The DOE SMART Initiative

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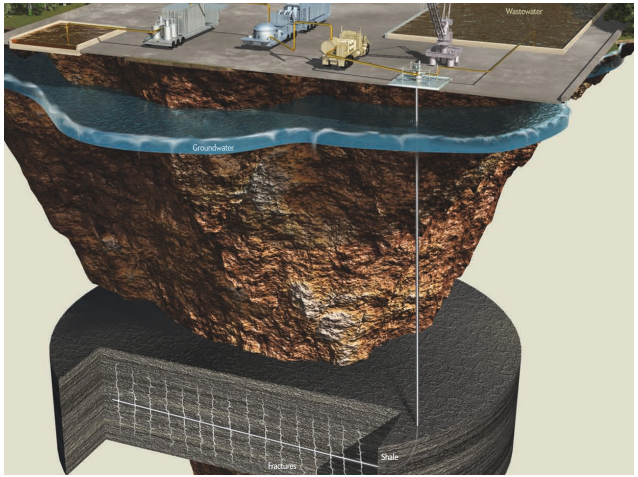
We are on the cusp of change in how we manage the subsurface

- We depend on the subsurface but we are relatively blind

- ***Full value of data is not realized:***
  - ***Lack of theory to connect data to decisions***
  - ***Data processing is overwhelming or not timely***

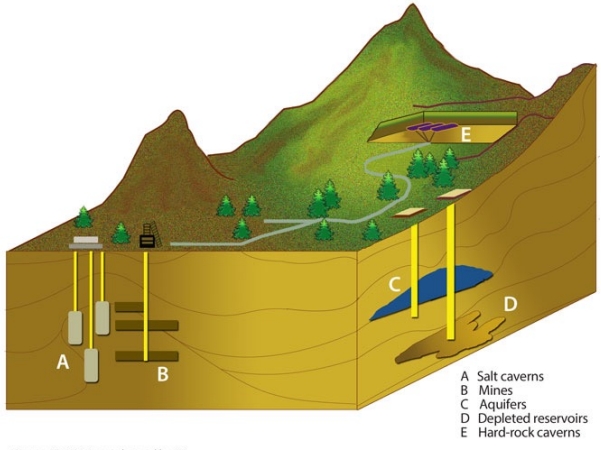
- We are on the cusp of major change:
  - Improved understanding through ongoing field experiments
  - More ubiquitous monitoring
  - More timely interpretation of multimodal data through machine learning

Empowering people to focus on the decision-making, rather than the laborious data-processing/integration = SMART

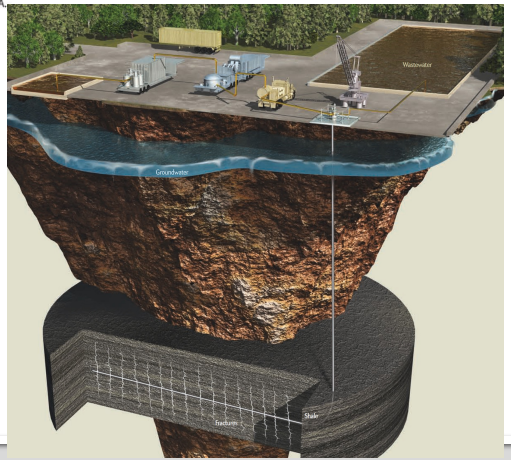


Civilization depends upon the subsurface…

- Water
- Infrastructure
- Resource extraction:
  - Minerals
  - Oil and Gas
  - Geothermal
- Natural gas storage
- Etc…



Source: PB-KBB, inc., enhanced by EIA.



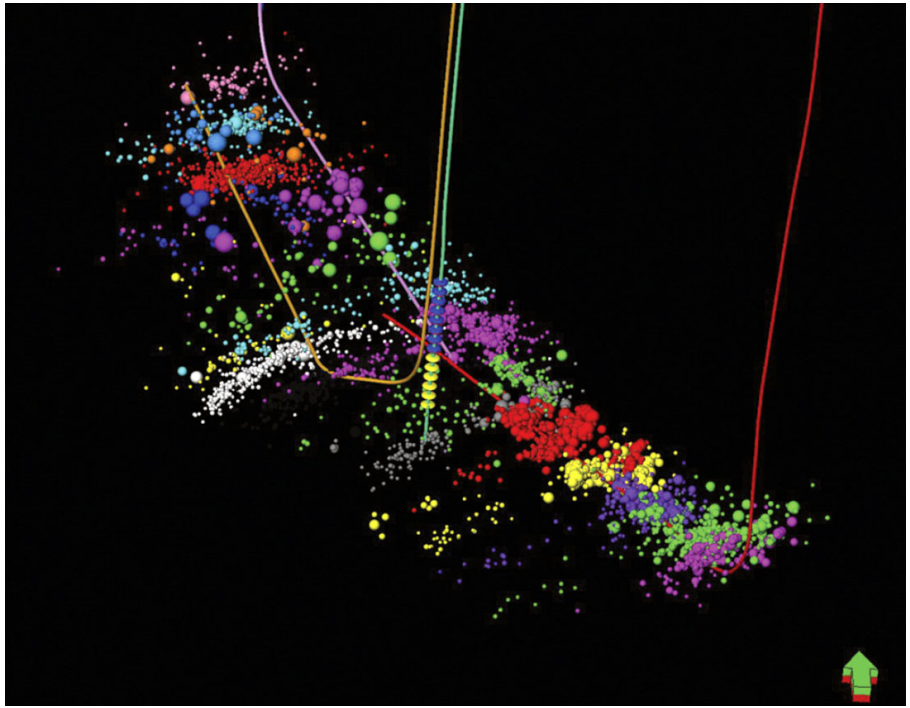
U.S. EPA

But we are often blind – That can have consequences

"South Korean government panel has concluded that a magnitude-5.4 earthquake that struck the city of Pohang on 15 November 2017 was probably caused by an ***experimental geothermal power plant***." (Nature online 2019)

We do have methods for characterizing the subsurface

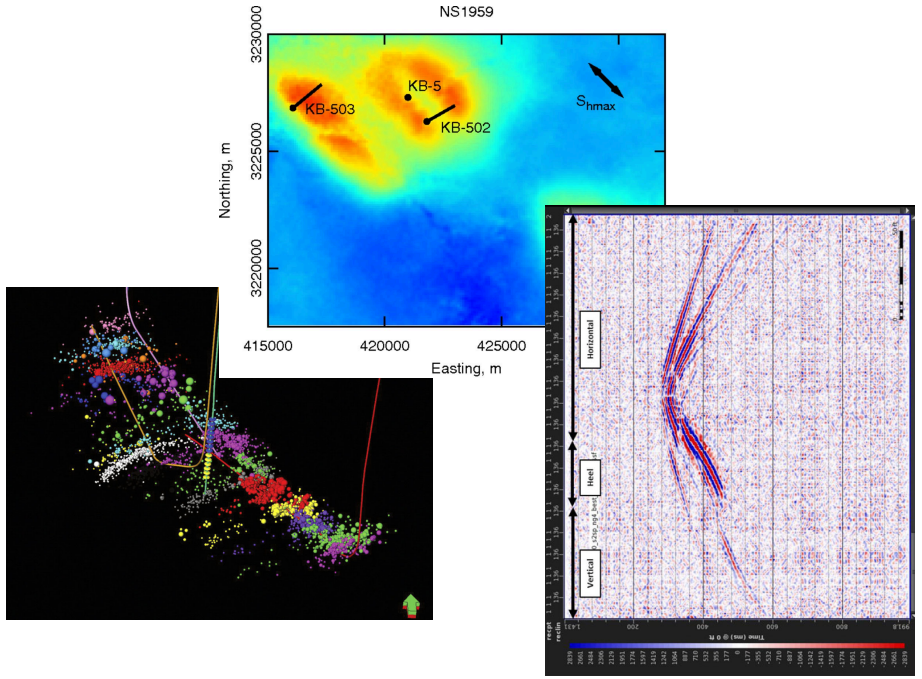
- Microseismic
- Seismic imaging
- Pressure/temperature at specific points
- Temperature by distributed temperature sensing (DTS)
- Distributed acoustic/strain by distributed strain sensing (DAS/DSS)
- Electromagnetic (EM)
- Electrical Resistance Tomography (ERT)
- Gravity, surface deformation, …



BUT: Many subsurface activities are executed with only one or *none* of these!

How can we be data starved? We have the technology…

- Data collection can be expensive
- Data interpretation may not be timely
- Lack of people to interpret the data
- Sometimes we lack the fundamental theory to connect data to interpretation and ***action***
  - ***Especially true of multimodal data interpretation***

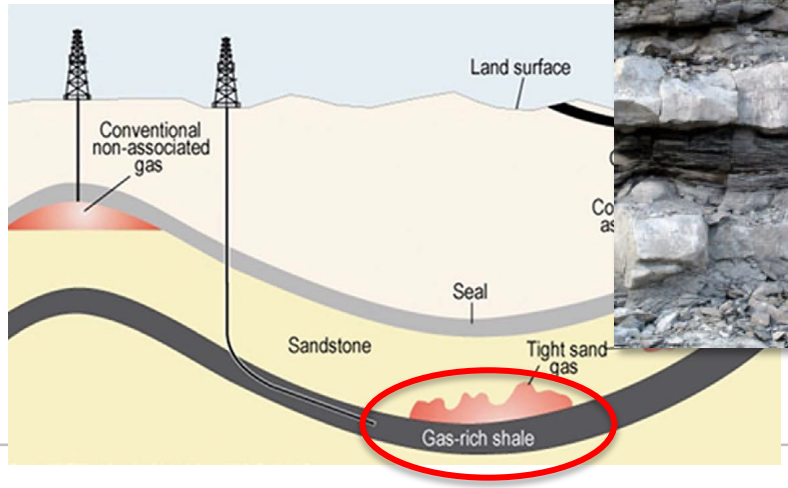


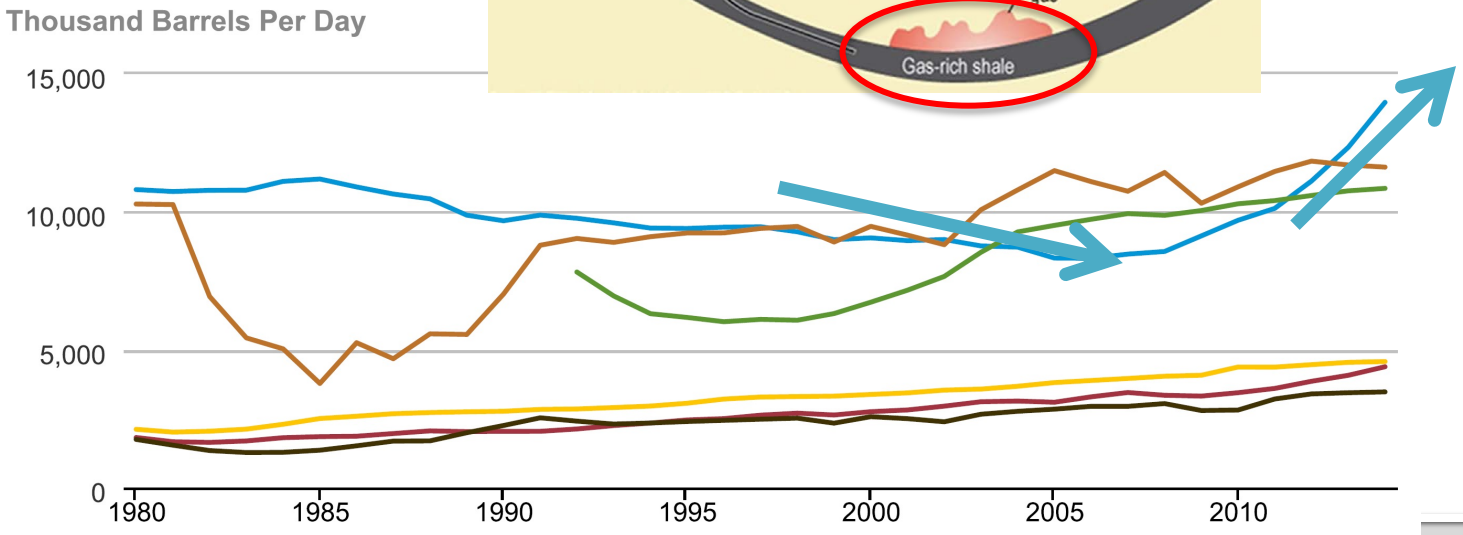
Perception that subsurface data collection is expensive and not linked to decisions

We will now look at examples from shale oil/gas and geothermal

Shale oil and gas: Huge impact, many questions

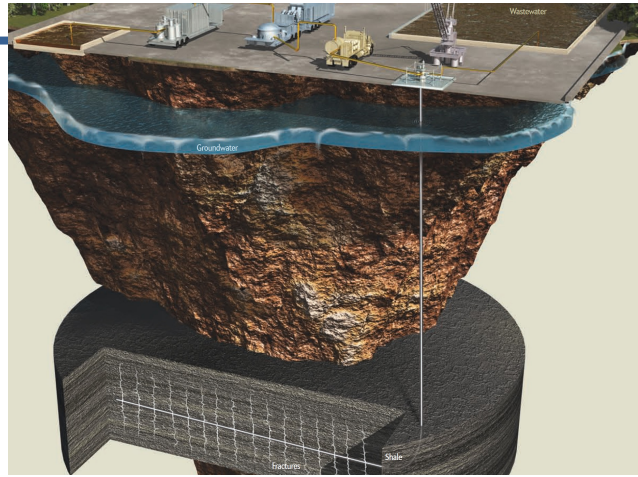
- Huge reserves
- Complex geology with low permeability
- Many gaps in understanding of the fundamental physics

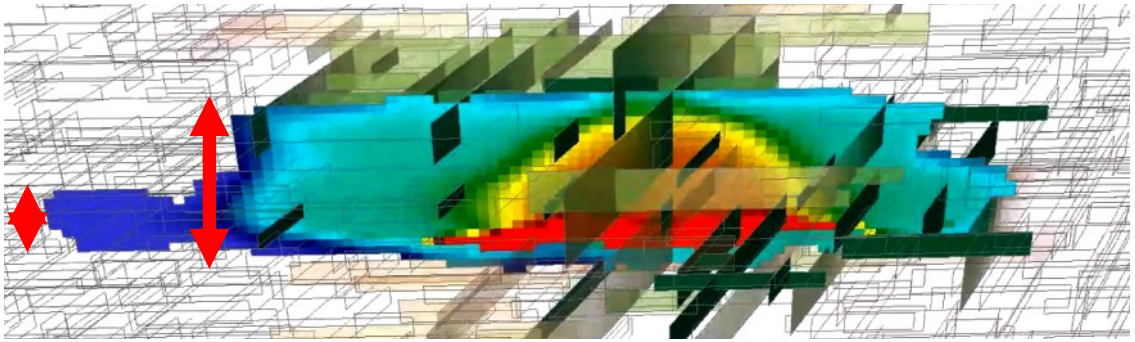




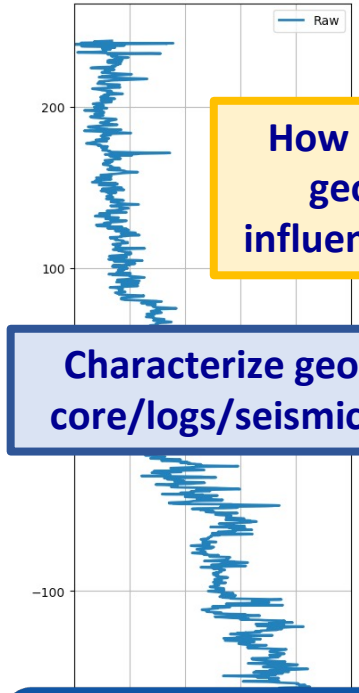
Challenges in Shale Oil and Gas Development

- Minimizing environmental footprint:
  - Reduce water use, water disposal
  - Height control to avoid contaminating overlying formations
- Economic optimization:
  - Landing depth? How may stimulations per well?
  - Best fluid rheology and pumping rates?
  - Avoid well interference
  - Understand height control to achieve optimal stimulation



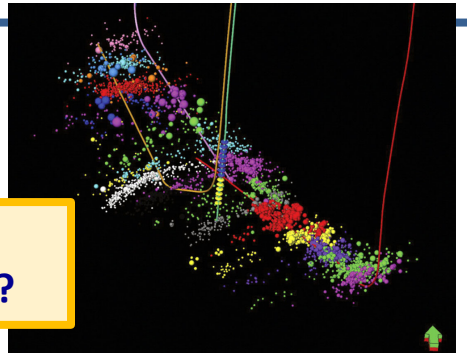


Typical Design Process in Shale Reservoirs Today



How does characterized geochem/geomech influence fracture growth?

What do geophysical observations really tell us?



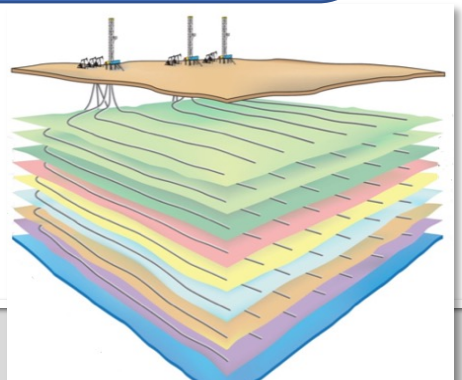
Characterize geology core/logs/seismic/etc. → Design and execute stimulation → Monitor stimulation → Produce from well

Experimentation

Data very local, interpretation not timely

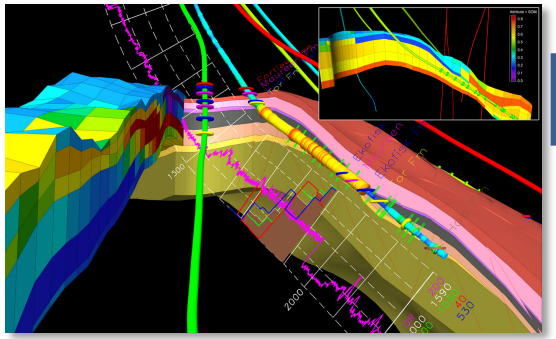
Full value of data not realized

How does well-to-well interaction affect performance?

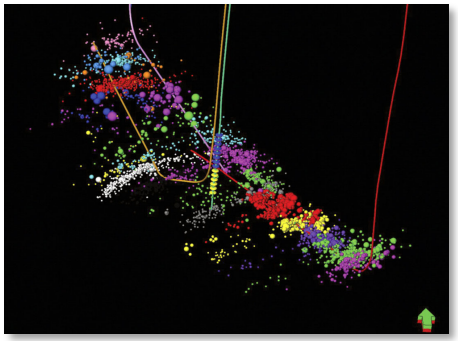


You need something to connect the observations to actions

Measurements ahead of time



Geophysical observations
E.g.: Microseismic



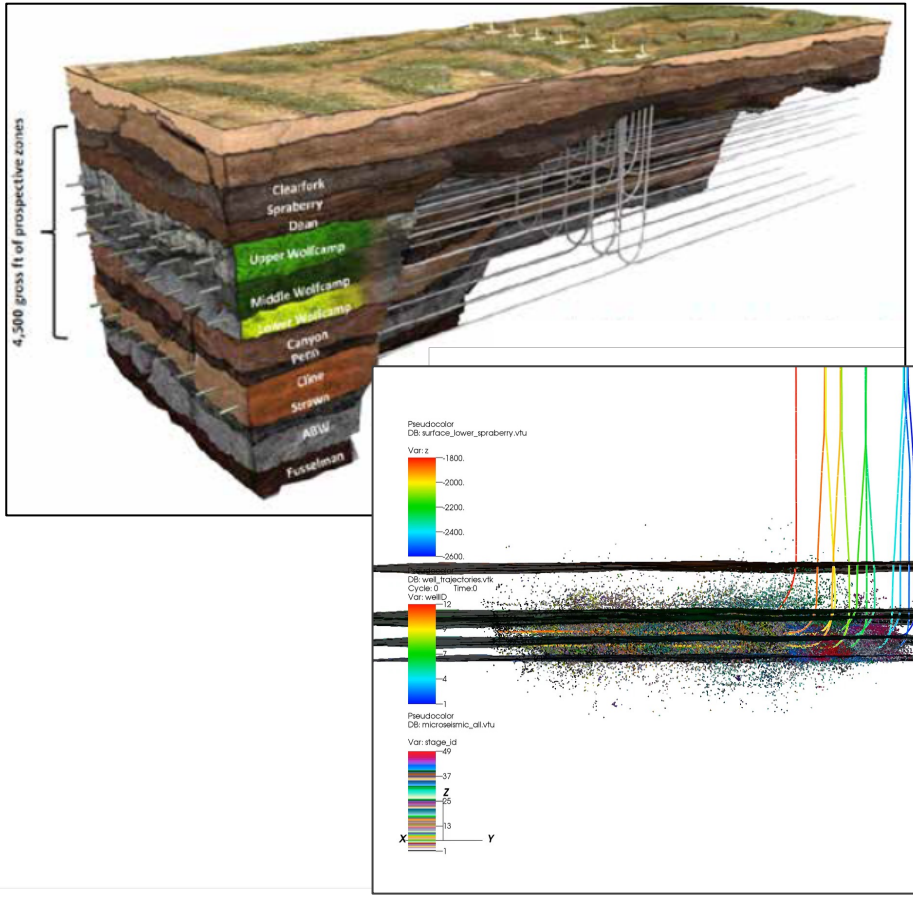
?

Decisions
E.g.: Pumping rate

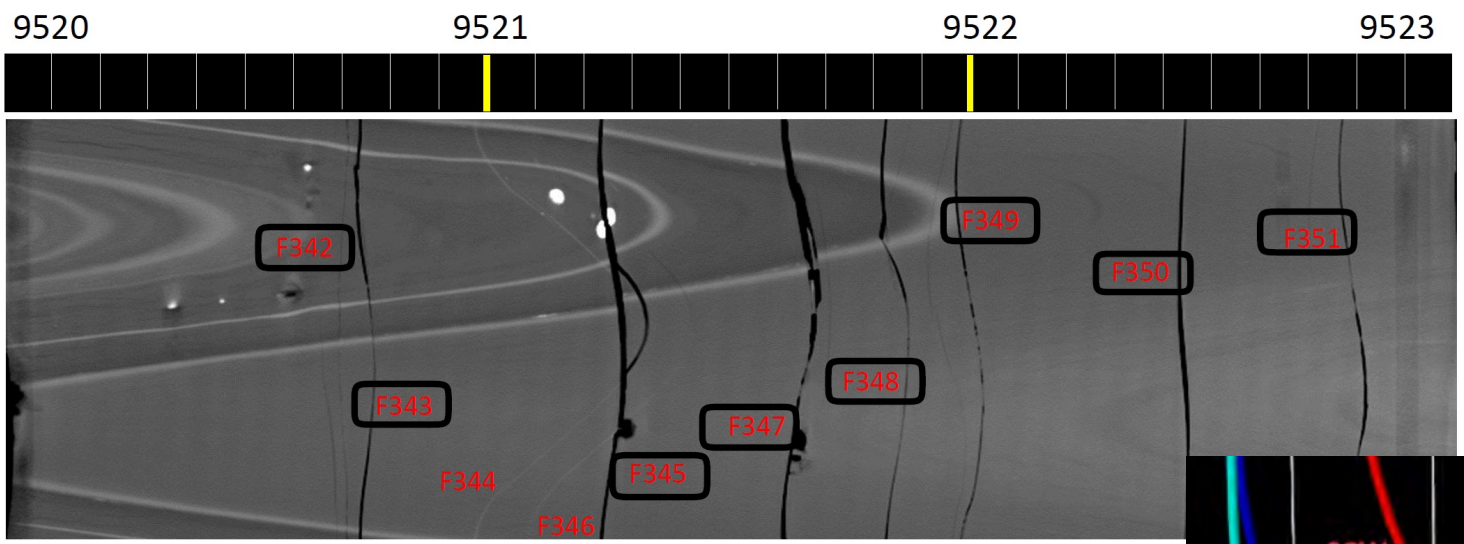
We often lack the fundamental theory to connect data to interpretation and ***action***

HFTS Field Experiment – Filling in a blind spot in the subsurface…

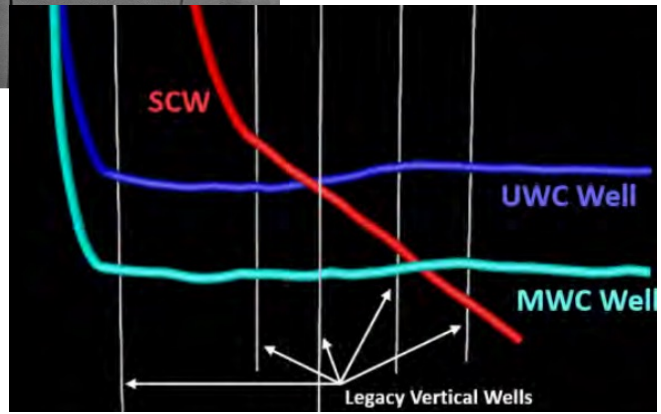
- DOE + Industry funded
  - Bulk of data becoming public
- Heavily instrumented
- Raw geophysical logs
- Fiber-based temperature data
- Extensive microseismic catalog
- Production and tracer data
- **Core-back well**



Core-back reveals hydraulic fractures propagate as *swarms!*

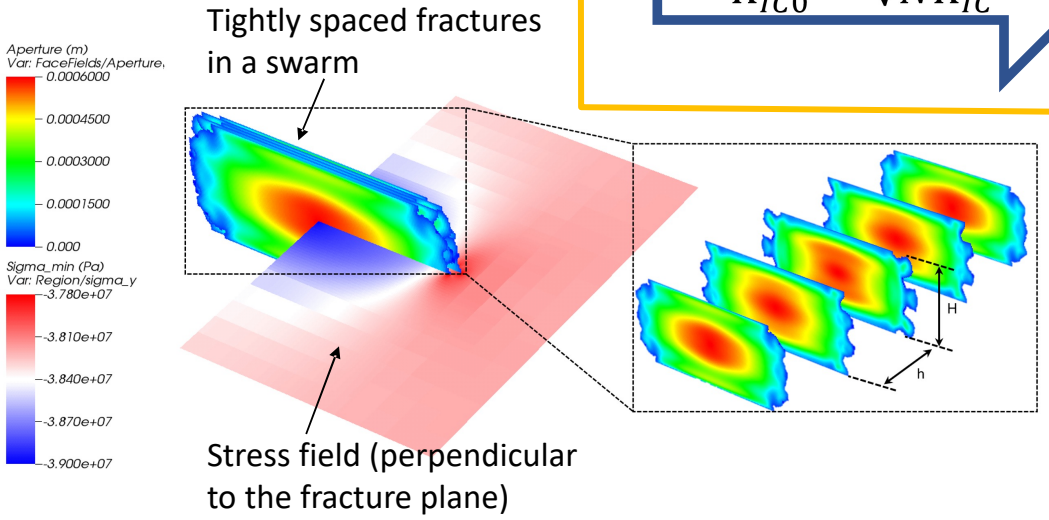


- Similar results have been observed in other field experiments
- Challenges traditional models!



We have developed an upscaled approximation for swarms

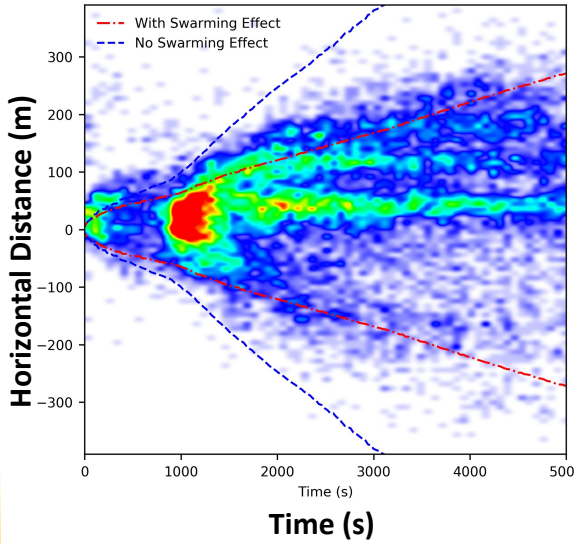
Detailed LLNL model of a swarm:



Fu et al. SPE-199689-MS

$$\mu_0 = N^2\mu$$
$$K_{IC0} = \sqrt{N}K_{IC}$$

Upscaled *fast-running*, approximation:



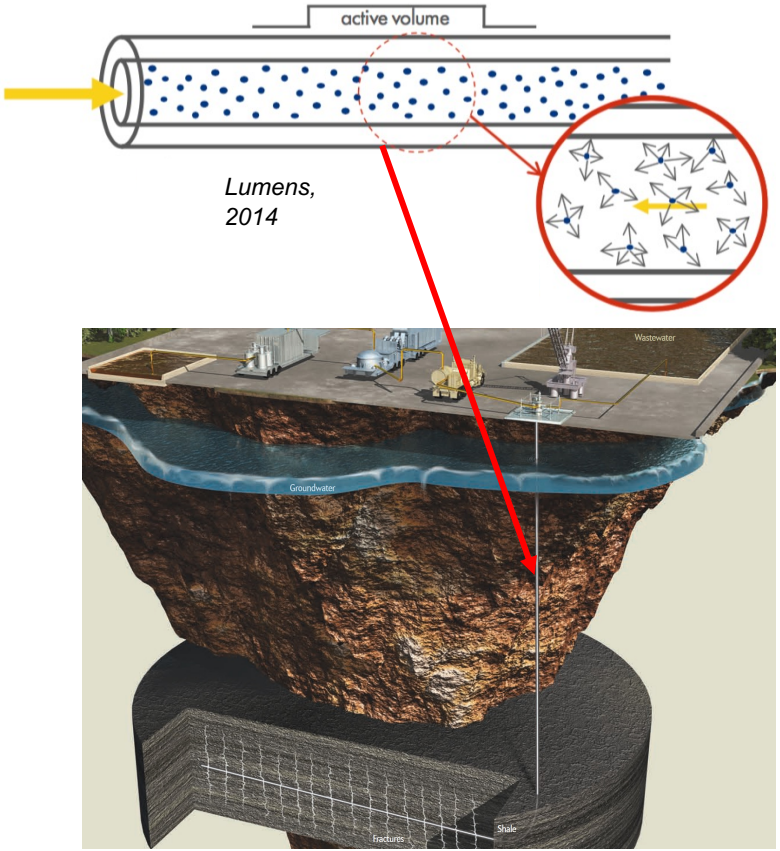
New approach is more predictive…

*…but you must have the **fundamental data/knowledge** to inform the model!*

Low cost/high value sensors: Fiber optic distributed sensors

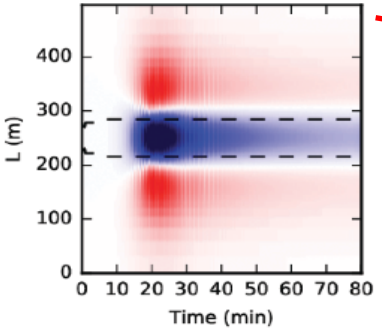
- Uses the fiber itself as a sensor to measure strain (or strain rate) along its length
- Designed to measure signals at a high spatial resolution (~1 m) over large distances (multiple km)
- Its development has opened up a massive source of data for subsurface characterization/monitoring
- Acoustic, strain, temperature,…

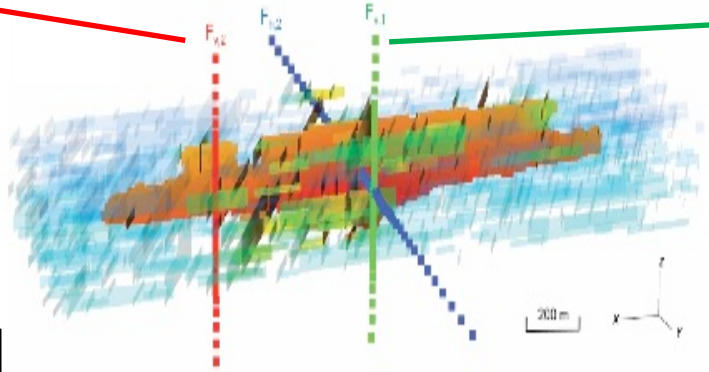
Fiber could enable real-time control …
Too much data for human interpretation

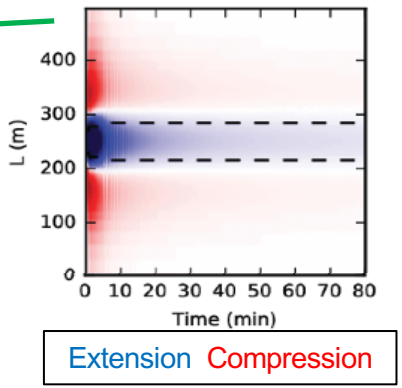


Enabling real-time fiber-based strain monitoring via machine learning

Distant vertical fiber

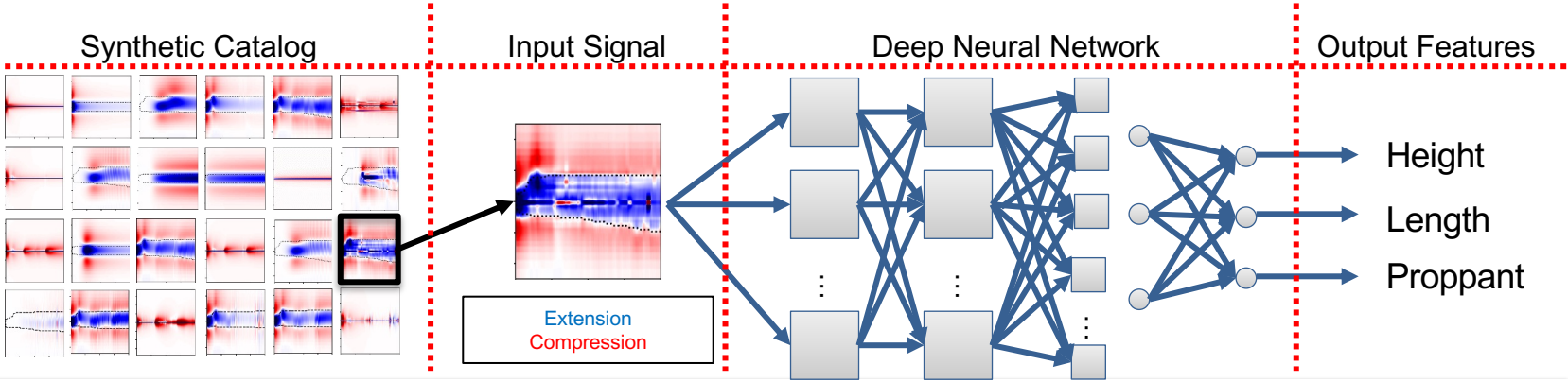






Close vertical fiber

Combining synthetic and field data to train a deep neural net

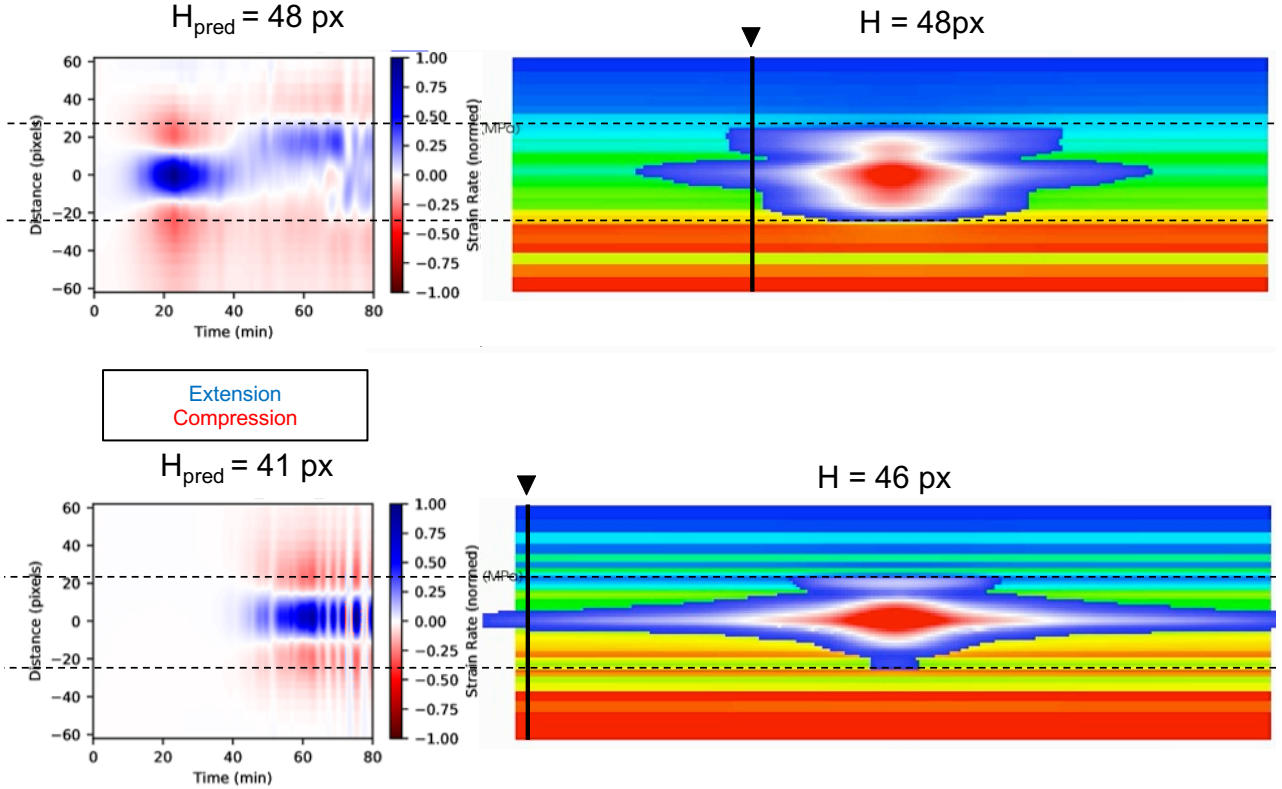


Trained neural net provides robust height estimates

"Easy" case: Fiber spans the hydraulic fracture

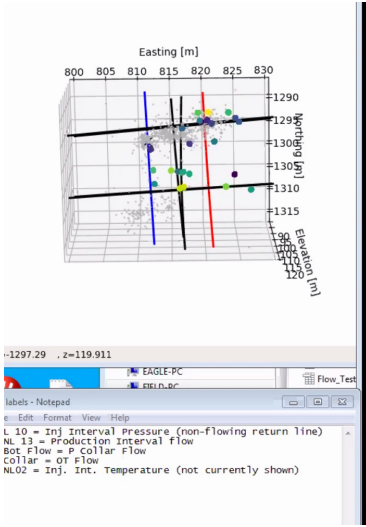
Tough case: Fiber is far from well

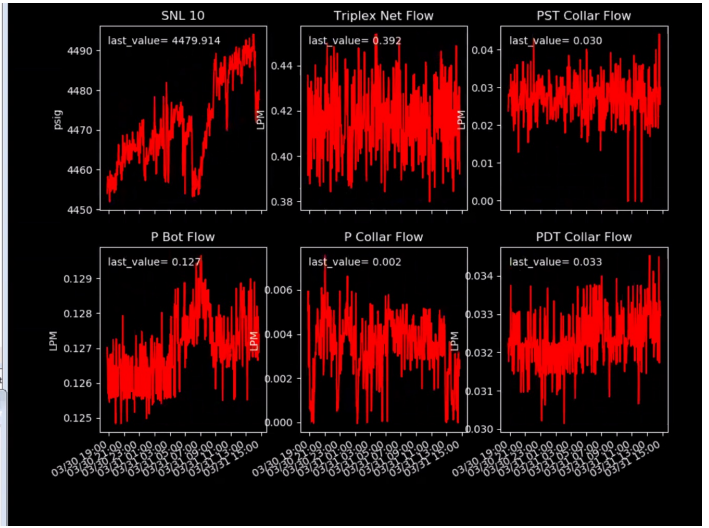
- NN estimates total height well!



We are on the cusp of massive changes in subsurface management

- **Coincidence of several factors:**
  - Massive data availability (e.g.: fiber)
  - Machine learning more accessible
  - AI compute doubling every 3.4 months (Stanford AI Index 2019)
- **Today: Multiple, highly qualified people in the loop, slow response**

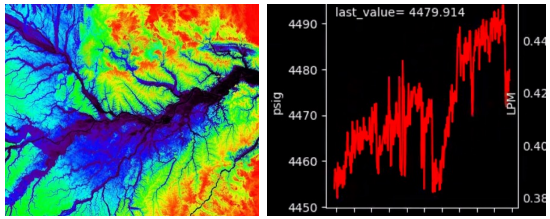




EGS Collab Geothermal Project: Amazing science & engineering with 6+ PhDs in the loop at all times!

Imagine a future: Rich in data and AI compute power, to empower/educate experts

Vision of the future for subsurface operations…



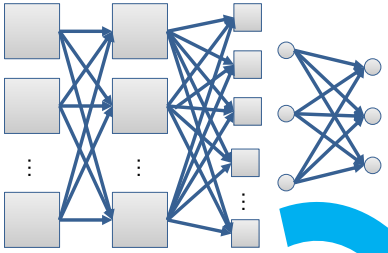
Novel visualizations

Engineering controls
(e.g.: viscosity, rate)

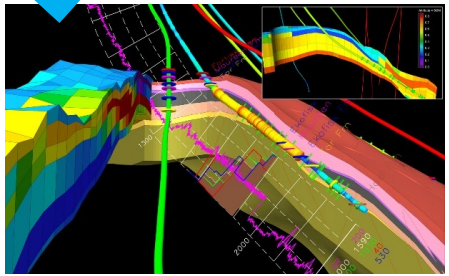
START

Operator(s)

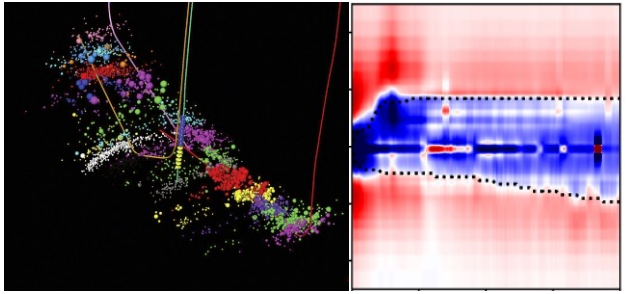
ML + fast
running models



Iteratively updated
site model



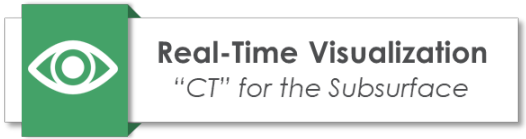
Observables (e.g. μseismic, fiber)



The Department of Energy seeks to make this a reality: SMART

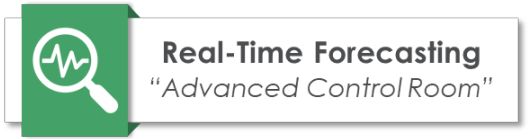
Science-informed Machine Learning for Accelerating Real-Time Decisions in Subsurface Applications (SMART)

Three goals:



Real-Time Visualization of key subsurface features and flows

Virtual Learning for rapid prediction of reservoir behavior

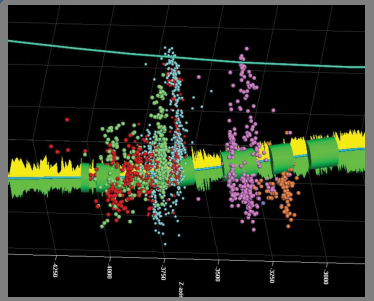


Real-Time Forecasting of actively managed subsurface systems

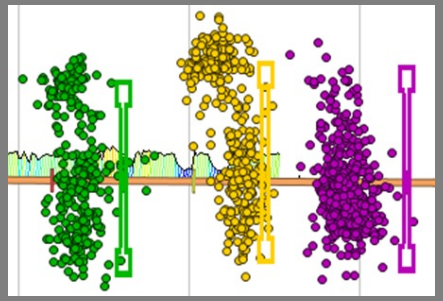
Ten-year, multi-organizational initiative with the goal of transforming interactions within the subsurface and significantly improving efficiency and effectiveness of field-scale **carbon storage** and **unconventional oil and gas** operations.

SMART O&G seeks better visualization/understanding of fractures

Here is how fracture networks and flow are currently visualized (current state-of-the-art)



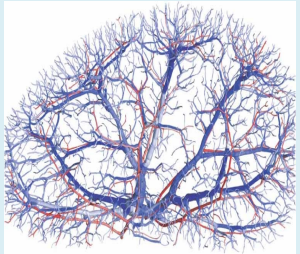
Schlumberger StimMap®



Halliburton FracHeight®

- Value of monitoring is not well quantified
- Interpretation does not inform flow paths
  - What do the dots *mean*?
- Interpretation is not timely:
  - Little/no impact on what we do in the moment

Here is how we envision visualizing flow and fractures that will transform insight for expert and non-expert decision makers.



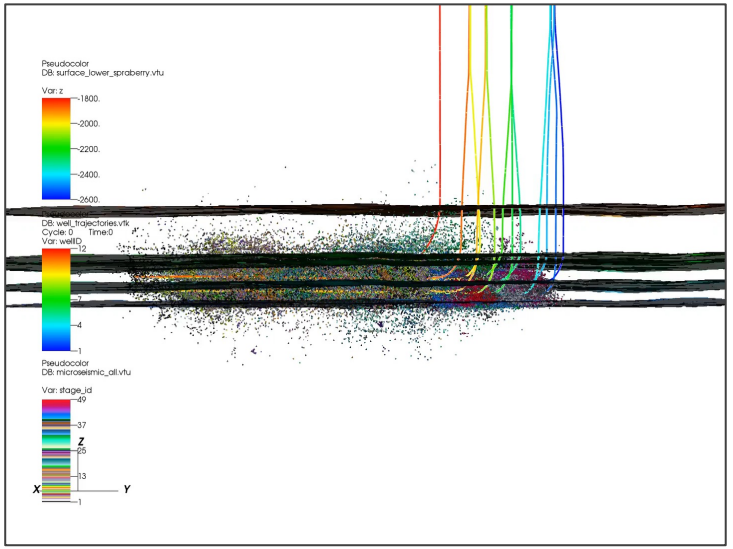
Vascular Networks

Transportation Networks

- Inform flow, production, and drainage implications
- Specialized visualizations for elucidating subsurface as an *engineered* network
- Interpretation and visualization will be in real time

SMART O&G: Field data is essential for training

- **Our ANNs are data hungry, and we need data for lots of fractures!**
- **We evaluated data from oil and gas field laboratories:**
  - HFTS 1
  - Marcellus Shale Energy and Environment Laboratory Eagle Ford Shale Lab
  - Bakken

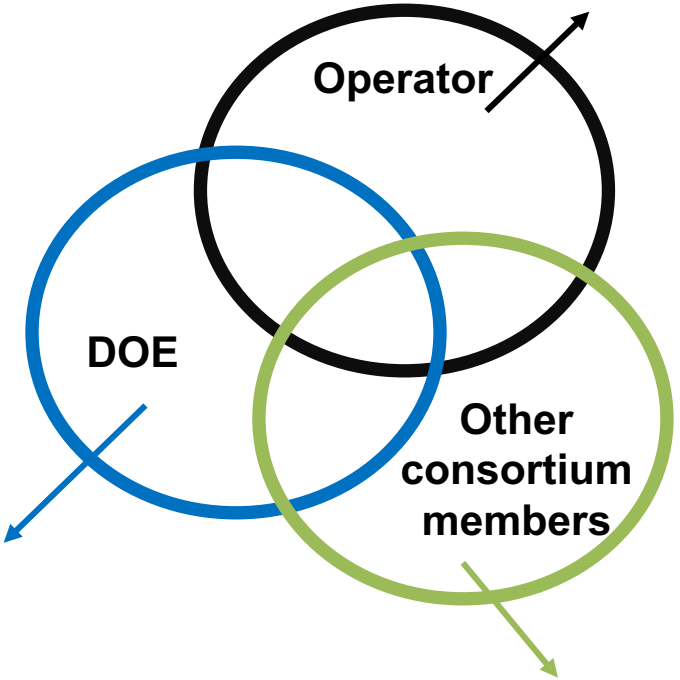


HFTS 1 microseismic data

There is lots of data our there, but…

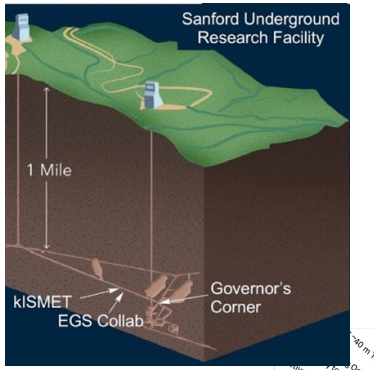
SMART O&G: Data Challenges – Some technical, some legal

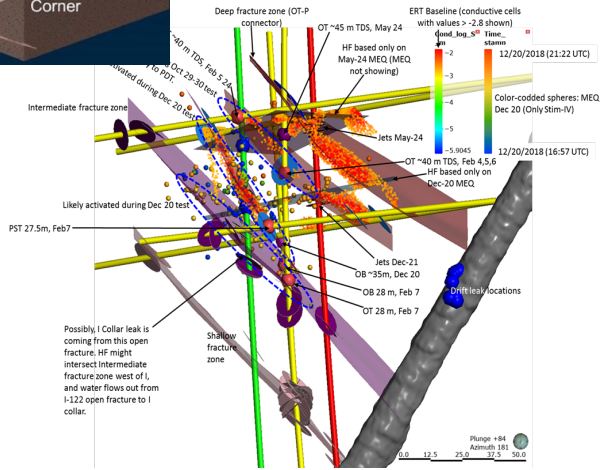
- **The data is almost always encumbered**
  - **Project participants have competing objectives**
  - Some background data owned by the operator
  - Some owned by DOE-led consortium, will *become* public
  - Some public: Unencumbered, but not all readily accessible…
- **The data often not organized**
  - Think: “Lots of files in an organically grown Google Drive”
  - The data is comingled: restricted mixed in with public
  - Data is often collected, some initial analysis done, then it is left
- **Ultimately, we abandoned using some key data types for training:**
  - 3D seismic data, oil/water/gas production data



Projects can have data sharing/curatorship baked-in…

- **Data needs to be worked on and integrated as it is collected**
- **The encumbrances should be minimal**
- The data should be accessible and well documented
- The EGS Collab (Geothermal) is a good example
  - Integration and analysis published alongside the curated, public data



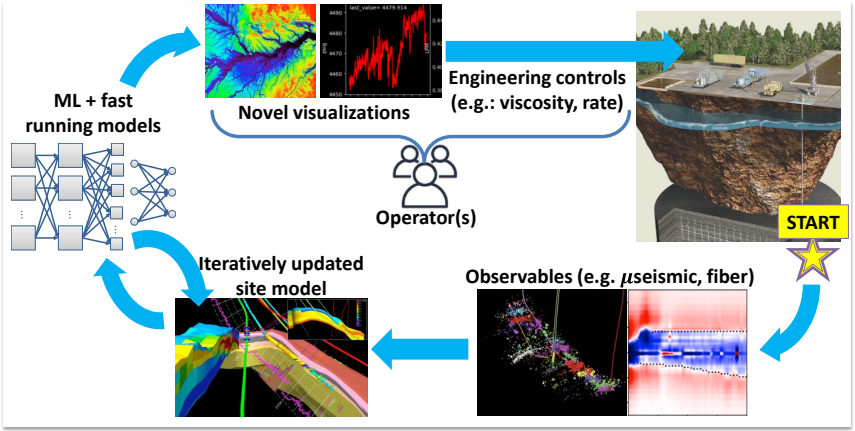


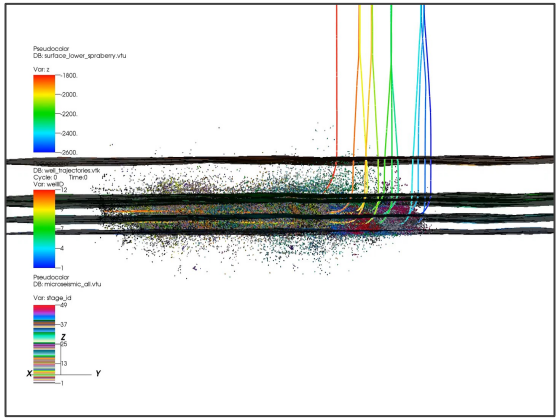
Some projects have better data access/organizaton, but none are perfect!

We are on the cusp of change in how we manage the subsurface

- Stronger connection from data to action through improved fundamental understanding (e.g.: HFTS core, EGS Collab)
- More ubiquitous monitoring (e.g.: fiber)
- More timely interpretation of multimodal data through machine learning

Empowering people to focus on the decision-making, rather than the laborious data-processing/integration = SMART



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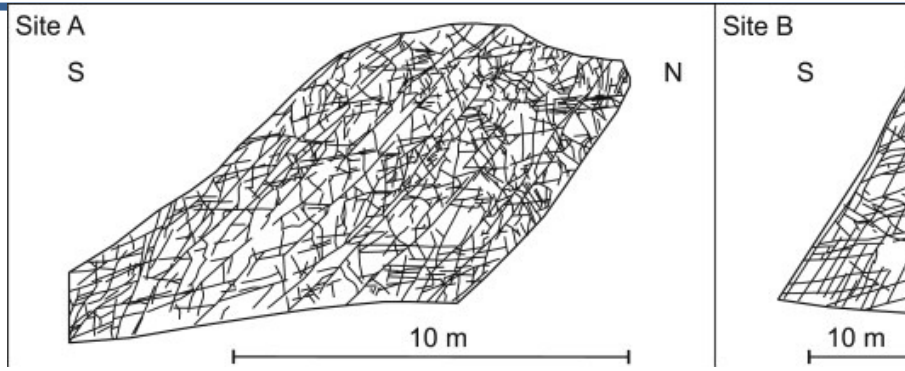
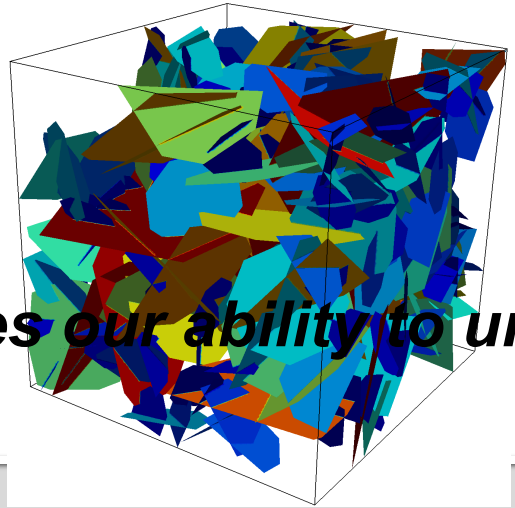
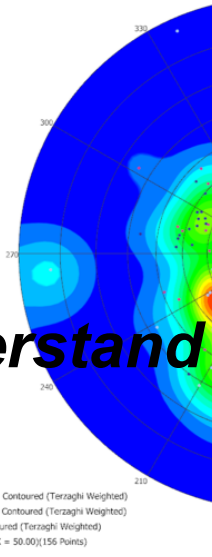
We are on the cusp of change in how we manage the subsurface

- Today: Even most geoscience experts don't understand fractures!
- Frequently we cannot see the wood for the trees
- What is the role of fractures in relation to the process I seek to optimize?
- Which fractures matter in the current application?

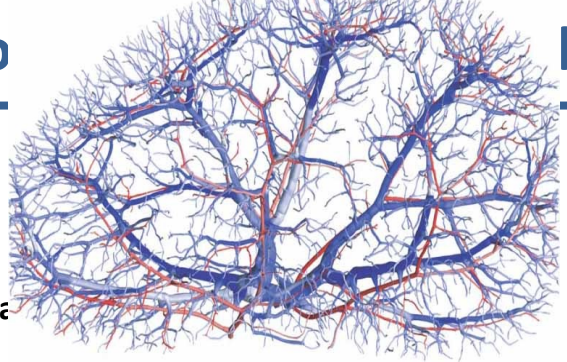


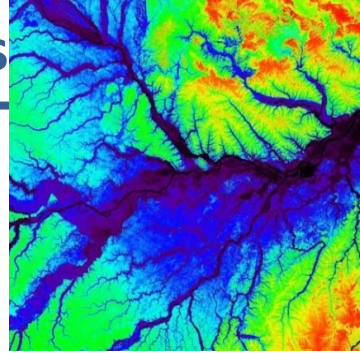




The way we look at fractures impedes our ability to understand

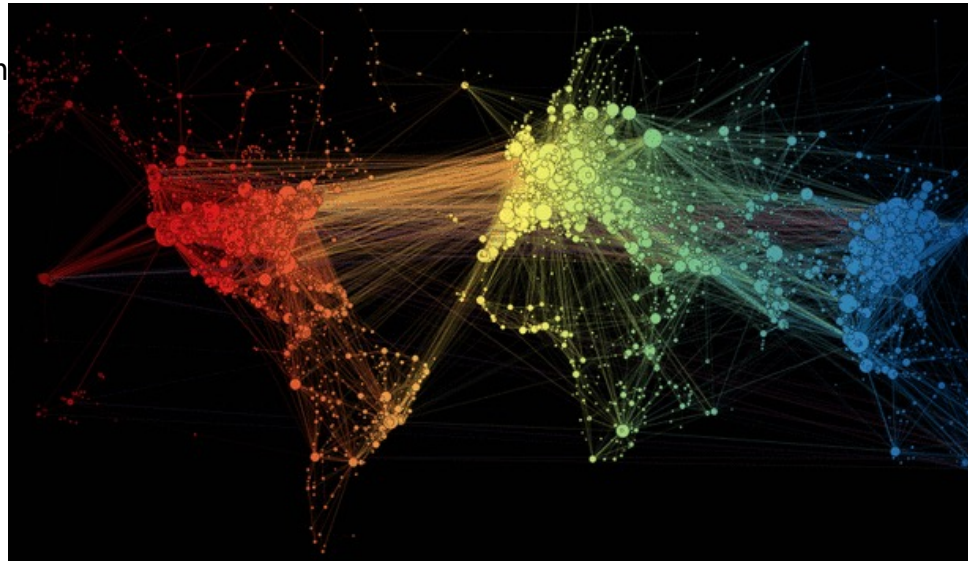
We are on the cusp of change in ho bs





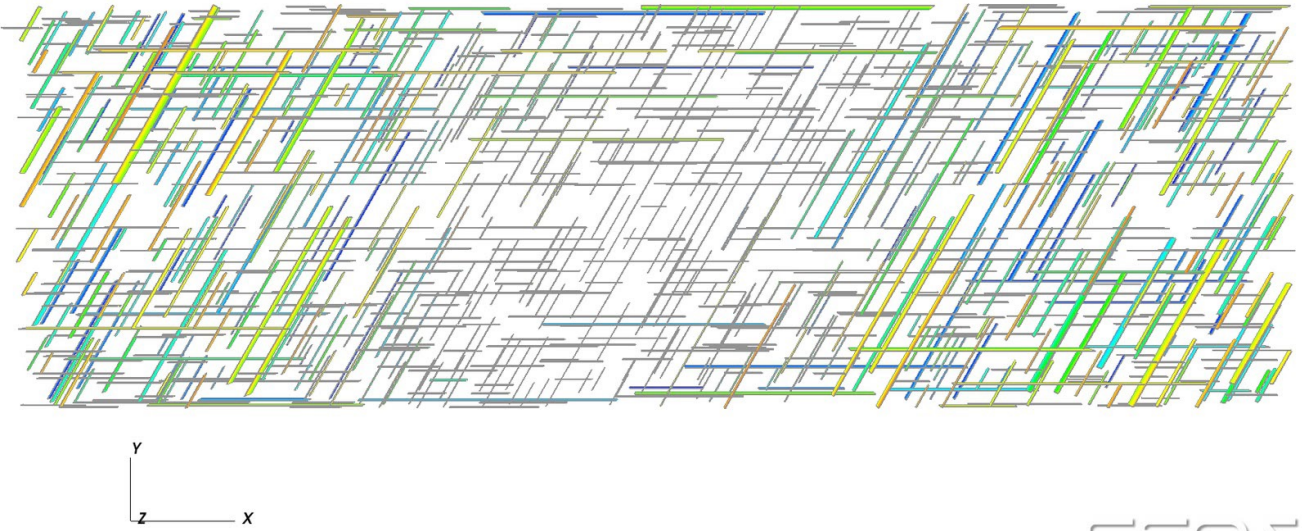
- **Today: Even most geoscience experts don't understand fractures!**
- **We will make the *role* and *evolution* of fractures evident to a**
- No more "plots by PhDs for PhDs!"
- Having rapid, responsive, interactive visualizations will inform new, ***robust intuition*** for the role fractures play in different applications

→ Empowers adaptive control

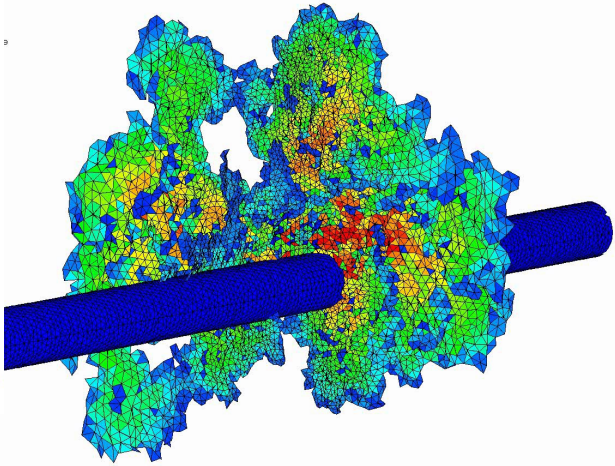


LLNL developed GEOS to investigate shale fundamentals

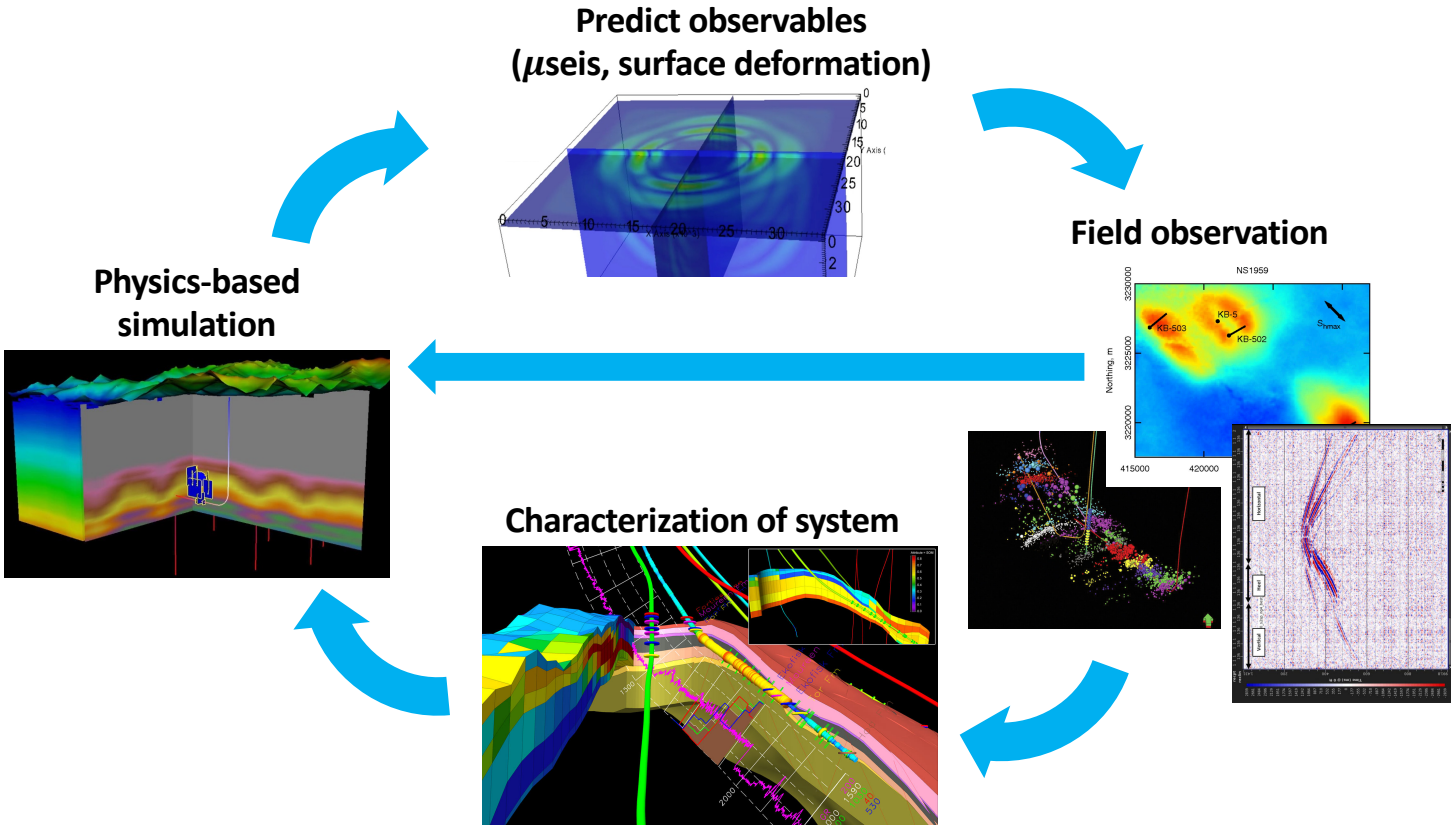
A discrete fracture network (DFN) consisting of 1000 fractures



GEOS
Lawrence Livermore National Laboratory

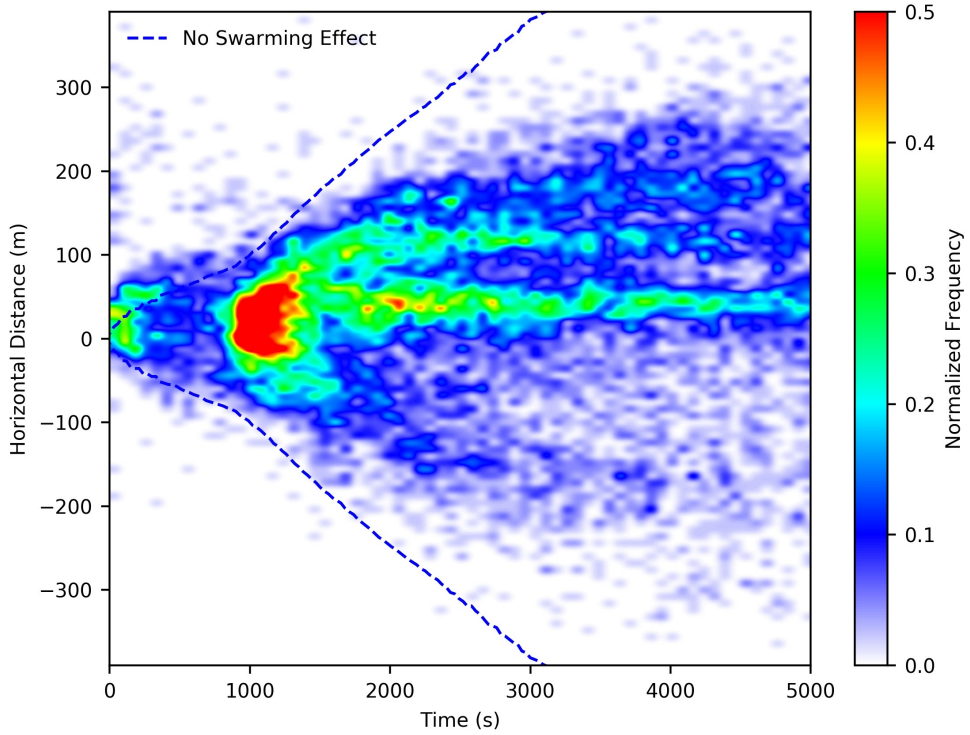


Recurring theme: Physical simulation brings value to data, enables data integration



One example: Traditional models do not match microseismic

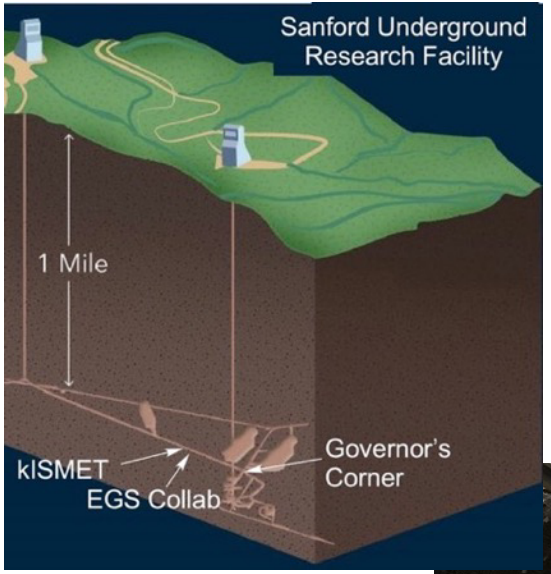
- Using measured rock toughness leads to unbounded fracture growth!



Most simulators use a "top-down" calibration to match observed microseismic: Tune parameters to *absurd* values

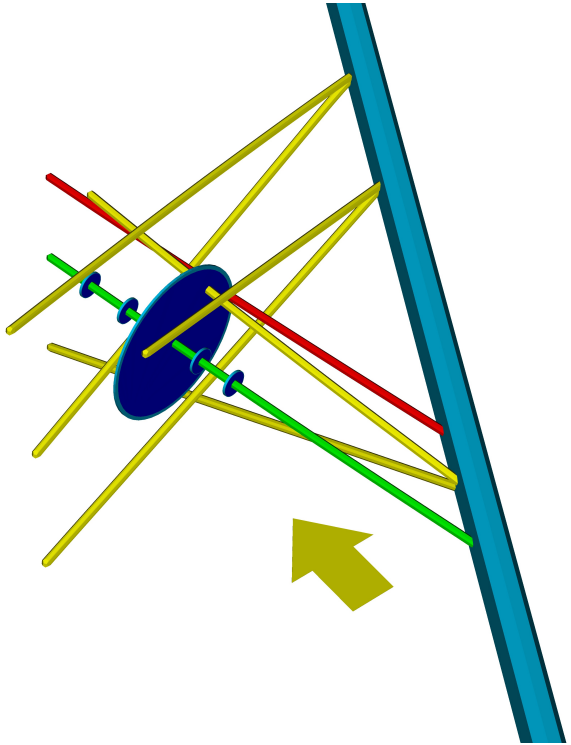
The EGS Collab project is allowing us to validate our understanding

- Funded by the Geothermal Technology Office
- Test geothermal stimulation concepts
- Bridge the vast scale gap between lab experiments and field-scale application
- Validate EGS codes in relevant environment
- Access to rock enables heavy investment in characterization and monitoring



The EGS Collab Experiment Involves Multimodel Data Acquisition

- A very complex experiment: Breaking rock, concurrent microseismic, temperature, resistive, tracer measurements
- Includes ***fiber***
- Integrating data, developing coherent understanding was imperative
- Limited real-time data interpretation
- Full interpretation took over a year



PIs: T. Kneafsey and D. Blankenship

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J. Feldman	M. Lee	B.Q. Roberts	P. Winterfeld
A. Foris	K. Li	M. Robertson	T. Wood
L.P. Frash	R. Lopez	W. Roggenthen	S. Workman
Z. Frone	M. Maceira	J. Rutqvist	H. Wu
P. Fu	P. Mackey	D. Rynders	Y.S. Wu
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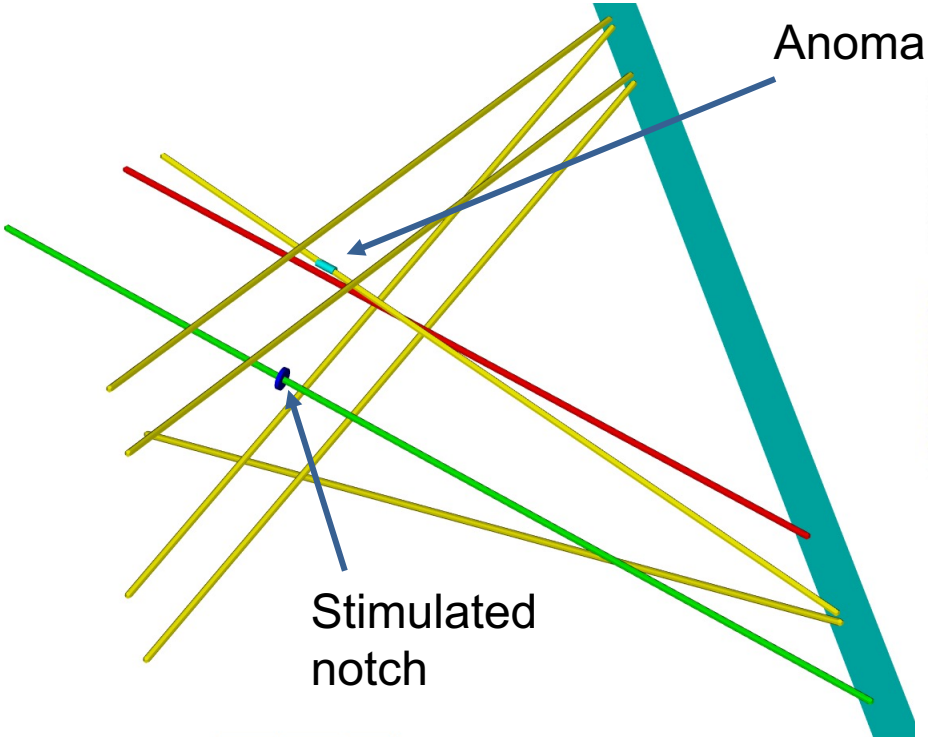
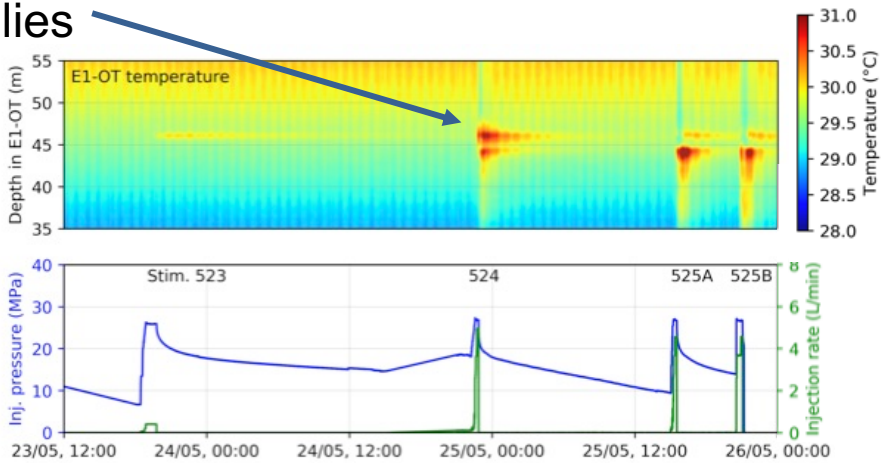
H. Gudmundsdottir	E. Mattson	P. Schwering	Y. Zhang
Y. Guglielmi	M.W. McClure	V. Sesetty	Y.Q. Zhang
G. Guthrie	J. McLennan	C.S. Sherman	J. Zhou
B. Haimson	T. McLing	A. Singh	Q. Zhou
A. Hawkins	C. Medler	M.M. Smith	M.D. Zoback
J. Heise	R.J. Mellors	H. Sone	

Fiber-based temperature was critical to understanding the system

While injecting into a fracture notch at 50 m depth in we saw temperature anomalies at 45 m on an observation well



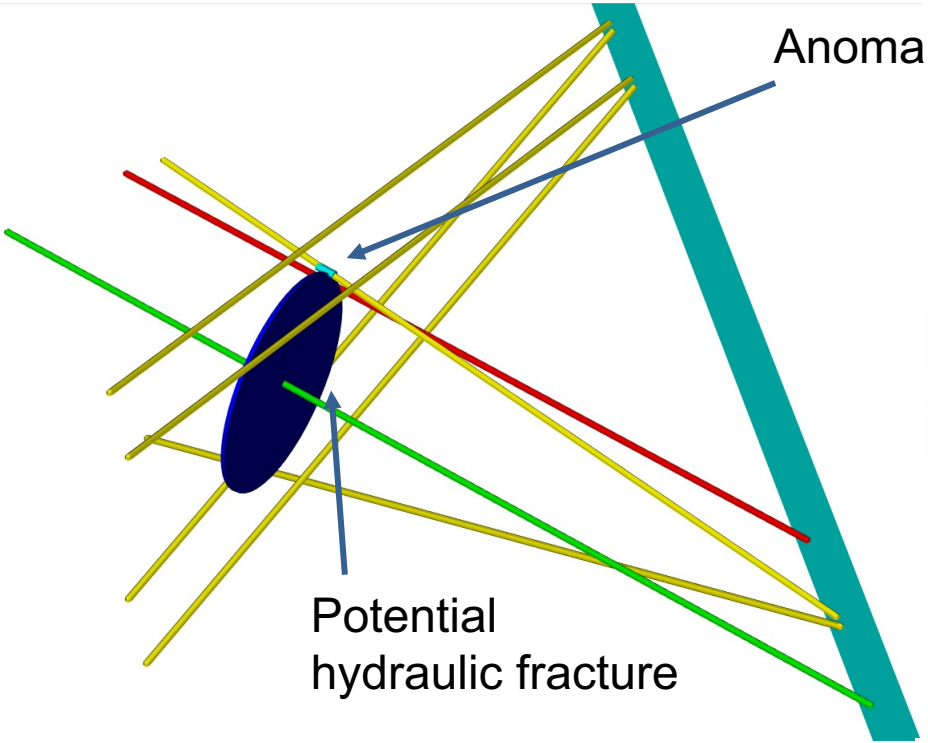
Anomalies



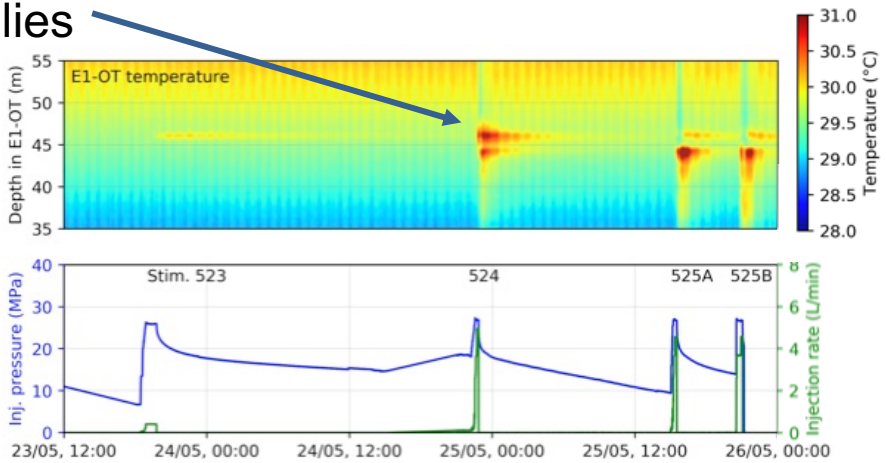
Time →

Fiber-based temperature was critical to understanding the system

The anomalies aligned with the expected hydraulic fracture growth

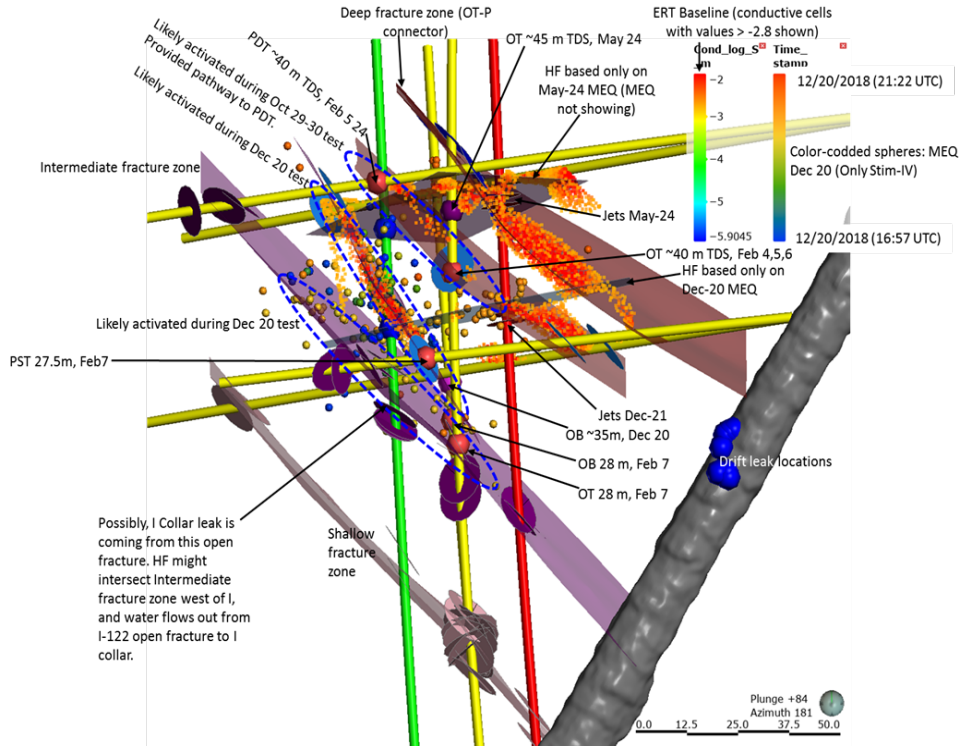


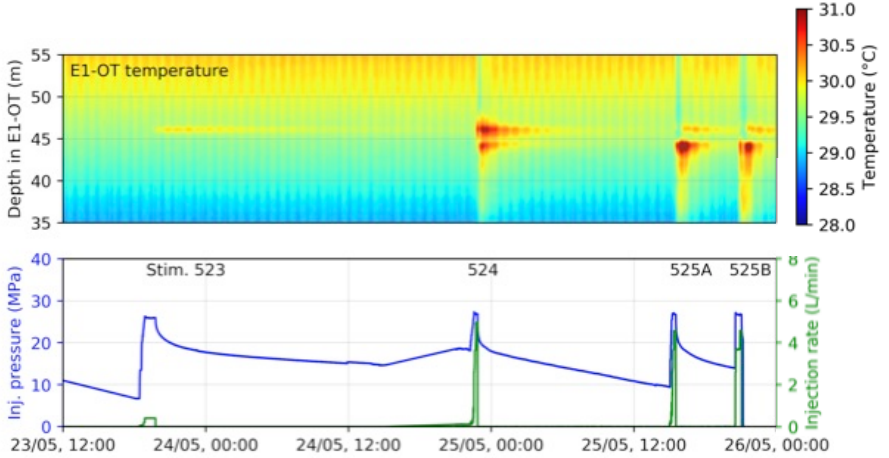
Anomalies



Time →

But DTS is one mode of data and the full picture is more complex





It took a massive team and *over a year* to collect and interpret this data: See Fu et al. (2020)