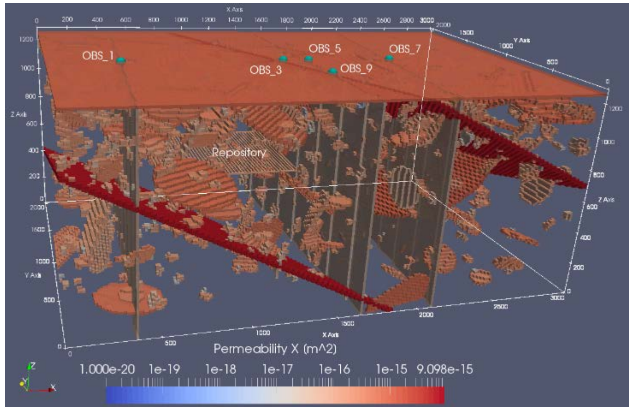

Geophysical Techniques for Site and Excavation Damage Zone (EDZ) Characterization

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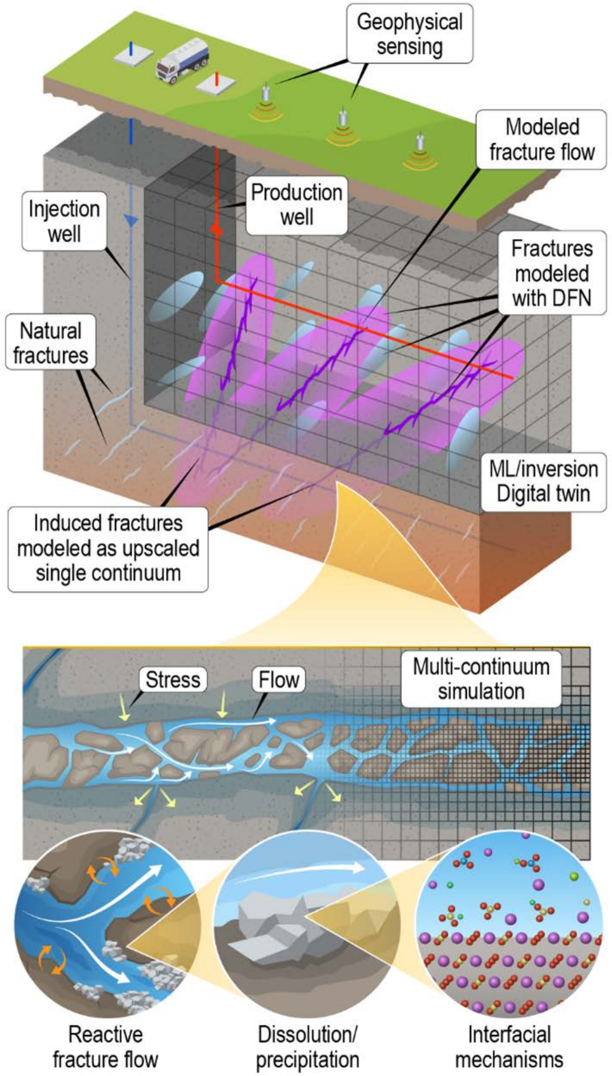
Spent Fuel and Waste Science and Technology (SFWST)

Key Questions

- **What are the challenges in and reasons for using geophysical techniques for characterizing deep geological repositories in crystalline rocks?**
  - Crystalline bedrock units may not have easily defined geometries
  - Imaging and characterization of fractures critical for safety case
- **Are there any lessons learned from other industries (e.g., geothermal, carbon sequestration, oil & gas industries)?**
  - Geothermal uses of geophysical methods may be most appropriate analogue, given that some geothermal resources are hosted in crystalline rocks (not the case for hydrocarbons, CO_2 storage)
- **What are the scales of investigation and imaging resolution required?**
  - Large-scale features (faults, major contacts) can be resolved using surface methods
  - Small-scale features (EDZ, fractures) detected using subsurface (borehole) techniques

What Types of Geophysical Methods Can Be Used?

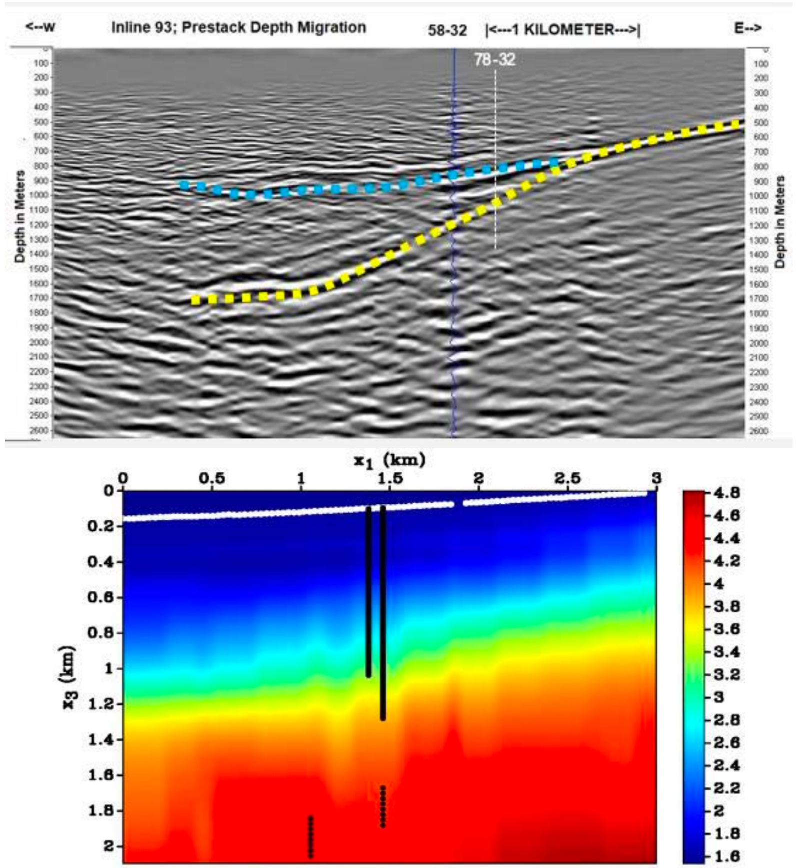
- **Seismic methods**
  - Active (reflection, vertical seismic profiling (VSP), cross-well seismic)
  - Passive (acoustic emissions, ambient noise, seismic monitoring)
- **Electrical methods**
  - Time-domain electromagnetics and magnetotellurics
  - Electrical resistance tomography
- **Potential field methods**
  - Gravity
  - Magnetics
- **Borehole logging methods**
  - Temperature, resistivity, neutron density, gamma, optical & acoustic televiewers, full waveform sonic
- **Fiber optic sensing methods**
  - Distributed temperature sensing (DTS)
  - Distributed acoustic sensing (DAS)
  - Distributed strain sensing (DSS)



Multiscale model of key elements of an enhanced geothermal system using geophysical sensing for characterization & monitoring (PNNL, 2024)

Geophysical Characterization Techniques – Seismic Methods

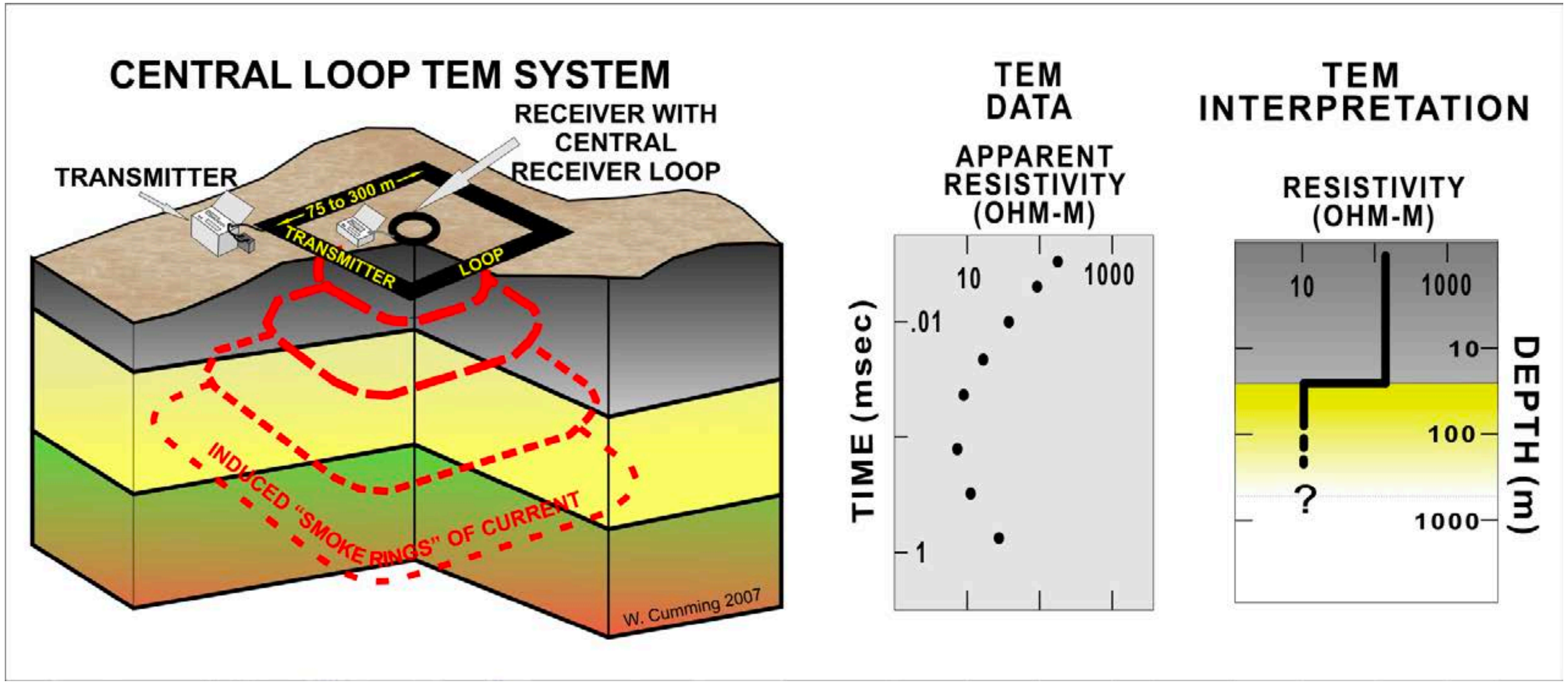
- **Seismic reflection - identify subsurface geology and structures**
  - 3D seismic methods not used often to characterize crystalline rocks due to lack of coherent structures & stratigraphy, cost
  - 2D seismic can be used to map out major subsurface structures
- **Cross-well seismic and vertical seismic profiling (VSP) - look for seismic velocity changes due to different lithologies and presence of fractures & damaged rock**
- **Seismicity – look for location of active faults and assess stress regime**



Utah FORGE site – Top: 2D seismic reflection profile (Simmons et al., 2021). Bottom: VSP profile with V_P model (Nakata et al., 2023)

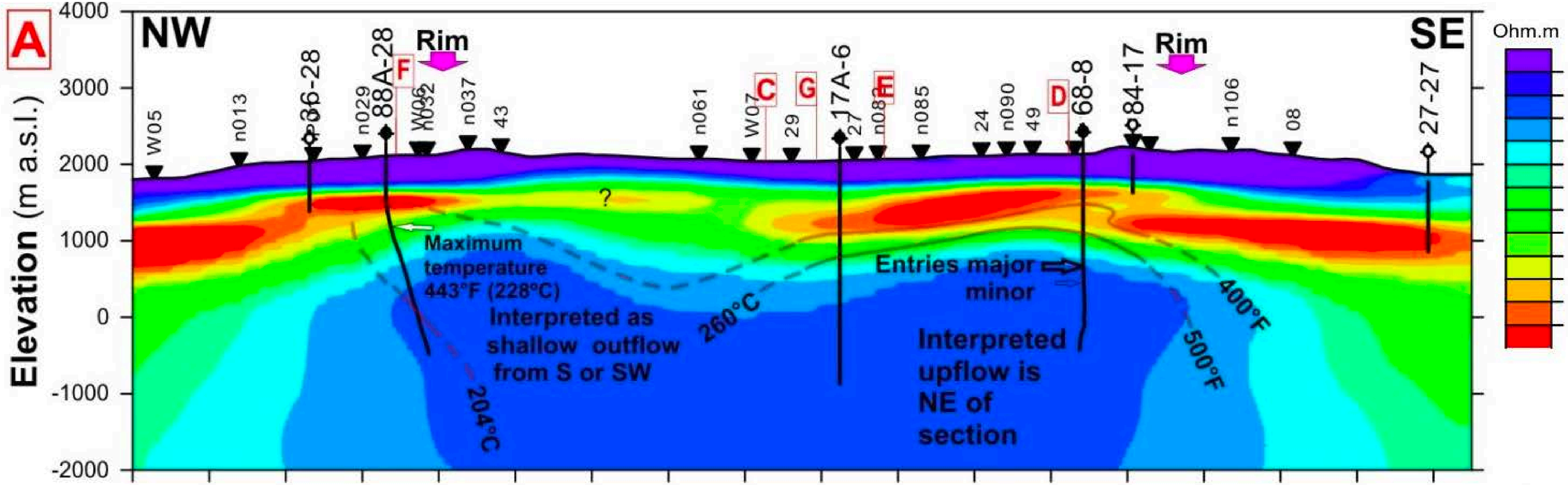
Geophysical Characterization Techniques – Electrical Methods

- **Electrical resistivity (time-domain electromagnetics (TDEM) & magnetotellurics)**
- **Streaming potential**
- **Electrical resistance tomography**
- **Electrical methods useful to detect changes in electrical conductivity**
  - Presence of saline brine
  - Presence of clays



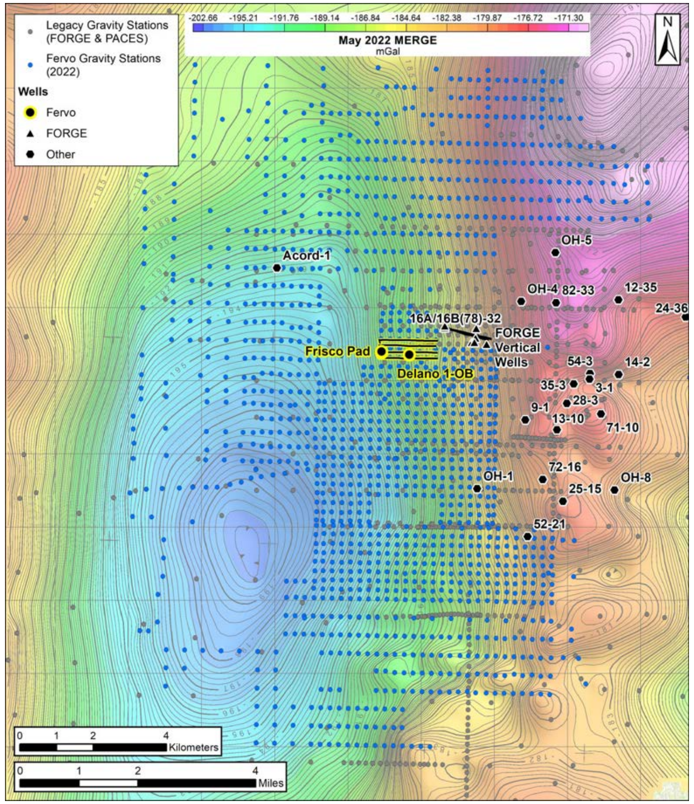
Example of TDEM station layout and results (Cumming & Mackie, 2010)

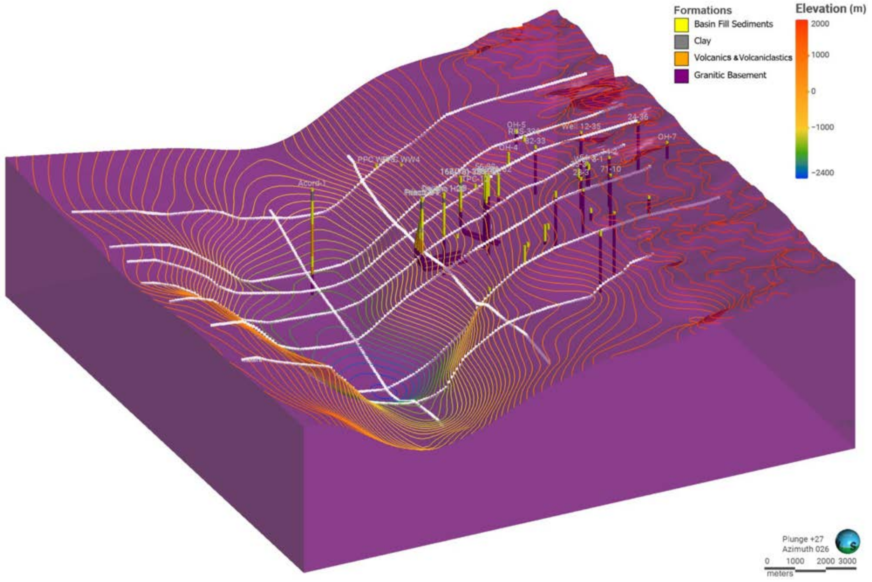
MT Cross Section – Medicine Lake, CA (Cumming and Mackie, 2010)



Geophysical Characterization Techniques – Potential Fields Methods

- **Gravity surveys**
- **Magnetic surveys**
- **Both methods can be used to identify buried structures, and interpretations are model-dependent**
- **Joint inversion can result in higher resolution subsurface imaging**

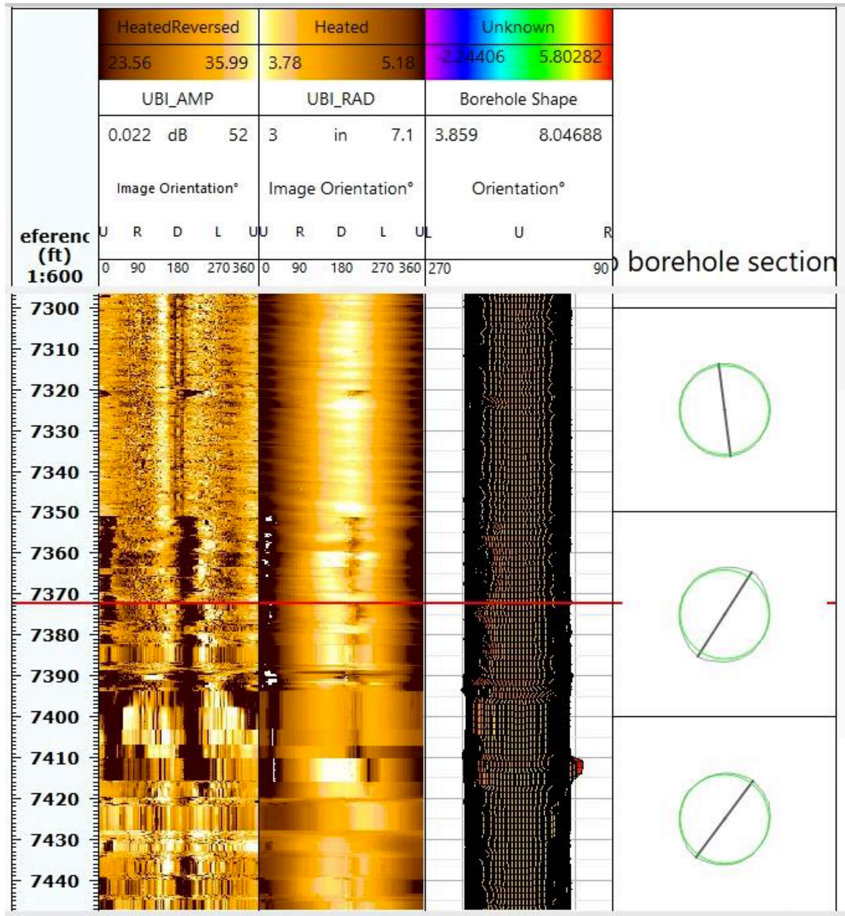




Complete Bouguer anomaly map of Milford Valley area and resulting granitic basement model (Fercho et al., 2024)

Geophysical Characterization Techniques – Borehole Logging Methods

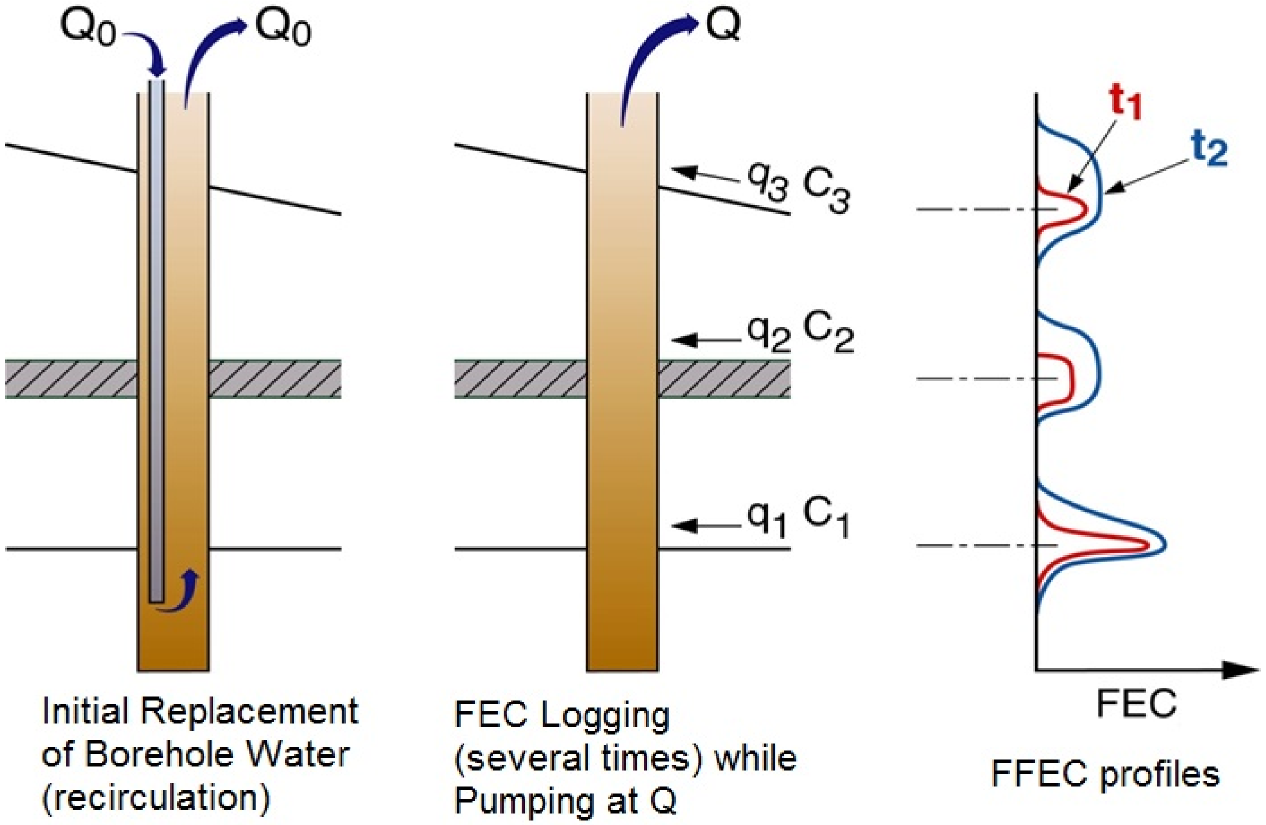
- **Optical and acoustic televiewers**
  - Imaging of foliation and fractures to determine their distribution and orientation
  - Identification of borehole breakouts and drilling induced tensile fractures to estimate stress orientations (S_{Hmax})
- **Resistivity logs**
- **Neutron density logs**
- **Gamma logs**
- **Fiber optic sensing (DTS, DAS, DSS)**
- **Full waveform sonic logs**
- **Extensive borehole logging conducted at Forsmark (Sweden), Beishan (China) & ONKALO (Finland) (Fabishenko et al., 2016)**



Borehole breakouts in 16A(78)-32 well, Utah FORGE (Xing et al., 2022)

The Flowing Fluid Electrical Conductivity Logging Method

Tsang et al. (2016), Doughty et al. (2017)

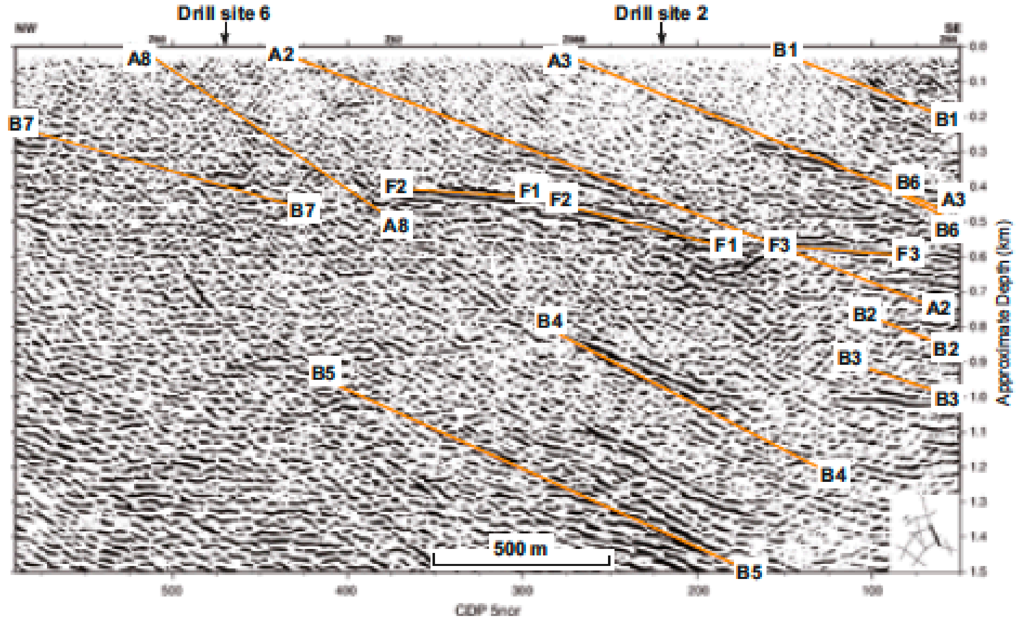


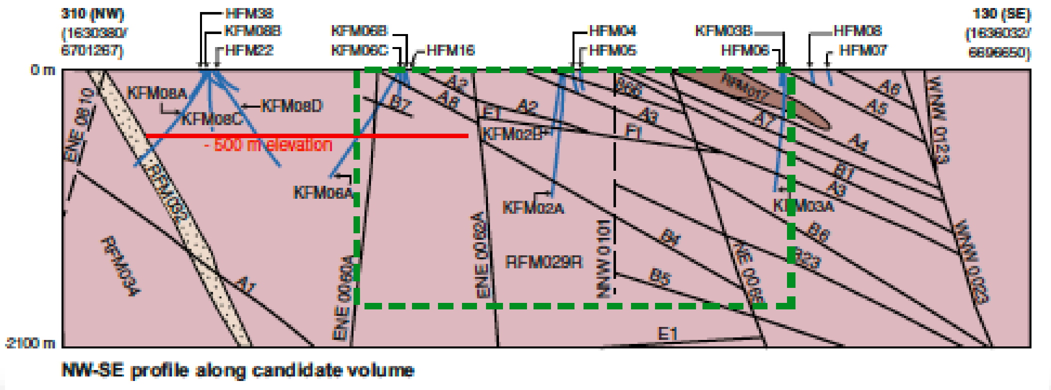
Parameters that can be estimated for each hydraulically conductive inflow zone:
- Depth z
- Inflow rate q
- Formation water salinity C (~ to FEC)

- **Peak height is proportional to product of inflow rate q and formation salinity C**
- **Flow up the wellbore will cause peaks to skew upward, proportionally to Σq**
- **Model peak growth with computer code BORE II to fit observed FFEC profiles and thereby infer parameters of inflow zones**

Integration of Geophysical Methods

- **Use of different geophysical methods at different scales can provide increased confidence in site characterization**
- **Joint inversion techniques can also be applied to improve resolution**



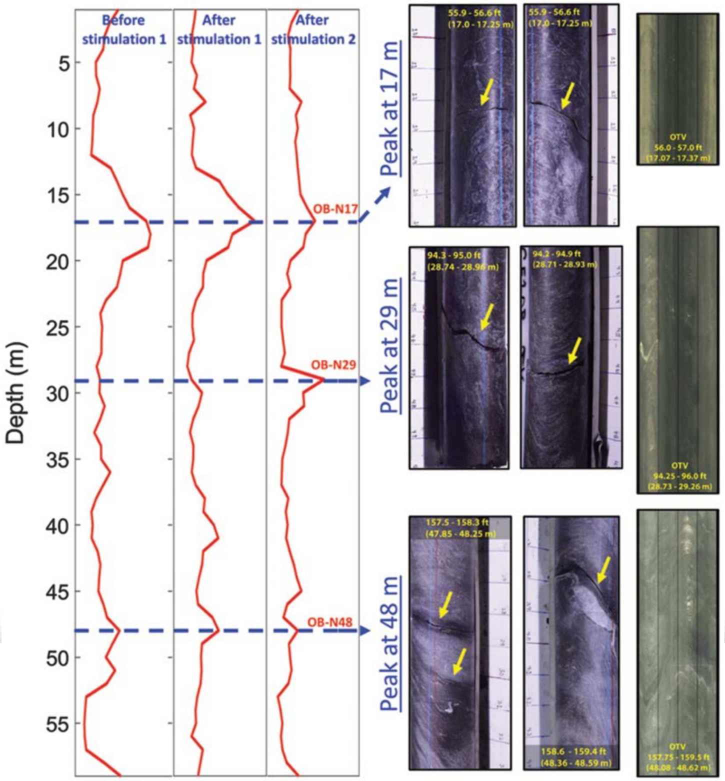


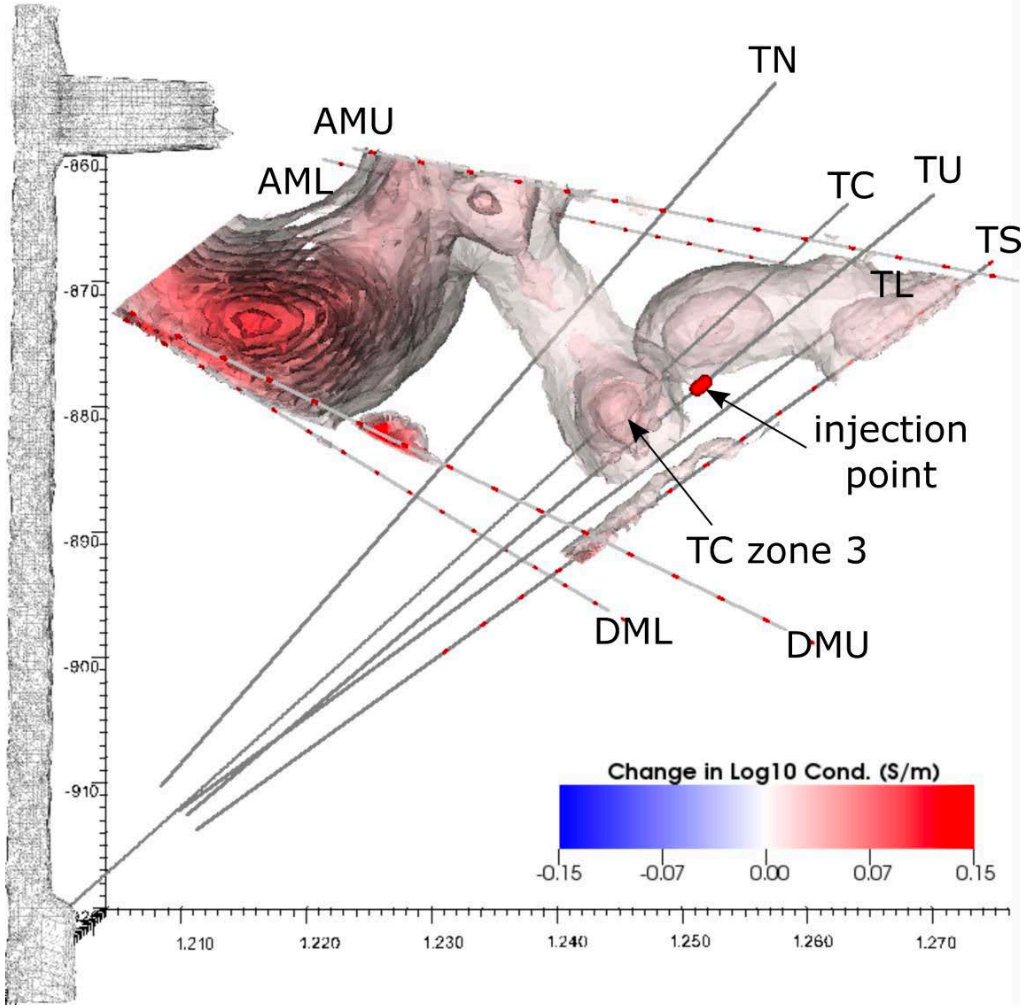
Seismic reflection data (above) with interpreted fracture zones, combined with borehole data to develop an improved fracture model for the Forsmark site (below). Blue lines depict boreholes, black lines are interpreted fractures; green dashed line shows location of upper seismic section (SKB, 2008).

Geophysical Monitoring

- **Detection of fluid movement in the subsurface**
- **Localized thermal and hydraulic stresses can impact fracture opening and fluid movement**

DAS ambient noise profiles before and after stimulation, with peaks corresponding to open fractures for well OB, EGS Collab project (Li et al., 2024)

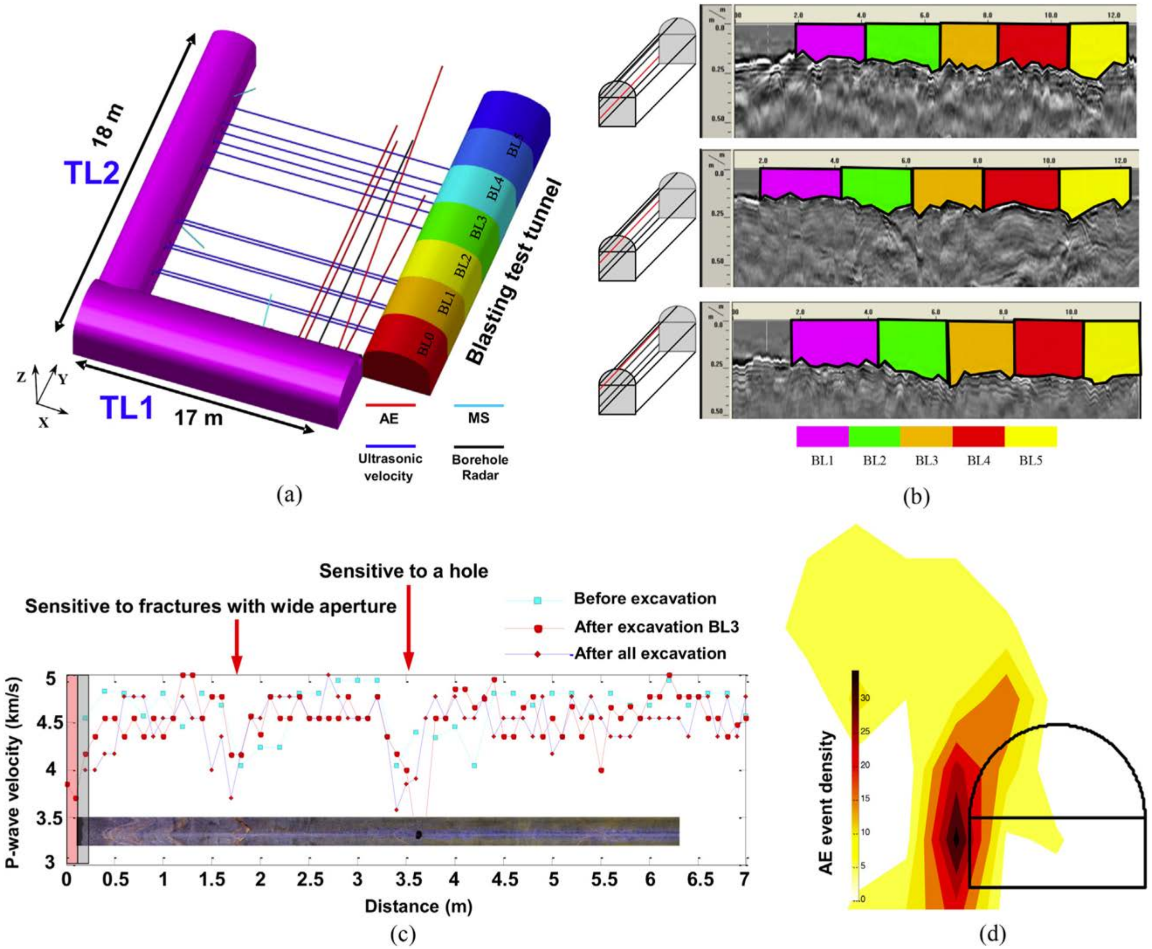




ERT image of saline tracer distribution after injection at TU 177.4 - 179.6 ft, EGS Collab project (Kneafsey et al., 2023)

Geophysical characterization of EDZ

- **Damage zone created by excavation could create hydraulic connections to open fractures in crystalline rock and change local stress conditions**
- **Extent of damage zone can be evaluated using variety of geophysical techniques, including ground penetrating radar (GPR), P-wave velocity, & acoustic emissions (AE)**

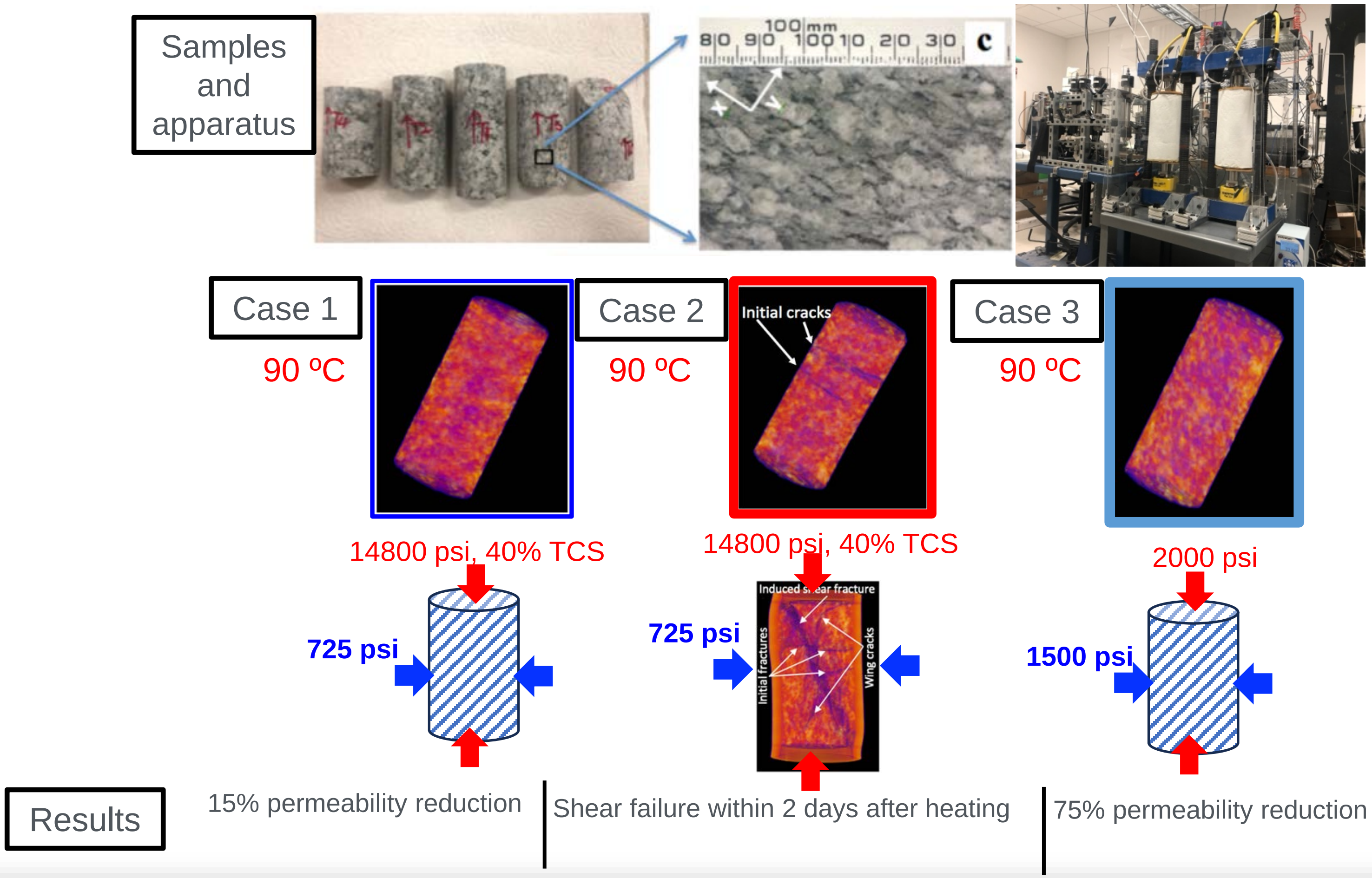


Characterization of EDZ at the Beishan Underground Research Laboratory using GPR (b), seismic velocity (c), and AE (d) (Wang et al., 2018)

Coupled THMC Behavior of Anisotropic Granite for Geologic Disposal of High-Level Radioactive Waste

Motivation

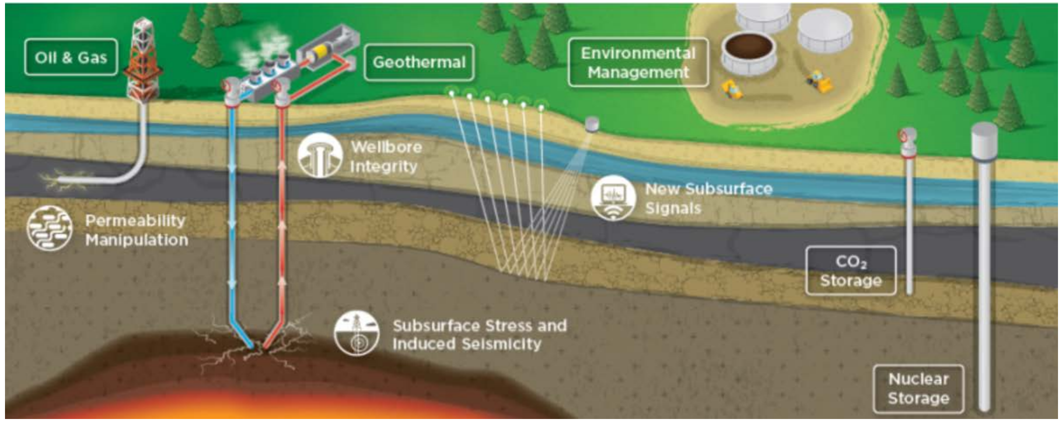
- **Rock failure and permeability evolution are time dependent**
- **Fractures, temperature and fluid/chemistry further complicate the time-dependent behaviors, while laboratory data are limited**
- **As another "bottleneck" issue in repository design and performance assessment, the anisotropic behavior of flow and deformation within EDZ rock needs systematic study**



Chang (in prep.); Hu et al. (2022)

Takeaway Messages

- **Fracture characterization key input into DFN models – critical for crystalline disposal safety case evaluation**
- **Geophysical techniques to be used depend on scale of measurement**
- **Some geophysical methods provide non-unique interpretations; use of multiple methods can improve resolution and increase confidence**
- **Collaboration between nuclear waste, geothermal, fossil energy, and geologic CO_2 sequestration R&D efforts for subsurface characterization is critical**



Pillars from previous DOE SubTER program

Subsurface Control for a Safe and Effective Energy Future

Adaptive Control of Subsurface Fractures and Fluid Flow

Wellbore Integrity and Drilling Technologies	Subsurface Stress & Induced Seismicity	Permeability Manipulation & Fluid Control	New Subsurface Signals
Improved well construction materials and techniques	State of Stress (measurement and manipulation)	Manipulating Physicochemical Fluid-Rock Interactions	New Sensing Approaches
Autonomous completions for wellbore integrity monitoring	Induced Seismicity (measurement and manipulation)	Manipulating Flow Paths to Enhance/Restrict Fluid Flow	Integration of Multi-Scale, Multi-Type Data
New diagnostics for wellbore leakage	Relate Stress and IS to Permeability	Characterizing Fracture, Dynamics and Fluid Flow	Adaptive Control Processes
Remediation tools and technologies	Applied Risk Analysis to Assess Impact of Subsurface Manipulation	Novel Stimulation Technologies	Diagnostic Signatures and Critical Thresholds
Fit-for-purpose drilling and completion tools (e.g., anticipative drilling, centralizers, monitoring)			
HT/HP well construction/ completion technologies			
Energy Field Observatories			
Fit For Purpose Simulation Capabilities			

https://www.energy.gov/subsurface-science-technology-engineering-and-rd-crosscut-subter

References

- Cumming, W., and Mackie, R. (2010) Resistivity imaging of geothermal resources using 1D, 2D and 3D MT inversion and TDEM static shift correction illustrated by a Glass Mountain case history. Proceedings, World Geothermal Congress 2010, Bali, Indonesia.
- Doughty, C., Tsang, C.F., Rosberg, J.E., Juhlin, C., Dobson, P.F., and Birkholzer, J.T. (2017) Flowing fluid electrical conductivity logging of a deep borehole during and following drilling: estimation of transmissivity, water salinity and hydraulic head of conductive zones. Hydrogeology Journal 25: 501-517.
- Fabishenko, B., Birkholzer, J., Sassani, D., and Swift, P. (eds). (2016) International approaches for deep geological disposal of nuclear waste: Geological challenges in radioactive waste isolation. Fifth worldwide review. LBNL Report 1006984.
- Fercho, S., Matson, G., McConville, E., Rhodes, G., Jordan, R., and Norbeck, J. (2024) Geology, temperature, geophysics, stress orientations, and natural fracturing in the Milford Valley, UT informed by the drilling results of the first horizontal wells at the Cape Modern Geothermal Project. Proceedings, 49th Workshop on Geothermal Reservoir Engineering, Stanford University.
- Hu, M., Guglielmi, Y., Chang, C., Doughty, C., Dobson, P., Sasaki, T., Borglin, S., Cook, P., Rutqvist, J., Soom, F., Kneafsey, T., Birkholzer, J., and Zheng, L. (2022) Crystalline Disposal R&D at LBNL: FY22 Progress, Milestone M4SF-22LB010302032, SFWD Working Document Report.
- Kneafsey, T., Blankenship, D., Burghardt, J., Johnson, T., Dobson, P., Schwering, P.C., Hopp, C., White, M., Morris, J.P., Strickland, C., Vermuel, V., Fu, P., Ingraham, M., Roggenthen, W., Doe, T., Ajo-Franklin, J.B., Huang, L., Rodriguez Tribaldos, V., Guglielmi, Y., Knox, H., Cook, P., Soom, F., Ulrich, C., Frash, L., Neupane, G., Pyatina, T., Weers, J., Mattson, E., Robertson, M., and The EGS Collab Team (2023) The EGS Collab – Discoveries and lessons learned from an underground experiment series. Proceedings, 48th Workshop on Geothermal Reservoir Engineering, Stanford University
- Li, D., Huang, L., Zheng, Y., Li, Y., Schoenball, M., Rodriguez-Tribaldos, V., Ajo-Franklin, J., Hopp, C., Johnson, T., Knox, H., Blankenship, D., Dobson, P., Kneafsey, T., and Robertson, M. (2023) Detecting fractures and monitoring hydraulic fracturing processes at the first EGS Collab testbed using borehole DAS ambient noise. Geophysics, 89(2), D131–D138.
- Nakata, N., Vasco, D.W., Shi, P., Bai, T., Lanza, F., Dyer, B., Chen, C., Park, S.E., and Qui, H. (2023) Elastic characterization at Utah FORGE: P-wave tomography and VSP subsurface imaging. Proceedings, 48th Workshop on Geothermal Reservoir Engineering, Stanford University.
- Pacific Northwest National Laboratory (2024) Center for Understanding Subsurface Signals and Permeability website, https://www.pnnl.gov/projects/cussp
- Simmons, S.F., Kirby, S., Allis, R., Bartley, J., Miller, J., Hardwick, C., Jones, C., Wannamaker, P., Podgorney, R., and Moore, J. (2021) The current geoscientific understanding of the Utah FORGE site. Proceedings World Geothermal Congress 2020+1, Reykjavik, Iceland
- SKB (2008) Site description of Forsmark at completion of the site investigation phase – SDM-Site Forsmark, Technical Report TR-08-05.
- Tsang, C.F., Rosberg, J.E., Sharma, P., Berthet, T., Juhlin, C., and Niemi, A. (2016) Hydrologic testing during drilling: application of the flowing fluid electrical conductivity (FFEC) logging method to drilling of a deep borehole. Hydrogeology Journal 24: 1333-1341.
- Wang, J., Chen, L., Su, R., and Zhao, X. (2018) The Beishan underground research laboratory for geological disposal of high-level radioactive waste in China: Planning, site selection and in situ tests. Journal of Rock Mechanics and Geotechnical Engineering 10: 411-435.
- Xing, P., Wray, A., Velez Arteaga, E.I., Moore, J., Jones, C., Borchardt, E., and McLennan, J. (2022) In-situ stresses and fractures inferred from image logs at Utah FORGE. Proceedings, 47th Workshop on Geothermal Reservoir Engineering, Stanford University.