Monitoring Fracture Dynamics with a Contrast Agent-Assisted Electromagnetic Method

DE-FE0031785

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Bureau of Economic Geology at

The University of Texas at Austin

U.S. Department of Energy

National Energy Technology Laboratory

October 26, 2022

Annual Review Meeting

Pittsburg

Acknowledgements

NETL/DOE
- **Scott Beautz**
- Gary Covatch

The University of Texas- at Austin
- **Mahdi Haddad**
- Darwin Mohajeri

Duke University
- Liangze Cui
- Qing Huo Liu

University of North Carolina
- **Alfred Kleinhammes**
- Patrick Doyle
- Yue Wu

DIT
- **Jeffrey Chen**

Project Overview

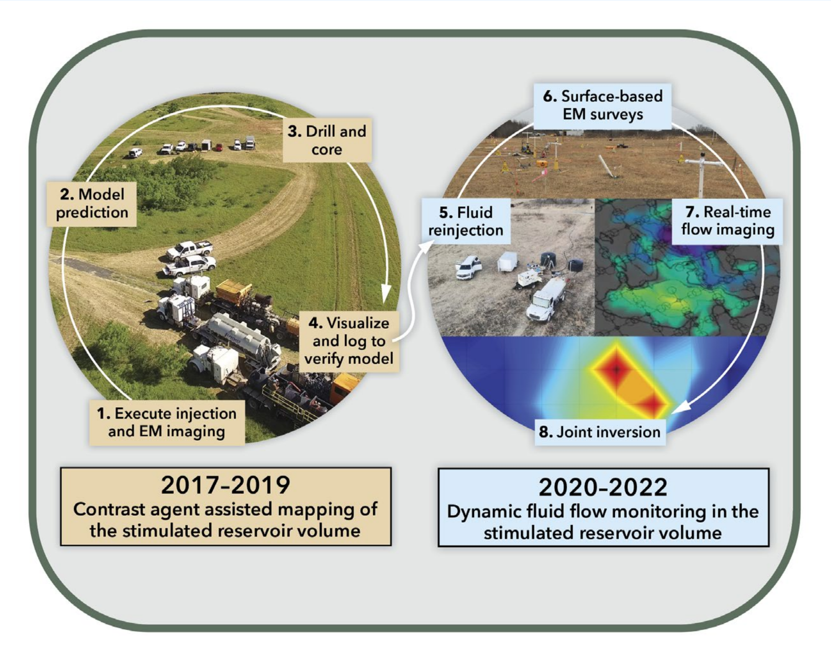
– Funding (DOE and Cost Share)
  - NETL Funded Project $1.7M DOE and $430K Cost Share

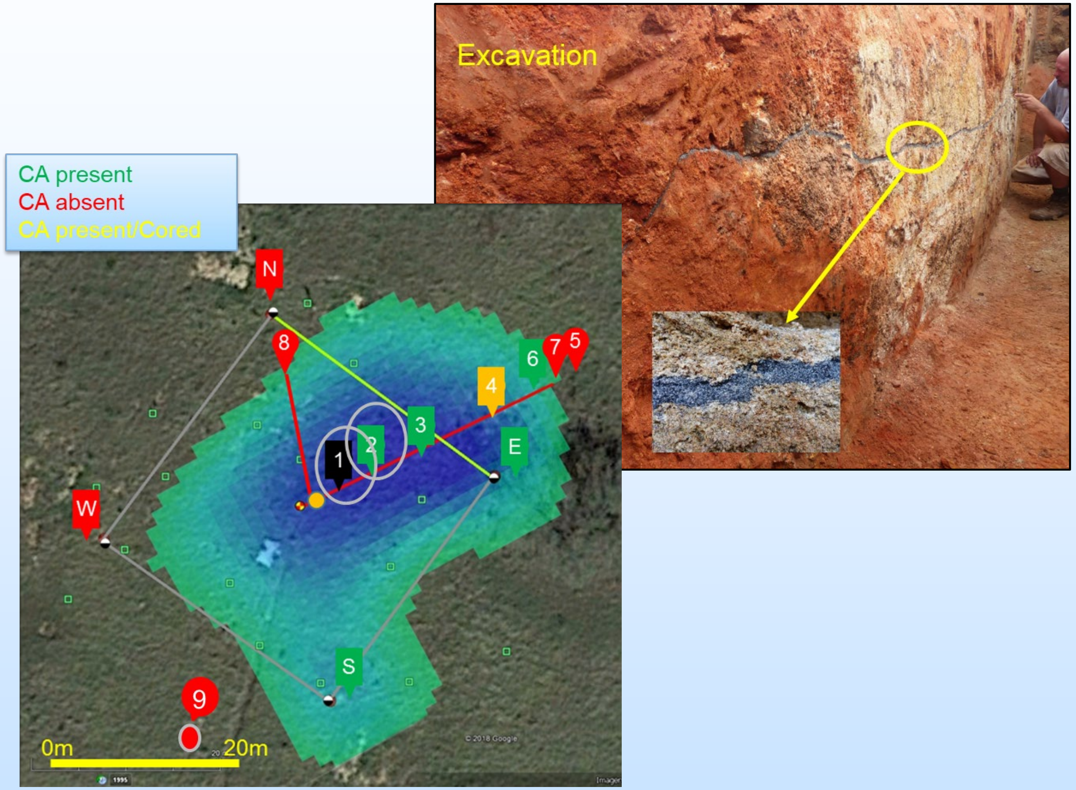
– Overall Project Performance Dates
  - September 2019 to December 2022 (15 months extension due to the pandemic)

– Project Participants (see acknowledgments)
  - UT Austin Bureau of Economic Geology: Prime recipient, hydro-geomechanical and seismic modeling, and coordinator of field activities
  - UNC: EM Lab studies
  - Duke: EM Modeling
  - Deep imaging technologies (DIT): CSEM vendor

Background and Overall Project Objectives

To demonstrate a real-time surface-deployed electromagnetic (EM) method for monitoring fractured network dynamics at TRL of 5 using pressure-responsive electrically active proppants (EAPs)





Monitoring subsurface flow for a safe and sustainable resource recovery

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Technical Approach/Project Timelines

BP1 Oct. 2019-Sept. 2020

BP2- Sept. 2020-Dec. 2022

10/1/2019

3.Lab studies,
4&5.Modeling,
6.Planning
6. Field deployment,
5. History Matching,
6. Planning for second deployment,
6. Field deployment,
7. Data Analysis

This Presentation

10/26/22 **12/31/2022**

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Technical Approach/Project Scope

BP1 Milestones:

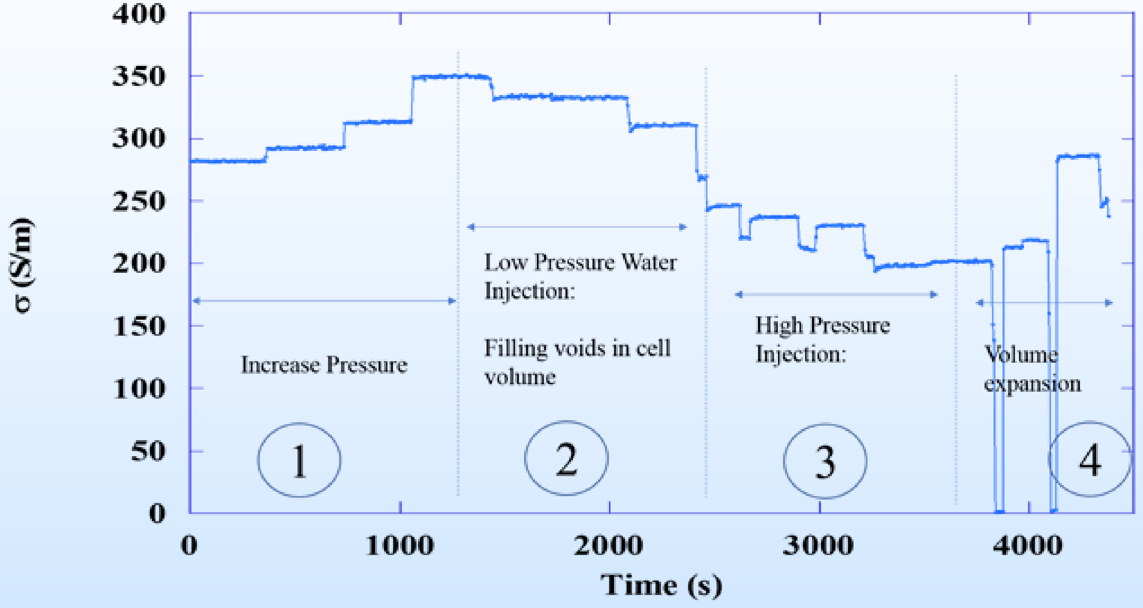
- ✓ 1. Obtaining the required permit for injection into the DFPS
- ✓ 2. Verification that pressure and salinity change can yield at least 1-5% change in electrical conductivity of 100% EAP pack.
- ✓ 3. Verification by EM forward modeling that a change in electrical conductivity of a propped fracture leads to a measurable change in under survey conditions.

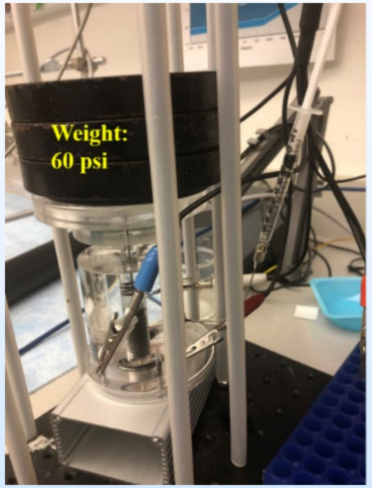
Success Criteria:

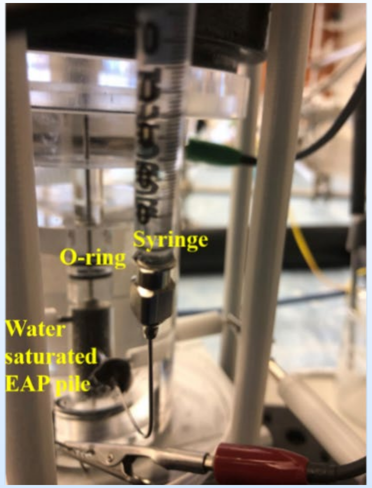
- ✓ Conduct field test to demonstrate that monitoring fracture dynamics with a contrast agent-assisted EM method is possible in real time

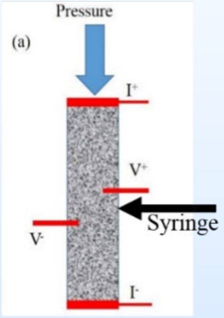
Monitoring subsurface flow for a safe and sustainable resource recovery

Impact of Pressure and Flow Rate on Frac Models



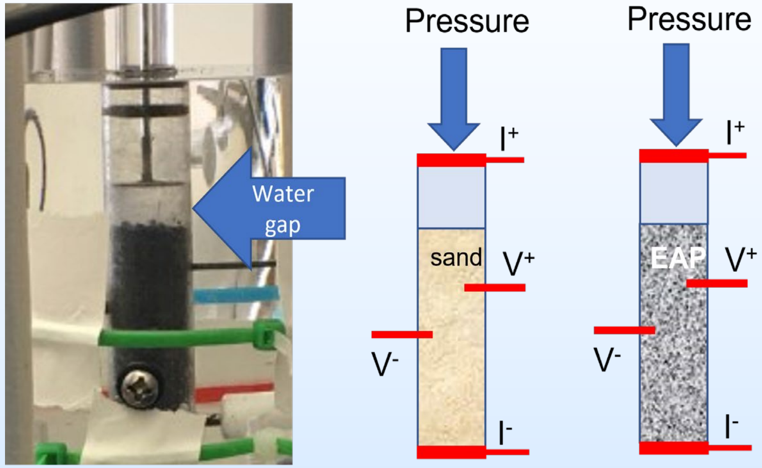


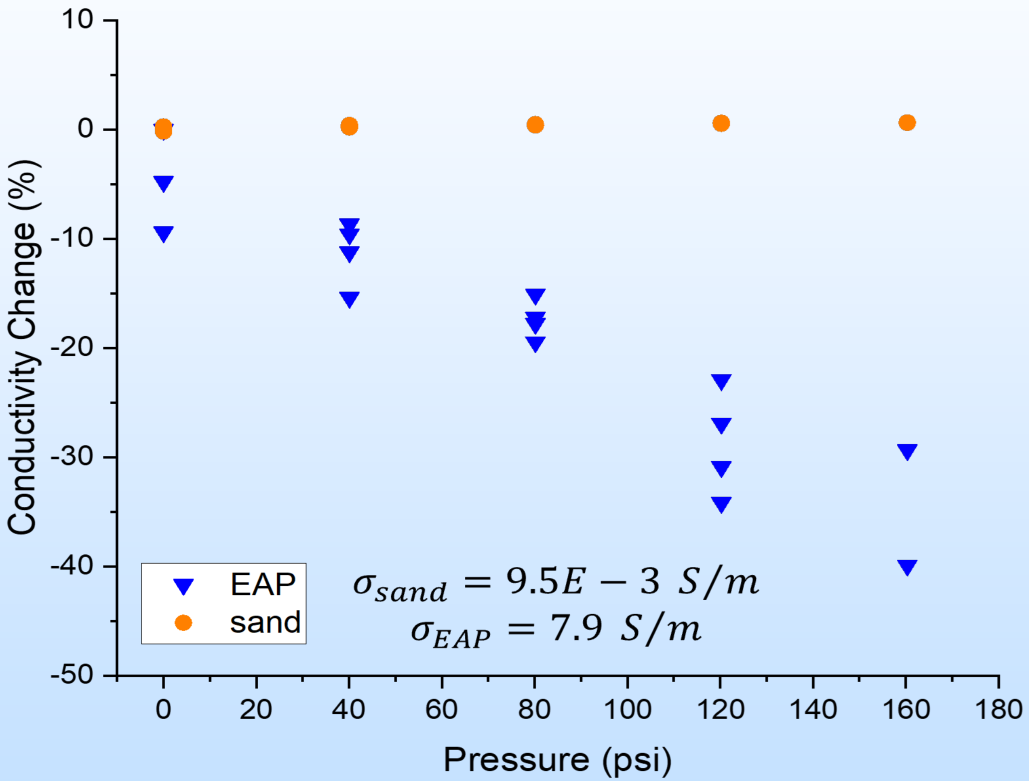




- Dilation due to stepwise injections changes the conductivity of the EAP pack
- This supports the capability of EM methods to detect flow within EAP

Progress - Electrical Measurements in the Lab: Pressure





- **Relative change in conductivity is large when hydraulic pressure is applied to the CA pack in a confined space.**
- **Sand does not respond to pressure as much as the CA**

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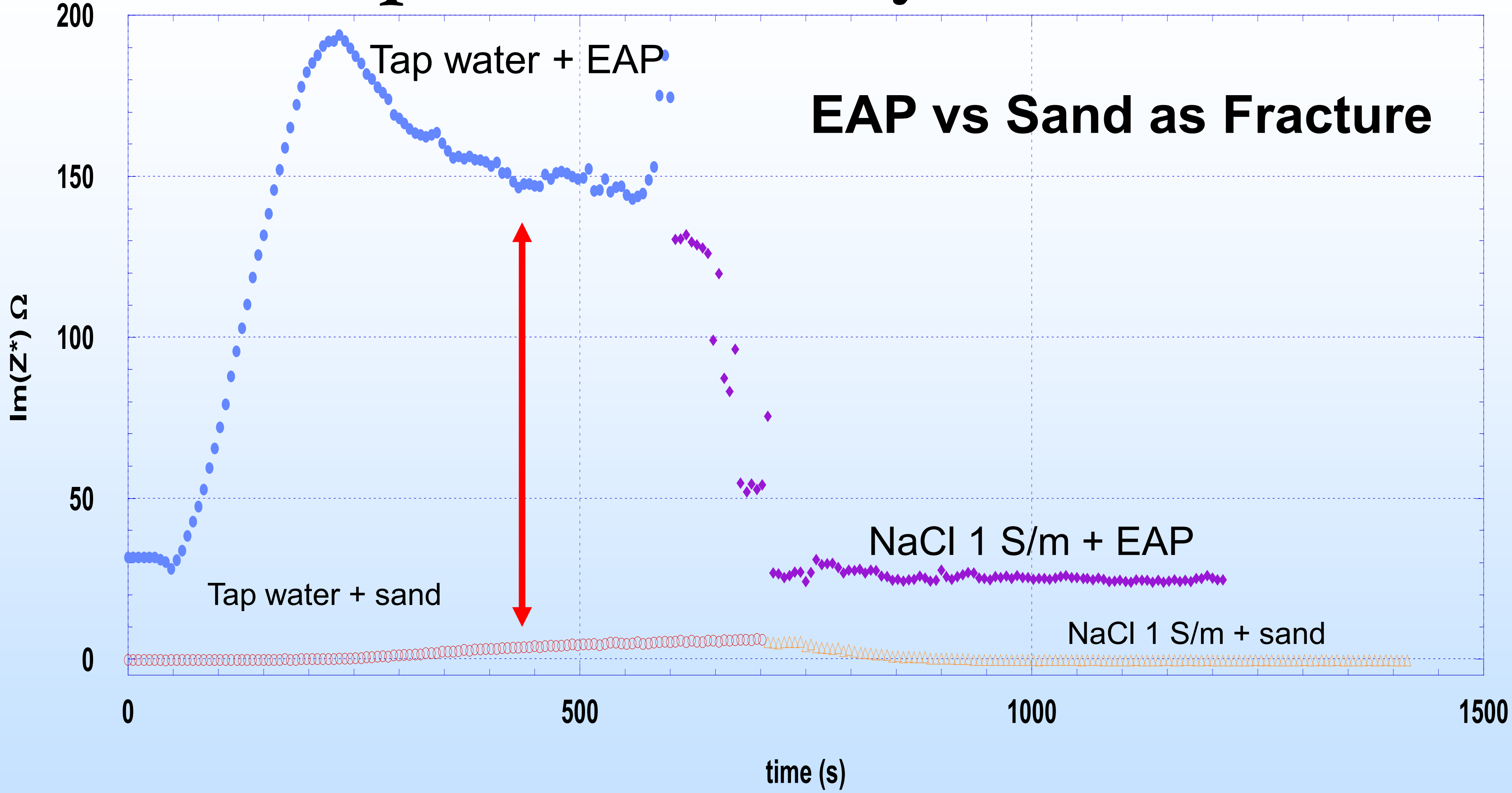
Impact of Salinity on Frac Models



- Two frac models:
a) consisting of sand only and b) system with a stratified EAP-alternate-sand fracture were studied.
- Large dielectric response difference between these two scenarios highlights the importance of EAP
- Increase in salinity leads to a reduction of the imaginary part of the impedance

Columns were Initially equilibrated with 1000 ppm NaCl solution. Then, tap water and 6000 ppm NaCl (1S/m) solution were injected sequentially.

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Field Study Plan-A hypothesis for the Expected Results

Proposed Work Plan:

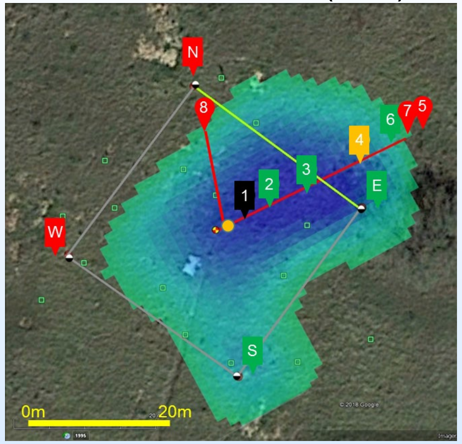
Baseline Packed CA
Low salinity/High Lithostatic Pressure (HLP)

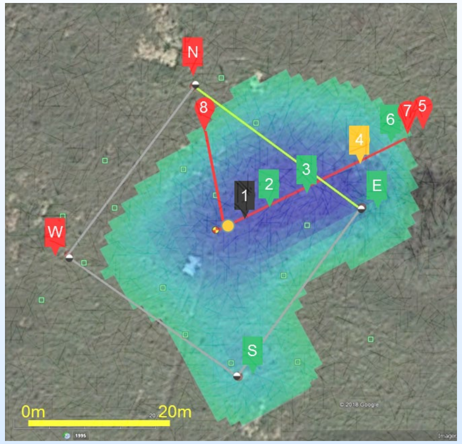
Inject with freshwater
Low salinity/High Hydraulic Pressure (HHP)

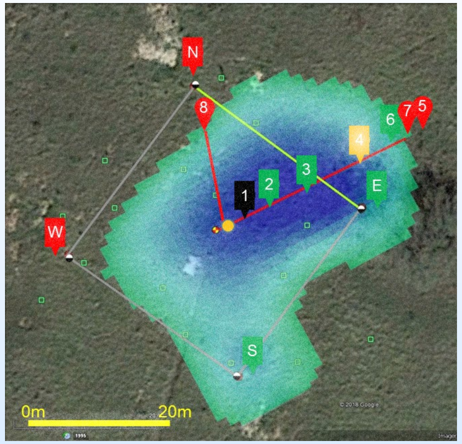
Inject with brine
High salinity/High Hydraulic Pressure

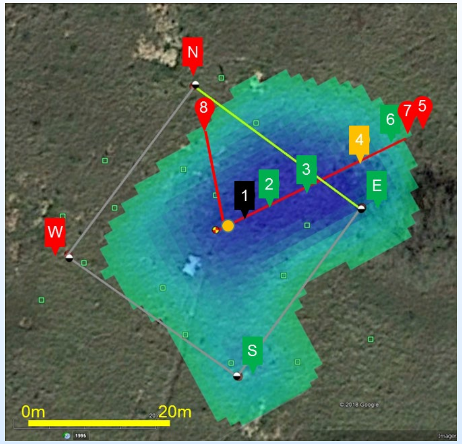
Rest period / extraction / leakoff
Low salinity/Low Hydraulic Pressure

Expected Outcome:









High e. conductivity

Decrease e- conductivity

Increase e. conductivity

Increase e. conductivity

e. conductivity of undisturbed CA under HLP >
e. conductivity of CA in freshwater <
e. conductivity of CA in brine + HLP (assumed -TBD)

Note: Due to Ohm's law, the measured surface e field is expected to change the opposite of the shown conductivity changes

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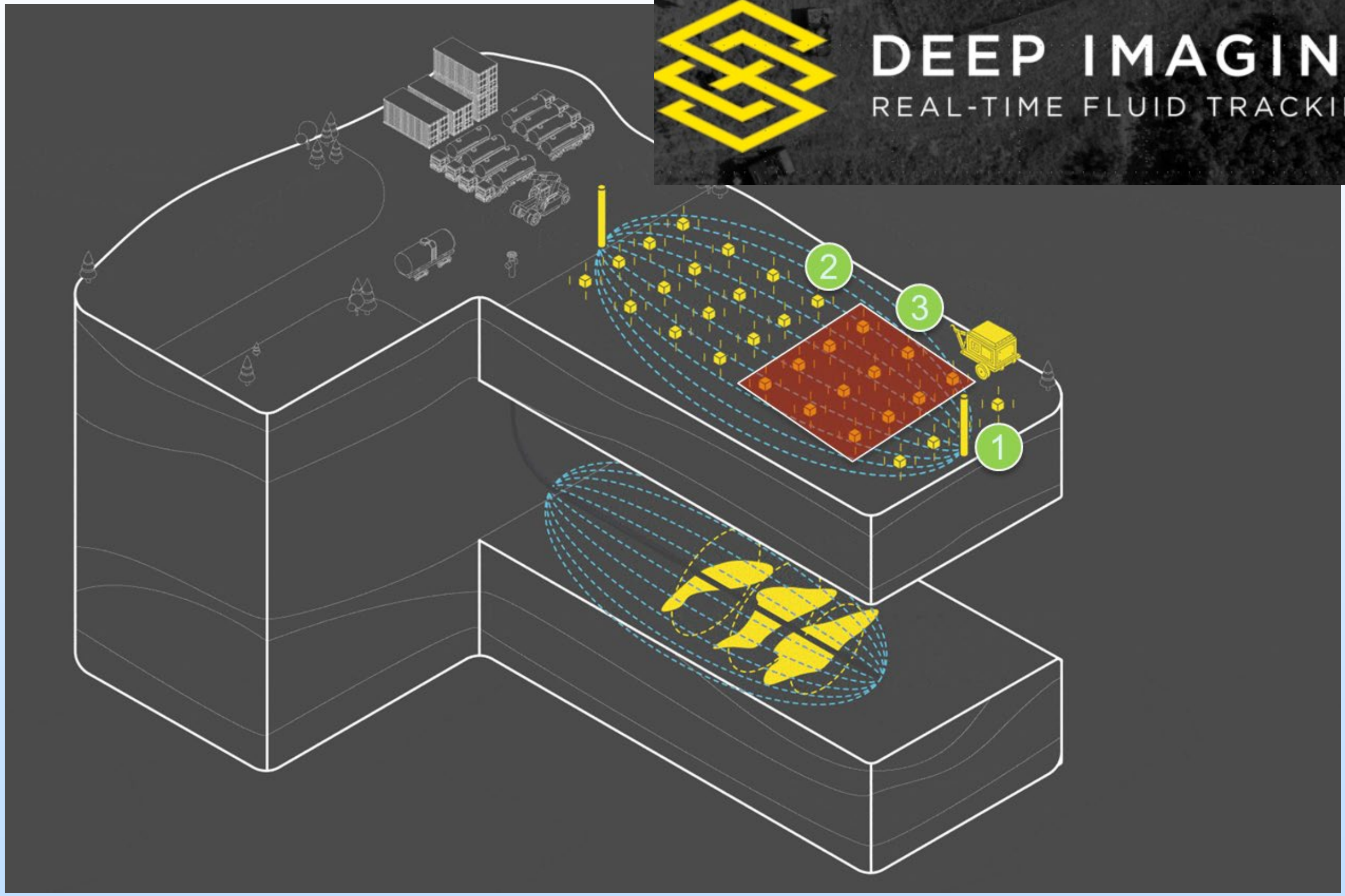
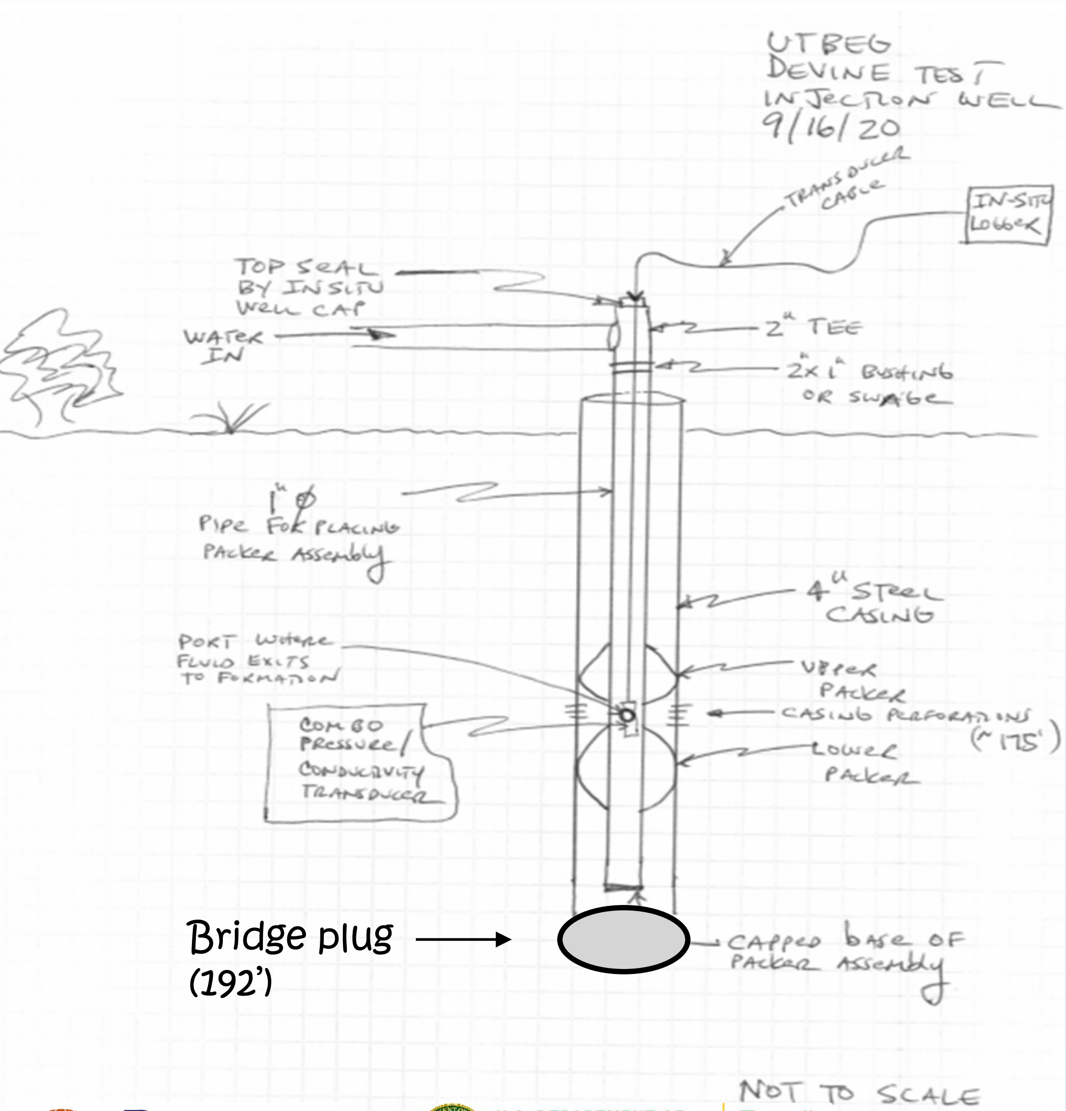
Used High Sampling Rate Surface-Based Controlled Source EM Geophysics Technology from DIT

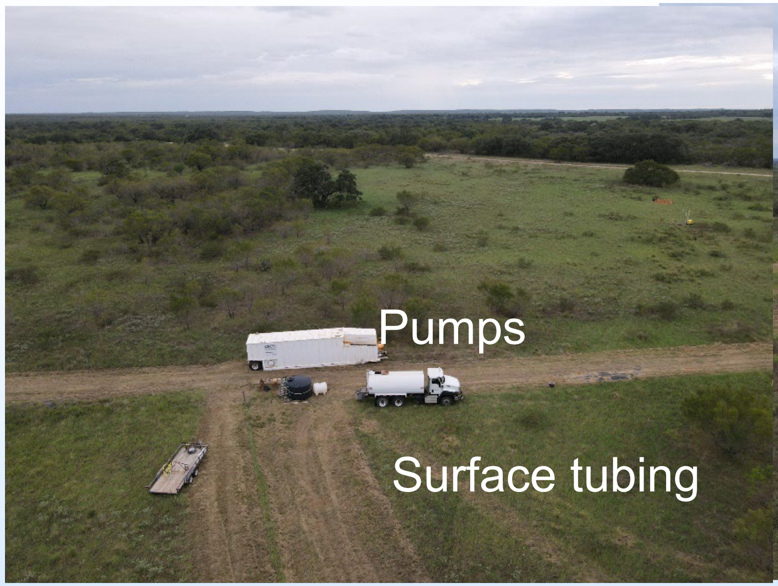
1. Transmitters installed on surface and electrical current is transmitted into the ground creating an EM field
2. A swath of receivers are turned on over the area being monitored and record a baseline measurement before injection commences.
3. Voltage changes are measured at <u>50 K samples per second</u> during the injection
4. Signals are processed for data quality
5. The baseline signal is subtracted from recorded signal each time step (32 seconds)
6. **The differences are imaged**

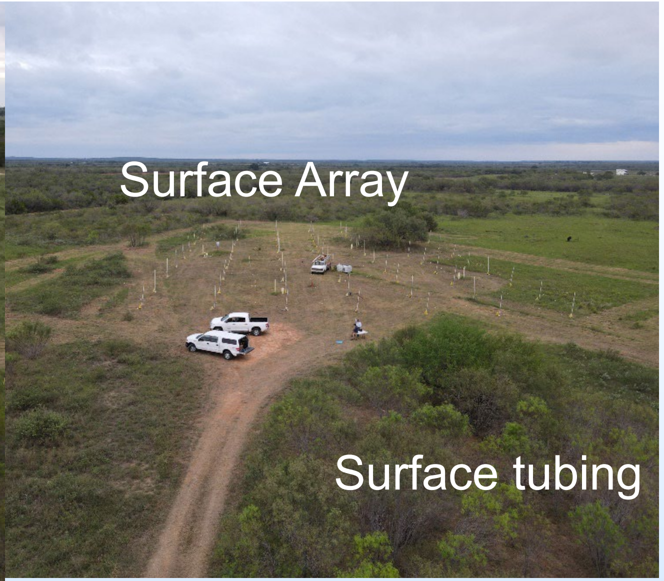


DEEP IMAGING
REAL-TIME FLUID TRACKING

Field Testing - Infrastructure

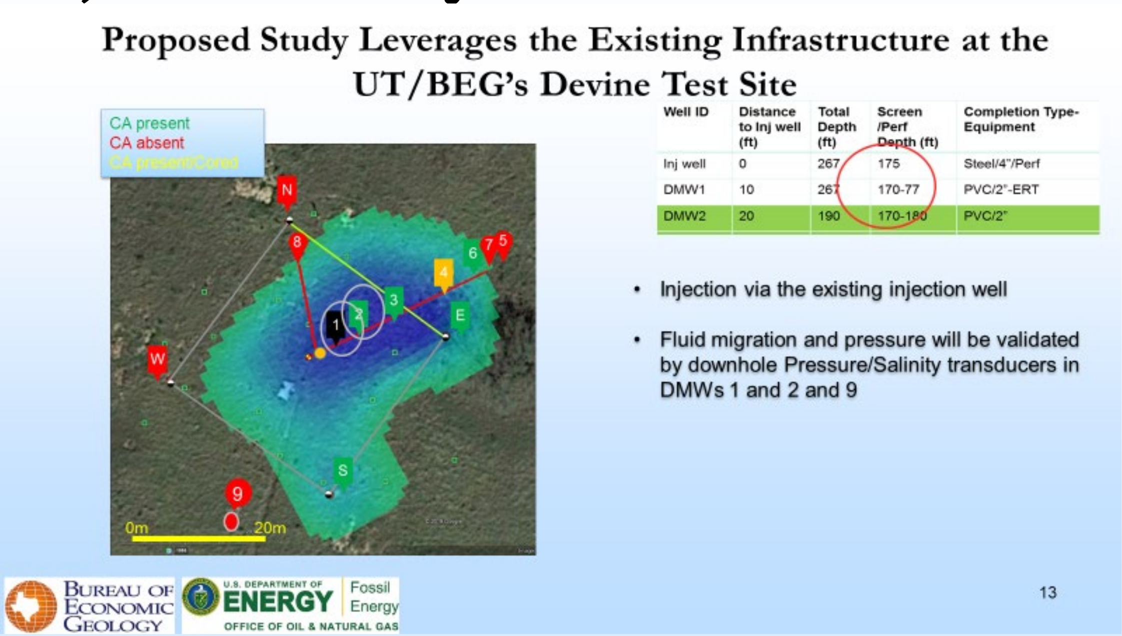






Planned and Executed Ten Injection Cycles at DFPS in 2022

Injection Cycle No.	Date (day/month/year)	Injection Scenario	Injection Slug	Refilling start time (hour: minute)	Refilling finish time (hour: minute)	Shut-in time (hour: minute)	Injected Volume (US Gallons)
1	1/21/2022	Repeating 9/20/2020	Freshwater	9:28	10:48	15:14	1126.02
2	1/23/2022	Flow-rate Test	Freshwater	11:31	11:41	16:50	603.38
3	1/24/2022	Freshwater Injection	Freshwater	12:00		16:35	952.1
4	1/26/2022	Freshwater+Chase Freshwater Injection	Freshwater	12:00	12:03	17:56	1200.2 (freshwater)
5	1/27/2022	Saltwater+Chase Freshwater Injection	Small Saltwater Slug+Large Freshwater Slug	12:00	12:06	18:06	215.6 (saltwater); 990 (freshwater)
6	1/28/2022	Saltwater+Chase Freshwater Injection	Large Saltwater Slug+Small Freshwater Slug	14:15	12:08	20:09	1000 (saltwater) 200.1 (freshwater)
7	1/29/2022	Freshwater Injection	Freshwater	11:20	14:25	23:07	2149.5
8	1/31/2022	Freshwater Injection	Freshwater	11:23	11:25	18:33	729
9	2/1/2022	Freshwater Injection	Freshwater	8:15	11:31	18:28	3485.4
10	2/2/2022	Freshwater Injection	Freshwater	8:51	8:16	13:00	1262.4



<u>For this presentation we will focus mainly on Jan 26 and 27 data:</u>

1. January 26, 1200 gal freshwater
2. On January 27, repeated the January 26 injection

with 200 gal freshwater, 200 gal 2500 ppm saltwater, and 800 gal freshwater

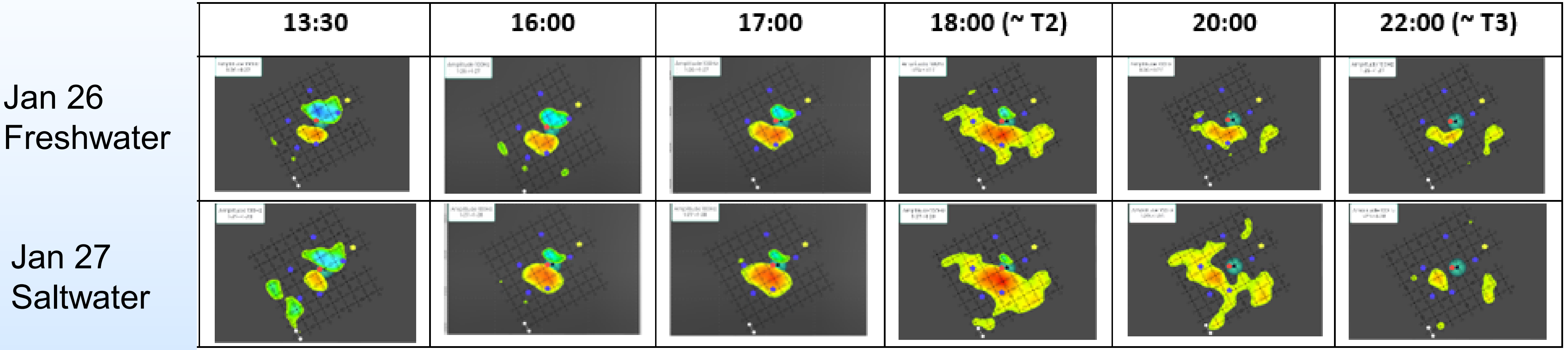
Exemplary Animated Data - January 26 Injection

Collected surface-recorded scattered electric field |E(t)|-|E(0)|, together with flow-rate and bottomhole pressure and salinity changes.

Observed:

- Rapid response in the first 10 min into the injection
- Signal grows much more prominently mid to end of high flow rate times, and decreases after the shut in.

Freshwater vs. Saltwater Injection at High Flow Rate and During Shut-in



Saltwater at the perforation on 1/27 4gpm

Start of Shut in

- Signal strength and trend appear the same after flowrate reaches 4 gpm on both days
- Signal grows during injection and subsides during shut-in
- Effect of 2500 ppm saltwater is minimal on magnitude of E field

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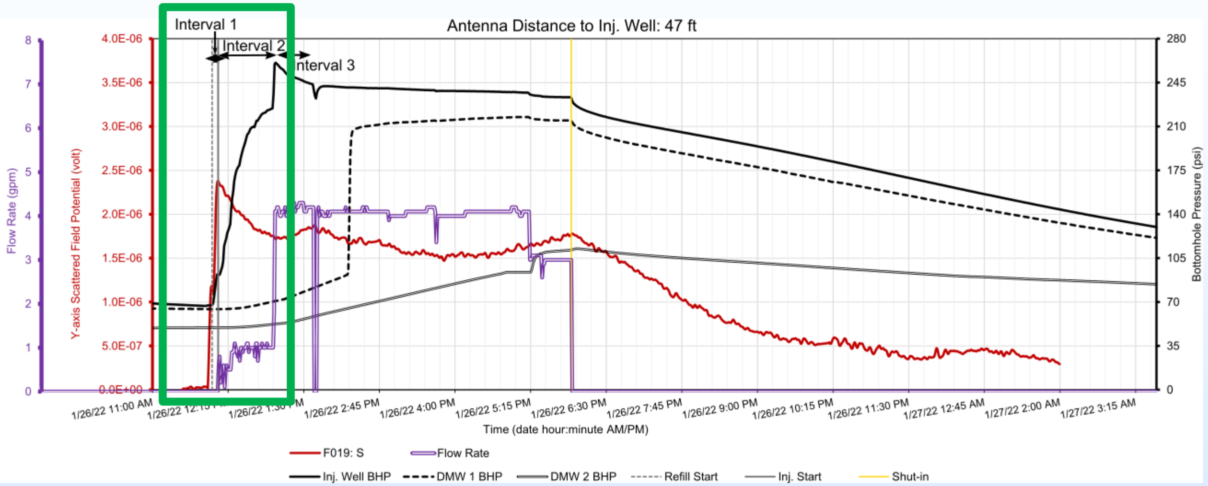
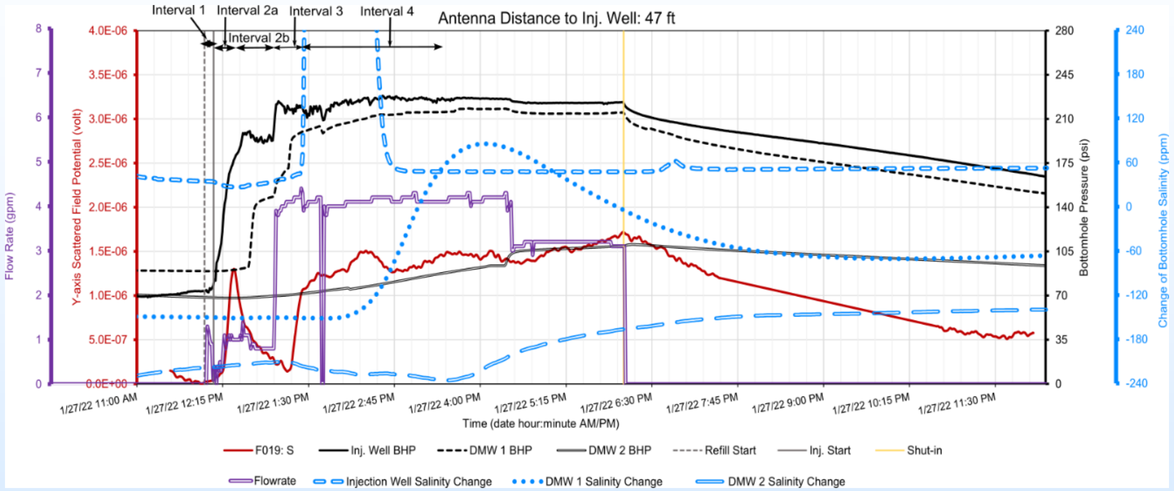
Scattered E Field at a Representative Receiver

Freshwater - January 26



Saltwater - January 27



Focusing on Low Flow Rate

Salt effect is dominated by Flow rate

Interval 1/2:

- Change in E trace is first detected with minimal injection volume,
  - Syphon effect with opening of wellhead valve

Interval 2/3:

- Signal drops and rises on but more noticeable on 1/27,
  - possibly due to channeling after multiple rounds of injections before 1/27
    - compare max injection well BHP for two days

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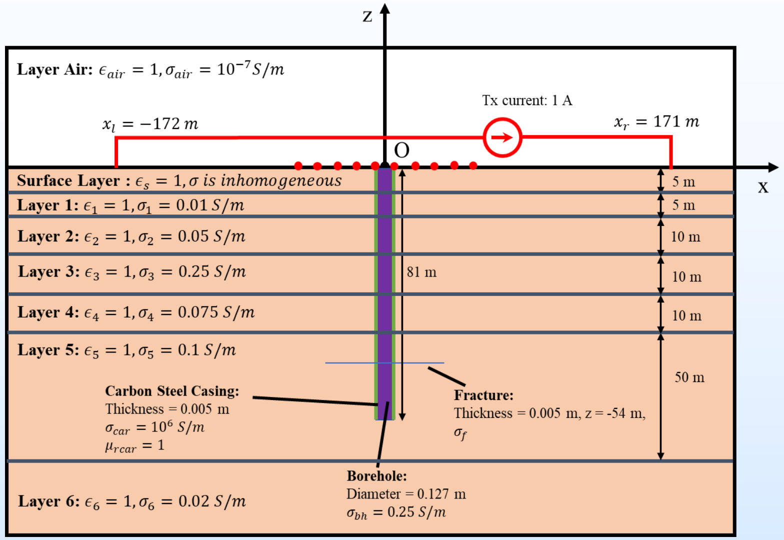
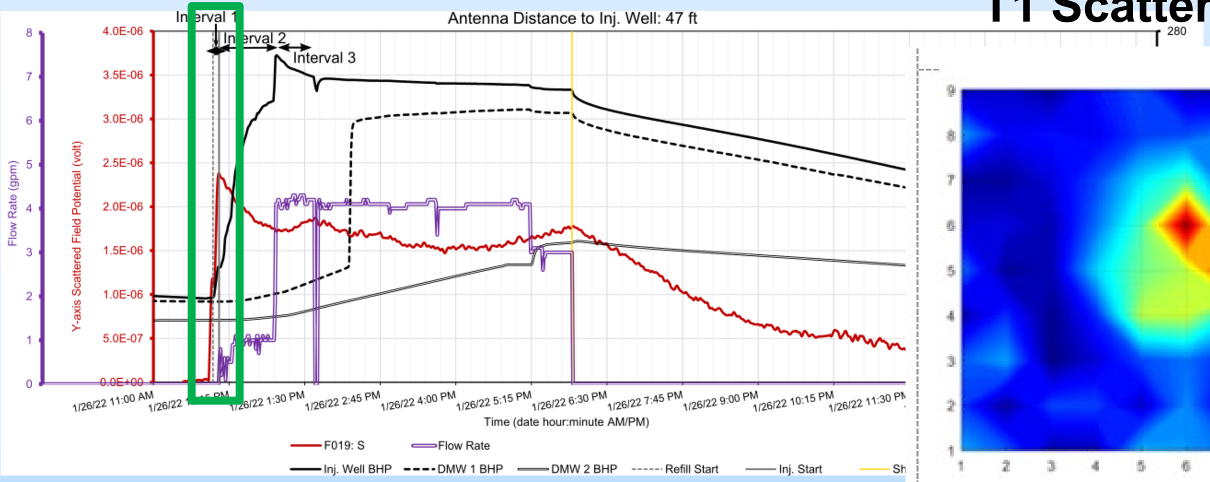
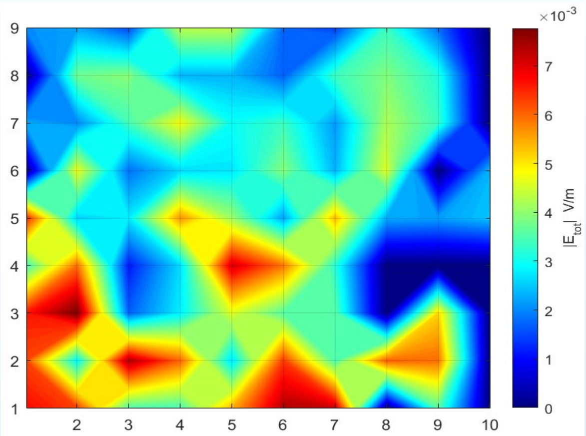
Forward Modeling of the Observed E Fields

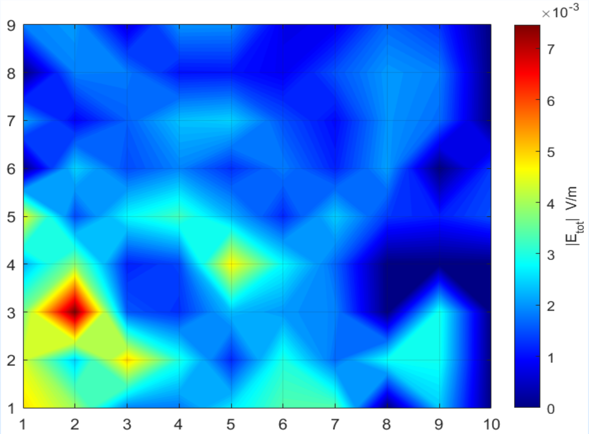




Total field data



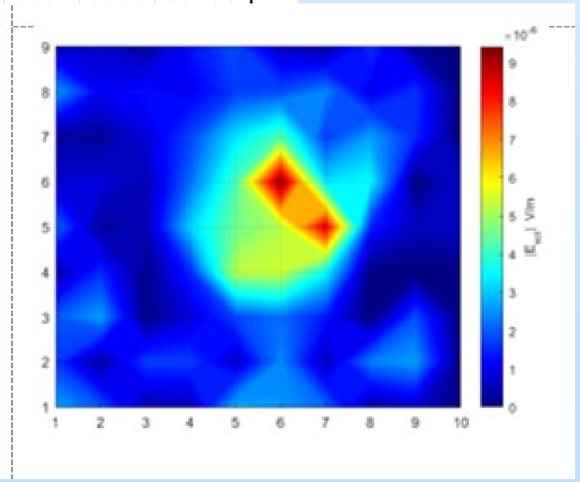
Total simulation data



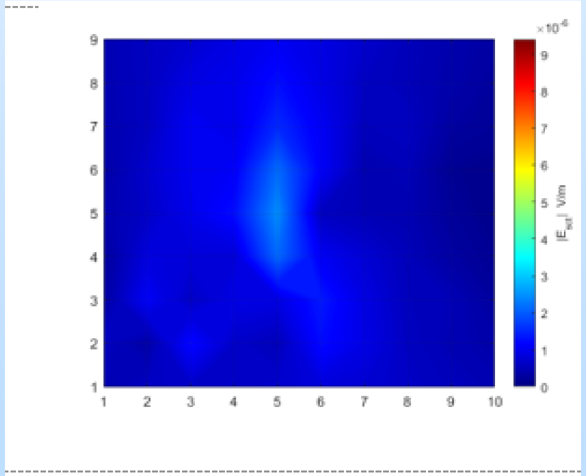
mismatch%

29%

T1 Scattered field



Scattered simulation



T1 mismatch%

228%

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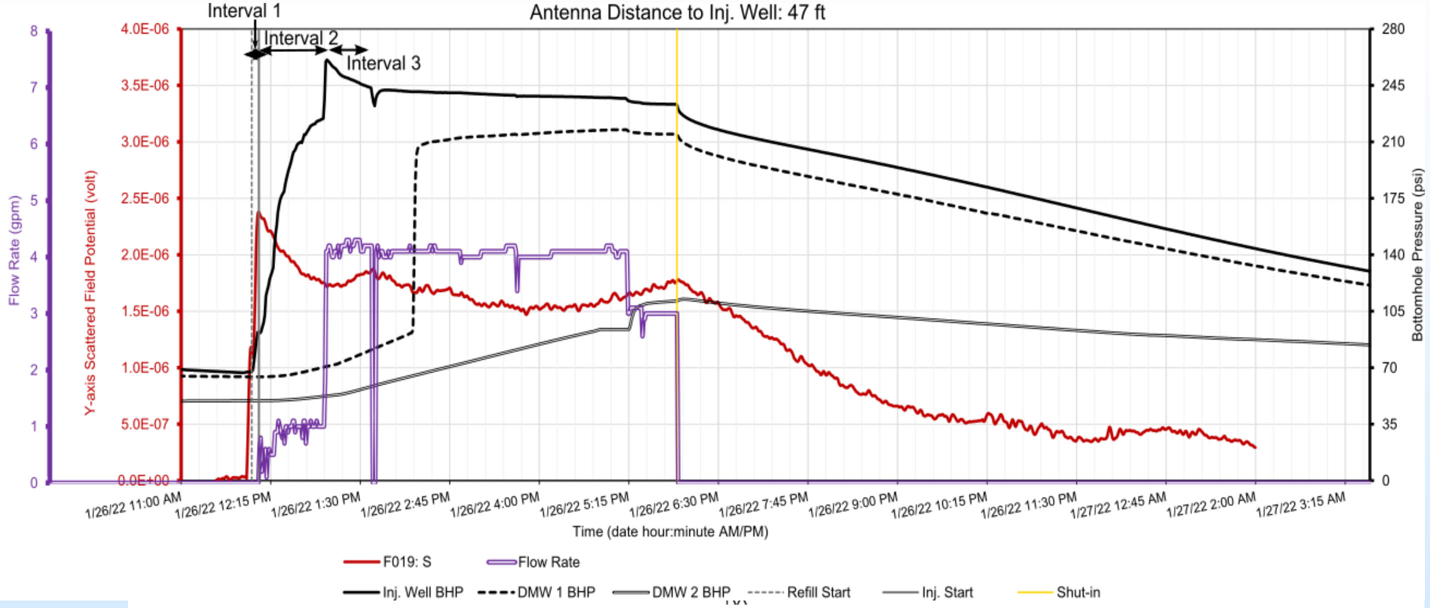
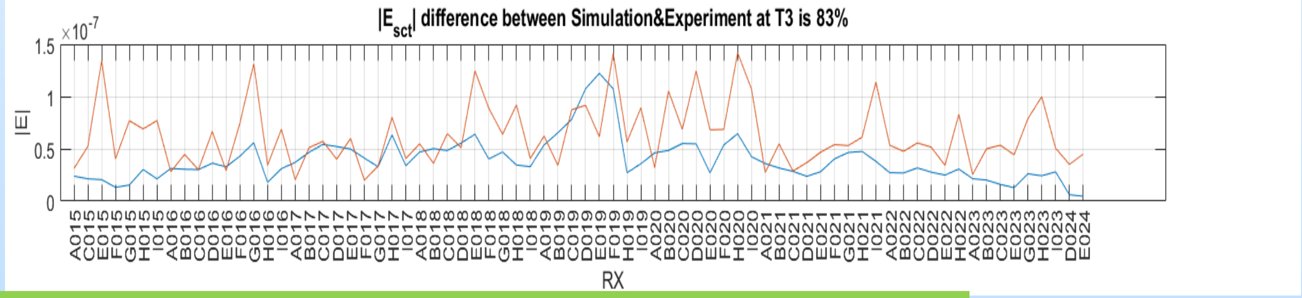
EM Forward Modeling: Mismatch at T1, T2, and T3

Injection time and assumed radius and conductivity (S/m)	Time	Mismatch (Average of all receivers)
T_1, 1.3 m, 40	12:18	228%
T_2, 7.65 m, 10	17:33	59%
T_3, 3.0 m, 40	22:26	83%

T1 T2 T3





Minimum mismatch at T2 compared to T1 or T3.
T2 is max dilation

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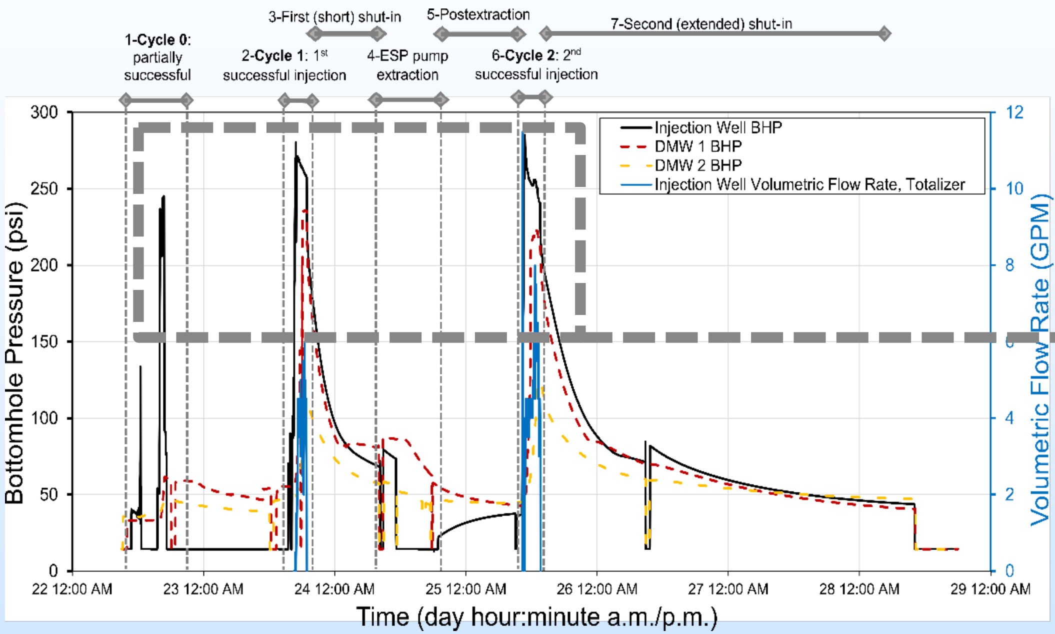
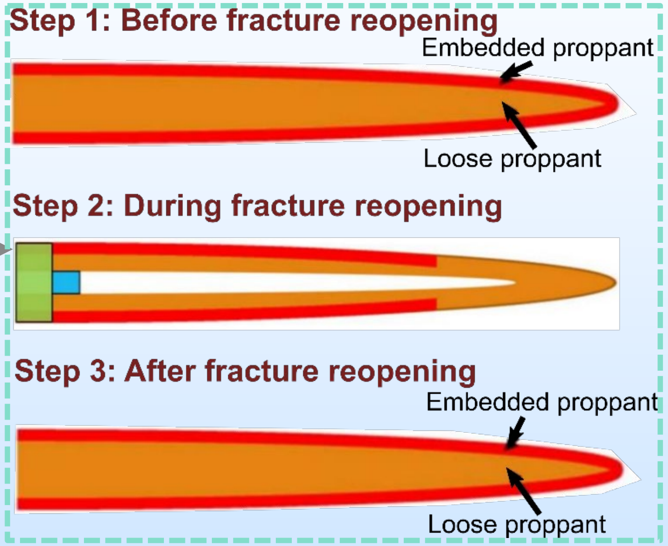
Geomechanical Model and Post-Shut-in Pressure Transient Analyses

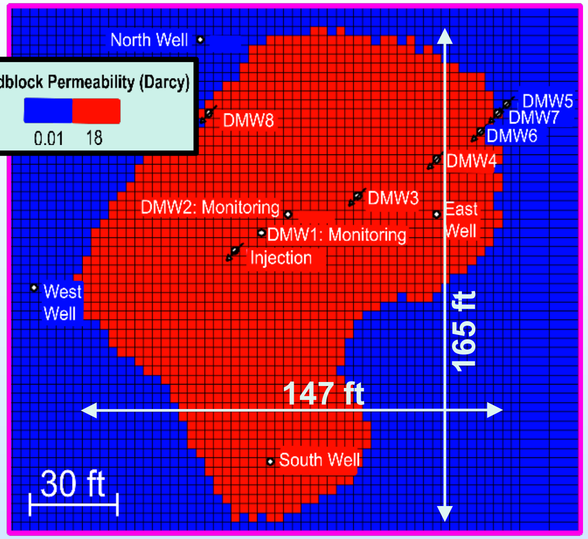
- Used injection test data to calibrate the hydromechanical properties of the formation through history matching and to develop tools for design of the future injection scenarios at the DFPS.



Large change of fracture permeability during fracture reopening (Step 2)



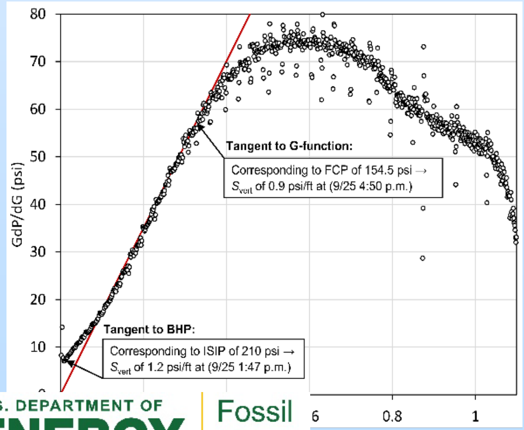
Plan view of model at fracture depth



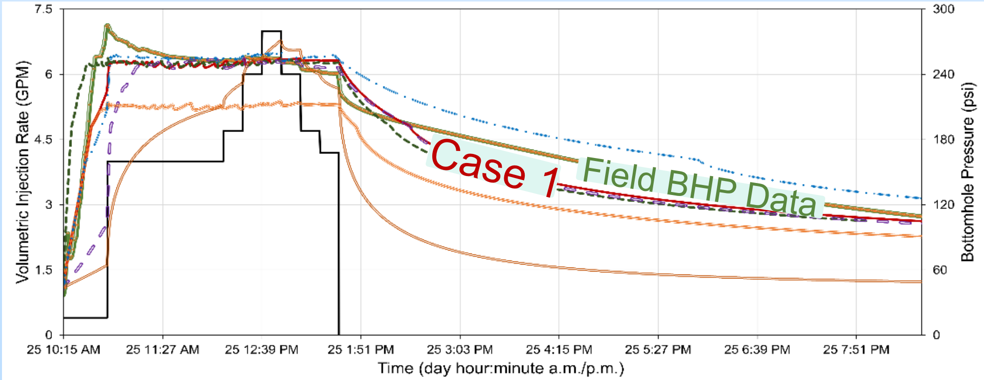
G-Function Pressure Analysis to obtain S_{vert}:

S_{vert} from FCP=0.9 psi/ft

S_{vert} from ISIP=1.2 psi/ft



History-Matching Parameter	Case 1
Initially open area of HF (ft^2)	1076
Fracture Initiation Stress (psi)	60
S_{vert} (psi/ft)	1.08
Formation k (mD)	0.15



Matched Inj. Well BHP; Haddad, Ahmadian, et al. 2021, 2023

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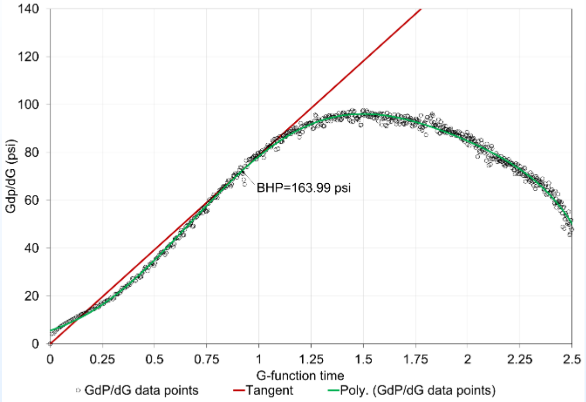
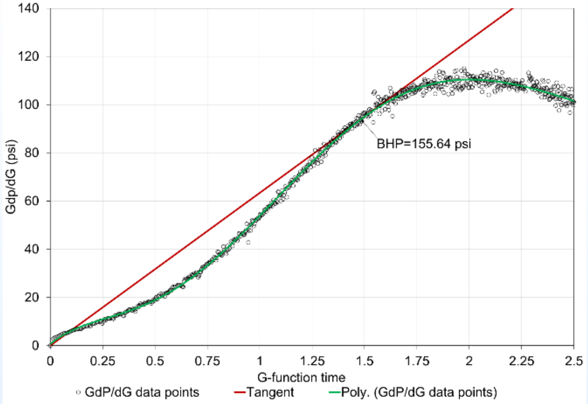
Post-Shut-in Pressure Transient Analyses and Geomechanical Modeling of Jan. 2022 Injections

1. G-Function Pressure Analyses of various inj. cycles on Jan. 2022, led to S_{vert} = 0.88±0.04 psi/ft

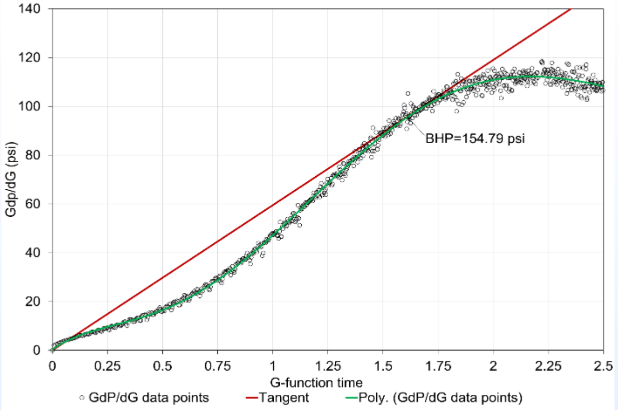
Jan. 23



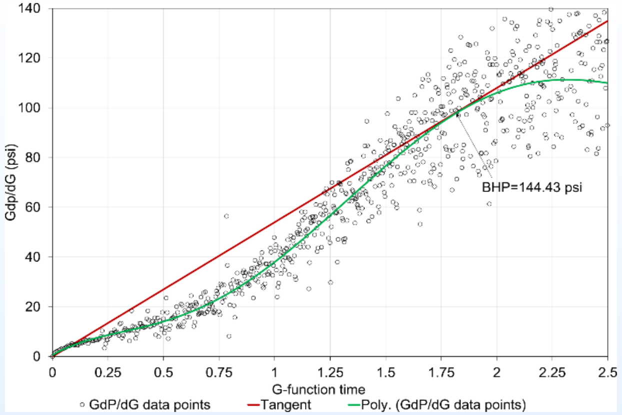
Jan. 24



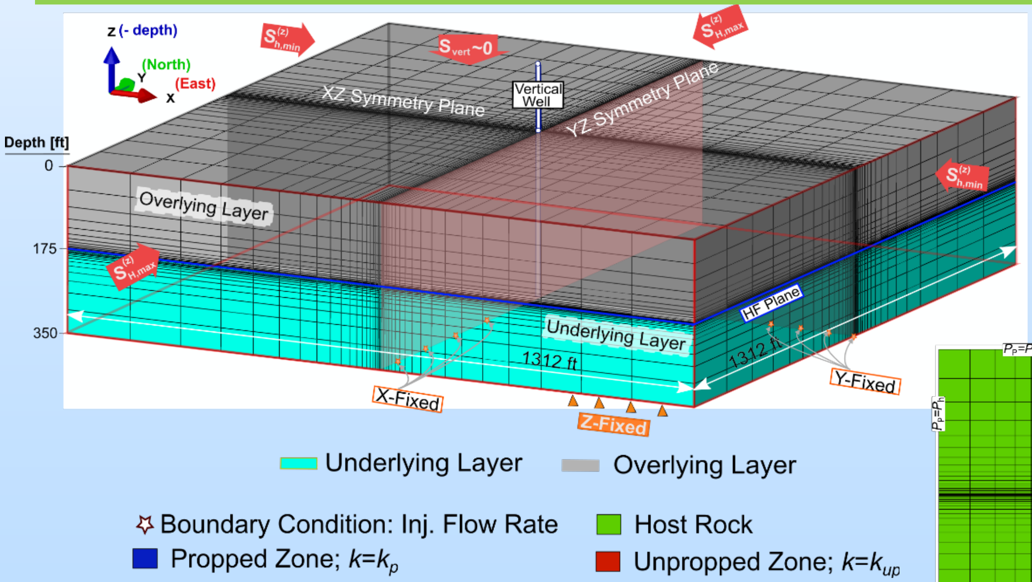
Jan. 26

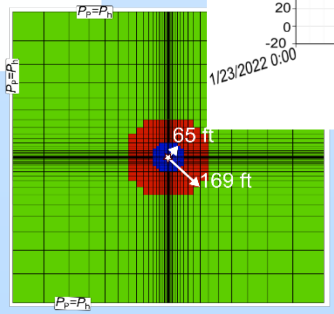


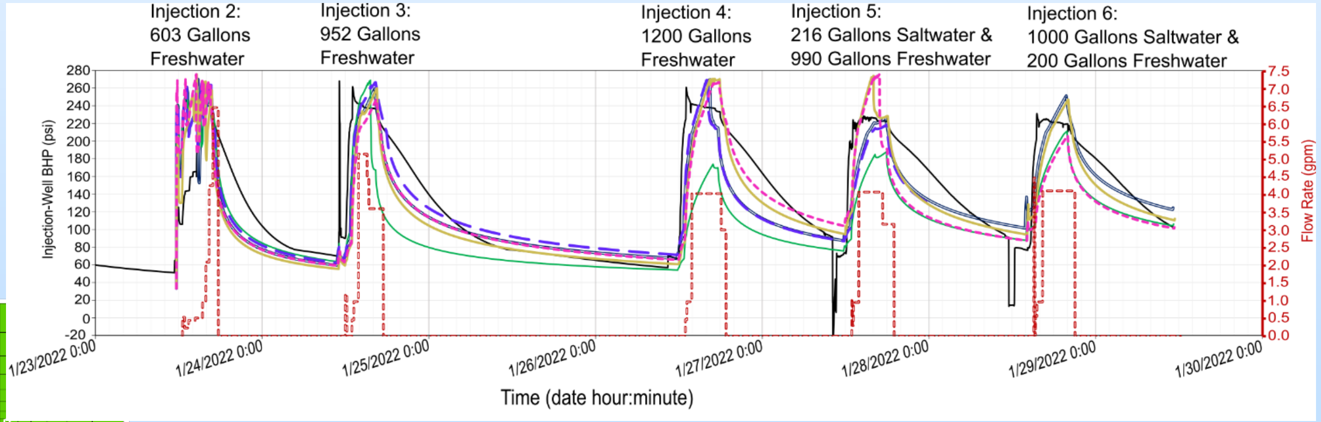
Jan. 27



2. Geomechanical models for Jan. 2022 injections: upgraded model to include propped and unpropped frac. permeabilities







Best fitting model: k_f=300 μD, k_{up}=30 mD, k_p=300 mD

Summary Slide

- A large pressure change within an EAP pack can be detected in lab and field
- A strong correlation between flow rate, fracture dilation, EAP pack compaction, and electric potential was observed using Real-time CSEM
- The fracture dilation/flow rate effect dominates the contribution of low salinity changes
- Our EM models based on only conductivity changes led to a large data mismatch especially at early times
- We are currently investigating the reason for this mismatch

Plans for future testing/development/commercialization

During the remainder of this project:

- Complete data analysis
  - Constrain inversions using salinity and DAS data and geomechanical model outcomes
  - Reduce mismatch in the models

After this project

- Compare sand and EAP in a parallel field study at DFPS
- Couple geomechanical and EM models

Scale-up potential

- Scale-up is low risk because we used commercial equipment
- CSEM signal at reservoir scale are routinely detected by the DIT during fracturing

Outreach and Workforce Development Efforts/Achievements

- Graduated 5 students and 3 PDs
- Promoted one PD to RA, 2 PDs found jobs in industry
- Four students interned in various companies
- Collaborated with DIT on developing a commercial surveys and analysis tool
- DFPS suitable for future work in fluid flow monitoring area
- Prepared 3 conference manuscripts and 2 journal articles so far (next slide)

Benefit to the Program

- The developed methods in this study lead to a better understanding of the extent of SRV, formation stress states, leakoff and invasion, helping with resource recovery and sustainability .
- Monitoring fluid flow is important in CCS, water management, solution mining of CE, P&A, E&P, and for a environmentally friendly resource use

Synergies to other works presented on Tuesday

- HFTS-1 Liner Refrac Project Update (FE0024292)
- Monitoring Well-to-Well Communication to Reduce Environmental Impacts (FWP-1022415)
- Fully Distributed Acoustic and Magnetic Field Monitoring Via a Single Fiber Line for Optimized Production of Unconventional Resource Plays (FE0031786)
- Novel 'Smart Microchip Proppants' Technology for Precision Diagnostics of Hydraulic Fracture Networks (FE0031784)

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2. Zhang, R., Sun, Q., Mao, Y., Cui, L., Jia, Y., Huang, W.F., Ahmadian, M. and Liu, Q.H., (2022). Accelerating Hydraulic Fracture Imaging by Deep Transfer Learning. IEEE Transactions on Antennas and Propagation. vol. 70, no. 7, pp. 6117-6121, doi: 10.1109/TAP.2022.3161325.
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Acknowledgements

NETL/DOE

- **Scott Beautz**
- Gary Covatch

The University of Texas- at Austin

- **Mahdi Haddad**
- Darwin Mohajeri

Duke University

- Liangze Cui
- Qing Huo Liu

University of North Carolina

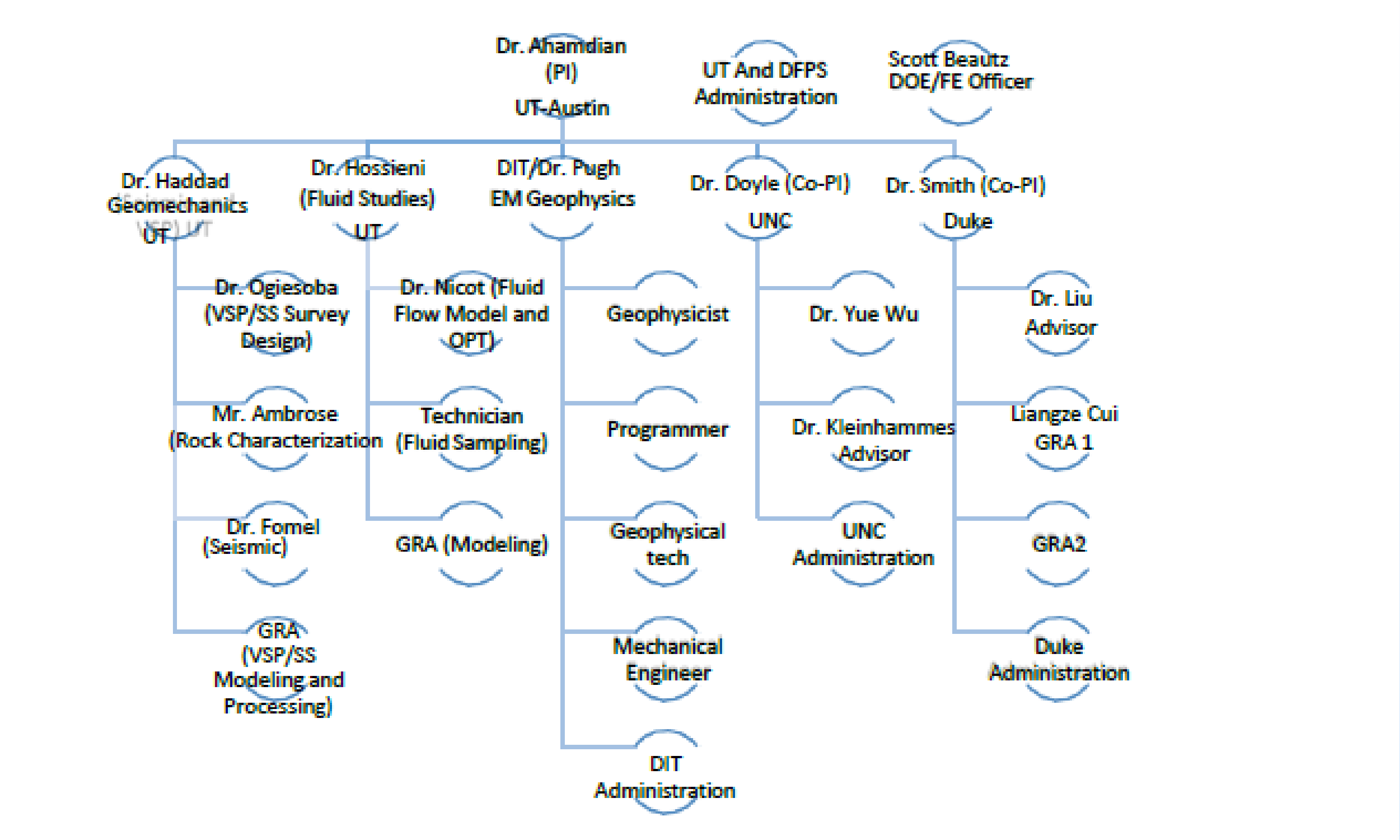
- **Alfred Kleinhammes**
- Patrick Doyle
- Yue Wu

DIT

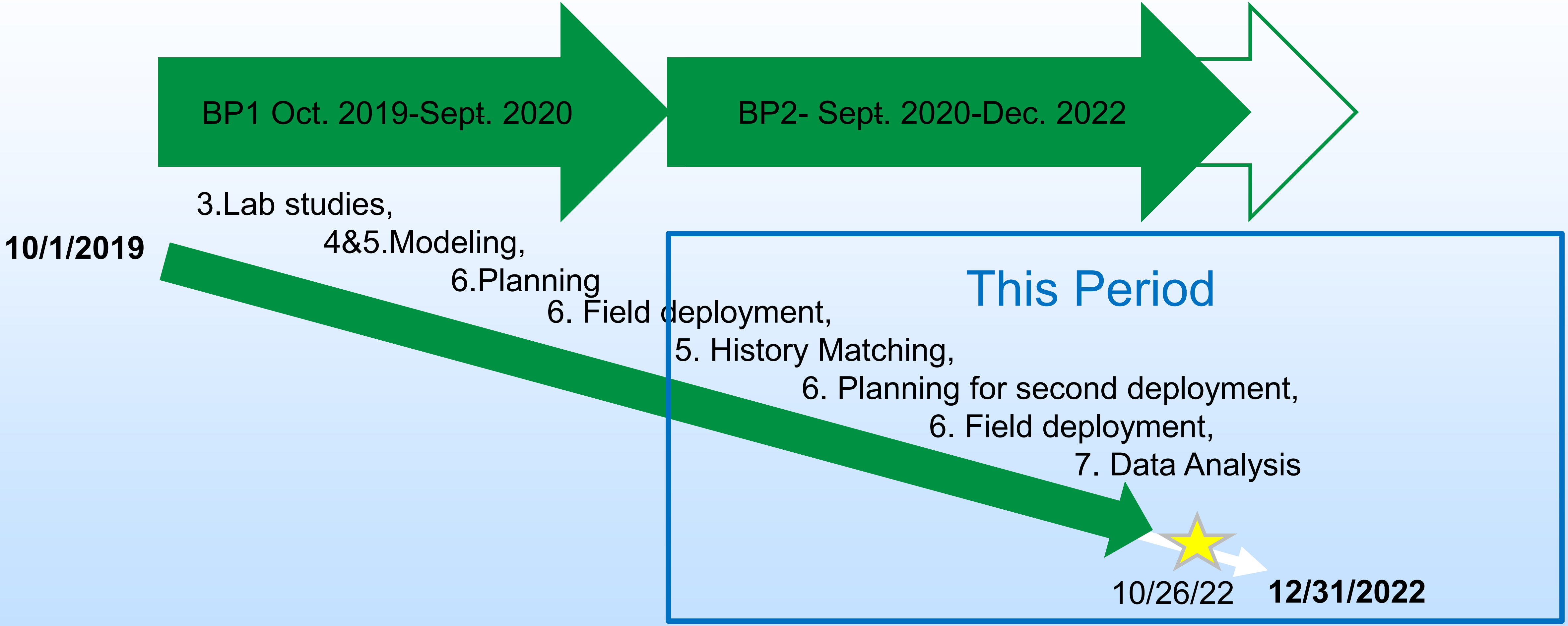
- **Jeffrey Chen**

Appendix and backup

Organization Chart



Technical Approach/Project Timelines



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Gantt Chart

Tasks		Leader/Backup	Q1 Y1	Q2 Y1	Q3 Y1	Q4 Y1	Q1 Y2	Q2 Y2	Q3 Y2	Q4 Y2	Q5 Y2	Q6 Y2	Q7 Y2	Q8 Y2	Q9 Y2
TASK 1: PROJECT MANAGEMENT AND PLANNING		Ahmadian & Co-PIs													
1.1	PROJECT COORDINATION AND COMMUNICATION	Ahmadian	A	A	A	A	A/B	A	A	A	A	A	A	A	A
1.2	PERMITTING & COORDINATION OF PILOT TEST ACTIVITIES	Ahmadian				C									
1.3	REPORTING	All	D	D	D	D	D	D	D	D	D	D	D	D	D
TASK 2: WORKFORCE READINESS FOR TECHNOLOGY DEPLOYMENT		Ahmedian, All					E								
TASK 3: EM RESPONSE OF LABORATORY FRACTURE MODELS AND INCORPORATION OF MIXING RULES		Kleinhammes, Ambrose													
3.1	ELECTRICAL MEASUREMENTS	Kleinhammes				F1									F2
3.2	ROCK CHARACTERIZATION	Ambrose				G									
TASK 4: APPLICATION OF EXISITNG SEISMIC AND EM MODELING TOOLS TO DEVINE		Liu, Fomel													
4.1	VSP/SEISMIC RTM VALIDATION	Liu, Fomel			H										
4.2	JOINT VSP/SEISMIC AND EM INVERSION	Liu				I									
TASK 5.0: DESIGN OF FIELD EXPERIMENT/SENSITIVITY ANALYSIS		Liu, Hosseini, Fomel													
5.1	FLUID FLOW MODELING	Hosseini, Nicot				J									
5.2	EM SENSITIVITY ANALYSIS	Liu				K									
5.3	VSP/SEISMIC SENSITIVITY ANALYSES	Liu, Fomel									L				
5.4	MULTISCALE/MULTIPHYSICS FORWARD MODELING	Liu					M								

Tasks		Leader/Backup	Q1 Y1	Q2 Y1	Q3 Y1	Q4 Y1	Q1 Y2	Q2 Y2	Q3 Y2	Q4 Y2	Q5 Y2	Q6 Y2	Q7 Y2	Q8 Y2	Q9 Y2
TASK 1: PROJECT MANAGEMENT AND PLANNING		Ahmadian & Co-PIs													
TASK 6: FIELD CONSTRUCTION/FIELD SURVEY STUDIES/DATA GATHERING		DIT, Hosseini, Ogiesoba													
6.1	FORMATION PULSE TESTING	Hosseini, Ahmadian				N					N				
6.2	VSP/SEISMIC SURVEYS	Ogiesoba, DeAngelo										O			
6.3	DEVELOPMENT OF STRATEGIES FOR REAL-TIME MONITORING	DIT				O						O			
6.4	SMART PROPPANT TEST 1: IN-SITU REMOTE PRESSURE TEST	DIT				O						O			
6.5	SMART PROPPANT 2: IN SITU REMOTE SALINITY TESTS	DIT										O			
6.6	TRACING FLUID BREAKTHROUGH	Nicot										O			
TASK7: DATA PROCESSING AND INTERPRETATION		Liu, Fomel, DIT													
7.1	EM INVERSION OF FIELD DATA	Liu, DIT													P
7.2	VSP/SEISMIC IMAGING AND MIGRATION	Liu, Fomel													Q
7.3	HISTORY MATCHING OF FLUID FLOW MODELS FOR TRACER	Hosseini, Nicot													R
7.4	JOINT VSP/SEISMIC AND EM INVERSION	Liu, Fomel													S

Back ups