Geothermal Exploration

Exploration Workflow for Deep Geothermal Systems

John Reinecker (GeoT)
Prior to any exploration activity a clear answer to

- Why should I put effort in exploring?
- Where is the energy needed?
- What is the planned usage?
- How high is the demand?

is needed.
Why Geothermal Exploration?

The distinguished purpose of exploration is to enhance the possibility of success and reduce the project risks.

The aim is to develop a ‘conceptual model’ of the heat source and fluid flow in a geothermal system.
Why Geothermal Exploration?

and:

Exploration is a necessary and integral part of any geothermal project development
Content of this Lecture

1. Workflow in project development
2. Project costs
3. Project risks
4. ‘Project success’
5. Goals of geothermal exploration
6. Challenges
7. ‘Best practice’
8. Exploration data and methods
9. Risk assessment
Pre-development Phase 0 (Drafting the Idea)

- Potential commercial/private consumer and their energy demand in the area of interest
- Business case (desire) with envisaged energy output ($\text{MW}_{\text{el}}$, $\text{MW}_{\text{th}}$, minimum temperature, ...),
- Project development strategy
Phase I (Geological Pre-Assessment)

- Area of interest by geographical and geological criteria (scoping)
- Exploration license (exploration permit) covering the area of interest
- Data mining (publicly available data and literature)
- Spatial analysis of georeferenced data (GIS study)
- Define geothermal potential (reconnaissance)
- Respect environmental regulations (water protection, nature conservation, ...)
- Respect competition in subsurface usage (hydrocarbon, gas storage, drinking water, repository of radioactive materials, ...)
- Regional energy demand (consumer) and power/heat grids (infrastructure)
- If necessary, acquire additional existing close-by 2D seismic lines (on low-cost)

A preliminary feasibility report shows the general feasibility of a hydrothermal project in the area of interest with different opportunities and recommendations for further project development

⇒ GO/NO GO decision whether to continue and make further investment

mainly desktop study
Project Development – Workflow

Phase II (Surface Exploration) going in the field

✓ Acquisition of exploration data (mainly 2D/3D seismic survey, borehole data)
✓ Setting up a detailed geological/structural reservoir model integrating all available data
✓ Geomechanical assessment of mapped fault zones bearing open fracture networks
✓ Validation of deep reaching convective structures (e.g. by means of an isotope study in groundwater wells or geothermal gradient wells)
✓ Outcrop analogue study

Outcomes:
→ Reservoir definition (spatial)
→ Reservoir characterisation (geological, geothermal, hydrological, hydro-chemical)
→ Target definition
Phase II (Surface Exploration) (continued)

- Exploitation strategy (possible well path trajectories from various potential drill sites)
- Numerical thermo-hydraulic simulation of long-term hydrothermal operation
- Environmental impact assessment (EIA)
- Seismological hazard assessment (regarding induced seismicity)

A site-specific feasibility report including a detailed risk assessment and a financial evaluation

- Adjust business case calculations to real conditions
- Discuss findings and possible other scenarios with local stakeholders in order to find acceptance for the project

⇒ GO/NO GO decision whether to continue and make further investment

For the further workflow let us assume we’re going for a hydrothermal doublet and we decide to drill the first well in full size.
Project Development – Workflow

Phase III (Subsurface Exploration)

✓ Drill site / project site
✓ Planning of well path and well design
✓ Operation plan for drilling, logging and testing
✓ Operation plan for seismic monitoring
✓ Operation plan for ground water monitoring
✓ Preparation/construction of drill site and testing pond
✓ Set up of a local seismological monitoring network
✓ Installation of shallow groundwater monitoring wells
✓ Drilling, logging and testing the first well
⇒ Evaluation of success (GO/NO GO decision)
✓ Drilling, logging and testing the second well
⇒ Evaluation of success (GO/NO GO decision)
Phase III (Subsurface Exploration) (continued)

✓ Long term circulation testing
⇒ Evaluation of success (GO/NO GO decision)

✓ Update numerical thermo-hydraulic simulation
✓ Assess area/volume of thermo-hydraulic influence
✓ Operation plan for long term operation
✓ Exploitation approval (mining authority)
Project Development – Workflow

Phase IV (Installation Heat and/or Power Plant)

- Building permit
- Planning and installation of the entire surface energy system
- Planning and installation of infrastructure to the existing grid

Phase V (Operation)

- Commissioning
- Reservoir management
- Maintain seismological monitoring
- Maintain groundwater monitoring
- Regular workover actions
- Apply regularly for renewal of exploitation approval
Project Development – Overview

Phase I
- 3 months
  - Data Mining
  - GIS-based Study
  - Conceptual Model

Phase II
- 9-18 months, depending on acquisition of seismic data
  - Geophysical Exploration (2D & 3D)
  - Geological Model
  - Simulations
  - Localization of Drilling Target
  - Localization of Well Site

Phase III
- 12-18 months
  - Drilling Plan
  - Drill Site Construction
  - Drilling
  - Testing
  - Circulation Test

Phase IV
- 12-24 months
  - Installation Heat and/or Power Plant

Phase V
- up to 3 years to ramp up

Diagram:
- Phase I: Geological Pre-Assessment
- Phase II: Surface Exploration
- Phase III: Subsurface Exploration
- Phase IV: Installation, Heat and/or Power Plant
- Phase V: Operation

Success?
- Pre-Feasibility Report
- Feasibility Report: Insurrance of Well(s)
## Project Costs

Approx. costs for a deep geothermal project (hydrothermal doublet) in Germany

<table>
<thead>
<tr>
<th>Phase</th>
<th>Items</th>
<th>Approx. costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Reconnaissance Study (Pre-Feasibility Report)</td>
<td>50 k€</td>
</tr>
<tr>
<td>II</td>
<td>Legal (application for permits, fees)</td>
<td>2 M€</td>
</tr>
<tr>
<td></td>
<td>Acquisition of existing 2D seismic lines (assuming 30 km)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acquisition of new 20 seismic lines (including planning; assuming 10 km)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acquisition of new 3D seismic survey (including planning; assuming 70 km²)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Re-)Processing of seismic data</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interpretation of seismic data</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acquisition of borehole data</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acquisition and interpretation of magnetic survey (optional)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acquisition and interpretation of gravimetry survey (optional)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrochemical (and soil gas) exploration (optional)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seismological hazard assessment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environmental impact assessment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Feasibility Study (Feasibility Report) including modelling and simulations</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Public relations</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>Legal (application for permits, fees)</td>
<td>30 M€</td>
</tr>
<tr>
<td></td>
<td>Insurance for exploration success (optional)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acquisition of real estate for drilling and power/heat plant (project site)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drill site planning, well planning, test planning, operation plans</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drill site preparation/construction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drilling 2 wells (including all services; 2.300 €/m)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Well logging (borehole geophysics)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Testing (production, injection, long term circulation)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reservoir enhancement (thermal, chemical, hydraulic)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seismological monitoring network (installation and operation)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Groundwater monitoring (installation and operation)</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Legal (application for permits, fees)</td>
<td>24 M€</td>
</tr>
<tr>
<td></td>
<td>Contractors’ all risks insurance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plant planning, operation plans</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Surface thermal system and line shaft pump</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Buildings, electrical and control technology</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ORC plant (1 M€ per MWel)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heat plant (0,3 M€ per MWth)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Infrastructure (connection to existing grid)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>District heating distribution</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Legal (application for permits, fees; per annum)</td>
<td>1.5 M€/a</td>
</tr>
<tr>
<td></td>
<td>Reservoir management (per annum)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seismological and groundwater monitoring (per annum)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maintenance and workover (per annum)</td>
<td></td>
</tr>
<tr>
<td>SUM</td>
<td></td>
<td>50-60 M€</td>
</tr>
</tbody>
</table>

- More than half of the total investment is venture-capital!
- The venture-capital is mainly related to exploration and drilling.
**Risk** = Probability of Occurrence \( \times \) Extent of Loss

Typical risks of a deep geothermal project

<table>
<thead>
<tr>
<th>Group of risk</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>geological risk</td>
<td>conditional to not influenceable, but technically solvable</td>
</tr>
<tr>
<td>technical risk</td>
<td>influenceable</td>
</tr>
<tr>
<td>economic risk</td>
<td>partly influenceable</td>
</tr>
<tr>
<td>environmental risk</td>
<td>influenceable</td>
</tr>
<tr>
<td>political risk</td>
<td>little to not influenceable</td>
</tr>
</tbody>
</table>
Exploration Risk is the risk of not successfully achieving (economically acceptable) minimum levels of thermal water production (minimum flow rates) and reservoir temperatures. (UNEP-Study, 2004)

Risk Reduction through Exploration

The quality of exploration work prior to drilling is a critical factor for reducing the risk of insufficient well productivity.

Geothermal exploration essentially involves the application of a number of geological, geochemical, and geophysical techniques.

The aim is to apply the most appropriate techniques to minimize uncertainties associated with estimates of temperature, depth, productivity, and sustainability of the geothermal resource in the specific circumstances of the project.
Investment and Risk of Geothermal Projects

![Pie chart showing investment and risk distribution for geothermal projects.]

**Project phase**

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
</table>

**Exploration**

- Pre-feasibility study
- Feasibility study
- Reservoir proven by testing
- Drilling 1. well
- Resource proven by drilling
- Drilling 2. well
- Heat/power plant construction
- Commissioning
- Operation

**Project idea**

---

17
The success of a geothermal project depends on the expectations of the operator/investor.

Hydrothermal projects may be considered successful when

1) the actual flow rate at wellhead reaches a minimum expected production rate at a maximum manageable draw down,
2) a minimum temperature is reached,
3) operation is sustainable for at least 25 years,
4) operation can be maintained without induced seismicity above a certain threshold, and
5) the project has public acceptance.
Questions so far?

In the following I’ll assume a
depth, open hydrothermal system
Goals of Geothermal Exploration

1. Resource and reservoir characterisation
2. High temperature
3. High flow rate / productivity
4. Sustainable heat extraction
5. Economic project
6. Safe project (i.e. low risk to the environment, induced seismicity)
Challenges in Geothermal Exploration

- Prediction of hydrothermal alterations (mineralogy, intensity, spatial extent)
- Mapping deep reaching convection cells
- Prediction of fault zone permeability
- Induced seismicity
- The unknown and the unexpected ...
“best practice” established by experience

but: every project is somehow unique/special regarding

• (hydro)geological complexity
• data availability
• applicability of methods
• money
• risks
• expectations
Exploration Data and Methods

Geology
- geological maps and cross sections
- characteristics of geothermal surface manifestations
- detailed description of regional stratigraphy and lithology
- detailed description of regional tectonics and structural geology
- identification and characterisation of potential heat sources
- identification and characterisation of potential reservoir formation(s)
- outcrop analogue studies
- presence of mineralisation associated with hydrothermal systems

(Hydro-)Geochemistry
- fluid samples from springs and offset wells
- cuttings / core samples from offset wells
- interpretations of (hydro)geochemical data
- geo-thermometry estimates
- isotope-geochemical interpretations

Geophysics
- remote sensing
- gravity survey
- geomagnetic survey
- magnetotelluric survey
- electromagnetic survey (CSEM)
- seismic survey (2D, 3D)
- heat flow / temperature gradient survey
- borehole geophysical logging
- seismological data

Hydrogeology
- hydraulic test data from offset wells
- long term production experiences from nearby projects
- hydrogeological maps

→ geological setting, geothermal play type
→ heat flow characteristics, source for deep geochemistry
→ reservoir characterisation, reservoir model, well planning
→ geological setting, reservoir model, geomechanics
→ geothermal play type, conceptual model
→ reservoir characterisation, reservoir model
→ reservoir characterisation
→ reservoir characterisation

→ thermal fluid characterisation
→ reservoir characterisation
→ rock-fluid interactions, conceptual model
→ reservoir characterisation
→ deep reaching permeability

→ neotectonics, surface heat flow
→ lithology
→ lithology
→ clay cap
→ mapping convection
→ structures, reservoir model
→ temperature field, reservoir temperature
→ detailed reservoir characterisation
→ seismic hazard assessment, Induced seismicity

→ permeability, reservoir characterisation
→ sustainability of different configurations
→ near surface groundwater situation
Exploration Data (existing subsurface data)
Exploration Methods – Aeromagnetics

Siemon et al. (2001)
Exploration Methods – Seismics
Exploration Methods – Seismics

Budach et al (2018)
Exploration (setting up a geological underground model)

2D-seismic lines
Exploration (setting up a geological underground model)

Cormorant Field, North Sea

1974 - 1975
2D-Seismic

1981
3D-Seismic

1983 - 1984
3D-Seismic

Graf (2013)
Exploration (setting up a geological underground model)

3D-seismic $\Rightarrow$ improved image of the subsurface

- faults
- structures
- formation depths
- formation thickness
Exploration (facies analysis)

Seismic facies $\Rightarrow$ sedimentary facies model  

(Together with borehole informations)

Rohrer (2012)
Reservoir Characterisation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Significance for reservoir characterisation / exploitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>type of reservoir</td>
<td>exploitation concept, well path planning</td>
</tr>
<tr>
<td>lithofacies</td>
<td>geometry of the reservoir, exploitation concept, sustainability</td>
</tr>
<tr>
<td>stratigraphy</td>
<td>heterogeneity, fracture network development, exploitation concept</td>
</tr>
<tr>
<td>thickness</td>
<td>productivity, sustainability</td>
</tr>
<tr>
<td>depth</td>
<td>temperature, drilling costs</td>
</tr>
<tr>
<td>distribution</td>
<td>location of drill site / power plant / heating station</td>
</tr>
<tr>
<td>temperature, geothermal gradient</td>
<td>energy content of geothermal fluid, wellhead temperature</td>
</tr>
<tr>
<td>fluid composition</td>
<td>energy content of geothermal fluid, scaling, corrosion</td>
</tr>
<tr>
<td>permeability</td>
<td>flow rate, sustainability</td>
</tr>
<tr>
<td>petrophysics</td>
<td>geomechanics, fracture stability, wellbore stability</td>
</tr>
<tr>
<td>in-situ stress</td>
<td>geomechanics, wellbore stability, well path planning</td>
</tr>
<tr>
<td>stress regime</td>
<td>structure geology, geomechanics, wellbore stability</td>
</tr>
<tr>
<td>fault zone geometry</td>
<td>permeability heterogeneity, well path planning, sustainability</td>
</tr>
<tr>
<td>fault zone activity</td>
<td>reopening of existing fractures, induced seismicity</td>
</tr>
<tr>
<td>fault sealing</td>
<td>permeability of fault core</td>
</tr>
</tbody>
</table>
### Permeability vs. Flow Rate

<table>
<thead>
<tr>
<th>No</th>
<th>Factor</th>
<th>Description</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>fault offset</td>
<td>non-linear increase of fault zone width (i.e. reservoir width) with higher fault offset, fault gouge generation and clay smear mainly with large fault-offset</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
<td>fault activity</td>
<td>ability to re-open clogged fractures; seismicity</td>
<td>+</td>
</tr>
<tr>
<td>4</td>
<td>fault orientation in stress field</td>
<td>tendency for reactivation (slip) and dilation of sub-parallel fractures</td>
<td>++</td>
</tr>
<tr>
<td>3</td>
<td>thickness of reservoir formation</td>
<td>vertical extend of open fracture network enabling hydrothermal convection</td>
<td>++</td>
</tr>
<tr>
<td>5</td>
<td>juxtaposition of hanging and footwall</td>
<td>cross hydraulic link</td>
<td>++</td>
</tr>
<tr>
<td>6</td>
<td>hanging wall vs. footwall</td>
<td>intensity of fracturing / density and width of fracture network</td>
<td>+</td>
</tr>
<tr>
<td>7</td>
<td>mineralization</td>
<td>clogging of fractures</td>
<td>o</td>
</tr>
<tr>
<td>8</td>
<td>well path</td>
<td>exploitation of fractures / fracture network</td>
<td>+</td>
</tr>
<tr>
<td>9</td>
<td>well design</td>
<td>area of effective cross section for fluid flow into well (length and diameter of open hole)</td>
<td>++</td>
</tr>
<tr>
<td>10</td>
<td>lateral well</td>
<td>enhancing fluid flow by enlarging effective cross section for fluid flow into well</td>
<td>++</td>
</tr>
<tr>
<td>11</td>
<td>well stimulation</td>
<td>enhancing fluid flow by opening near borehole fluid pathways</td>
<td>++</td>
</tr>
</tbody>
</table>

**Legend:**
- **affect permeability / flow rate**
  - ++ very positively
  - + positively
  - o no positive impact
Geothermal Gradients within Hydraulic Active Fault Zones

**Rittershoffen**  (Baujard et al. 2017)

**Soultz-sous-Forêts GPK-2**  (Vidal et al. 2015)
Stakeholder Management
Project Development – Roadmap

1. Review all data (well logs, well tests, hydrochemistry, temperature, seismics, surface manifestations, other geophysical exploration data)
2. Setup a geological/geothermal model based on all available data
3. Define “hot spots” and need for further surface exploration to mitigate exploration risks and model validation
4. Milestone 1: Pre-feasibility study, decision GO/NO GO
5. Acquire additional surface exploration, processing, and interpretation
6. Update geological/geothermal model
7. Define well locations in “hot spot” areas for subsurface exploration to prove hydrothermal resource
8. Setup a thermo-hydraulic model
9. Milestone 2: Feasibility study, decision GO/NO GO
10. Prepare drilling and permitting
11. Drill first well with full size diameter (well logging, well testing)
12. Milestone 3: Evaluation of success, decision GO/NO GO
13. Scid rig to drill second well for a geothermal doublet
14. Drill second well (well testing)
15. Optional: stimulation of wells
16. Circulation testing (long term)
17. Power plant engineering
18. Construct power plant
19. Commissioning
20. Operation
Summary

At the conclusion of the exploration phase for a geothermal project, the exploration geologist should have a clear idea of the nature and location of the target geothermal reservoir. He/she should be able to present a geological model of the relevant region and the underlying basement. The model should encompass information about the stratigraphy, depth, composition, structural elements, temperature field, porosity/permeability distribution, stress field, and surface features of the location.

Based on this work the decision has to be made whether to spend the money for expensive drilling.

Importantly, the exploration geologist should be able to communicate the uncertainties in predictions of the key reservoir parameters: location, depth, thickness, lateral extent, temperature, and permeability.
Summary

- don’t invent the wheel again but be innovative
- look what is already known
- evaluate the needs to reduce risks
- acquire new data where necessary only (this is a commercial project!)
- respect value for money (and time)
- set up a reservoir model focused on the geothermal aspect
- define geothermal targets
- well path planning (drill sites provided)
- simulate thermo-hydraulics on a long term (be aware of the assumptions to be made!)
- adjust well-target configuration
- reporting: feasibility study
- planning drilling the first (exploration) well to proof the resource
- drilling
- borehole geophysical logging, mud logging, drilling parameter
- evaluation of well data → proof and detailed characterisation of the reservoir
Thank you for your attention!

Questions?