Deep fractured EGS, concepts & reservoir assessment in the Upper Rhine Graben

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Dr Albert Genter
Es-Géothermie
Motivation

EGS: Enhanced/Engineered Geothermal Systems
EGS: a geothermal concept or a technology?
Focused on Upper Rhine Graben: operating EGS plants
From concrete examples from the URG
  • Concept evolution based on Soultz-sous-Forêts / Rittershoffen sites (France)
  • Naturally fractured reservoirs with hydrothermal alteration

Stimulation and geothermal exploitation of fractured reservoir
Who we are?

Geothermal operator in Alsace (Central Upper Rhine Graben, France)

- Electricité de Strasbourg ES, main energy company in the Strasbourg area (Alsace, France)
- ES co-owners of two operational geothermal plants in the Central Upper Rhine Graben (URG): Soultz-sous-Forêts and Rittershoffen
- ES is developing new geothermal projects in the URG
- ES-Géothermie (ESG), subsidiary of ES, scientific and technical staff specialized in deep geothermal energy
- ESG is exploiting the two geothermal plants
Two operating EGS plants

Fractured granite reservoirs with very saline brines

<table>
<thead>
<tr>
<th>Two operating EGS plants</th>
<th>Fractured granite reservoirs with very saline brines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brines, ~100g/L, NaCaCl</td>
<td>Brines, ~100g/L, NaCaCl</td>
</tr>
<tr>
<td>Lithium 160mg/L</td>
<td>Lithium 180mg/L</td>
</tr>
<tr>
<td>1.7MWe for electricity production</td>
<td>24MWth for a heat application</td>
</tr>
<tr>
<td>Three wells @ 5000 m</td>
<td>Two wells @ 2500m</td>
</tr>
</tbody>
</table>

Q>30L/s T>150° C

Q>70L/s T>168° C
Life cycle of an industrial EGS project

Main technical phases

- Concept
- Site selection
- Permitting
- Drilling
- Stimulation
- Testing
- Build & test power plant
- Operate and circulation
- Site abandonment

Duration:
- Fracture on outcrops: 1 second
- Concessional scale: 1 year
- Borehole Image: ½ year
- Micro-seismic cloud structure: 1 week
- Power plant exploitation: >25 years
- Power plant dismantlement: >1 year

Cost:
- Induced seismicity: >> €
  - High risk
  - Low risk

Risk:
- Induced seismicity: High risk
- Low risk
EGS concept/technology
From HDR to EGS

From Stefan Wiemer (2018)
Soultz project presentation

Location
• Geothermal anomaly in the Upper Rhine Graben
• Non volcanic area
• No surface hydrothermal manifestation
• Unconventional reservoirs: deep-seated granite

Technology
• 4 deep geothermal wells (3.6 & 5 km): 200°C @ 5 km depth
• 1st binary geothermal plant in France
• Organic Rankine Cycle (ORC) technology: 1.7 MWe
• Down-hole submersible pump: Long Shaft Pump (LSP)

Feed-in tariff in France
• Geothermal electricity 246 € per MWh
• No heat application on site

One of the highest geothermal anomalies in Western Europe
Soultz HDR concept: no exploration

1st step: from 1987 to 2003: the Hot Dry Rock concept

- Hydraulic fracturing
- Water injection
- Hard and tight rocks
- Induced seismic cloud
- Correlation with permeability

➢ Artificial heat exchanger
Soultz EGS concept: learning by doing

2nd step since 2004: on the route of EGS

- Hydraulic & chemical stimulations
- 3 vertically distributed reservoirs? Or 1 large reservoir?
- Hydrothermally Altered & Fractured Granite Zones
- Occurrence of natural brine
- Low natural permeability
- Connexion between the geothermal wells with the reservoir

➢ EGS concept or technology?
The Upper Rhine Graben
Upper Rhine Graben activity

Over the last 30 years:
• 9 geothermal projects
• 23 wells drilled
• >75 km of geothermal boreholes were drilled

Status on 2021
• 3 geothermal power plants and 2 heat plants operating
• 2 projects under development in Strasbourg area but stopped due to recent felt induced seismic events (M>3)
• 6 exploration permits for geothermal energy
• 3 licences for lithium extraction
Temperature anomalies
- Localized around local normal faults / strike slip faults
- Traces of the fluid circulations related to these faults

Geothermal reservoirs
- Muschelkalk limestone
- Buntsandstein and/or Permian clastic sandstone
- Palaeozoic granitic basement

Fluid circulation in natural fractures
- Hydrothermal alteration & fractured zones
- In the granitic basement: 3 types of alterations
  - propylitic alteration, argillic alteration, paleoweathering alteration

Reinecker et al., 2019
Local geology in Northern Alsace

Open-hole section: fractured Triassic sandstone & fractured Carboniferous granite
Geothermal target: a local normal fault in the basement
Stress field: transitional from normal faulting to strike-slip

Reinecker et al., 2019
Upper Rhine Graben tectonics

Villemin & Bergerat, 1987

Glaas, 2021
Vintage exploration from 2D seismic survey

Geothermal target is a deep crystalline rock
Soultz monzogranite

Core K21, GPK-1 (3510 m)

Monzogranite

Crystals of FK (1 to 4 cm)

Granite matrix:
plagioclase, quartz, biotite and hornblende

Accessory minerals: magnetite, zircon, apatite, titanite, hematite, leucoxene

7 cm
Hydrothermal deposits within fractured granite

- Illite in fractures
- Carbonates in fractures
- Iron oxide in fractures
- Illitization of biotite in the damaged zone

GPK1 well 1400 m
Site map

• EPS1 fully cored ➔ exploration well
• GPK1 ➔ Not used
• GPK3/GPK4 ➔ Injection wells
• GPK2 ➔ Production well

BHT=200° C
Orientation of fractures

Fracture zones

N160E ± 10°

σ_H N170E
(Valley, 2007)

Small-scale fractures

Dezayes et al, 2010

Orientations of deep fractures are not // to main Rhine graben faults
Present-day stress field

Regional scale: $\sigma_H$ NW-SE, Compressive event
Soultz: Borehole measurements, $\sigma_H$ NNW-SSE
NNW-SSE fractures are critically stressed

Borehole scale (Soultz): $\sigma_H$ N170E (Valley, 2007)
Transitional stress field between normal and strike-slip
Low to moderate seismic hazard area
Last natural earthquake in 1952 with M4.8 @ 20 km SE of Soultz

Peters, 2007
Thermal profiles @ Soultz

Natural circulations in fractured & altered zones
Top basement is a geothermal resource target

Conduction

Convection

Trias sandstone

Carboniferous granite

Fractured & altered granite

Fractured sandstones

Genter et al, 2010

GPK-2

GPK-3

GPK-4
Hydrothermal alteration

Vein Alteration related to fractures
- Biotite, Hornblende
- Plagioclase
- K-Feldspar
- Quartz
- illite
- illite
- Stable or illite
- Stable

Pervasive Alteration: Standard monzogranite
- Biotite
- Plagioclase
- Chlorite
- Corrensite

Genter, 1989
## Native brine composition

**Fluid Sample**  
06/02/2013  

<table>
<thead>
<tr>
<th>Fluid Sample 06/02/2013</th>
<th>Na mg/l</th>
<th>K mg/l</th>
<th>Ca mg/l</th>
<th>Mg mg/l</th>
<th>Cl mg/l</th>
<th>SO$_4$ mg/l</th>
<th>NO$_3$ mg/l</th>
<th>SiO$_2$ mg/l</th>
<th>Br mg/l</th>
<th>Sr mg/l</th>
<th>Li mg/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPK2-PROD</td>
<td>25200</td>
<td>3360</td>
<td>7440</td>
<td>142</td>
<td>57300</td>
<td>228</td>
<td>&lt;2</td>
<td>174</td>
<td>237</td>
<td>418</td>
<td>169</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>F mg/l</th>
<th>PO$_4$ mg/l</th>
<th>B mg/l</th>
<th>NH$_4$ mg/l</th>
<th>Fe$_{total}$ mg/l</th>
<th>Mn mg/l</th>
<th>Ba mg/l</th>
<th>As mg/l</th>
<th>Rb mg/l</th>
<th>Cs mg/l</th>
<th>Zn mg/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>4</td>
<td>41</td>
<td>24</td>
<td>30</td>
<td>18</td>
<td>26</td>
<td>11</td>
<td>18</td>
<td>11</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Al µg/l</th>
<th>Pb µg/l</th>
<th>Cd µg/l</th>
<th>Cr µg/l</th>
<th>Cu µg/l</th>
<th>Ni µg/l</th>
<th>Hg µg/l</th>
<th>Ag µg/l</th>
<th>U µg/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>66</td>
<td>66</td>
<td>14</td>
<td>5</td>
<td>&lt;1</td>
<td>1</td>
<td>&lt;0.4</td>
<td>0.8</td>
<td>&lt;0.05</td>
</tr>
</tbody>
</table>

*(Sanjuan, 2010)*

- Na-Cl-Ca dominated brine
- TDS ≈ 97 g/l, Density = 1.065 g/cm$^3$ (20°C)
- pH ≈ 4.7-5.0
- Gas Liquid Ratio of 1:1 (mainly CO$_2$, 85%, N$_2$, 10%, and CH$_4$, 2.5%)

→ Soultz operation conditions are highly aggressive and corrosive
Hydraulic stimulation

Cuenot et al., 2008

Dorbath et al., 2009
The Rittershoffen project (France)
Local geology

Open-hole section: fractured Triassic sandstone & fractured Carboniferous granite

Geothermal target: a local normal fault in the basement
Rittershoffen project: main technical phases

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>ECOGI JV creation</td>
</tr>
<tr>
<td>2012</td>
<td>Drilling, Platform construction</td>
</tr>
<tr>
<td>2013</td>
<td>GRT1 Well @2560 m, Drilling and well development, Seismic Survey</td>
</tr>
<tr>
<td>2014</td>
<td>GRT2 Well @3196 m, Drilling and tracer tests</td>
</tr>
<tr>
<td>2015</td>
<td>Surface construction, Thermal plant, Transport loop, Bio-refinery</td>
</tr>
<tr>
<td>2016</td>
<td>ECOGI plant, Commissioning, Commercial exploitation</td>
</tr>
</tbody>
</table>

Technical Data:
- 2 Wells: 2500-3000 m deep
- Operating hours: 8,000 h/year
- Temperature: 170°C
- Transport loop: 15 km
- Thermal power: 24 MW
Exploration and well targeting

- Thermal anomaly identified from old oil wells
- Reprocessing and interpretation of 5 old seismic lines
- Acquisition of 2 new lines
- PSDM processing of all lines
- 3D Structural modeling with Petrel

*GRT-1* vertical @ 2600m MD
*GRT-2* deviated well @ 3200m MD
Deep fractured reservoir: clastic versus granite

Tertiary Jurassic Sediments (clays, marls)

Marls Keuper
Limestones Muschelkalk
Sandstones Buntsandstein
Granite Basement

Naturally fractured reservoir
Diagram showing geological layers and borehole depths for two boreholes, GRT-1 and GRT-2.

- **Paleogenèse (Tertiaire) (~50 – 30 Ma)**
- **Trias (~250 – 200 Ma)**
- **Socle Varisque (~330 Ma)**
- **Jurassique (~200 – 170 Ma)**

Layers include:
- **Socle granitique**
- **Buntsandstein**
- **Muschelkalk**
- **Keuper**
- **Complexe dolomitique**
- **Couches de Péchelbronn**
- **Couches à Mélettes**
- **Schistes à Poissons**
- **Pli-Quaternaire**

 Depths and equipment stages:
- **FORAGE 8''**
  - 1/2
  - Tubage 8" 5/8
  - Sabot 8" 5/8
  - Fin forage 2580 m
- **FORAGE 12''**
  - 1/4
  - Tubage 9" 5/8
  - Sabot 9" 5/8
  - 1922 m
- **FORAGE 17''**
  - 1/2
  - Tubage 13" 3/8
  - Sabot 13" 3/8
  - 1178 m
- **FORAGE 24''**
  - 1/2
  - Tubage 18" 5/8
  - Sabot 18" 5/8
  - 446 m

**TUBAGE**
- 30''
- 18" 5/8
- 13" 3/8
- 18" 5/8

**Top liner hanger**
- 1073 m
- 1120 m TVD / 1190 m MD
- 1200 m TVD / 1290 m MD
- 1920 m TVD / 2190 m MD

**Fin forage**
- 2600 m TVD
Temperature profiles @ Rittershoffen

Baujard et al., 2017, *Geothermics*

Depths are expressed in TVD
Focus on temperatures in the reservoir

Depths are expressed in TVD

Baujard et al 2017
Geothermics
GRT-1 well testing & development strategy

Well testing GRT-1
- Low initial productivity (< 0.5L/s/bar)
- Low initial injectivity
- Economic threshold not reached

GRT-1 Well development
- Thermal stimulation
- Chemical stimulation
- Hydraulic stimulation

Baujard et al 2017 Geothermics
Hydraulic stimulation of GRT-1

- Objective: increase reservoir permeability using hydro-shear processes
- High rate water injection with stepwise rate (Qmax 80L/s)
- Real-time seismological monitoring

Results: Injectivity increase by a factor 2

Baujard et al 2017, Geothermics
Seismological activity during GRT-1 hydraulic stimulation

- Real-time location
- > 300 events automatically picked and located
- Max magnitude 1.6 Ml
- Max Well-Head Pressure: 30 bar

Critical threshold (MI 1.7) never reached  
From Maurer et al. 2020
Conclusions

EGS technology for URG:
There is a kind of continuum between an EGS well (ex GRT1) and a hydrothermal well (ex GRT2)
Fluid flow signature in the basement
  - High fracture density & low geothermal gradient in the top basement
  - Argillic alteration with illite in the basement (damaged zone)
  - Complexe architecture of fractured zones (fault core, quartz vein)
  - Induced seismicity during stimulation but with very low magnitude
  - Induced seismicity during exploitation but with very low magnitude at reinjection side

Geothermal energy from deep fractured granite reservoir is a reality

Electricity, heat, lithium, greenhouses, industrial applications are possible!
Thank you very much for your attention

This work was performed in the framework of the H2020 MEET EU project which has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 792037
Questions

Soultz-sous-Forêts

Question 1: The Soultz geothermal project

The Soultz site is located within a high geothermal anomaly inside the Upper Rhine Graben, with a temperature of about 110°C at 1 km depth. This first km of sediments is dominated:

a) By a convective thermal regime. ☐

b) By a conductive thermal regime. ☐

c) By both convective and conductive thermal regimes. ☐

Question 2: The Soultz geothermal project

The EGS Soultz site is under exploitation by using one production well, GPK2, and two injection wells, GPK3 and GPK4. In 2019, about 800’000 m³ of geothermal water were circulated within the geothermal installation. Where comes from this water?

a) Fresh water is injected from water supply. ☐

b) Natural brine is permanently pumped in the reservoir and re-injected. ☐

c) Natural brine is not sufficient and fresh water is regularly injected. ☐
Questions
Rittershoffen

Question 3 : Power or heat production?
The Rittershoffen geothermal project, located close to Soultz, was designed?

a) To produce power generation with a gross electricity capacity of 2.4MWe
b) To produce heat for a bio-refinery located 15 km away from the geothermal wells
c) To produce geothermal fluids with a surface temperature range of 160-170°C and a production flow rate of 70 L/s

Question 4 : Top basement
At Rittershoffen, the geological interface between the sedimentary clastic cover and the top crystalline basement is exploited by deep boreholes.

a) At Soultz, the sediment-basement interface is localized at 2.2 km depth
b) At Rittershoffen, the sediment-basement interface is deeper than at Soultz
c) At Rittershoffen, the geothermal fluid is much more saline than at Soultz