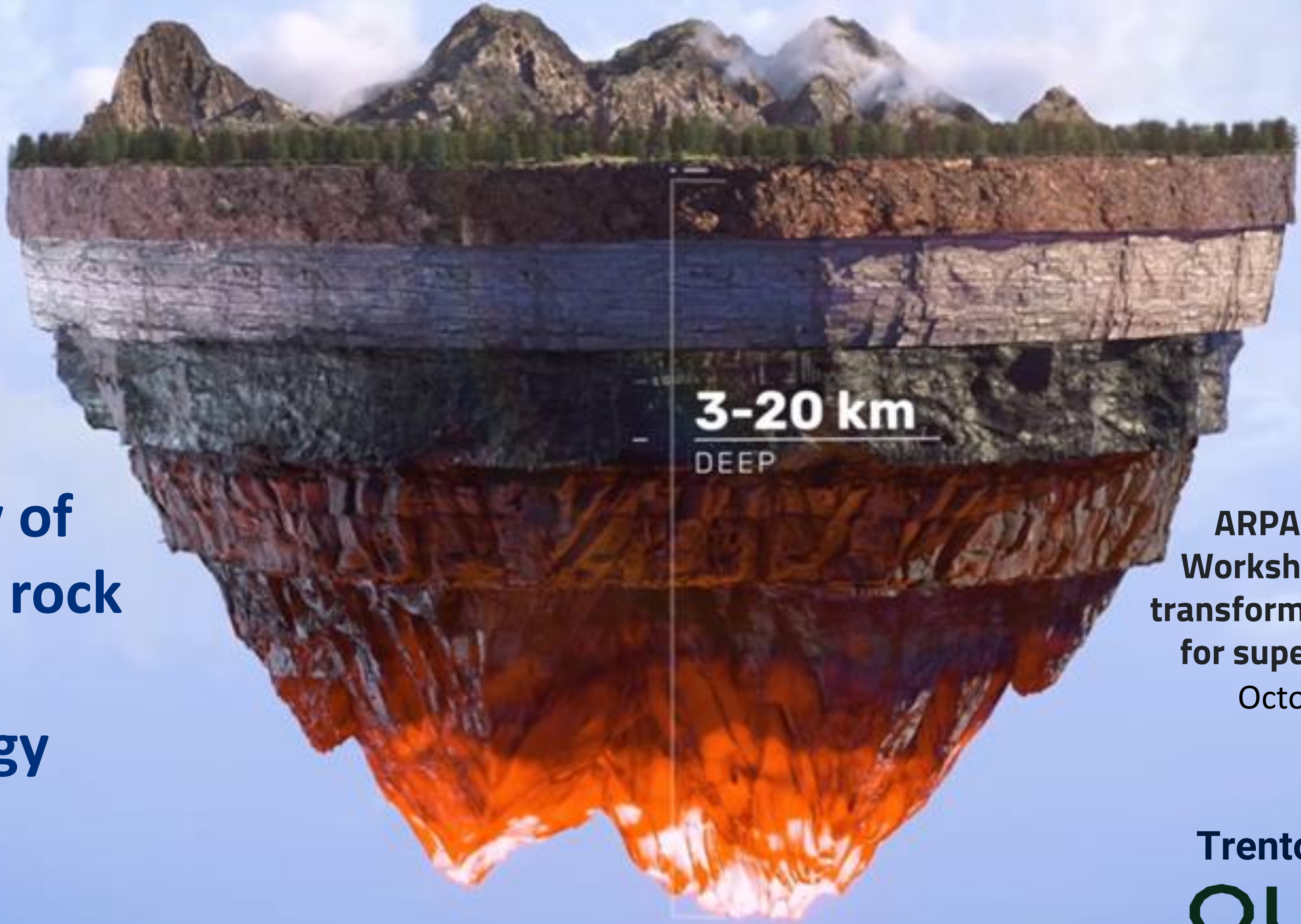
Overview of Superhot rock Energy: Technology Needs

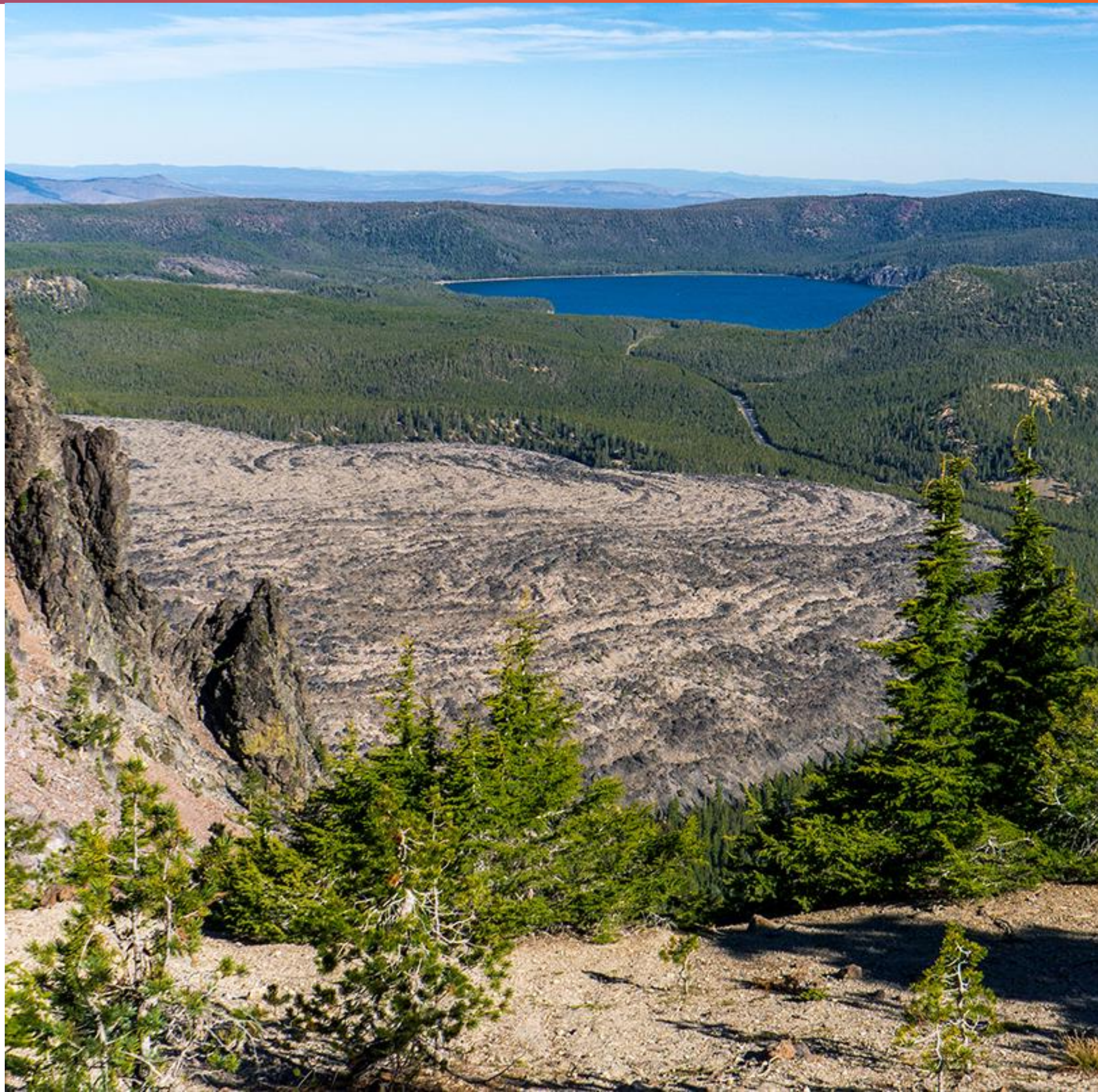


ARPA-E Geothermal Workshop: Enabling and transformative technologies for superhot geothermal
October 1-2, 2024

Trenton Cladouhos
QUAISE

Outline

- Prior Experience with SHR wells Milestones and Challenges
- Technology Needs
- What we must learn from Demonstration Projects



Why Superhot Rock?

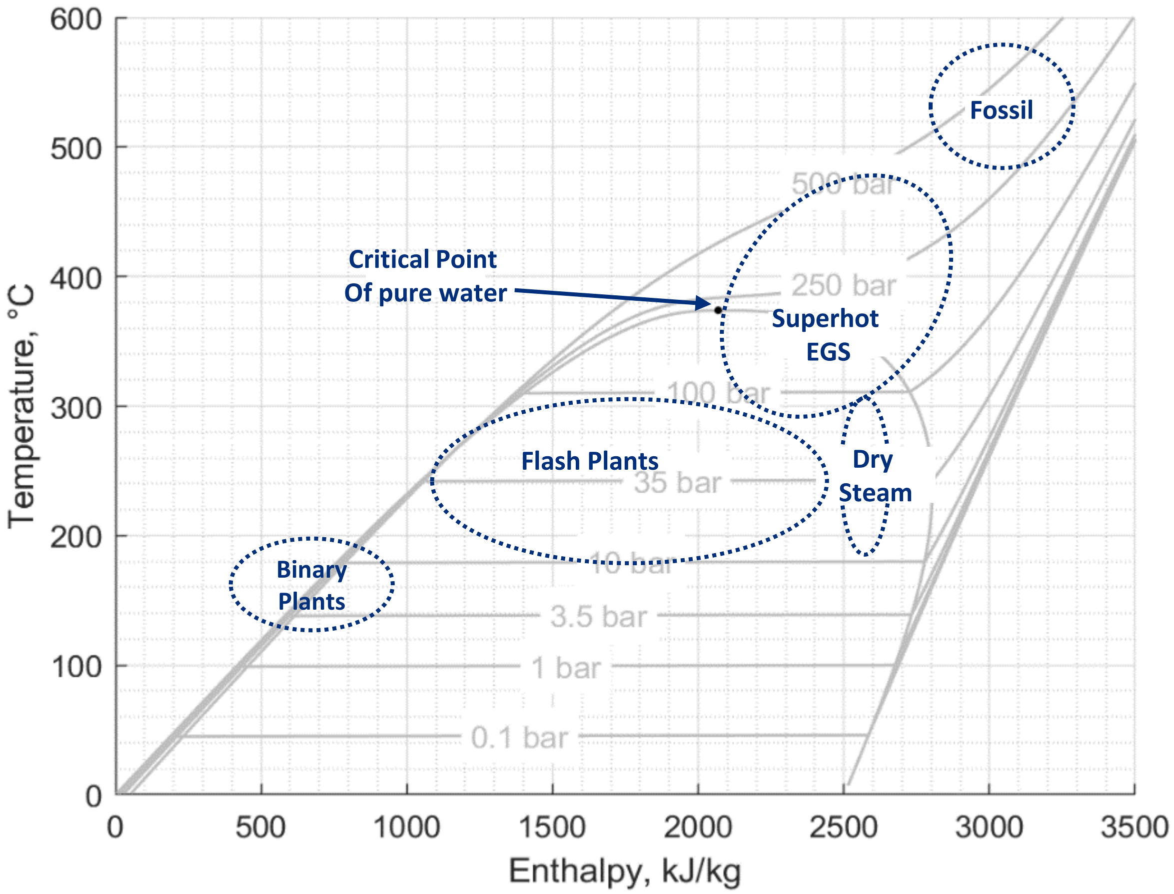
Accessing superhot temperatures drastically increases the power density of the geofluid reaching the surface, enabling increased power output per well, less parasitic pumping loads, and a reduction in LCOE

Superhot Rock

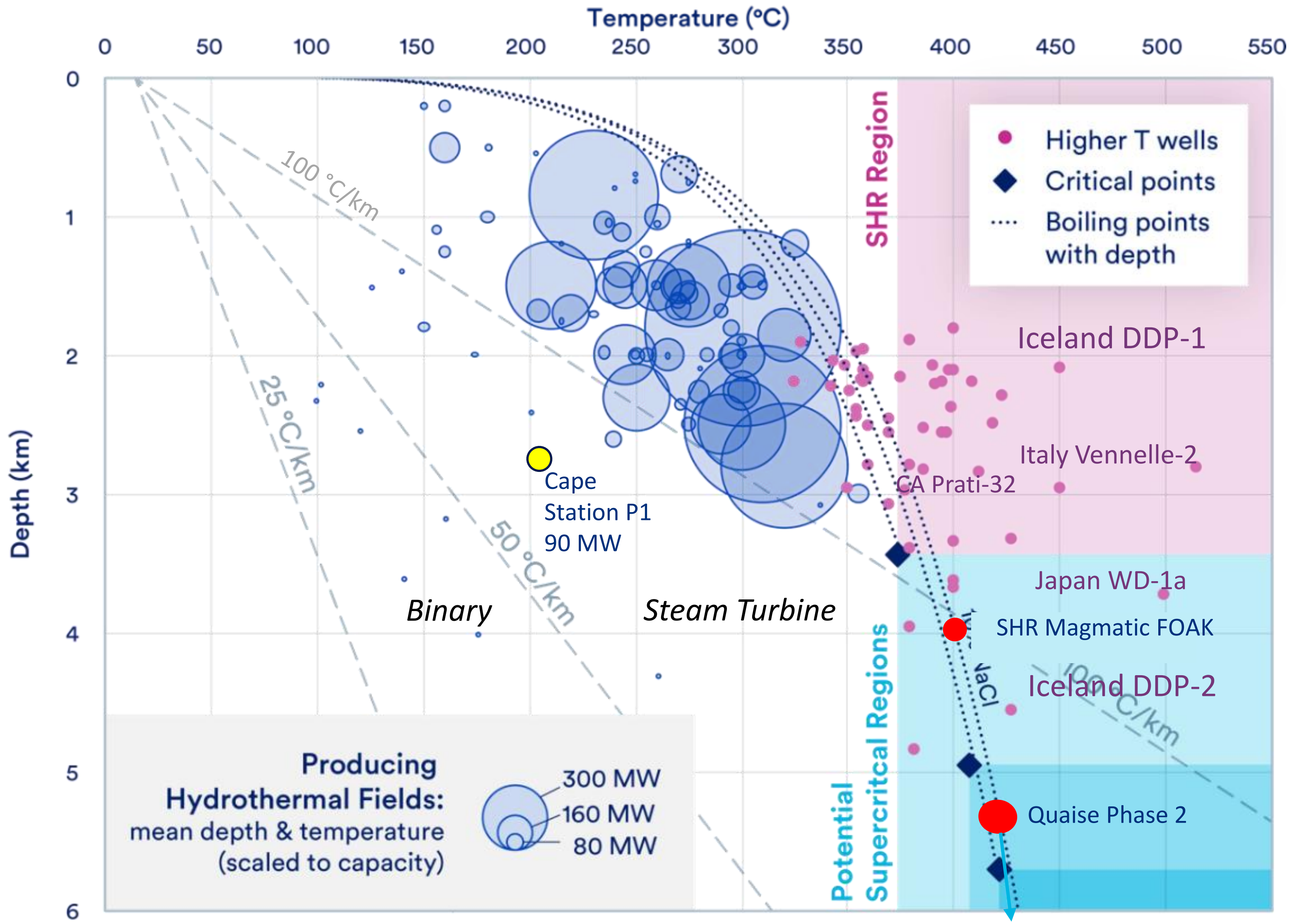
- Rock Formation with T>375 °C (>707° F),
- Enthalpy >2,100 kJ/kg
- 30-50 MWe per production well

Compared to <200 °C (400 °F)

- **~3x** heat content
- **~3x** conversion efficiency to electricity
- **~50%** reduction in LCOE
- **$45/MWh** DOE Earthshot LCOE possible on broad geographic basis



Producing geothermal fields and SuperHot Rock wells



Key Insights

Most current geothermal production in the **200-300 ° C** temperature range

>20 wells drilled to T> 375 °C

Including IDDP-1, IDDP-2, Vennelle-2, Prati-32

Supercritical conditions in reservoir also requires:

- Pure water
- P_f > 22 MPa
- ~3.5 km column of hot water

Native supercritical fluids in geothermal wells are rare

Supercritical fluids will circulate in deep engineered geothermal systems

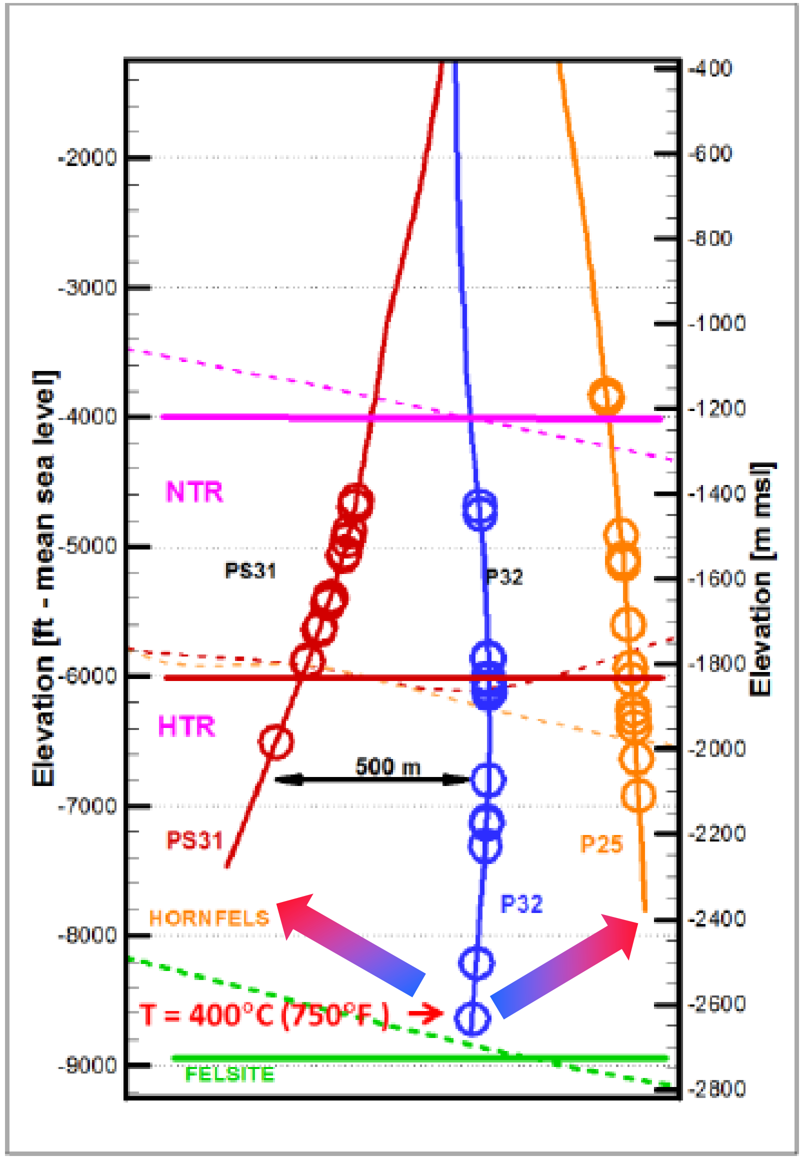
Source: Cladouhos & Callahan, 2023 GRC

Prior Experience: Drilling Successes > 390 C

Prior Experience: Milestones

- 1995 - Kakkonda WD-1a, Japan
  - Early, intentional, **conventionally drilled SHR well (500 °C)**
- 2010 – NW Geysers EGS demo, California
  - Open hole stimulation: 25 kg/s at 400 °C
  - Up to 42 microseismic events per day
  - Reduced NCG and corrosive chloride in nearby PWs
- 2009 - Iceland IDDP-1
  - Unexpected rhyolite magma intersected at 2104 m
  - 16 month, **30 MW** flow test
  - Native permeability above 500 °C
  - Follow-up Krafla Magma Testbed (kmt.is)
- 2017 - Iceland IDDP-2
  - **Core** obtained at 410 °C
  - 30° inclination above 400 °C
- 2018 - Italy – DESCRAMBLE Vennelle-2
  - **520 °C** reached in low perm reservoir

NW Geysers wells connected at 400 °C



Producer Injector Producer

Prior Experience: Challenges

- NW Geysers EGS demo
  - While air drilling at 400 °C, last bit lasted only 33m
  - Near surface corrosion in PS-31 (PW)
- Iceland IDDP-1
  - Emergency quenching caused shallow casing failures
- Iceland IDDP-2
  - Took 186 days to deepen well by 2159 m
  - Well failed due to gap in cement at 2300-2400 m
- Italy – DESCRAMBLE Venelle-2
  - Unexpectedly high pressures, stuck pipe, bad cement

Hartline et al, 2019

IDDP-1, Ingason & Sigurosson, 2021

Heat Extraction from SuperHot Rock

- Overall Status
  - SuperHot Rock has been reached with conventional drilling
  - Limited attempts at directional drilling
  - Well completions are challenging
  - EGS in low-permeability SHR not yet attempted
- Summary of Gaps and Pathways Forward
  - Basic Science
  - Stimulation Methods & Reservoir Technology
  - Well Completion

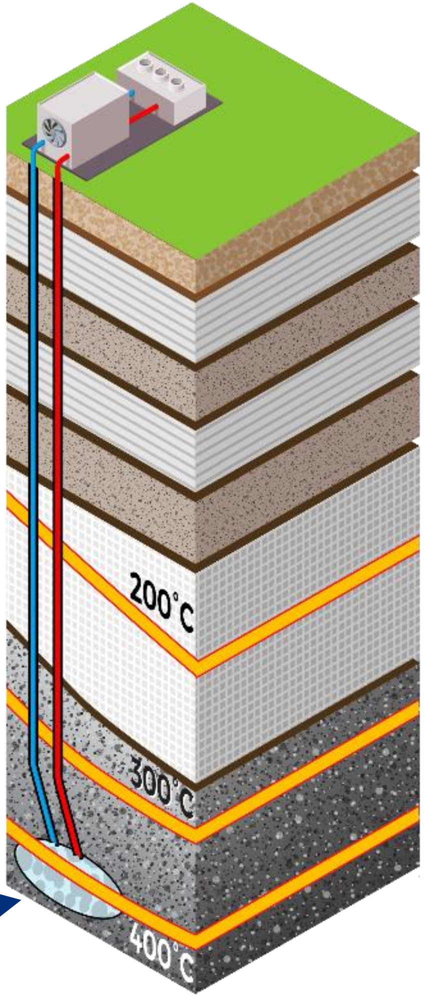
Technology Needs for Heat Extraction from Superhot Rock at 3-20 km depth

Require collaboration: domestic & international government + **O&G** + mining

Drilling/Well Completion for SHR

Reservoir Creation & Management

SHT Materials



Powerplant Design/Optimization

Modeling and Analytics

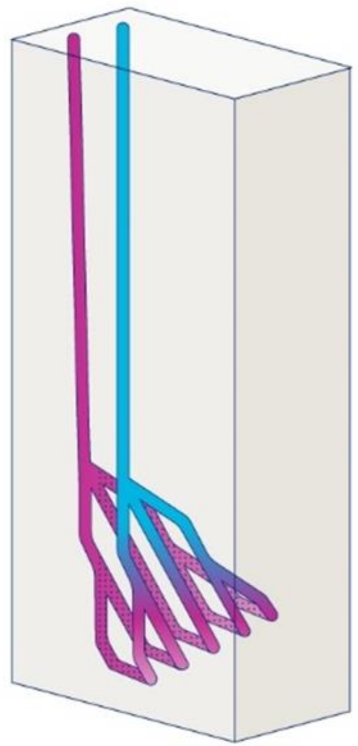
Resource Characterization & Monitoring

Rock/Fluid Mechanics and Geochemistry

This is too vague!

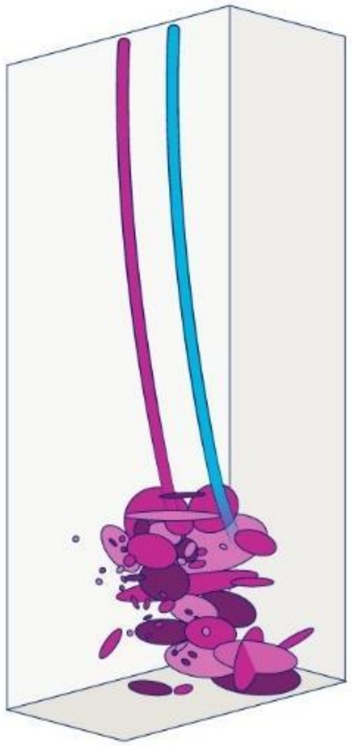
Conceptual Models: Engineered Systems for Heat Extraction

Closed Loop



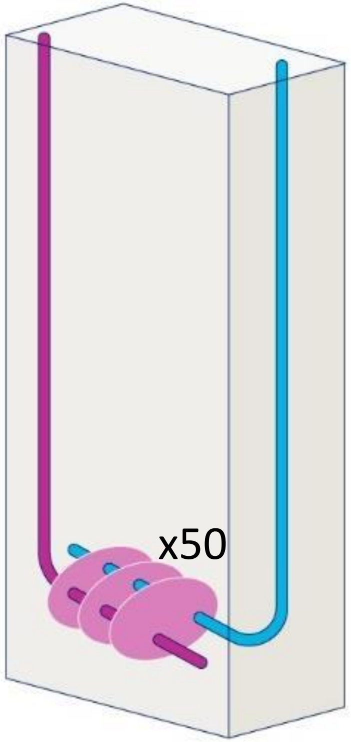
Example: Eavor Geretsreid

Shear Stimulation of existing fractures



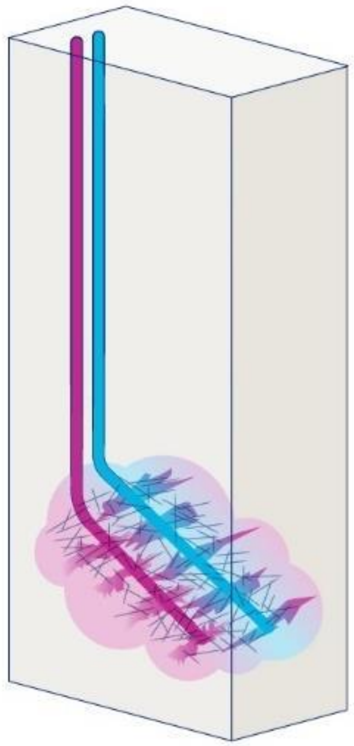
Soultz, France

Planar Hydraulic Fractures



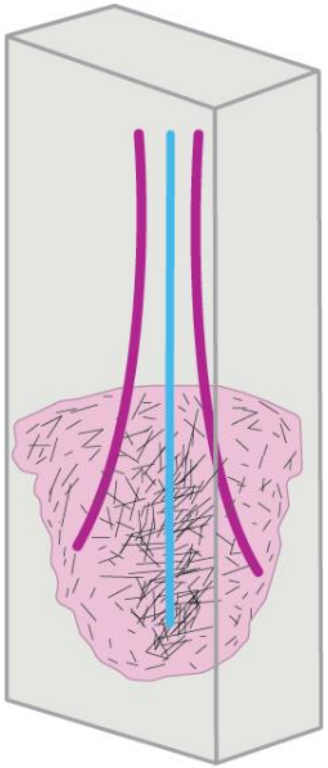
FORGE/Fervo Project Red

Hybrid Fracture Network



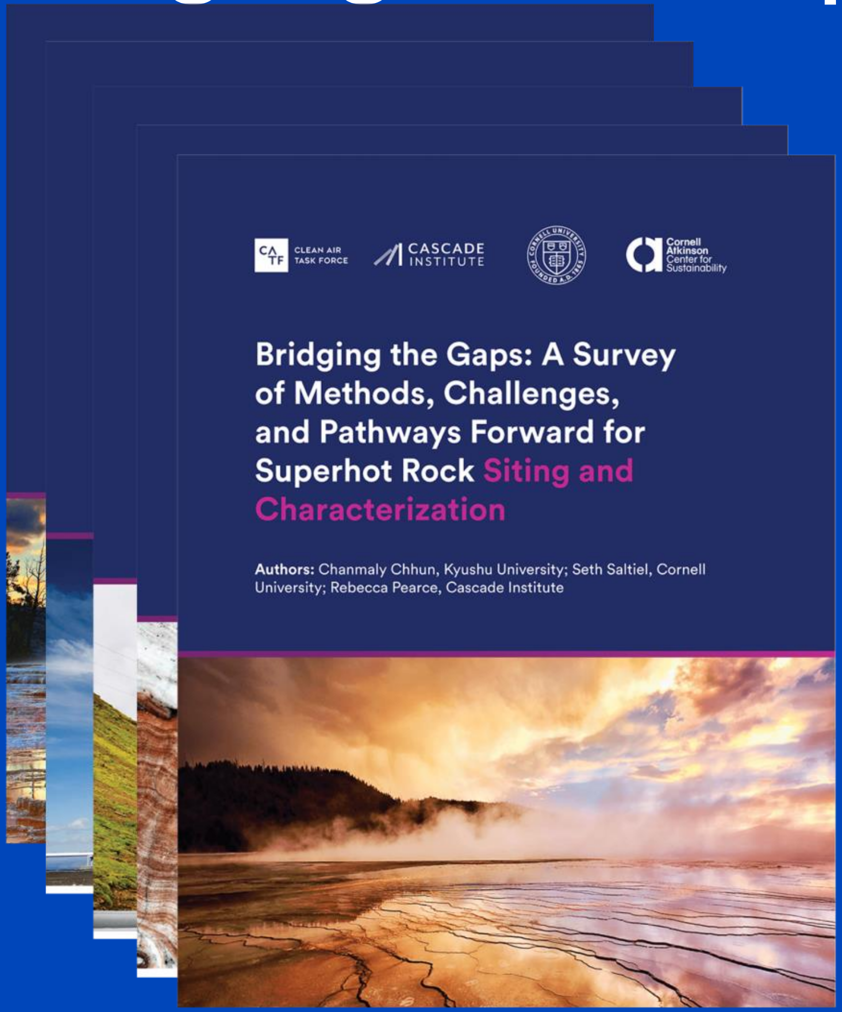
Alternative Interpretation of planar fractures

Failure of Near Ductile Rock Cloud and thermal fractures



Superhot Hydrothermal Field
The Geysers
Iceland

Bridging the Gaps

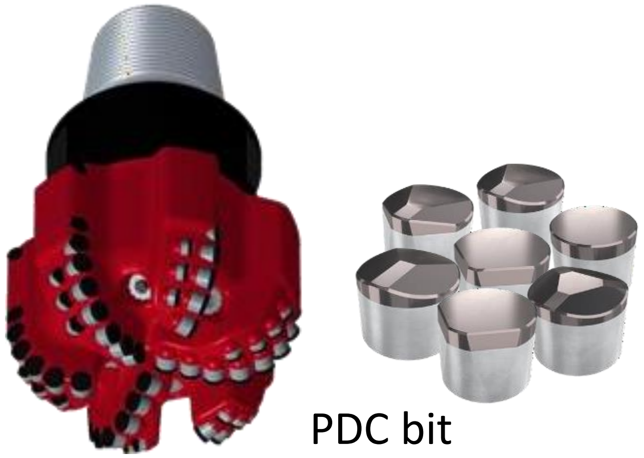


Clean Air Task Force
Workshop in Iceland, May 2024
Scan to view reports or
https://www.catf.us/superhot-rock/

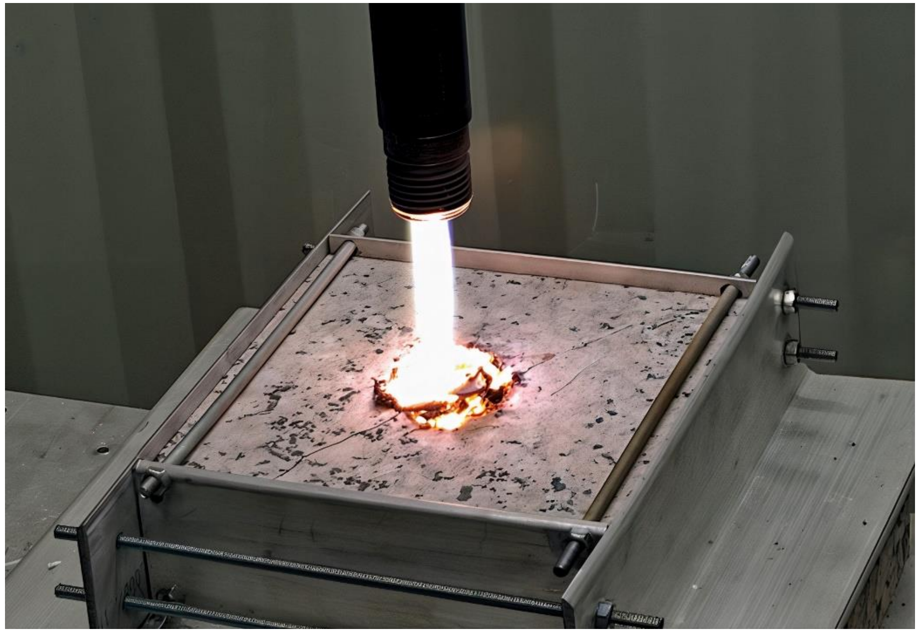
SHR Geothermal Drilling Challenges

ROP Generation

- Rig Capabilities
  - Available but few and far flung
- Rock Destroying Equipment
  - Conventional rotary drill bits
    - PDC
    - Roller Cone
  - Hybrid conventional
    - Particle Impact Drilling
    - Water Jet
    - Percussive
  - Direct Energy
    - Plasma
    - Millimeter Wave (Quaise)



PDC bit



MMW in Quaise's Houston Lab

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SHR Geothermal Drilling Challenges

Temperature Management

- Hi Temperature tools
- Insulated Drill Pipe
- Low Heat Coefficient Coatings
- Mud Coolers
- Drilling Fluids
- Fluid Dynamics
- MPD
- Continuous Circulation, Fast Connections, Automation

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Tools: Directional drilling

Need

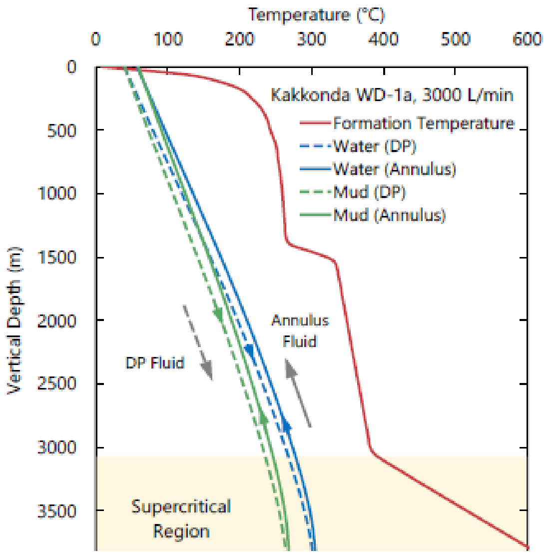
- Closed loop geothermal systems – efficient drilling will make or break
- EGS reservoirs - intersect vertical fractures and maximize surface area

Status

- Rotary Steerable Systems & MWD good to ~200 °C
- Circulation, insulated drill pipe, mud cooling extend temperature limits

Solutions

- Directional drilling in SHR feasible with incremental upgrades
- Demonstrate future market for SHR RSS & MWD to service companies



Pump Rate: 3000 L/min

Simulated wellbore temperature profiles during drilling 8-1/2 in hole section from 3500 to TD 4000 m.

Ando and Nagawawa, (2020).

Finger et al., (2000)

Casing: Key Challenges

"No matter the resource, it appears that in SHR, the well always gives up first!"

- **Extremely high temperatures**
- **Potentially high pressures**
- **Challenging material selection**
- **Inclusion of a stimulation load**
  - **temperature and pressure**
- **Day 2 Expert Talk and Panel**
  - *Tatiana Pyatina, BNL*
  - *Ravi Krishnamurthy, Blade Energy*
  - *Sebastian Kube, U. of Wisconsin*

Coupling failure of the IDDP-1. 450°C well killed with cold water

Suri Suryanarayana and Ravi Krishnamurthy, Blade Energy

Summary of drilling superhot rock

needs engineering iteration with R&D support from labs and universities

ROPs are getting faster every well, driving downcosts and improving project economics

Insulated drill pipe combined with drill string optimization can keep tools under 175° C.

If near well bore temps can be lowered as modelled, then advanced completions can be run semi normally.

Casing and Cement still a challenge but being worked on by commercial companies, Labs and universities

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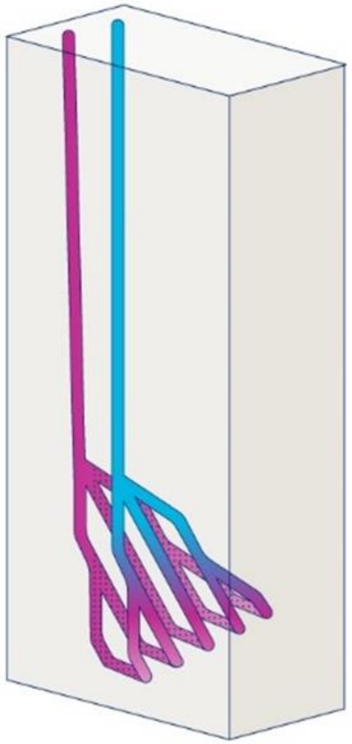
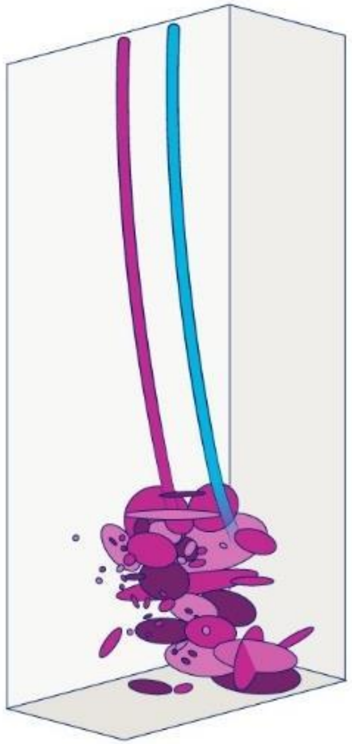
Conceptual Models: Engineered Systems for Heat Extraction

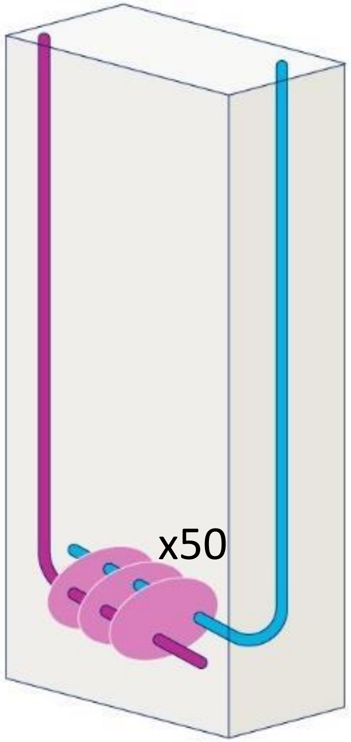
Closed Loop



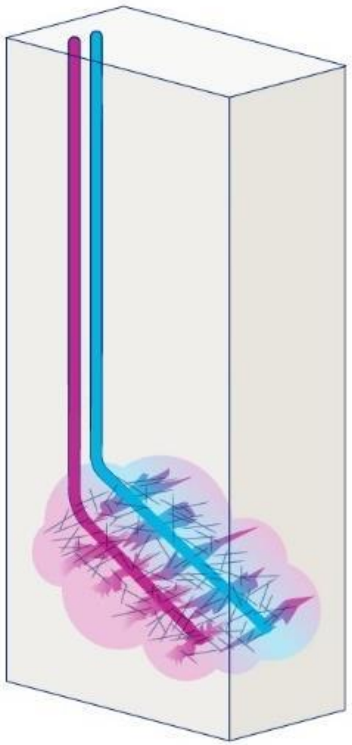
Shear Stimulation of existing fractures



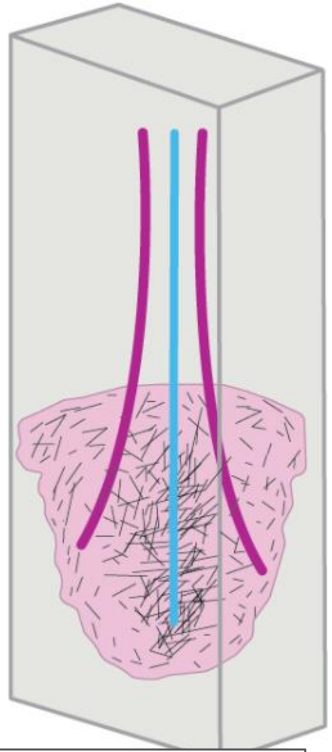
Planar Hydraulic Fractures



Hybrid Fracture Network



Failure of Near Ductile Rock Cloud and thermal fractures



Models indicate that thermal stability near rock temperature requires 10^6 - 10^7 m^2 of heat exchange area, 150-500 m well spacing

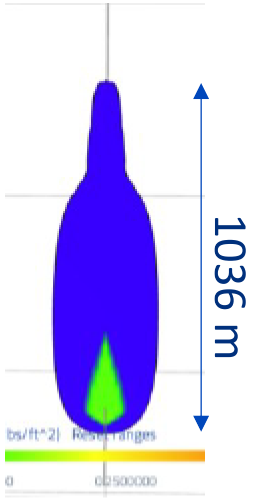
Closed Loop	Shear Stimulation of existing fractures	Planar Hydraulic Fractures	Hybrid Fracture Network	Failure of Near Ductile Rock Cloud and thermal fractures
Surface Area: 10^4 m^2	geology dependent	10^6 – 10^7 m^2	10^6 – 10^7 m^2	Volume: 10^8 m^3
Rock Temp: 200 °C	150 °C	200 °C	>310 °C	**425°C**
Example: Eavor Geretsreid	Soultz, France	FORGE/Fervo Project Red	Mazama Energy	Quaise Magmatic Test Site

Modeling

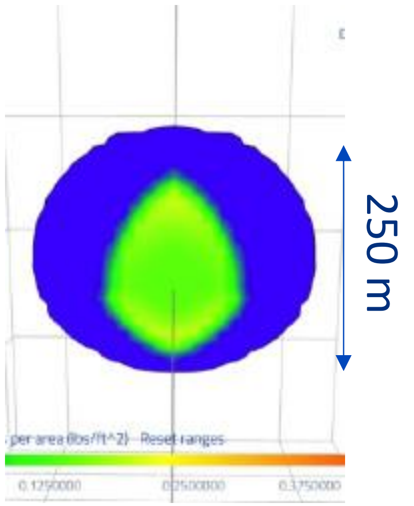
- Fracture propagation models
  - Status - Most software designed and validated for O&G fracturing
- THMC and Reservoir models
  - Status (conductive models) - Sufficient for closed loop
  - Status (open reservoirs) - Many research codes simulate some SHR challenges
- Solutions
  - Survey of capability of existing codes
  - Codes that include properties of cold to supercritical fluids, geomechanics of SHR, heterogeneity (NF)
  - Laboratory experiments at SHR conditions
  - Model validation from field demos
    - Current: FORGE and Fervo,
    - Future: SHR Demonstration projects
  - Cross-code comparison

FORGE fracture models, McClure (2023) proppant density

Unadjusted (default) parameters (prediction)

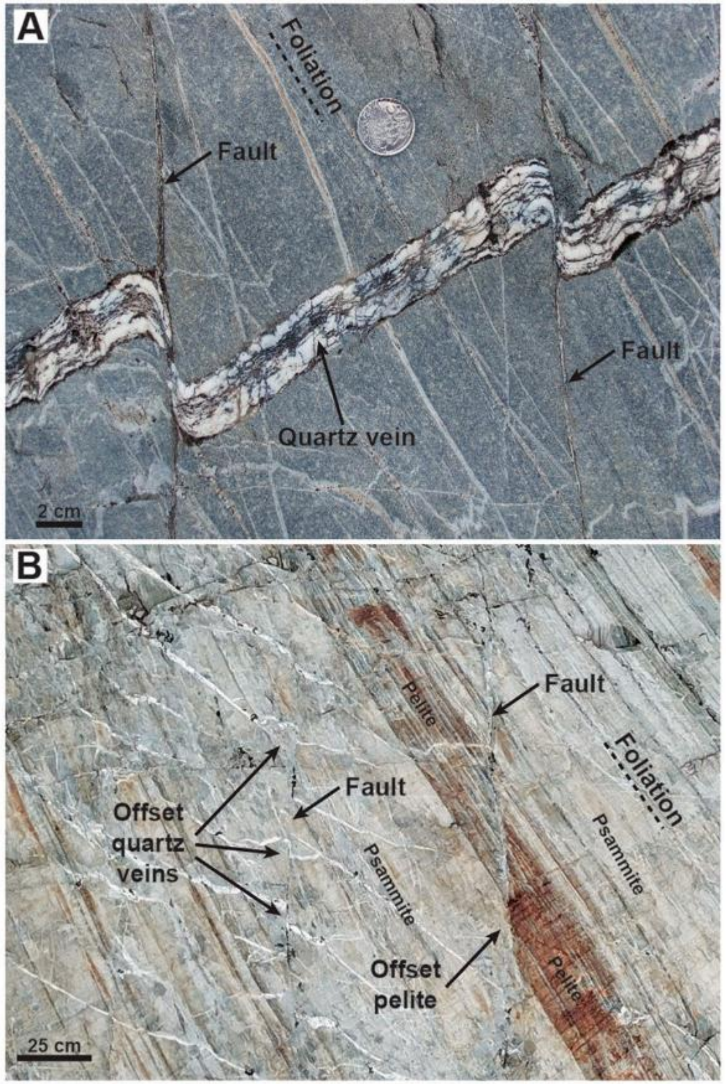


History matching algorithm



Basic Science: Paths Forward

- Modeling and Testing benefit from SHR outcrop analogs
  - Models difficult validate without demonstrations
  - SHR difficult to replicate in the lab
- Examples:
  - Labs predict changing fractures at BDT (Goto et al., 2021)
  - Evidence for changes in porphyry systems (Amanda et al., 2022)
- Best SHR analogs identified with **new collaborations**
  - Economic Geologists
  - Metamorphic and Igneous Petrologists
  - Geothermal Industry



Cycles of Brittle-Ductile Deformation
Alpine Fault, NZ (Ellis et al., 2023)

Fracturing Hypotheses

Advantages of Superhot Rock for EGS

Fracturing in superhot rocks

- Nominally ductile rock made brittle by high strain rate and extreme cooling
- Lower viscosity fluid

Complex fracture network

- Preexisting fractures stimulated to create a microfracture "cloud"
- Hydraulic fracture branching will increase surface area

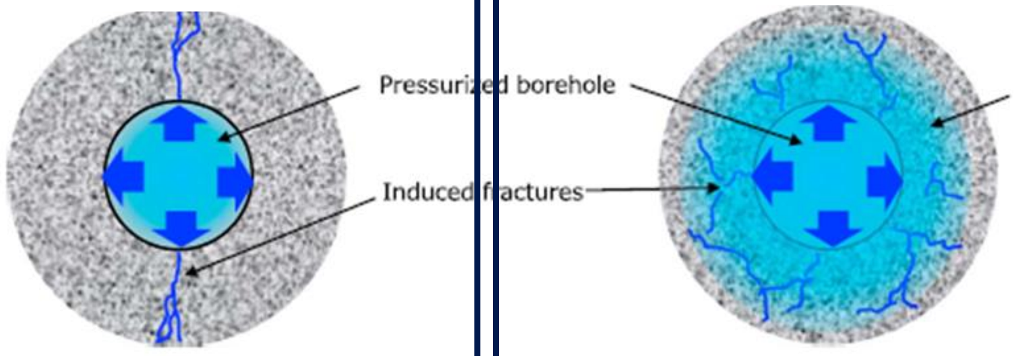
Thermal and chemical impacts

- Fracture growth (aperture, radius) from cooling
- Reaction kinetics accelerated at SH conditions
  - Can silica solubility be controlled?
  - Function of temperature, pressure, pH, and salinity
  - Lab investigations in progress

Lab results from Watanabe et al, 2017

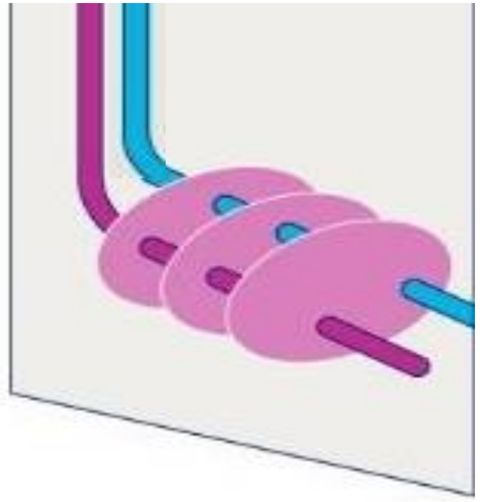
200 °C

450 °C

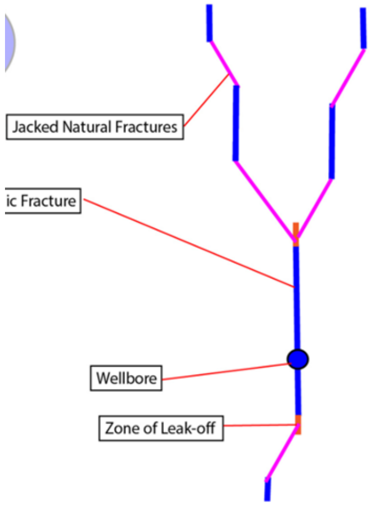


Tensile Fracture

Cloud Fractures



Planar fractures



Complex fracturing

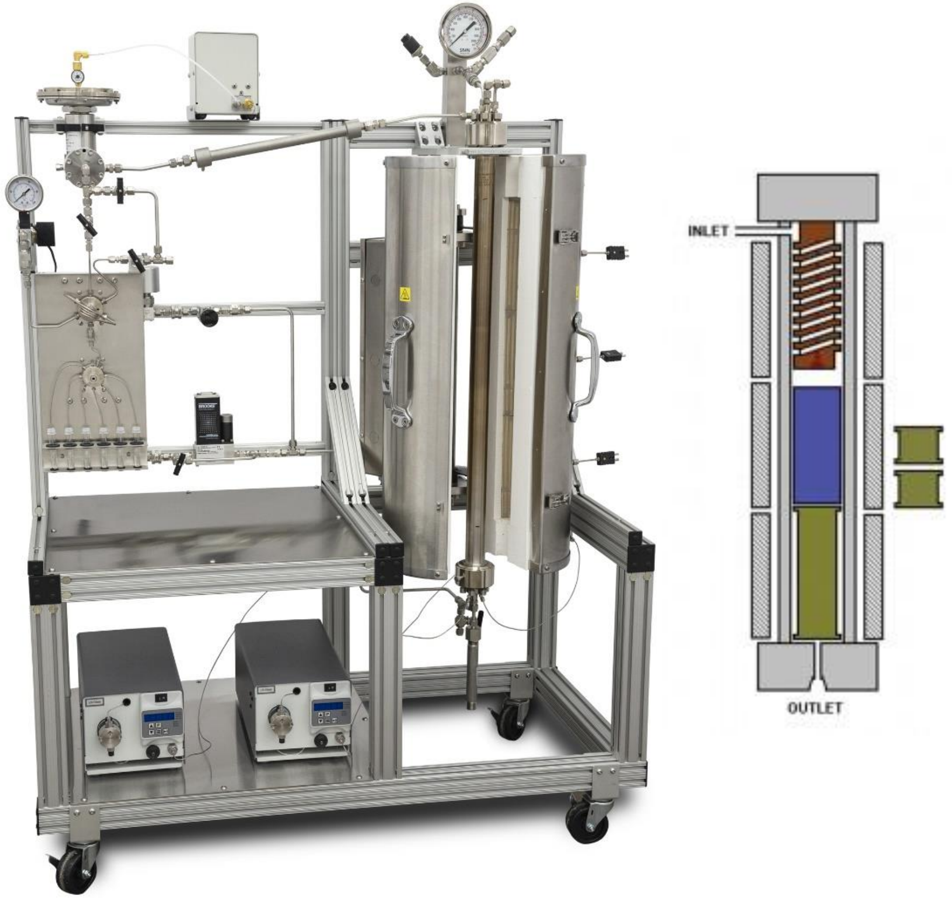
Rock/Fracture Mechanics into Brittle-Ductile Transition

Gaps

- Impact cold to supercritical fluids on fracture propagation in near ductile rock.
- Longevity of well materials and engineered permeability.
- Fracture mechanical testing of diverse lithologies at high T.

Solutions

- Involve facilities beyond O&G and geothermal.
- Survey and expand capabilities at existing facilities.
- Geologic analogs for reservoirs and fracturing.
- Field data for model validation.



Flow Reactor for testing alteration

Stimulation & Reservoir Tech: Zonal isolation

Status

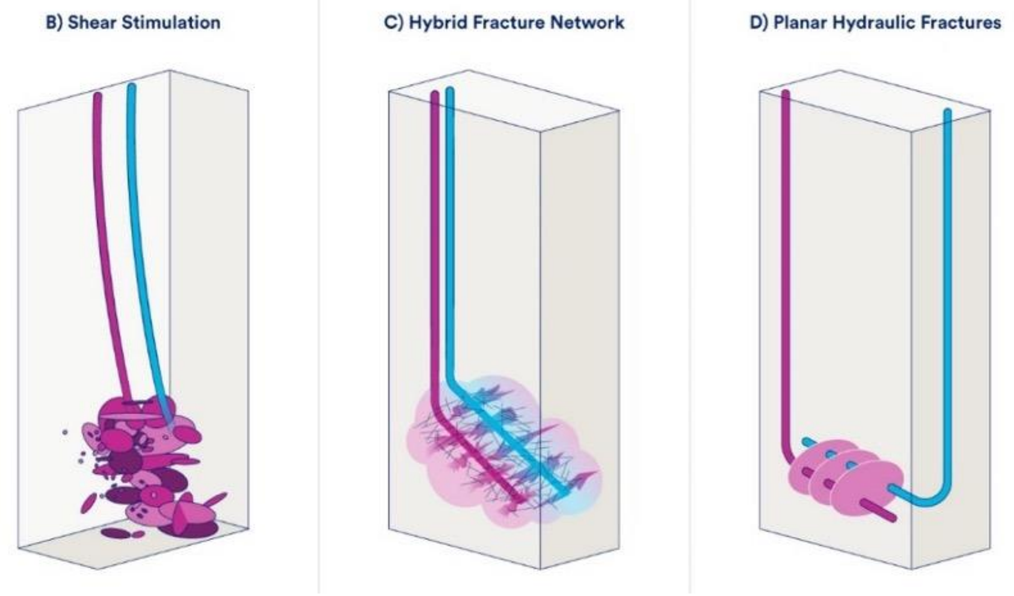
- Open-hole hydroshearing with diverter at 320 °C.
- Cementing, plug, and perf in variety of rock types at ~200 °C.

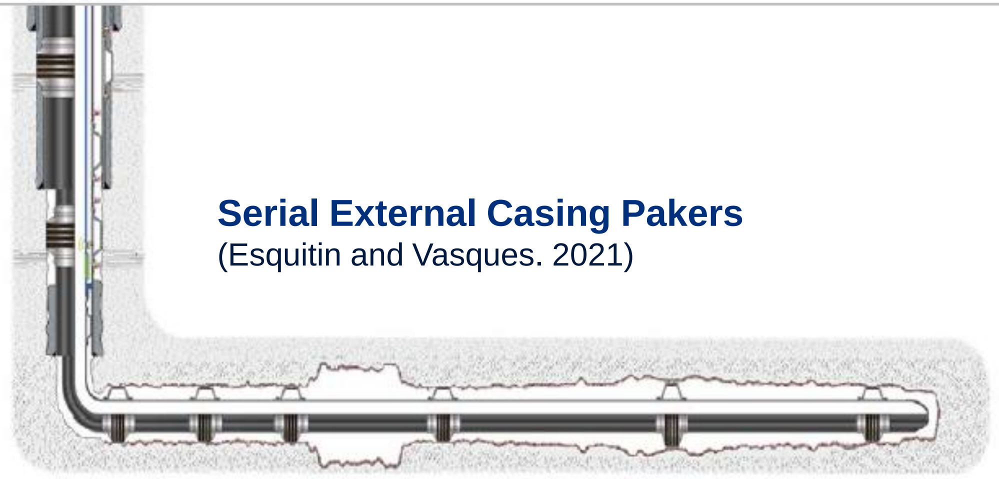
Gaps

- Successful placement of cement above 350 °C.
- Field deployment of zonal isolation in SHR.
- Reliable high temperature perforation tool.

Solutions

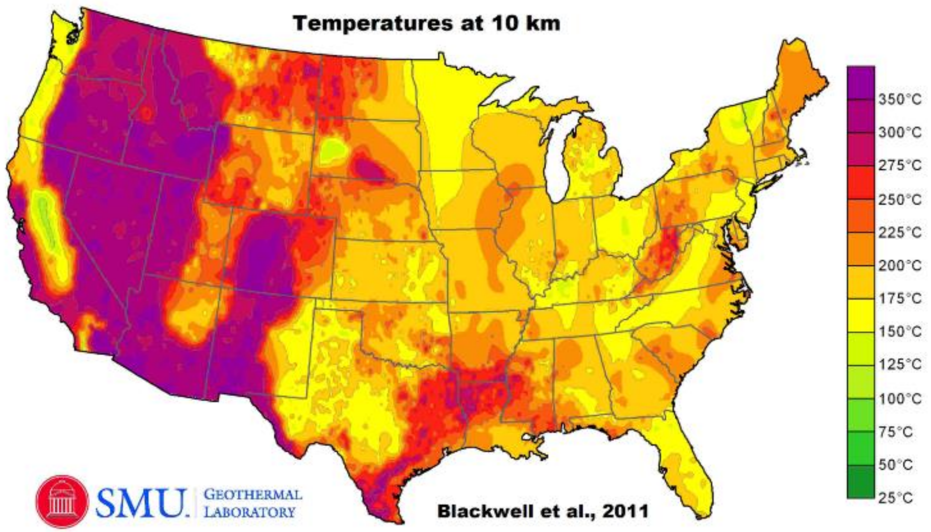
- Materials testing and development.
- SHR durable cements
- All metal external casing packers (ECPs) and other sealants.
- Demonstration projects for field testing.





Serial External Casing Pakers
(Esquitin and Vasques. 2021)

Pathway to enable cost-competitive, scalable geothermal



Superhot rock resources are widely available in the western US at depths of 7-15 km

SHR technology development has two prongs:

- Superhot Rock EGS
  - Engineered Geothermal Systems > 350 °C
- Advanced drilling (i.e. MMW drilling)
  - Low-cost drilling to reach 450 °C anywhere

Tier 1: Magmatic Sites

Target Temp: 425 °C
Target Depth: 4.5 km

Conventional Drilling
First SHR EGS
2025 Goal

Tier 2: Above average gradients

Target Temp: 425 °C
Target Depth: 8-15 km

Millimeter Wave Drilling
Brownfield conversion to reduce or replace fossil-fuel use

Tier 3: Below average gradients

Target Temp: 425 °C
Target Depth: >15 km

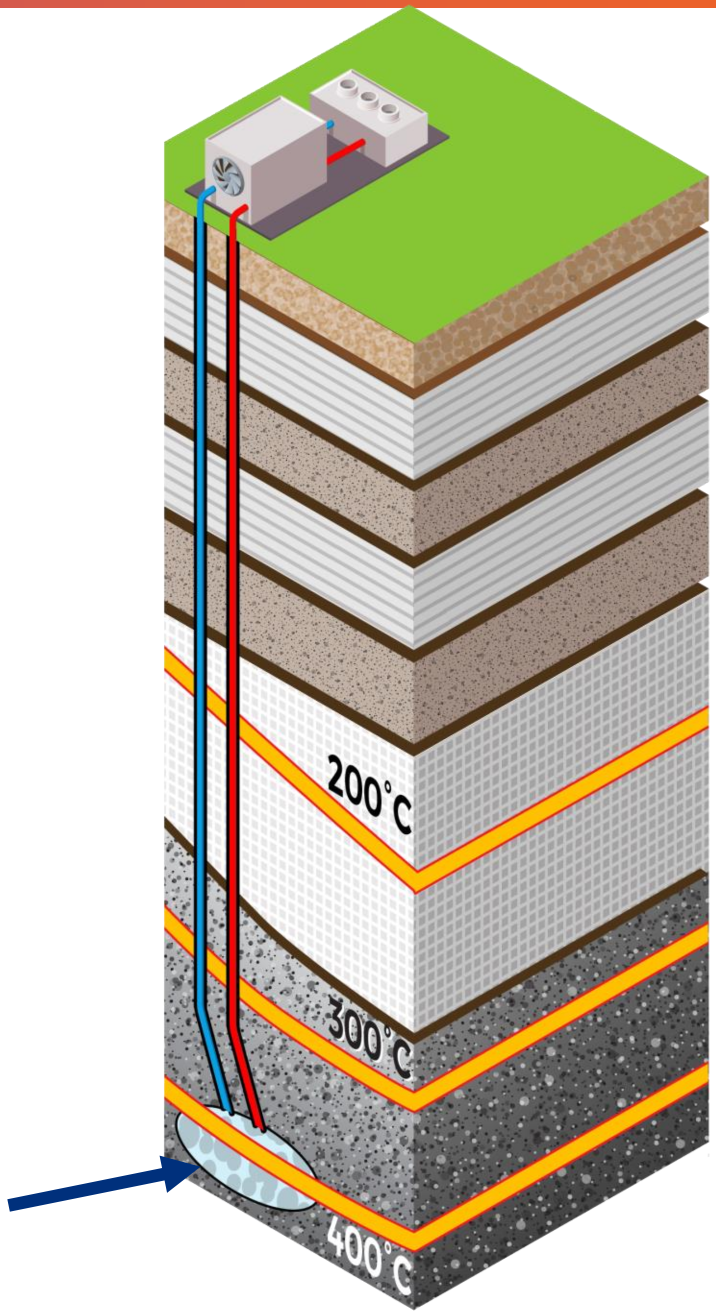
Goals of an Nth of a Kind (NOAK) SHR EGS project

1. Net electricity generation >20 MW per production well,
2. Produced fluid specific enthalpy >2100 kJ/kg,
3. Projected sustainable field operation >20 years,
4. Levelized cost of electricity of <$50 MW/hr, and
5. Low risk of impacts from induced seismicity.

First of a kind (FOAK) will not achieve 1-4.

All projects must achieve #5

This is too vague!

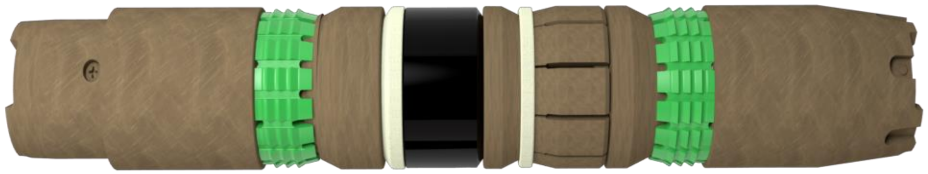


SHR EGS Demonstration Wells

Objective - Connect two wells in superhot rock and circulate at parity with fossil fuels

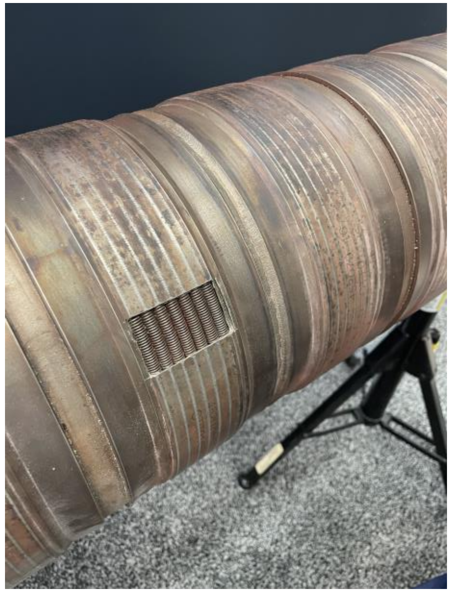
Drilling, casing, and completion

- Directional Drilling to 400 C
- Installation of casing and cement above the production zone
- Well completion and methods for zonal isolation in the production zone
    - Cement
    - Metal-metal ECPs
    - Fracture initiation tools
    - Frac plugs



Frac Plug

Perforation tool



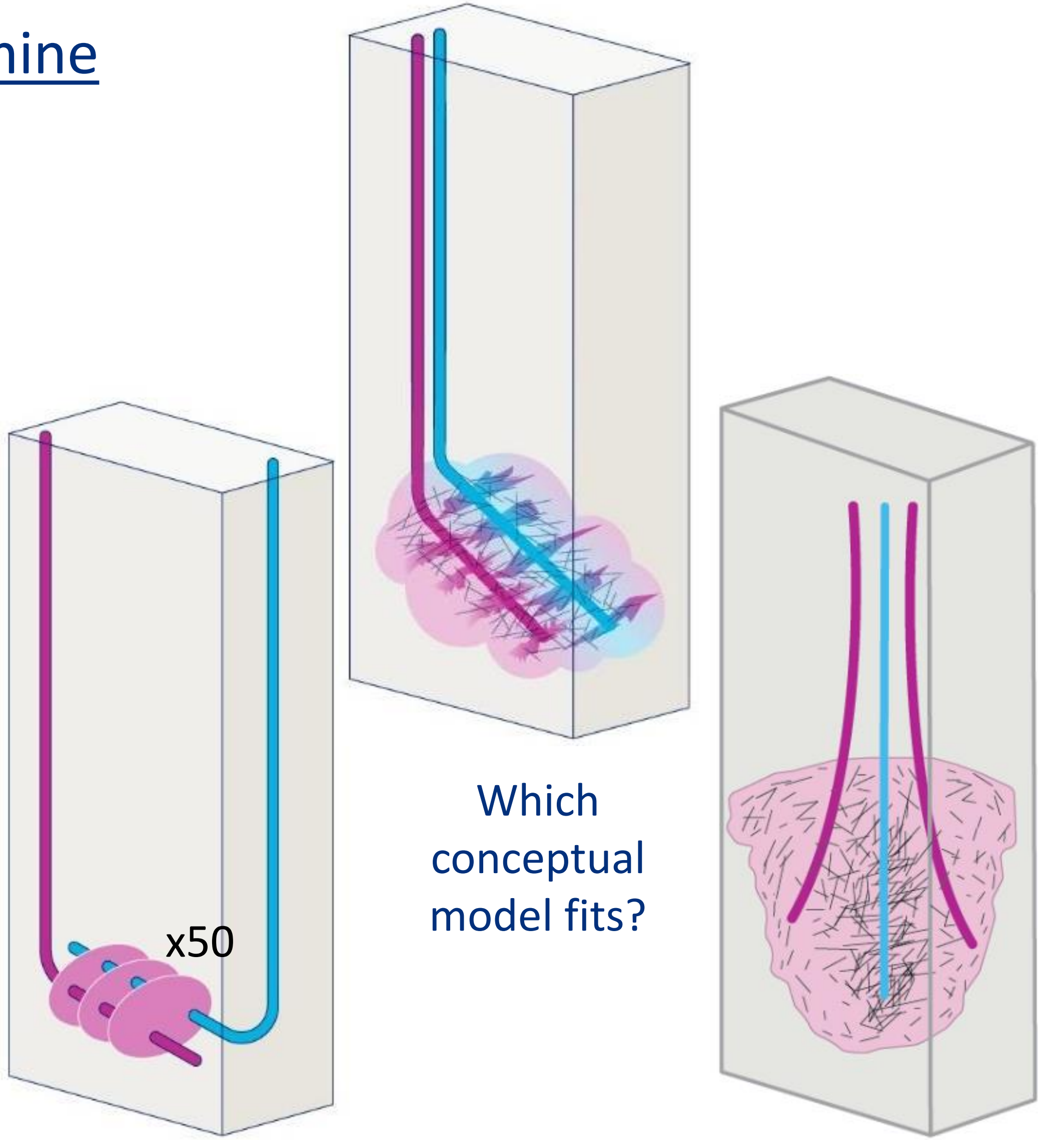
External Casing Packer

SHR EGS Demonstration Wells

Objective - Connect two wells in superhot rock and circulate at parity with fossil fuels

<u>Geomechanical and geochemical parameters to determine</u>

- Fracture propagation direction
- Fracture initiation/propagation pressure
- Maintaining open fracture
    - To prop, or not to prop
- Maximum fracture length
    - Determine well separation
    - Critical for cooling rate
- Fracture complexity and fracture surface area
    - Experiment with innovative slurries & pumping
- Chemical treatment



Which conceptual model fits?

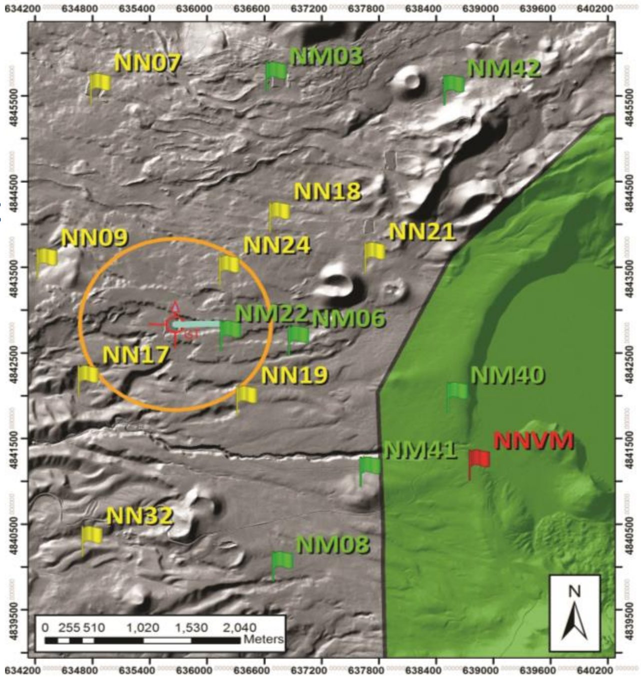
SHR EGS Demonstration Wells

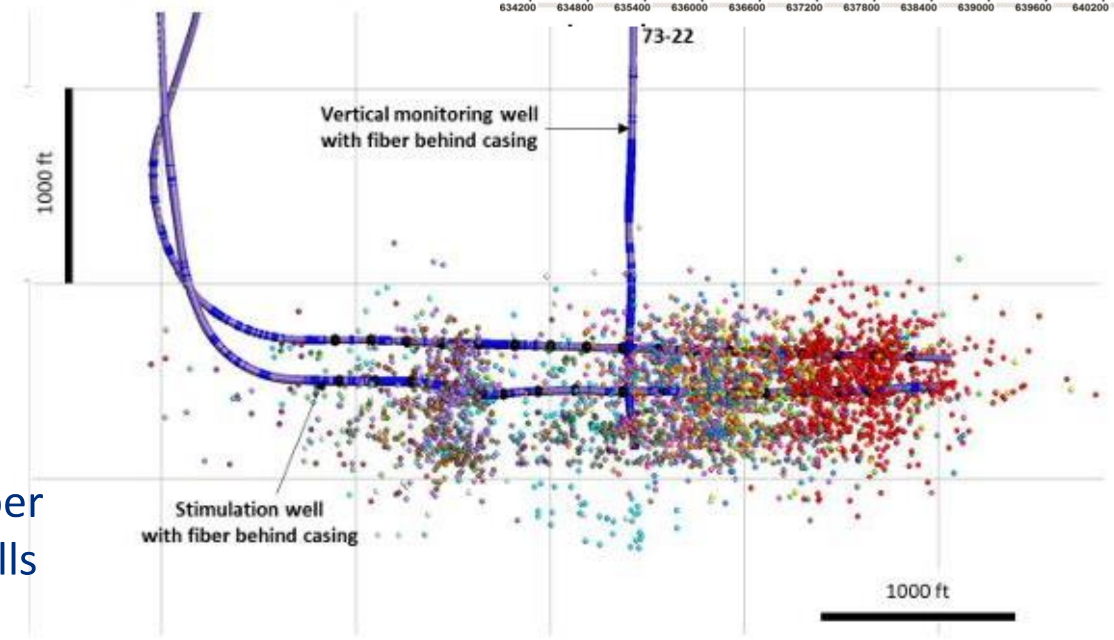
Objective - Connect two wells in superhot rock and circulate at parity with fossil fuels

<u>EGS Characterization</u>

- Real-time fracture monitoring
- Real-time fracture optimization
- Microseismic monitoring for induced seismicity mitigation and reservoir mapping
- Downhole Fiber Optic -DAS

Shallow borehole microsesimic array at Newberry Demo, 2012



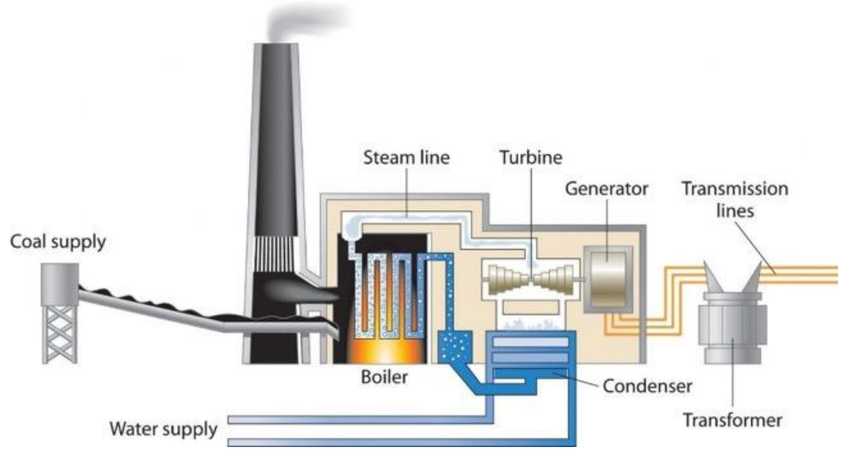


Fervo Project Red fiber optic cables in 4 wells for DAS, DSS, DTS

Current and future SHR demonstration projects

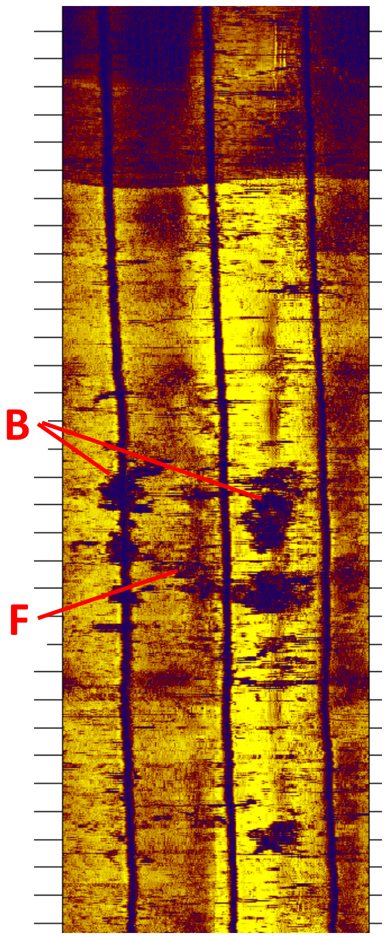
Conclusions

- SuperHot IS NOT that hot!!
- Coal power plants burn at 550 °C
- Nuclear power plants at 700 °C
- Pizza ovens at 400 °C
- If we can build and operate these why can’t we build and operate SHR Geothermal systems?



Thank You!

Tools: Well Characterization



Need –stress orientation/regime and natural fracture characteristics

- Determine stress orientation, regime, magnitude, and variability with depth
- Natural fracture characteristics – orientation, intensity, etc.
- Heterogeneity – foliation, lithologic contacts, dykes, etc.

Status

- Stress measurement (minifrac or XLOT) not attempted yet but possible if retrievable SHR open hole packer is available.
- Geophysical and image logs good to 260-280 °C

Solutions

- Well bore cooling during logging / Logging with drilling and tripping
  - Risk: Misinterpretation of cooling induced thermal stresses (Soultz)
- Higher temperature or better heat shielded instruments.

Stimulation & Reservoir Tech: Permeability Creation

Steps

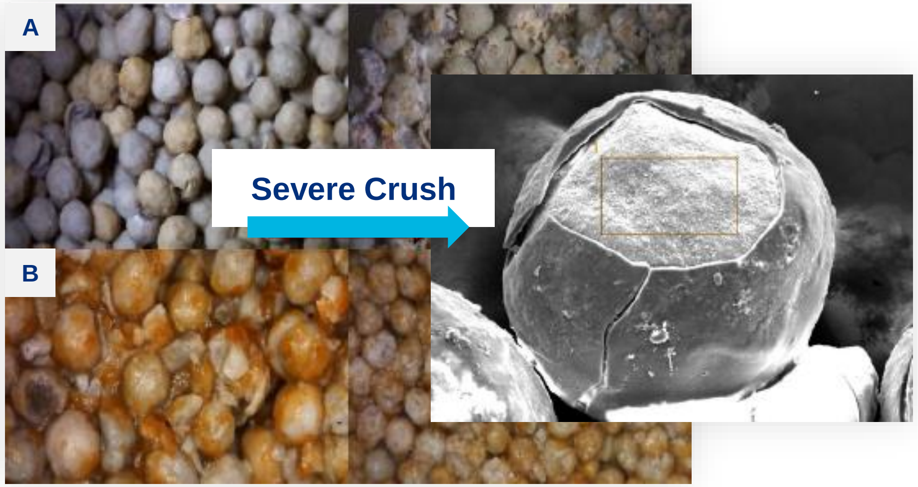
- New fracture initiation and growth
- If tensile fracs, permeability needs to be maintained by proppants, chemical treatments, or fluid pressure.

Gaps

- Standard fracture initiation tools (perf guns) limited to 200 °C
- Hydraulic fracturing not yet attempted above 220 °C
- Quartz sand proppant will alter above 300 °C

Solutions

- Development of SuperHot fracture initiation tools and proppant
- Demonstration projects of fracturing systems



Proppant (Ko et al, 2023)