Determining key parameters and suitable measures for successful EGS developments

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Key Components

Various site properties that should be known for successful creation of the reservoir include:

- Temperature gradient and heat flow
- Stress field
- Lithology and stratigraphy
- Structure and faulting
- In situ fluids and geochemistry
- Geologic history
- Seismic activity
- Proximity to transmission
- Land availability
- Demographics
Fenton Hill - First HDR Project
1974-1992
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1974-1992
Some Lessons Learnt from Fenton Hill

• Deep (~5 km), high-temperature wells can be completed in hard, abrasive rock.
• Low-permeability crystalline rock can be stimulated to create hydraulically conductive fractures.
• Hydraulic-pressurization methods can create permanently open networks of fractures in large enough volumes of rock (>1 km³) to sustain energy extraction over a long time period.
• The EGS reservoir can be circulated for extended time periods and used to generate electricity.
• Creating the connection between wells was a crucial step in developing the EGS reservoir. Connection was easier to establish by drilling into the fractured volume, once it was stimulated and mapped.
• The fracture pattern that was observed did not match that predicted by early modeling.
• If water was injected at high enough pressures to maintain high flow rates, the reservoir grew and water losses were high. If injection pressures were lowered to reduce water loss and reservoir growth, the flow rates were lower than desired, due to higher pressure drop through the reservoir.
• The high pressures needed to keep the joints open caused operational problems and required substantial amounts of power.
Rosemanowes, UK

1977-1991
Lessons Learnt from Rosemanowes

• The fractures created by hydraulic stimulation, which best connect across the reservoir, are not formed through tension. Instead, they are created by shearing on pre-existing joint sets.

• Stress fields in crystalline rock are invariably anisotropic, so the natural fractures fail in shear. Having sheared, the natural fractures then self-prop and stay open.

• It is possible to stimulate natural fractures and improve permeability – and create a connected volume of hot rock.

• A prediction of the direction of fracture growth is difficult in the absence of precise downhole data. Even with near-wellbore data from image logs, the fractures may not grow exactly as predicted. As a result, it is better to create the reservoir first, and then drill into it (Batchelor, 1987).

• Probably the most important single lesson from this experiment is that hydro-fracturing and artificial fractures are almost irrelevant. The natural fracture system dominates everything (Batchelor, 1989).

• Overstimulating pre-existing fractures can result in a more direct connection from injector to producer than is desired, so that cool fluid can “short-circuit” through the reservoir.
Ogachi and Hijori, Japan

1989-2002
Lessons Learnt from Hijori

• The reservoir continued to grow during the circulation test.
• If natural fractures already connect the wellbores, stimulation may result in an improved connection that causes short circuiting, particularly if the well spacing is small.
• The acoustic emissions (AE) locations from the deep circulation test suggest that the stimulated fractures or the stress field change direction away from the well.

Lessons Learnt from Ogachi

• The complex geologic history at Ogachi made it difficult to predict the direction of fracture growth.
• The stress state in the original boreholes was not well understood until borehole televiewer data was collected and analyzed after the wells had been stimulated.
• Stress changes with depth in the boreholes
Soultz-sous-Fôrets

1987-

Schematic cross-section from Le Carlier et al., 1994
Fractured zones in the granite from Dezayes et al., 2008

Fractured zones in the granite

Miocene, Pliocene et IV
Trias
Oligocene
Jurassic
Granite
The European EGS test site Soultz-sous-Forêts, France

Objective 2 x 1.5 MW electrical power (1.5 MW capacity currently installed)

Wells 3

Vertical Depth 5.000 m

Temperature > 180°C

Flow Rate 2 x 125 m³/h

Reservoir EGS/HDR/petrothermal

Power Plant ORC

Research 1987 to 2005

Construction 2005 to 2008

Status feed-in of up to 1.5 MWe

- target horizon 5000 m
- temperature 200°C
- 35 l/s → 2.0 MWe (well distance 600 m)

1987-1997
1998-2001
2001-2004
2004-2008
Monitoring fracture growth

Development of seismic events during stimulation

Asanuma et al. 2002
Monitoring fracture growth

Orientation of seismic events

Asanuma et al. 2002
The European EGS test site Soultz-sous-Forêts, France

- 22 years of research, from first site investigation to operation and electricity production in 2008
- 80 MEuros spent on RTD and installations: 30 M€ EU, 25 M€ France, 25 M€ Germany.
- The initial French-German cooperation was enlarged by adding the UK experience (Camborne School of Mines -> Rosemanowes)
- 15 research institutions and numerous subcontractors involved
- More than 40 PhD theses, 1000+ scientific publications
- Regional spin-offs in Landau, Insheim, Bruchsal, Rittershoffen, Strasbourg …
- Now operated by ES Géothermie
Enhanced geothermal systems (EGS)

- The EGS concept: artificial improvement of hydraulic performance of a reservoir
- Enhancement is required to develop and exploit geothermal resources that are not economically viable by conventional methods
- Enhanced vs Engineered
Geology - fractures

Properties
- Fracture sets
- Fracture intensity
- Fracture orientation
- Fracture size
- Fracture conductivity
- Mechanical properties

Exploration
- Well logs (e.g. FMI, PLT,...)
- Seismics (active, passive)
- Production data & well tests
- Outcrop studies

Implications
- Hydro-shearing of critically stressed pre-existing fractures
- Interaction with existing fractures
- Locally fracture follows fabric

McLennan and Potocki (2013)
Geology – fractures from well logs

PLT = Production logging tool
FMI = Formation Micro Imager

Exploration of fractures with well logs
EXERCISE

Fracture mapping: Scanlines from analogue sites

.....structural data within each square......
EXERCISE

....TOWARDS PERMEABILITY.....
PERMEABILITY \( (m^2) \)

\[
k = \left( \frac{2}{3} \times \frac{b^3}{L} \right) \times (f \times 10^{-6})
\]

- Gale (1982)
- Nicholl et al. (1999)
- Zimmerman and Bodvarsson, 1996

- \( b \) = average fracture width
- \( L \) = fracture length
- \( f \) = assumed as 0.4

- Connectivity among fractures: \( 0.1 < f < 1 \)
- \( f \) = constant of connectivity
Fracture mapping: Scanlines from analogue sites
Fracture mapping: Scanlines from analogue sites
EXERCISE

Fracture mapping: Scanlines from analogue sites
Fracture mapping: Scanlines from analogue sites
Las Minas analogue site
Acoculco

N70°

Borehole

NE

SW

GEMex: Geothermal energy research Europe-Mexico

www.gemex-h2020.eu
Mapping at Acoculco

Hangingwall

Footwall

N70°

Borehole

Fault Zone

Silicicous sinter

Volcanic and volcanoclastic succession

Limestone/earthy succession

Boreholes

13.45 - Brogi et al.

GEMex: Geothermal energy research Europe - Mexico

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Lithological Units at Las Minas

Analogue site for Accoculco and Los Humeros
Las Minas
Stereographic projection plots

All fracture sets, from every scanlines

Fracture set (F1) Fracture set (F2) Fracture set (F3) Fracture set (F4)

Fracture set (F5) Fracture set (F6) Fracture set (F7)
Fracture mapping: Scanlines from analogue sites

1. Boquillas - Skarn

2. Eldorado

3. Pueblo Nuevo - Marble

4. Tatatila

5. Rinconada - Limestone

6. San Antonio Tenextepec

Lepillier (2020)

GEMex: Geothermal energy research Europe-Mexico

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Computed DFNs using the MPS method

Skarn

Marble

Limestone
Fracture controlled fluid flow simulation
Fractures as result of forces

- Stress and forces in 3 main axes
- Material: fracture strength, shear strength
- Characteristic angle +/- 30° from max. main stress direction to shearing

f10-cm, porous aeolian sandstone

Ian Main

Inga Moeck
Stress Regimes

Normal Faulting
$\sigma_V > \sigma_H > \sigma_h$

Strike-slip Faulting
$\sigma_H > \sigma_V > \sigma_h$

Reverse Faulting
$\sigma_H > \sigma_h > \sigma_V$

Extensional Regime

Strike-slip Regime

Compressional Regime
Critically oriented fractures
Stress field

Locally, fracture follows fabric; globally, fractures follow stress fields

Joint system in the rock

Local stress field around the borehole (10 D max)

Dusseault
WSM WORLD STRESS MAP
North German Basin

Heidbach et al. (2007)
Stress Decoupling in Eastern NGB

Zang + Stephansson (2010)

Quality
A
B
C
BBO
HF
Upper level
Lower level

Upper level 1.5 - 3.3 km
Lower level 3.4 - 4.1 km

Smoothing parameters:
R = 15 km  n = 3  λ = 12

Quaternary Tertiary
Upper Cretaceous
Lower Cretaceous
Keuper
Muschelkalk,
Upper Buntsandstein
Middle and
Lower Buntsandstein
Zechstein
Sub-reservoir

S_H decoupled EW
S_H far field NNE-SSW

TUDelft

Geothermal Winter School 2021

GFZ

7 km
13 km
Local stress field may differ from regional stress field.
Stress field

Properties
- Stress magnitudes
- Stress directions
- Stress gradients
- Pressure

Exploration
- SV: Density log
- Sh: Minifrac/LOT
- Orientations:
  - Breakouts
  - Tensile fractures
  - HF orientations
  - Focal mechanisms
  - Shear velocity anisotropy
  - Geological indicators
- SH: constrained based on the parameters above
- P: direct measurement

Implications
- Fracture growth directions
- Containment
- Critical pressures for fracture opening/shearing/closure
- Active/inactive faults
- Shear failure potential

Hofmann (2012)
After Gaarenstroom et al. (1993)

Leakoff test to determine minimum principle stress magnitude
Influence of well path and stress on fracture growth
Stress field

Stress variations with depth in different lithologies
Stress Concentration Around Borehole
Wellbore Fracture Initiation: Impermeable Borehole Wall, $\sigma_h \neq \sigma_H$

$$p_{w}^{frac} = 3\sigma_h - \sigma_H - p + T_0$$

For the isotropic stress case $\sigma_h = \sigma_H$

simply replace $3\sigma_h - \sigma_H$ with $2\sigma_h$

$$p_{w}^{frac} = 2\sigma_h - p + T_0$$
Pore pressure vs. stress

- Pore pressure
- Vertical stress (overburden)
- Mean stress
- Effective stress (Terzaghi, 1936)

\[
p = \rho gh + p_0
\]
\[
\sigma_V = \rho_s gh
\]
\[
\sigma = (\sigma_V + \sigma_H + \sigma_h)/3
\]
\[
\sigma_{eff} = \sigma - p
\]
Fracture height growth containment due to stress barriers

Hofmann et al. (2014)
Different fracture geometries in different target horizons

Hofmann et al. (2014)
# Rock properties - hydraulic

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**Mass balance:**

\[ V_i = V_{Lp} + V_f \]

![Diagram of wellbore with injection and leak-off](image)

- Wellbore
- Injection \( Q_0 \)
- Leak off \( q_l \)
- \( \sigma_{\text{min}} \)
- \( \sigma_{\text{max}} \)
- \( L_f \)
Rock properties - hydraulic

Leak-off barrier

Dusseault
Rock properties - mechanical

Properties
- Young’s modulus
- UCS
- Tensile strength
- Cohesion
- Friction angle
- ...

Exploration
- Core samples (lab tests)
- Well logs

Implications
- Fracture aperture
- Self-propping
- Fracture mechanics

![Diagram of rock properties](image)

![Graph of stress-strain relationship](image)
If stresses are not a factor, fractures will tend to be blunted in stiffer strata, propagating laterally more easily than vertically.

Stiffness governs fracture aperture during treatment.
Key Components for EGS

Rock properties

- Varying rock Material Properties $(E, v)$

Fracture networks

- Varying fracture geometry, frequency, and interactions

Stress

- The fracture propagation is calculated using the non-local damage approach, combined with a cohesive-zone model
Thank you very much for your attention

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