student
Theme: Pore-scale Pressure Transmission
Xiao Ma is a PhD student in the Civil Engineering Department at the University of Illinois at Urbana-Champaign under the supervision of Dr. Ahmed Elbanna. He earned his bachelor’s degree from Jilin University, China, and an MS in civil engineering from the UIUC. His research focuses on modeling solid amorphous material and earthquake mechanics.
Textural factors affect the variance of petrophysical properties in a sedimentary reservoir

Understanding the relationships between sedimentary architecture in geologic formations and the variation in petrophysical attributes provides a better evaluation of how injected CO₂ migrates through a reservoir. Dr. Robert Ritzi (Wright State Univ.), Jared Freiburg, and Nathan Webb (UIUC) have published a paper that provides a hierarchical analysis of textural factors affecting the sample variance of petrophysical attributes in a sedimentary reservoir. This analysis allows for a useful, simple, and straightforward quantitative description of how a sample (co)variance arises from a hierarchy of textural factors of the reservoir rock, such as depth, grain size, bedding, and bleaching alteration.

The authors used a data set from the deep subsurface observatory, where CO₂ was injected into a saline geologic formation with sedimentary architecture. The results quantify the magnitude that each textural factor contributes to the (co)variance, and thus clarify each textural factor’s relative contribution within the hierarchy. These results provide a basic understanding of how the sample (co)variance arises within sedimentary architecture and which factors are important in defining it. The quantitative analysis of textural factors contribution to (co)variance aids in the development of an efficient textural-facies based system for modeling petrophysical attributes within reservoir modeling workflow.


Differences in physical systems affect CO₂ plumes in deep saline reservoirs

Drs. Naum Gershenzon, Robert Ritzi Jr., David Dominic, Mohamadreza Soltanian (Wright State University), Edward Mehnert, and Roland Okwen (UIUC) have published a paper that compares Brooks-Corey- and van Genuchten-type capillary pressure curves when heterogeneity and hysteresis are represented. For example, the Brooks–Corey-type capillary pressure curves represent heterogeneity in capillary entry pressures; CO₂ is trapped by capillary pinning. In the van Genuchten-type capillary pressure curves, however, capillary entry pressure is negligible, but the way in which the method simulates a connected pore-pathway slows the spread of CO₂. The authors demonstrate how the differences in physical systems represented by these capillary pressure curve types, at the small scale, ultimately affect the mass, shape, and position of CO₂ plumes at the large scale. For example, in their simulations, mobile CO₂ eventually reached the caprock when using van Genuchten-type capillary pressure curves but never reached the caprock when using Brooks-Corey-type capillary pressure curves.

This work builds on a 2015 paper titled “Influence of small-scale, fluvial, sedimentary architecture on CO₂ trapping processes in deep saline aquifers,” which demonstrated the importance of representing the heterogeneity of small-scale features in saturation functions, as well as the hysteresis in those saturation functions, when simulating capillary trapping processes in CO₂ storage reservoirs.


Variation in bedforms and grain sizes in braided fluvial deposits in the Lamotte Sandstone (equivalent to the Mt. Simon Sandstone) at Pickle Springs Natural Area in Missouri. Charles Monson and Ruisong Zhou are studying depositional facies characteristics and distribution (particularly with respect to Precambrian basement highs) in the Lamotte to help inform geologic facies simulation in the Mt. Simon and the underlying Argenta Formation. Photo credit: Charles Monson, UIUC.
Annually, the GSCO2 has an external review by the Center Science Advisory Council (CSAC) and Center Industry Advisory Board (CIAB). The CSAC consists of university professors and scientists of national laboratories with expertise in various aspects of each research theme but not necessarily specific to the geologic storage of CO$_2$. The CIAB represents natural gas storage, oil and gas industry (upstream services and consulting), and utilities. Their purpose is to provide advice to the Director and Executive Committee with regards to areas of research, research accomplishments, and relevance and usefulness of research.

Center research integrates the basic and applied science expertise of researchers from academic institutions, research organizations, and industry, which provides a “technological pull” rather than the “scientific push” described in the US Department of Energy’s 2010 report titled *Science for Energy Technology: Strengthening the Link between Basic Research and Industry*. Basic-science results from the themes will contribute to developing deployable technology that achieves the central theme of the Center: use-inspired basic research. Because basic-science research is the root of each theme, there is risk present that this research will not lead to industry-ready technology. To ensure the Center’s research leads to industry deployable technology, the two advisory boards represent the nexus of science and industry.

### GSCO2 Advisory Committees

#### Center Industry Advisory Board

<table>
<thead>
<tr>
<th>Name</th>
<th>Company/Institution</th>
<th>Title</th>
<th>Term of Service</th>
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<tbody>
<tr>
<td>Charles Christopher</td>
<td>CO$_2$ Store</td>
<td>CO$_2$ Geological Storage Consultant</td>
<td>2014–2018</td>
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<tr>
<td>Tom Davis</td>
<td>WEC Energy Group</td>
<td>Supervisor, Petroleum Engineering Consultant</td>
<td>2014–2018</td>
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<tr>
<td>Albert Giussani</td>
<td>Oxy</td>
<td>Reservoir Engineer</td>
<td>2015–2017</td>
</tr>
<tr>
<td>George Koperna</td>
<td>Advanced Resources International</td>
<td>Vice President</td>
<td>2014–2018</td>
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<tr>
<td>Ian Lunt</td>
<td>Statoil</td>
<td>Principal Geologist</td>
<td>2015–2017</td>
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<td>Yongqi Lu</td>
<td>Univ. of Illinois at Urbana-Champaign</td>
<td>Chemical/Environmental Engineer</td>
<td>2014–2018</td>
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<td>Shawn Maxwell</td>
<td>ITASCA-IMaGE</td>
<td>President/CTO</td>
<td>2014–2018</td>
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<tr>
<td>Carl Sisk</td>
<td>Ingrain</td>
<td>Chief Reservoir Engineer</td>
<td>2015–2017</td>
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<td>Rob Trautz</td>
<td>Electric Power Research Institute</td>
<td>Principal Technical Leader</td>
<td>2014–2018</td>
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<tr>
<td>Robert (Bo) Tye</td>
<td>DeGolyer and MacNaughton</td>
<td>Vice President, Geological Advisor</td>
<td>2014–2018</td>
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#### Center Science Advisory Council

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<tr>
<td>Donald DePaolo</td>
<td>Lawrence Berkeley National Lab.</td>
<td>Assoc. Lab. Dir. for Energy Sciences; Prof. and Isotopic Geochemist</td>
<td>2014–2018</td>
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<td>Neeraj Gupta</td>
<td>Battelle Memorial Institute</td>
<td>Senior Research Leader</td>
<td>2014–2018</td>
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<tr>
<td>George Guthrie</td>
<td>Los Alamos National Laboratory</td>
<td>Program Manager for Applied Energy</td>
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<td>Thomas Johnson</td>
<td>Univ. of Illinois at Urbana-Champaign</td>
<td>Prof. and Head of Department of Geology</td>
<td>2015–2017</td>
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<td>Young Shin Jun</td>
<td>Washington University in St. Louis</td>
<td>Assoc. Prof. in the Depart. of Energy, Environmental, and Chemical Eng.</td>
<td>2014–2018</td>
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<td>Larry Lake</td>
<td>University of Texas at Austin</td>
<td>Prof., Petroleum and Geosystems Eng.; Dir., Center for Frontiers of Subsurface Energy Security</td>
<td>2014–2018</td>
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<td>John McBride</td>
<td>Brigham Young University</td>
<td>Prof. and Chair, Department of Geological Studies</td>
<td>2014–2018</td>
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<td>Henrique Reis</td>
<td>Univ. of Illinois at Urbana-Champaign</td>
<td>Prof. Departments of Industrial and Enterprise Systems Eng. and of Civil and Environmental Eng.</td>
<td>2014–2018</td>
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<td>Dorthe Wildenschild</td>
<td>Oregon State University</td>
<td>Prof., School of Chemical, Biological and Environmental Engineering</td>
<td>2014–2018</td>
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<tr>
<td>Lesli Wood</td>
<td>Colorado School of Mines</td>
<td>Endowed Chair Prof., Geology and Geological Eng.</td>
<td>2014–2018</td>
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</table>
Who is the GSCO2?

Senior/Key Personnel

- Ange-Therese Akono
- Calvin Barnes
- Melanie Barnes
- Robert Bauer
- James Best
- Alexey Bezryadin
- Pierre Cerasi
- Kenneth Christensen
- Dustin Crandall
- David Dominic
- Jennifer Druhan
- Ahmed Elbanna
- Scott Frailey
- Naum Gershenzon
- Bettina Goertz-Allmann
- Angela Goodman

Postdoctoral Scholars and Students

- Sahar Bakhshian
- Peter Berger
- Gianluca Blois
- Yu Chen
- Laura Dalton
- James Damico
- Hassan Dashtian
- Gabriela Dávila
- Jared Freiburg
- Samantha Fuchs
- Ahmed Ghareeb
- Ritu Ghose
- Setare Hajarolasvadi
- Pooyan Kabir

Partner Institutions

- Illinois State Geological Survey
- University of Illinois at Urbana-Champaign
- Wright State University
- University of Notre Dame
- NORSAR

- Kristian Jessen
- Michael Jordan
- Roman Makhnenko
- Stephen Marshak
- Edward Mehnert
- Roland Okwen
- Volker Oye
- John Popovics
- Robert Ritzi
- Muhammad Sahimi
- Sergey Stanchits
- Dustin Sweet
- Paul Sylvester
- Theodore Tsotsis
- Albert Valocchi
- Charles Werth
- Steve Whittaker
- Amir Kohanpur
- Nadège Langet
- Yaofa Li
- Xiaojun Ma
- Kavya Mendu
- Charles Monson
- Jami Moore
- Mahsa Rahromostaghim
- Arjan Reesink
- Zhuo Fan Shi
- Ali Tarokh
- Mary Tkach
- Ruisong Zhou

Portrait in a Paragraph

Ange-Therese Akono, PhD
Principal Investigator in the GSCO2
Theme: Geochemical Reactions

Dr. Ange-Therese Akono holds a PhD (2013) and an MSc (2011) from the Massachusetts Institute of Technology (United States), along with an MSc (2009) from the École Polytechnique (France). Dr. Akono’s honors include the ASCE New Faces of Civil Engineering Professionals Award (UIUC, 2016), the ASCE nomination for the DiscoverE New Faces of Engineering Award (UIUC, 2016), the Academy for Excellence in Engineering Education Collins Fellowship (UIUC, 2015), and the MIT Energy Initiative Fellowship (MIT, 2009). Dr. Akono’s laboratory investigates fracture and failure mechanisms in complex materials systems from the molecular level up to the macroscopic scale. This research is articulated over three main thrusts: environment-friendly and high-performance structural materials, natural and nano-engineered biomaterials, and geological materials such as shale or rock. Dr. Akono’s areas of expertise include nanomechanics, fracture analysis, nanotechnology, advanced experimental testing, and multiscale modeling.

Contact: dklen2@illinois.edu