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Seismic Contrast Agents for CO_2 Monitoring

New Imaging and CO_2 Storage Technologies for Unconventional Subsurface Reservoirs

Project 70066

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Management Project Review Meeting
August 5-9, 2024
Carbon Transport and Storage
2:15 p.m. - 2:40 p.m.

Quin R.S. Miller

Photo: Andrea Starr (PNNL

U.S. DEPARTMENT OF ENERGY BATTELLE

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Key Takeaways

- Nanofluid injectates can operate at seismic frequencies and be multimodal contrast agents for far- and near-field/wellbore monitoring
- This technology works with established, conventional, seismic and other geophysical monitoring approaches.
- Disruptive approach to tracking subsurface CO_2 catalyzed by new metamaterial insights
- We can tailor colloid surface chemistry to control transport and strategic deposition in different environments
- Early career scientist and student mentoring is a key component of our subsurface portfolio
- **Enhanced monitoring with functional injectates will be used to help accelerate commercial-scale carbon storage**

Presentation Outline

- Goals and Objectives
- Project Overview
- Technical Discussion
- Accomplishments to Date
- Synergy Opportunities
- Project Summary

Project Overview

Goals and Objectives

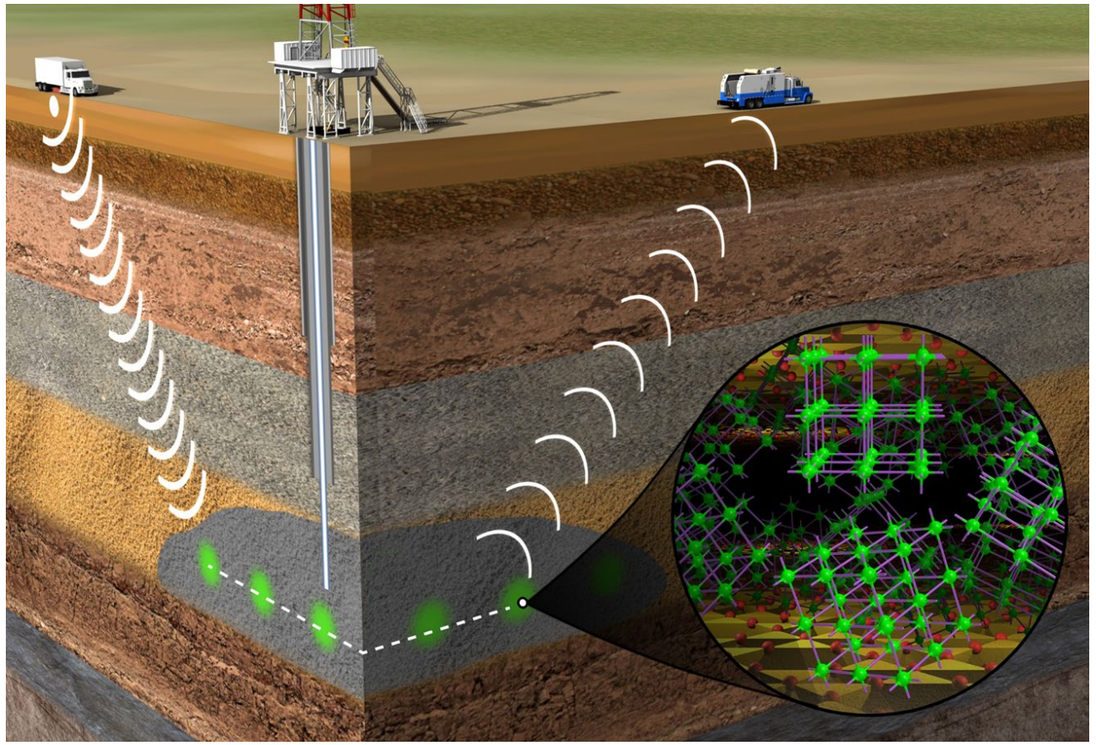
- The purpose of this project is to support NETL and the Office of Fossil Energy to develop technologies that efficiently and effectively characterize engineered subsurface systems. The proposed work aims to advance a new class of acoustically-responsive and injectable contrast monitoring agents that are specifically engineered for 1) mapping fracture networks associated with energy extraction processes, 2) improved delineation of storage reservoirs in multi-scale complex subsurface geological systems, and 3) enhancement of current near/far-field geophysical monitoring technologies.

Enhanced Contrast Agents for CO_2 Monitoring

Problem Statement: Current monitoring techniques for detecting and surveying injected CO_2, other fluid mixtures, and fracture networks suffer from low detection sensitivity and limited volumetric resolution

- Engineering functional material injectates for subsurface implementation
- Dispersion of injectates in formation water to form colloidal suspensions
- Detection through conventional seismic imaging

Goal: Develop contrast agents for enhanced time-resolved monitoring/mapping of subsurface fluids and structures, including injected CO_2



PNNL Carbon Mineralization Team is Working to Advance Low-Carbon Technologies and Accelerate Development of Commercial-Scale Solutions

Quin Miller
Carbon Mineralization
Geochemist

Emily Nienhuis
Fluid-Rock Interactions
Chemist/PI

Nabajit Lahiri
DAC and Carbon Storage
Geochemist

Stephanie DiRaddo
Class VI Permitting
Geologist

Matt Villante
CDR/Mineralization
Geologist

Seunghwan Baek
Reservoir Modeling
Reservoir Engineer

Katie Muller
Reservoir Modeling
Environmental Engineer

Janie Vickerman
Contracting and
Project Management

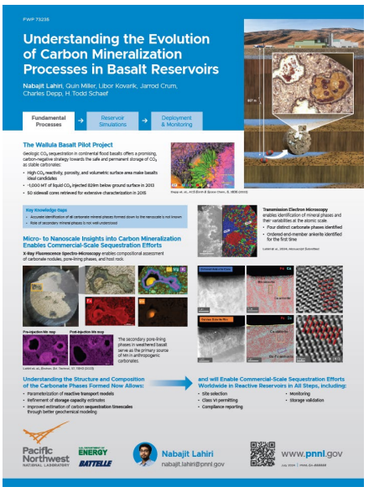
Ross Cao
Carbon Storage
Geologist

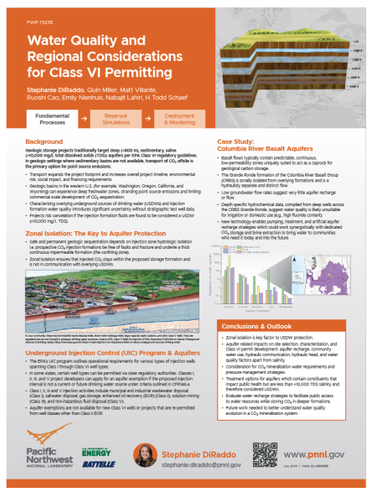
Heath Stanfield
Geochemist

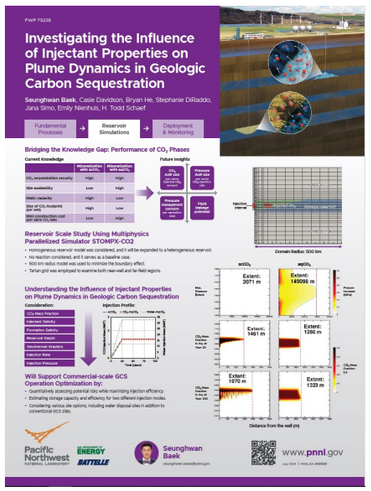
Casie Davidson
FECM Manager
Economic Geologist

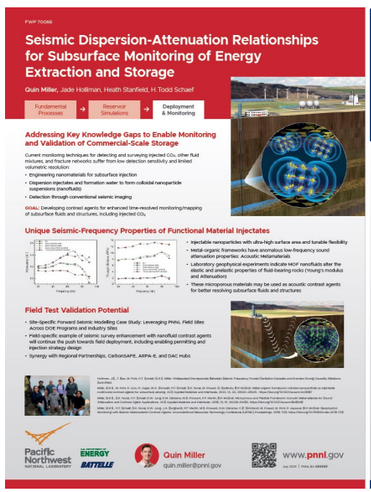
Todd Schaef
Chief Scientist

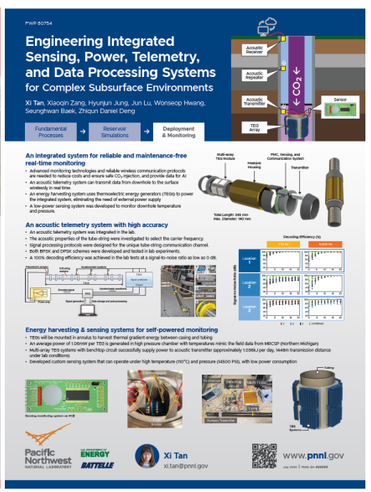
Carbon Mineralization Research Portfolio at PNNL connects Fundamental Processes to Field Scale Deployment

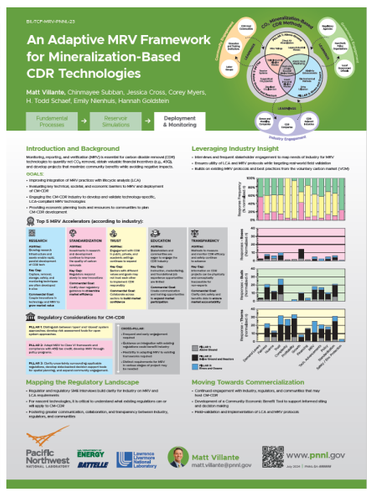












Pore-scale to nanoscale studies inform molecular mechanisms of carbonate nucleation and growth

Reactive Transport Simulations help derisk permitting and deployment of carbon storage at the field scale

Advanced **subsurface monitoring** and **deployment** technologies enable commercial-scale carbon sequestration in reactive reservoirs, including community and stakeholder engagement

Posters in the Ballroom Gallery and Available Online

Early Career Contributions Driving Low-Carbon Technology Advances

Maddie Bartels (SULI)

Madeline Murchland (MLEF)

Ellen Polites (MLEF/SCGSR)

Arianna Morfin (CCI)

Heath Stanfield (SULI)

Charlie Depp (SULI)

Jade Holliman (MSIPP/GEM)

Julian Stapper
Visiting PhD Student

Prof. Briana Aguila (VFP)

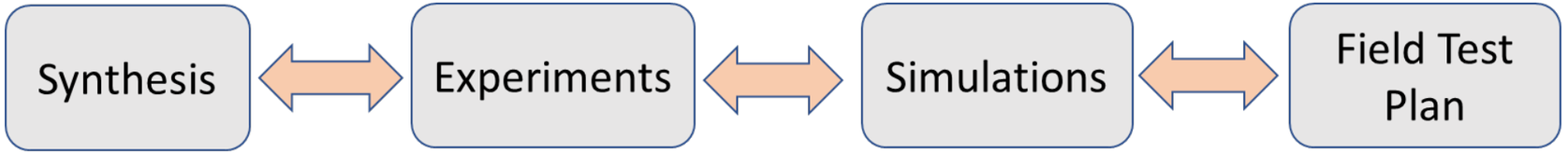
Landon Hardee (VFP)

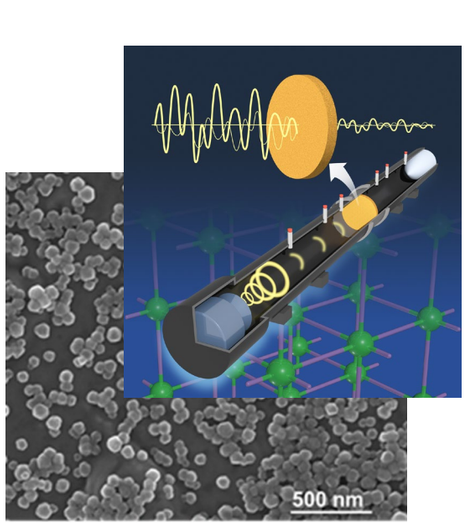
Joey Jacobs (ARPA-E)

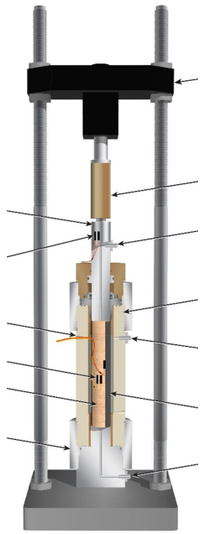
- Outreach and community engagement are keystones of our program
- Early career researchers include interns, postdocs, staff, visitors
- Product-driven research experience cultivates and unleashes talent
- Diversity and inclusion enables innovation and creativity, breadth of perspectives needed for global challenges

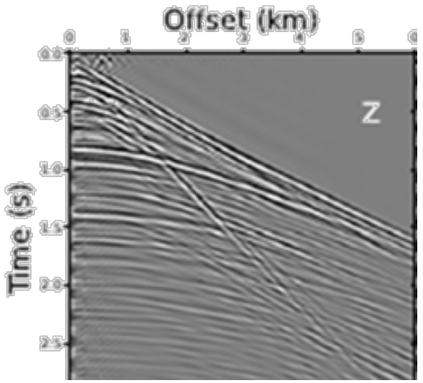
Innovation Enabled by Interconnected and Interdisciplinary Tasks

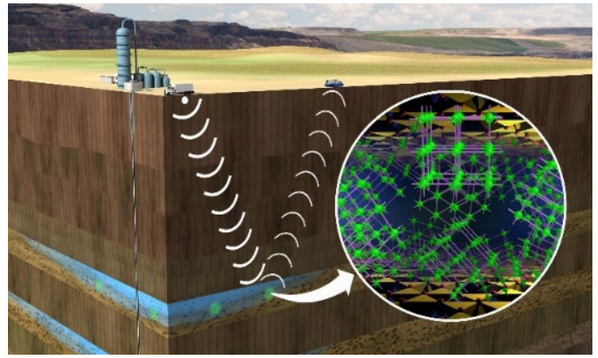
- Task 1 Synthesis and Stability Testing
- Task 2 Laboratory-Based Core Test Experiments
- Task 3 Predictive Seismic Simulations
- Task 4 Field Test Plan Development









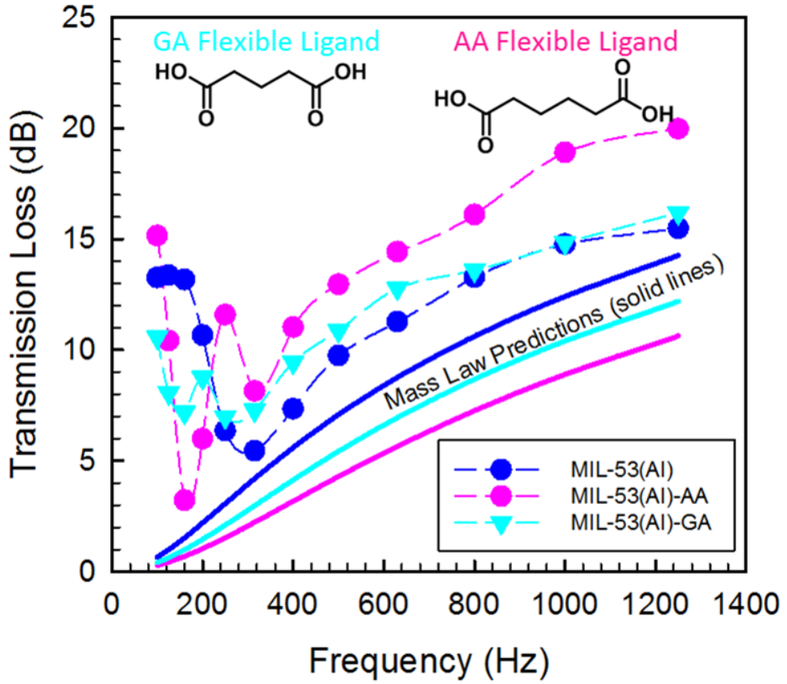


Injectable Acoustic Metamaterials Influence Elastic/Anelastic Properties of Rocks

Applications/Significance/Novelty

Our functional material fluid approach enhances conventional seismic monitoring by substantially altering the velocity *and* amplitude of low-frequency waves

- Injectable materials with ultra-high surface area and tunable flexibility
- Metal-organic frameworks have anomalous low-frequency sound attenuation properties: Acoustic Metamaterials

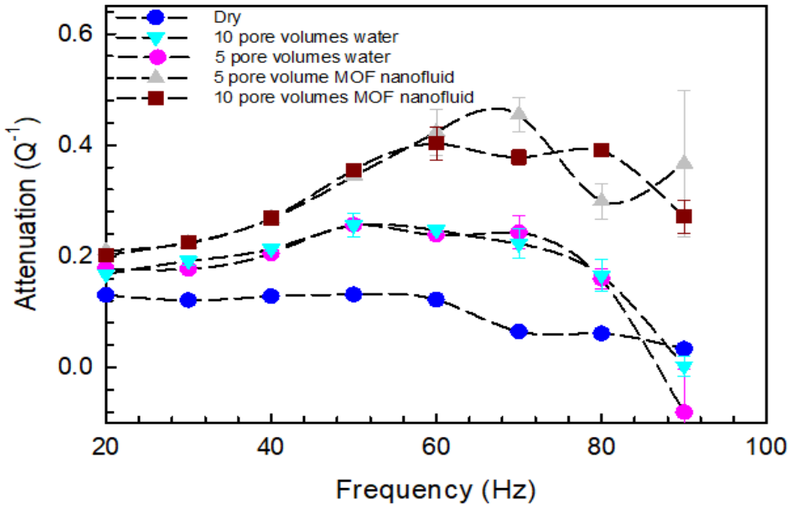


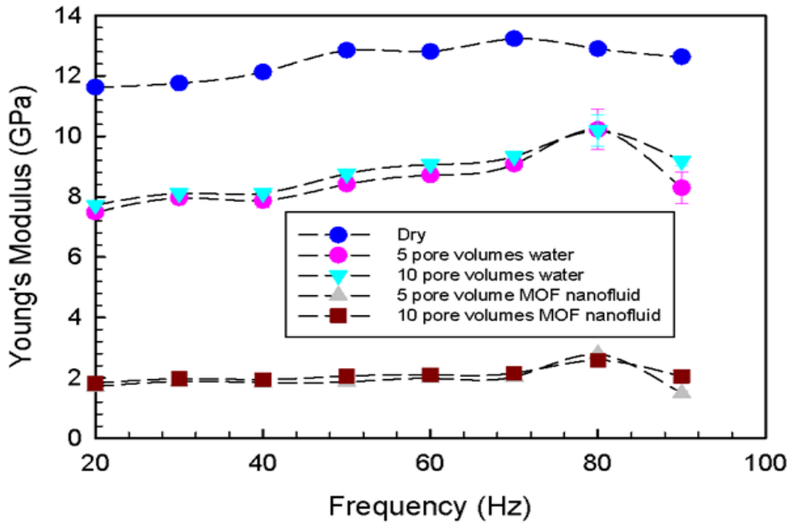
ACS APPLIED MATERIALS & INTERFACES Letter
Cite This: *ACS Appl. Mater. Interfaces* 2018, 10, 44226−44230 www.acsami.org

Microporous and Flexible Framework Acoustic Metamaterials for Sound Attenuation and Contrast Agent Applications

Quin R. S. Miller,[*,†] Satish K. Nune,[‡] H. Todd Schaef,[†] Ki Won Jung,[‡,§] Kayte M. Denslow,[⊥] Matthew S. Prowant,[⊥] Paul F. Martin,[‡] and B. Peter McGrail[‡]

Injectable Acoustic Metamaterials Influence Elastic/Anelastic Properties of Rocks





- Injectable materials with ultra-high surface area and tunable flexibility
- Metal-organic frameworks have anomalous low-frequency sound attenuation properties: Acoustic Metamaterials
- Laboratory geophysical experiments indicate injectates alter the elastic and anelastic properties of fluid-bearing rocks (Young's modulus and Attenuation)
- These microporous materials may be used as acoustic contrast agents for better resolving subsurface fluids and structures

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Available online at www.sciencedirect.com — ScienceDirect — Energy Procedia
13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland

Injectable Contrast Agents for Enhanced Subsurface Mapping and Monitoring

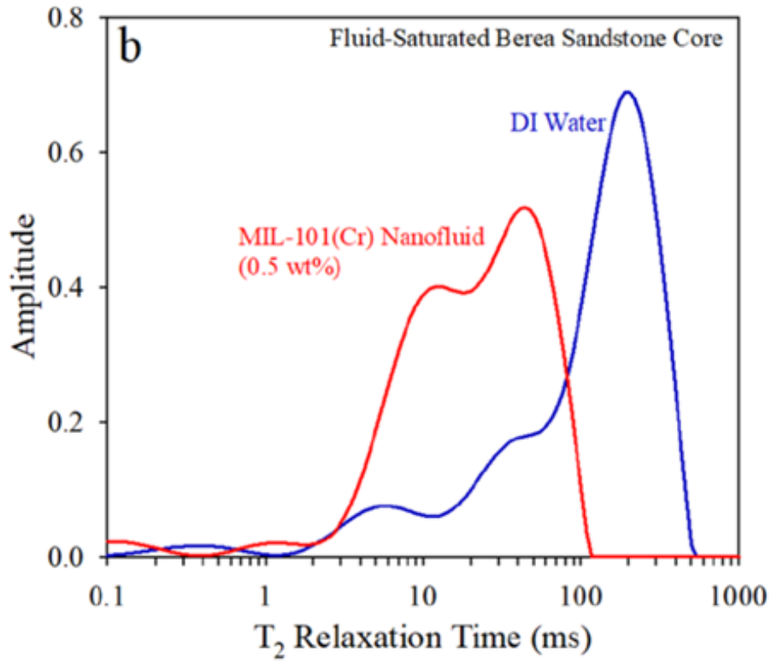
H. Todd Schaef*, Chris E. Strickland, Ki W. Jung, Paul F. Martin, Satish K. Nune, John S. Loring, and B. Peter McGrail
Pacific Northwest National Laboratory, P. O. Box 999, Richland, Washington 99352

UNCONVENTIONAL RESOURCES TECHNOLOGY CONFERENCE

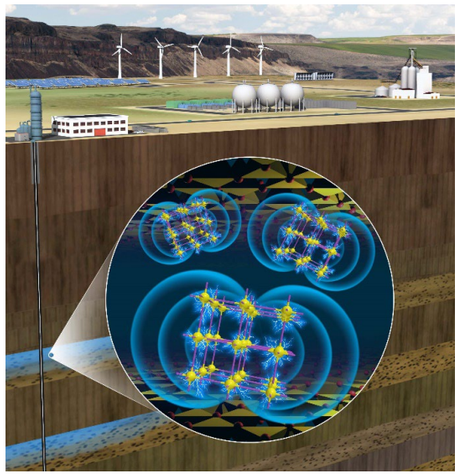
Geophysical Monitoring with Seismic Metamaterial Contrast Agents

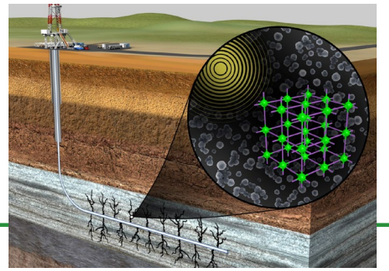
Quin R. S. Miller*[1], H. Todd Schaef[1], Satish K. Nune[1], Ki Won Jung[1], Jeffrey A. Burghardt[1], Paul F. Martin[1], Matthew S. Prowant[1], Kayte M. Denslow[1], Chris E. Strickland[1], Manika Prasad[2], Mathias Pohl[2], Piyoosh Jaysaval[1], and B. Peter McGrail[1];
1. Pacific Northwest National Laboratory, 2. Colorado School of Mines

Seismic Contrast Agent Injectates also Influence Near-Wellbore Geophysical Signatures



- Injectates also exhibit distinct NMR and electrical signatures
- Three prototypical MOFs investigated
- Multimodal signatures complement the seismic contrast agent application with monitoring of near-wellbore processes
- Key result involved NMR measurements of contrast agent fluids in Berea sandstone core
- Manuscript co-lead by PNNL and CSM (Pohl, Livo, Prasad)





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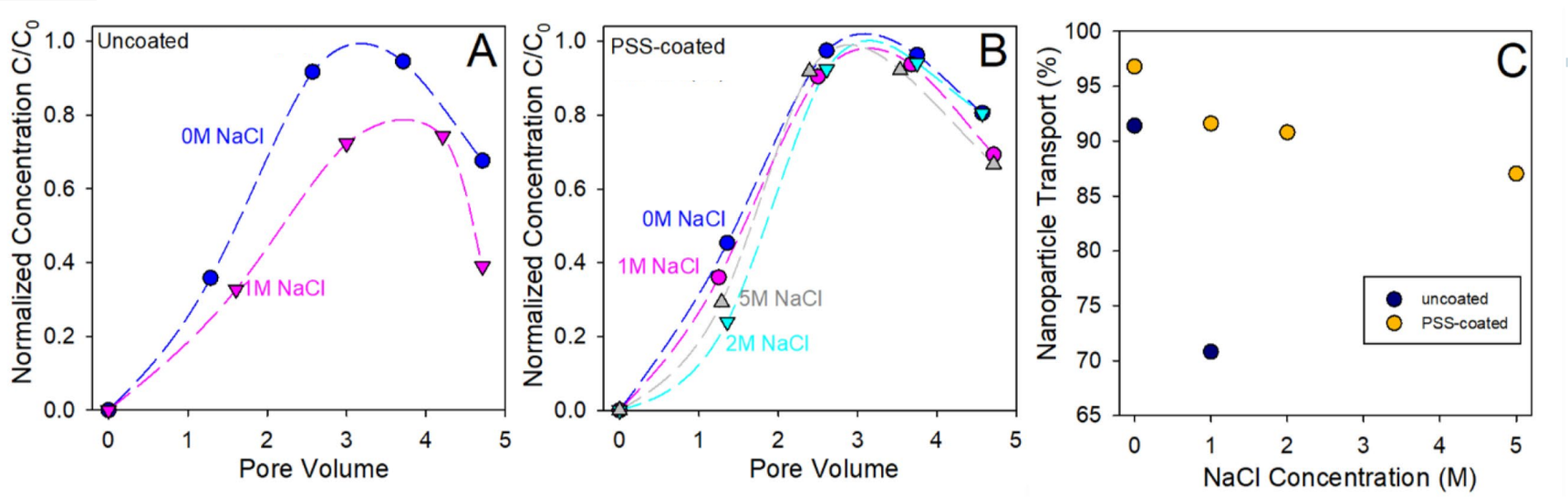
Research Article

Porous Colloidal Nanoparticles as Injectable Multimodal Contrast Agents for Enhanced Geophysical Sensing

Quin R. S. Miller,* Mathias Pohl,* Kurt Livo, Hassnain Asgar, Satish K. Nune, Michael A. Sinnwell, Manika Prasad, Greeshma Gadikota, B. Peter McGrail, and H. Todd Schaef

Polymer Coatings Enhance Stability and Transport

- Polymer coatings may be used to tailor engineered fluid properties for different reservoir types
- PSS-70K, poly(sodium 4-styrenesulfonate) was the best candidate due to surface charge, zeta potential magnitude, radius, and low retention in column
- Polymer (PSS) coatings reduced retention of particles in the column experiments relative to DI water conditions
- Breakthrough curves for MOF transport are similar due to PSS coatings
- Only small decreases observed in particle transport with increasing ionic strength
- Repulsion from silica surfaces and other nanoparticles promotes efficient transport



www.nature.com/scientificreports

scientific reports

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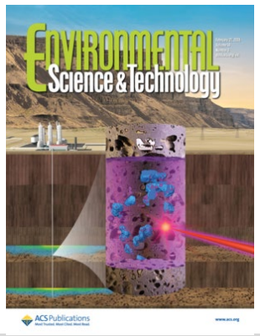
OPEN

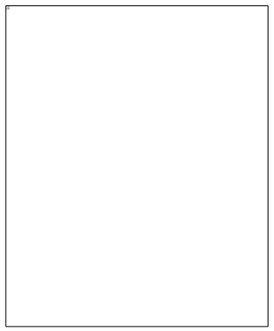
Transport of polymer-coated metal–organic framework nanoparticles in porous media

Satish K. Nune[1,3], Quin R. S. Miller[2], H. Todd Schaef[2], Tengyue Jian[2], Miao Song[2], Dongsheng Li[2], Vaithiyalingam Shuttanandan[1] & B. Peter McGrail[1]

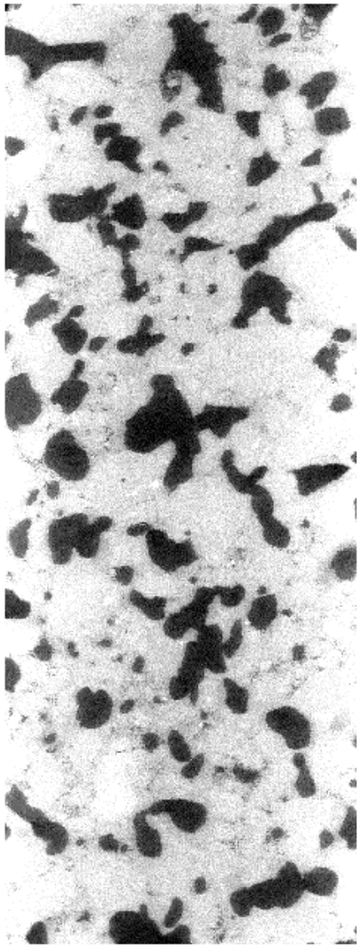
Ongoing Work: Tackling Knowledge Gaps for Seismic Properties of Basalt

- Seismic attenuation will fill a glaring literature data gap, leverages basalt XMT experience
- Prepared a porous picrite basalt core for seismic core testing in collaboration with Penn State (Dong, Menefee, Karpyn)
- Total porosity is 24% with 93% of the pores connected
- Reactive lithology for mineralization and critical mineral recovery

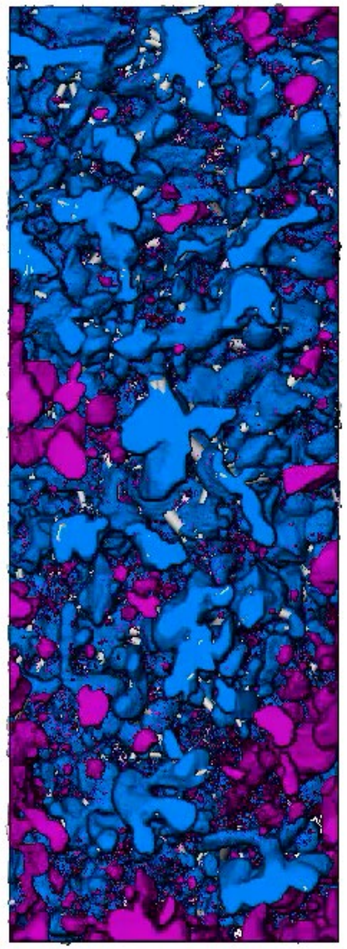




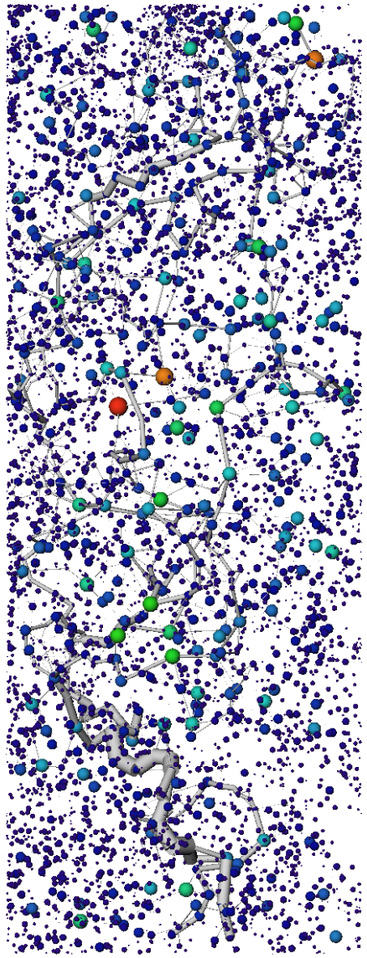
Stanfield et al. 2024, Carbon Mineralization and Critical Mineral Resource Evaluation Pathways for Mafic–Ultramafic Assets, ACS Earth & Space Chem.



Grey Scale Tomography Moving Through the Core by Each Layer



Pore Structure: Blue are connected, Pink are unconnected, Ball and Stick is the Pore Network Model (PNM)



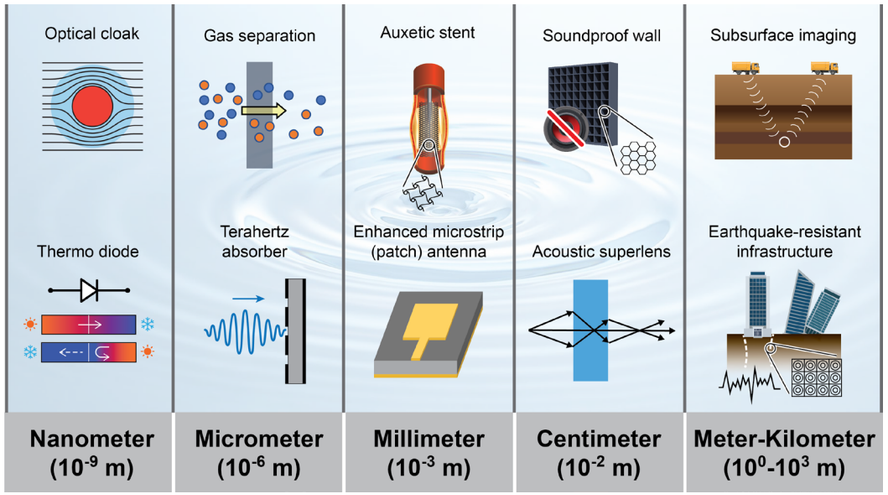
Fluid Path Between Connected Pores At Either End of the Core

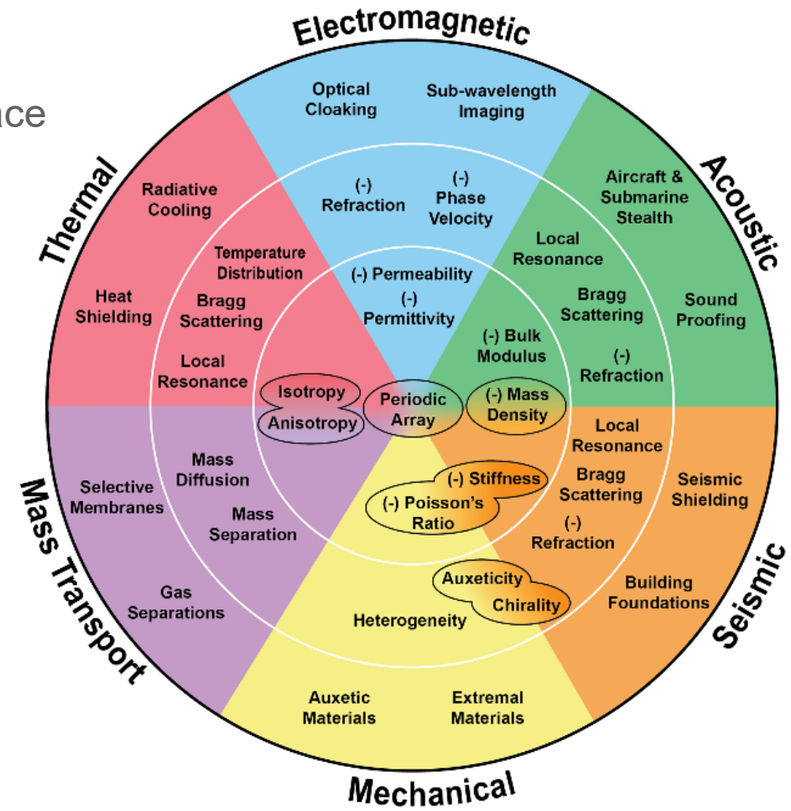
Extending Principles of Metamaterial and Design to the Subsurface

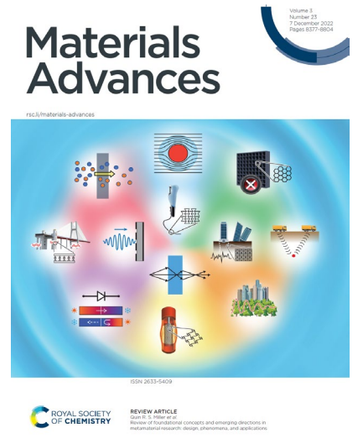
Metamaterials are comprised of composite media with periodic subwavelength structure engineered to exhibit unique optical, magnetic, or acoustic properties etc.

Composed of unit cells that work collectively to produce unusual, unique physical properties not found in natural materials or traditional composite materials, used to manipulate propagation of waves

- Contrast agent injectates allow for generating periodic subsurface structures
- Driving forward the emerging field of seismic metamaterials to enhance monitoring of subsurface fluids and structures
- Multiple length scales key to our monitoring technology







Holliman Jr. et al., 2022 Review of foundational concepts and emerging directions in metamaterial research: Design, phenomena, and applications, RSC Materials Advances

Training the Next Generation of DOE Science Leaders

Pacific Northwest NATIONAL LABORATORY

Jade Holliman

Arianna Morfin

Maddie Bartels

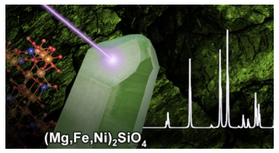
Heath Stanfield

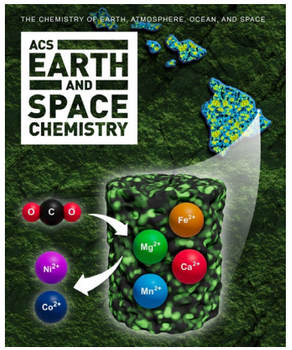
Charlie Depp

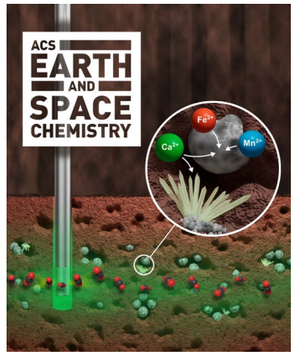
Ellen Polites

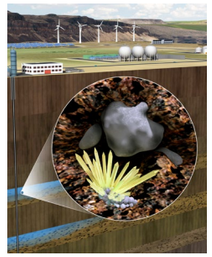
Briana Aguila

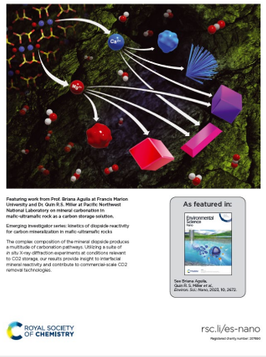
Madeline Murchland

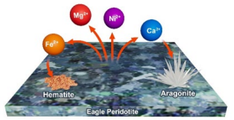


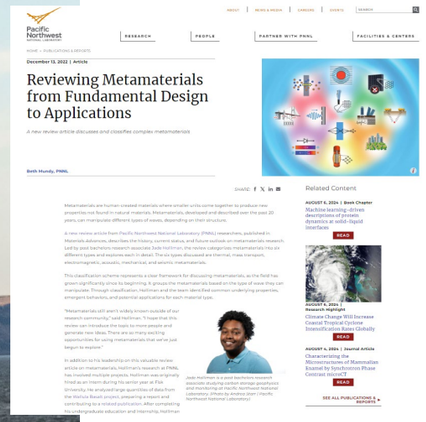


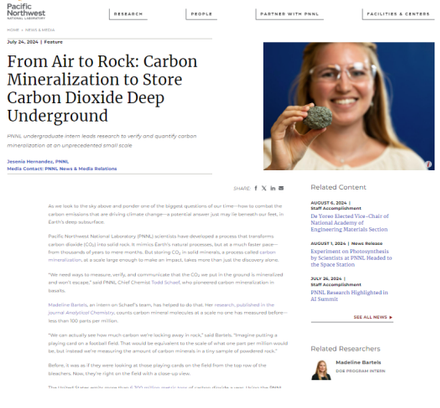






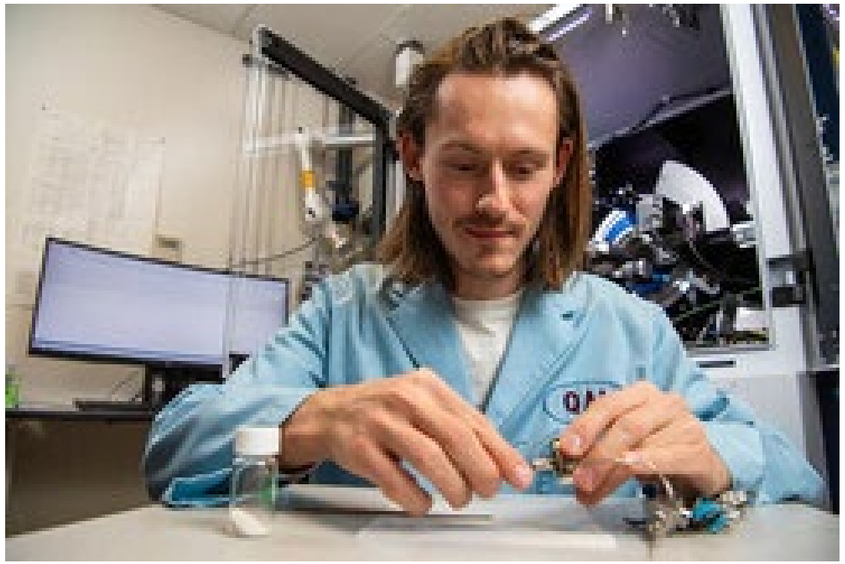


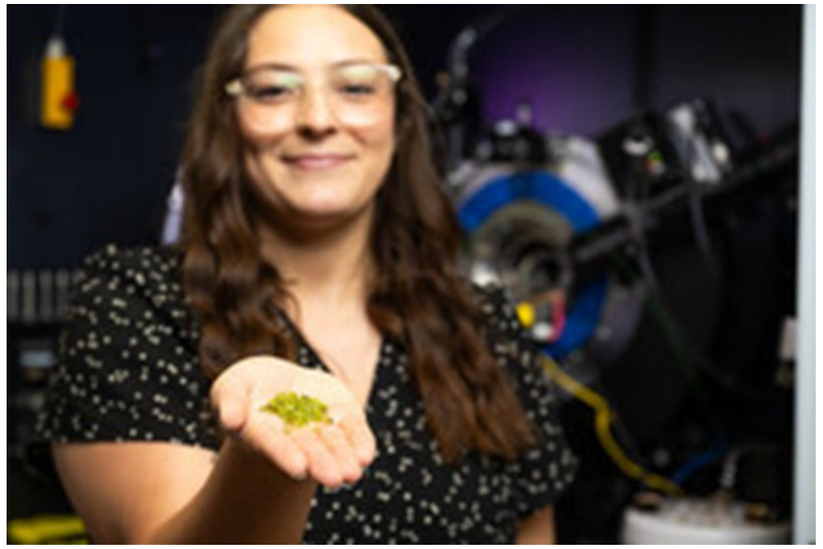


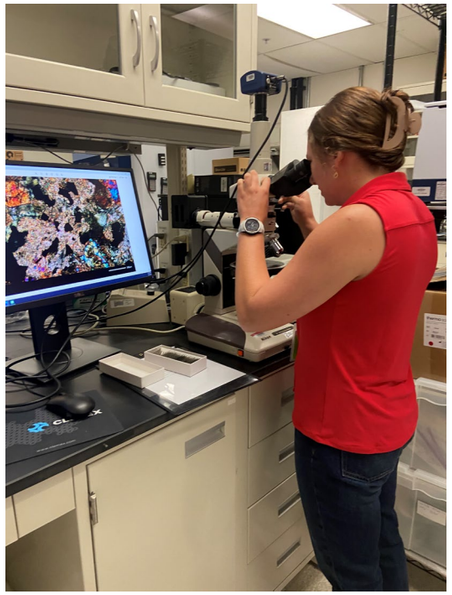


DOE Internship and Fellowship Opportunities quin.miller@pnnl.gov

- MLEF: Mickey Leland Energy Fellowship
- SULI: Student Undergraduate Laboratory Internships
- VFP: Visiting Faculty Program
- SCGSR: Office of Science Graduate Student Research Program
- NNSA/EM- MSIPP: Minority Serving Institutions Partnership Program
- CCI: Community College Internship Program
- GEM: Graduate Education for Minorities Fellowship Program







Synergy Opportunities

- Contrast agent approach may be used with conventional seismic imaging technologies
- Technology we are developing is tunable for different lithologies and fluid compositions
  - Mafic and Ultramafic rocks across the DOE and Private Industry portfolio
- Injection at a field location or test bed may be monitored with multiple approaches, from far-field to near-wellbore technologies

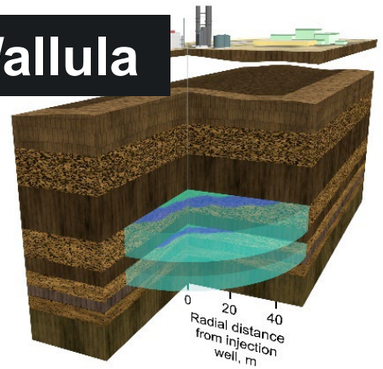
Key Opportunities for Subsurface Monitoring Technology Testbeds

Site-Specific Forward Seismic Modelling Case Study Possibilities: Leveraging PNNL Field Sites Across DOE Programs and Industry Sites

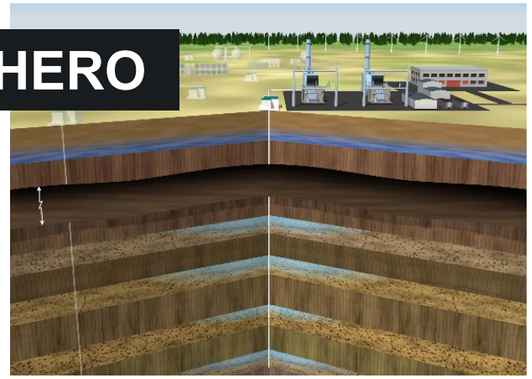
Field-specific examples of seismic survey enhancement with contrast agents will continue the push towards field deployment, including enabling permitting and injection strategy design

FORGE

Wallula



HERO



Tamarack

Pacific Northwest
NATIONAL LABORATORY

Project Summary

- Nanofluid injectates can operate at seismic frequencies and be multimodal contrast agents for far- and near-field/wellbore monitoring
- This technology works with established, conventional, seismic and other geophysical monitoring approaches.
- Disruptive approach to tracking subsurface CO_2 catalyzed by new metamaterial insights
- We can tailor colloid surface chemistry to control transport and strategic deposition in different environments
- Early career scientist and student mentoring is a key component of our subsurface portfolio
- Enhanced monitoring with functional injectates will be used to help accelerate commercial-scale carbon storage

Acknowledgements

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Benefit to the Program

- Derisking geologic carbon storage by enhancing monitoring of injected CO_2
- This research addresses the following Priority Research Directions recommended in the Mission Innovation CCUS Workshop report:
  - **S-1: Advancing Multiphysics and Multiscale Fluid Flow to Achieve Gt/year Capacity**
  - **S-4: Developing Smart Convergence Monitoring to Demonstrate Containment and Enable Storage Site Closure**

Synergy with PRDs

Mission Innovation CCUS Workshop Report

Enhanced Caprock Monitoring

- PRD S-1, S-4, and CC-2
- PRD CC-1: Integrating Experiment, Simulation, and Machine Learning across Multiple Length Scales to Guide Materials Discovery and Process Development

Mapping of Subsurface Structures

- Spatial resolution enhancement for fluid interfaces and fracture networks
  - PRD S-1, S-4, U-9, and CC-2
  - PRD S-6: Improving Characterization of Fault and Fracture Systems

Wellbore Integrity Monitoring

- Incorporation of acoustically-active materials for wellbore infrastructure monitoring

Deployment in Reactive Storage Reservoirs

- PRD S-9: Establishing, Demonstrating, and Forecasting Well Integrity