MEET

Multi-sites EGS Demonstration

Geothermal Winter School 2021

Geothermal Exploration

Exploration Workflow for Deep Geothermal Systems

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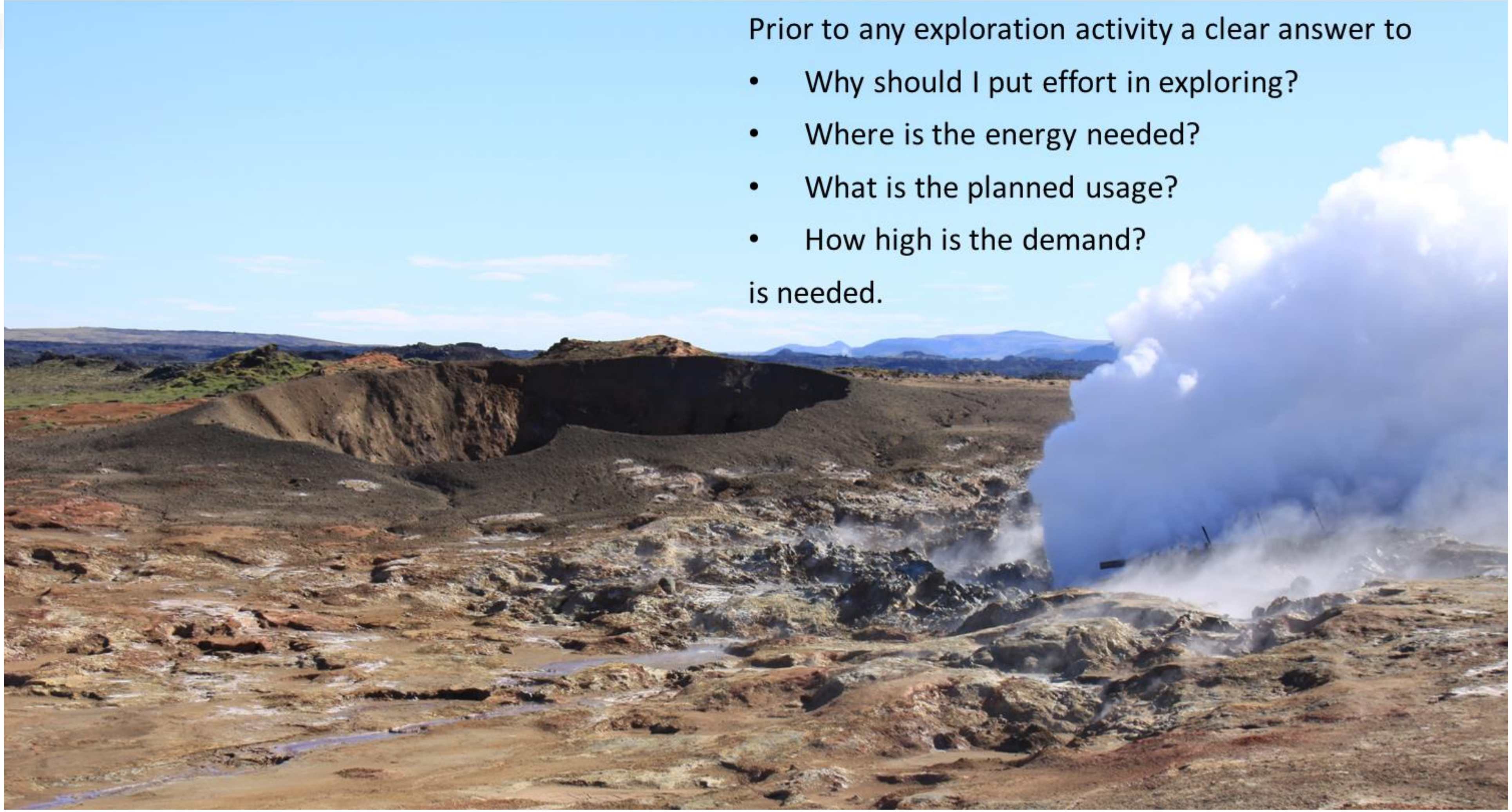
Why Geothermal Exploration?



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

Project Development – Workflow

Pre-development Phase 0 (Drafting the Idea)

to be identified or defined

- ✓ Potential commercial/private consumer and their energy demand in the area of interest
- ✓ Business case (desire) with envisaged energy output (MW_{el}, MW_{th}, minimum temperature, …),
- ✓ Project development strategy

Project Development – Workflow

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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)

mainly desktop study

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

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

Project Development – Workflow

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)

communicate findings

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)

going deep for validation and exploitation

Phase III (Subsurface Exploration) (continued)

quantify the success

✓Long term circulation testing

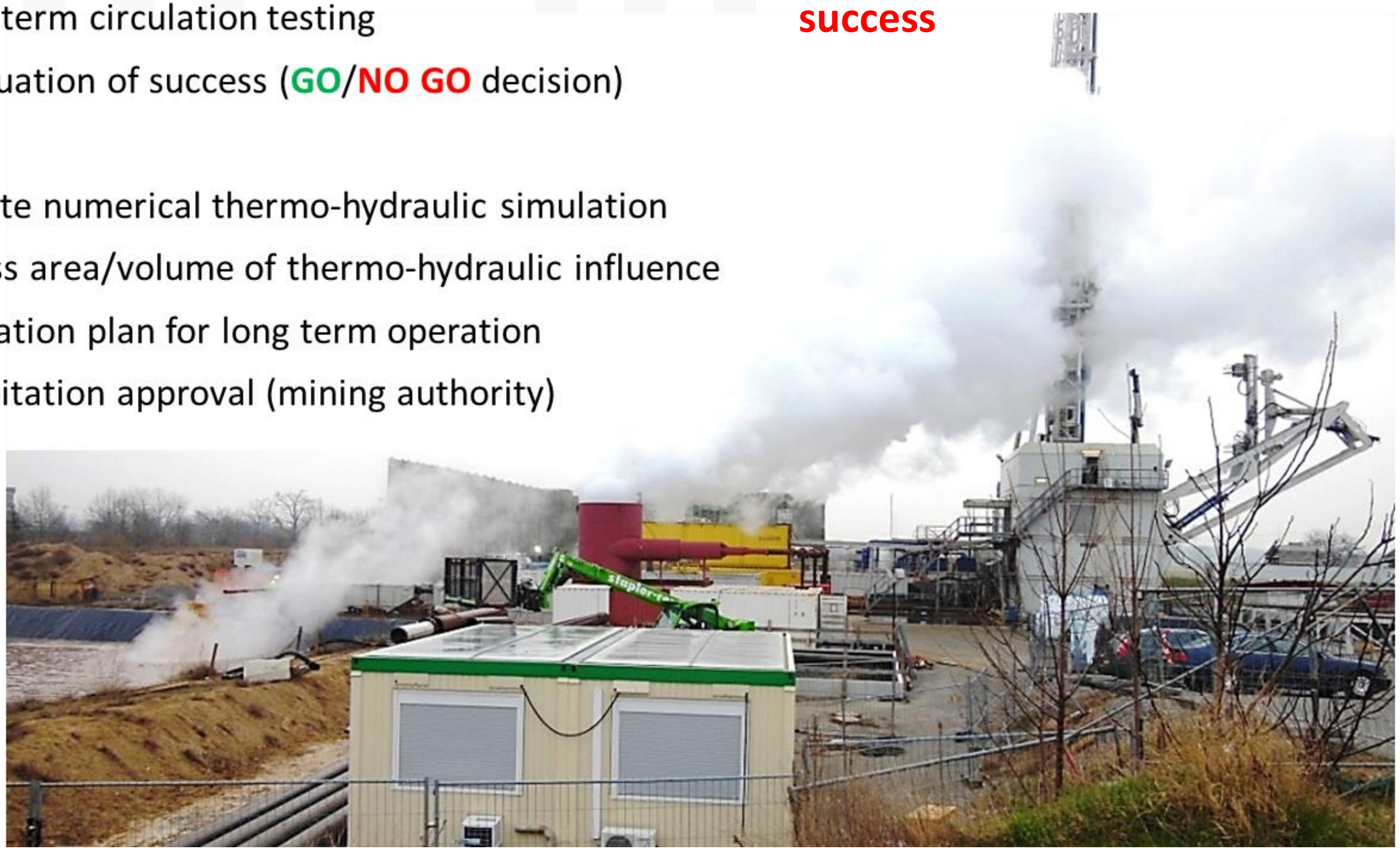
⇒ Evaluation of success (GO/NO GO decision)

✓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)

not part of exploration

- ✓ 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

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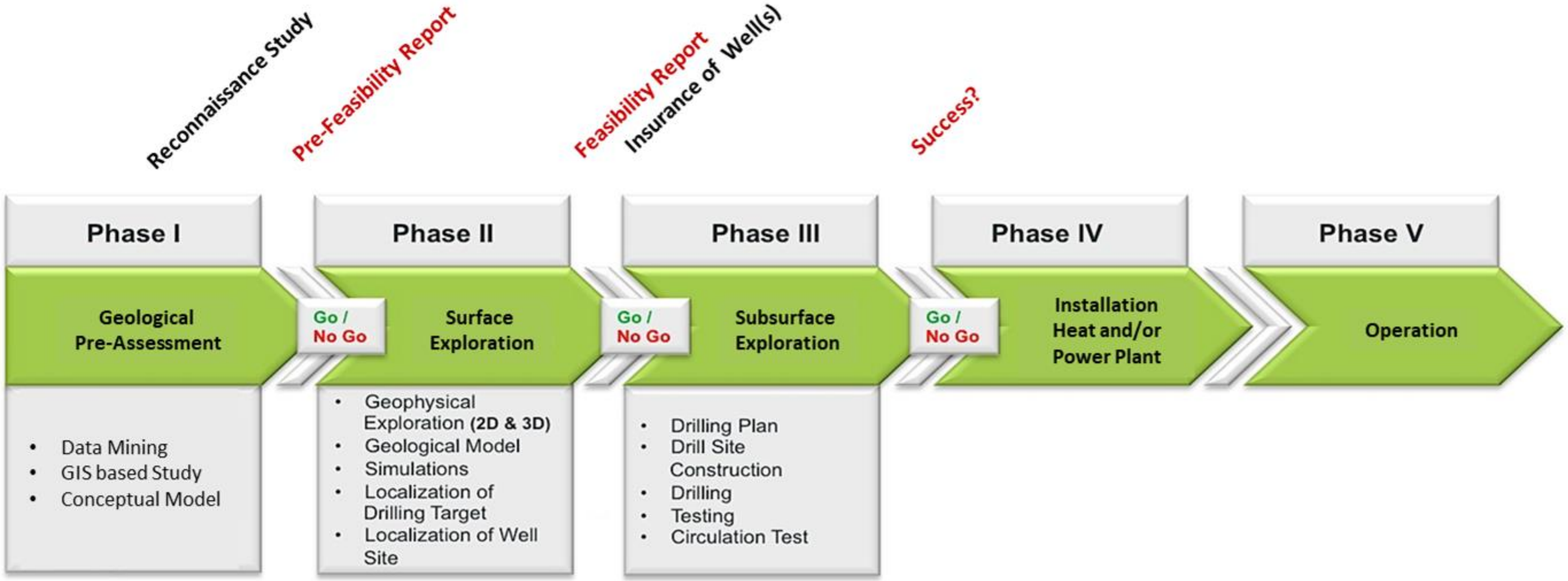
Project Development – Overview



Phase I	3 months
Phase II	9-18 months, depending on acquisition of seismic data
Phase III	12-18 months
Phase IV	12-24 months
Phase V	up to 3 years to ramp up

Project Costs

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

Reservoir depth	4.000 m TVD
Temp. @ well head	165 °C
Flow rate	70 l/s
Thermal output	27 MWth
Electrical output	4 MWel

- More than half of the total investment is venture-capital!
- The venture-capital is mainly related to exploration and drilling.

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

Project Risks

Risk = Probability of Occurrence x Extent of Loss

Typical risks of a deep geothermal project

Group of risk	Type
geological risk	conditional to not influenceable, but technically solvable
technical risk	influenceable
economic risk	partly influenceable
environmental risk	influenceable
political risk	little to not influenceable

Exploration Risk

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)

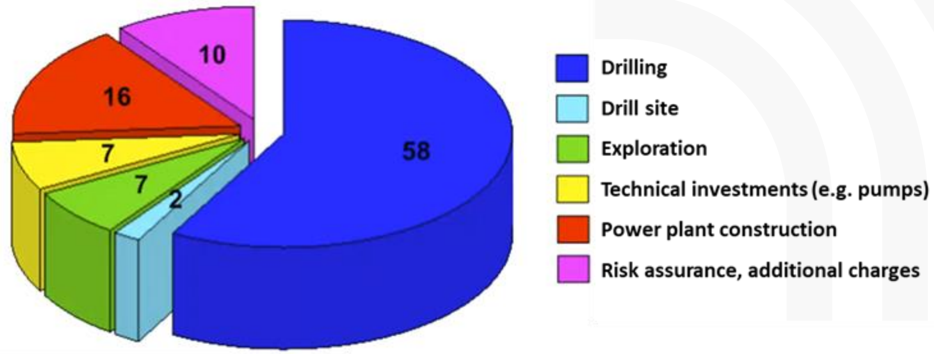
Risk Reduction through Exploration

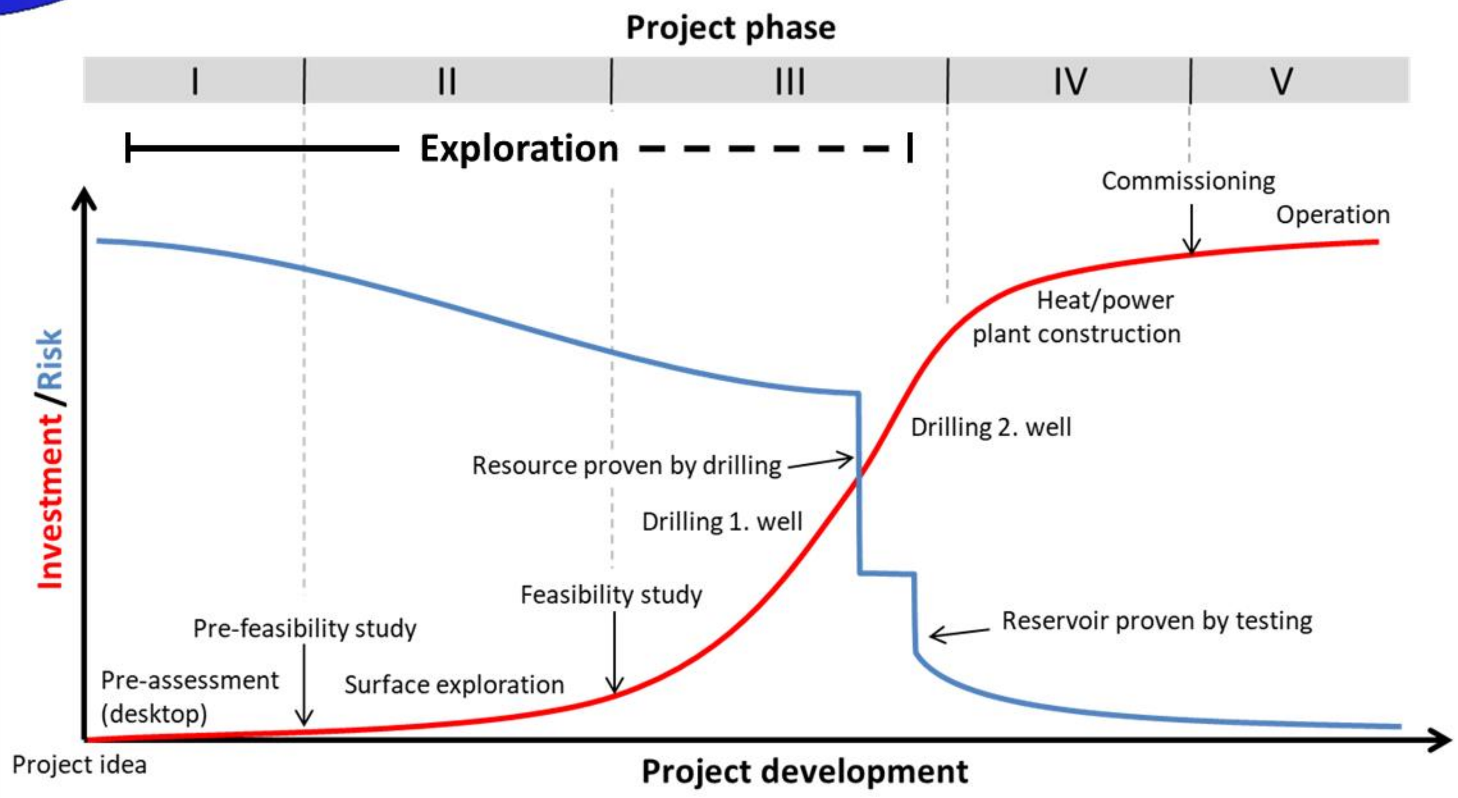
The quality of exploration work prior to drilling is a critical factor for reducing the risk of insufficient well productivity.

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





‘Project Success’ (definition)

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

deep, open hydrothermal system

Goals of Geothermal Exploration

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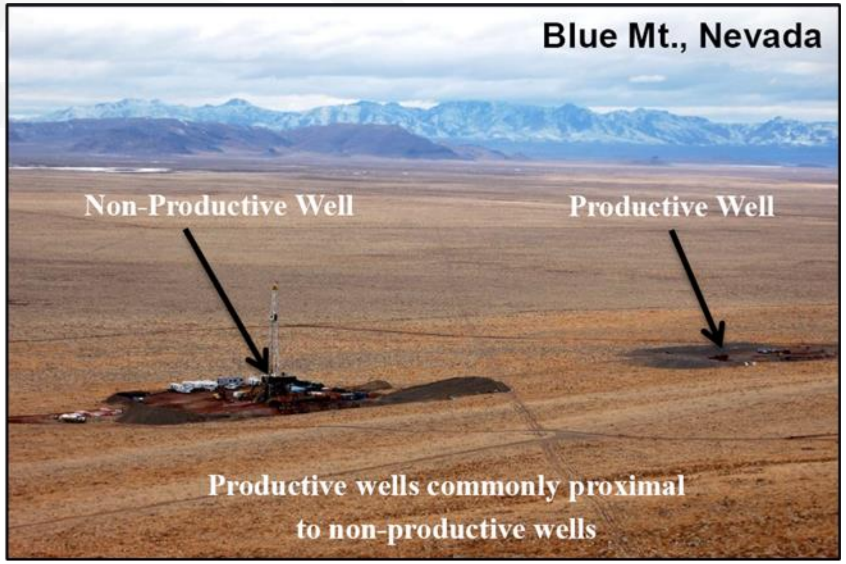
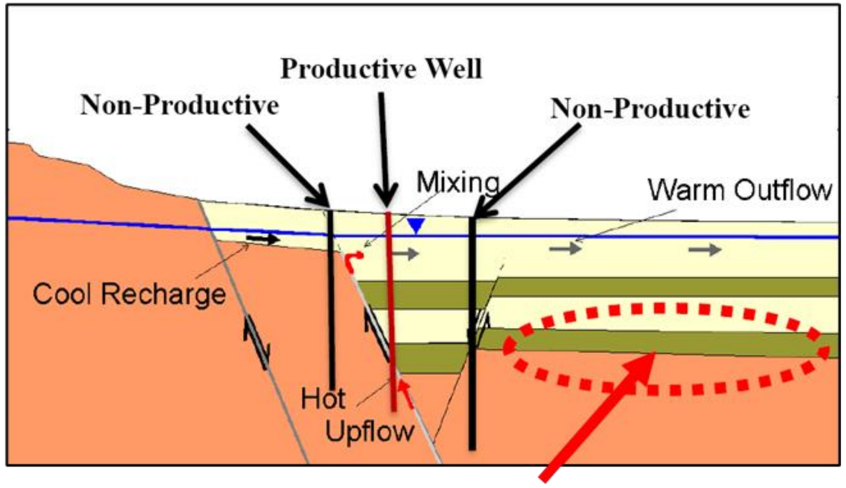
1. Resource and reservoir characterisation
2. High temperature
3. High flow rate / productivity
4. Sustainable heat extraction
5. Economic project
6. Safe project (i. e. low risk to the environment, induced seismicity)

Challenges in Geothermal Exploration





J. Faulds et al.

Sedimentary Hosted System

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 practise" 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 → geological setting, geothermal play type
- characteristics of geothermal surface manifestations → heat flow characteristics, source for deep geochemistry
- detailed description of regional stratigraphy and lithology → reservoir characterisation, reservoir model, well planning
- detailed description of regional tectonics and structural geology → geological setting, reservoir model, geomechanics
- identification and characterisation of potential heat sources → geothermal play type, conceptual model
- identification and characterisation of potential reservoir formation(s) → reservoir characterisation, reservoir model
- outcrop analogue studies → reservoir characterisation
- presence of mineralisation associated with hydrothermal systems → reservoir characterisation

(Hydro-)Geochemistry

- fluid samples from springs and offset wells → thermal fluid characterisation
- cuttings / core samples from offset wells → reservoir characterisation
- interpretations of (hydro)geochemical data → rock-fluid interactions, conceptual model
- geo-thermometry estimates → reservoir characterisation
- isotope-geochemical interpretations → deep reaching permeability

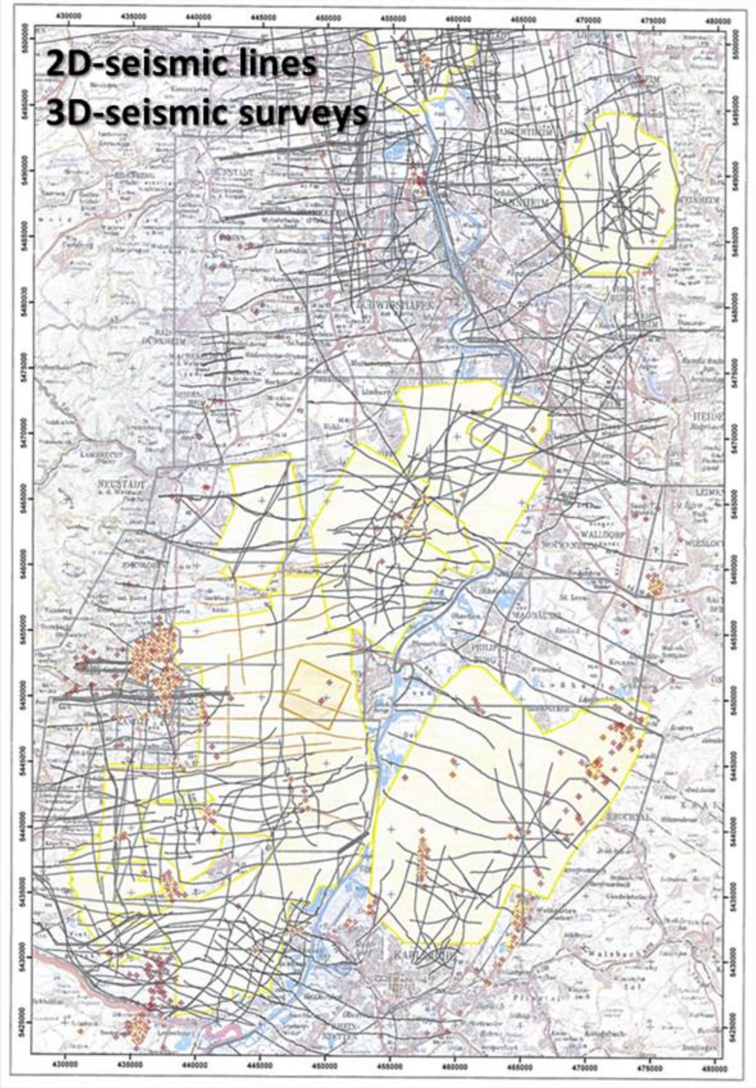
Geophysics

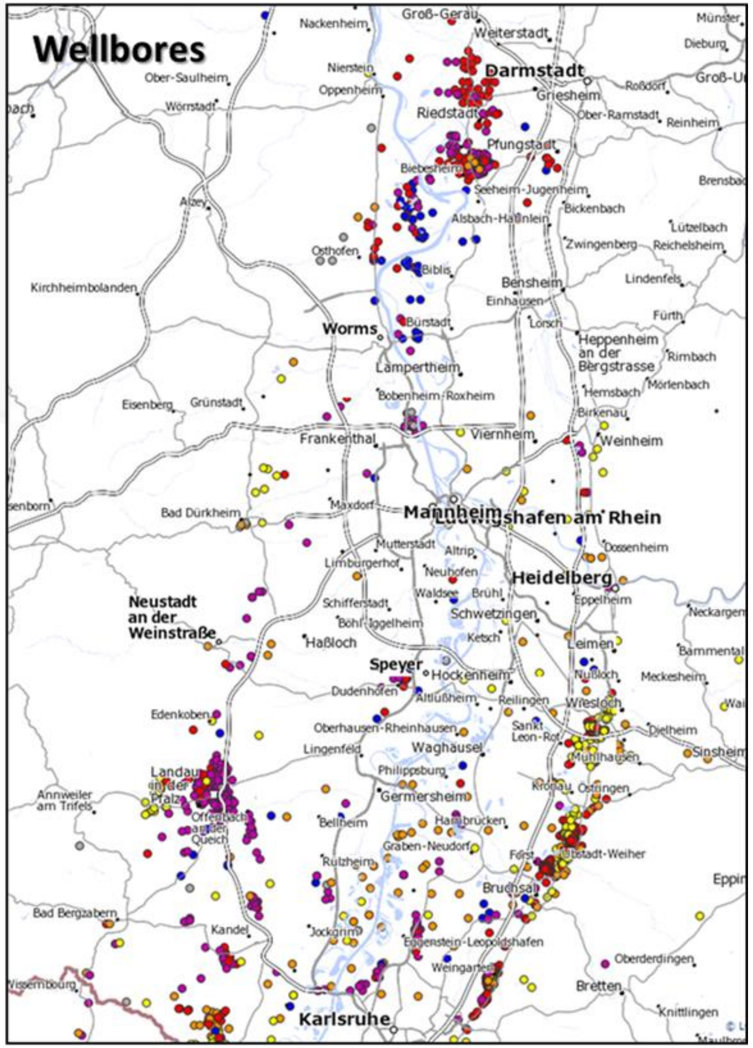
- remote sensing → neotectonics, surface heat flow
- gravity survey → lithology
- geomagnetic survey → lithology
- magnetotelluric survey → clay cap
- electromagnetic survey (CSEM) → mapping convection
- seismic survey (2D, 3D) → structures, reservoir model
- heat flow / temperature gradient survey → temperature field, reservoir temperature
- borehole geophysical logging → detailed reservoir characterisation
- seismological data → seismic hazard assessment, induced seismicity

Hydrogeology

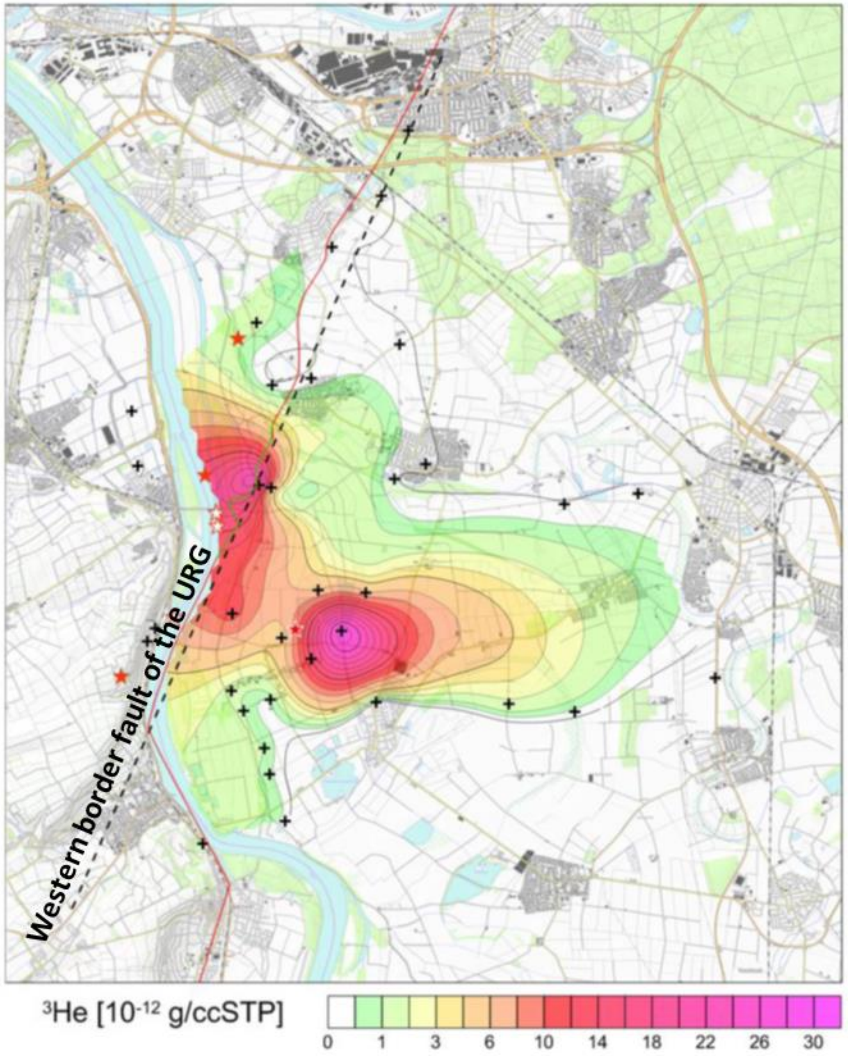
- hydraulic test data from offset wells → permeability, reservoir characterisation
- long term production experiences from nearby projects → sustainability of different configurations
- hydrogeological maps → near surface groundwater situation

Exploration Data (existing subsurface data)

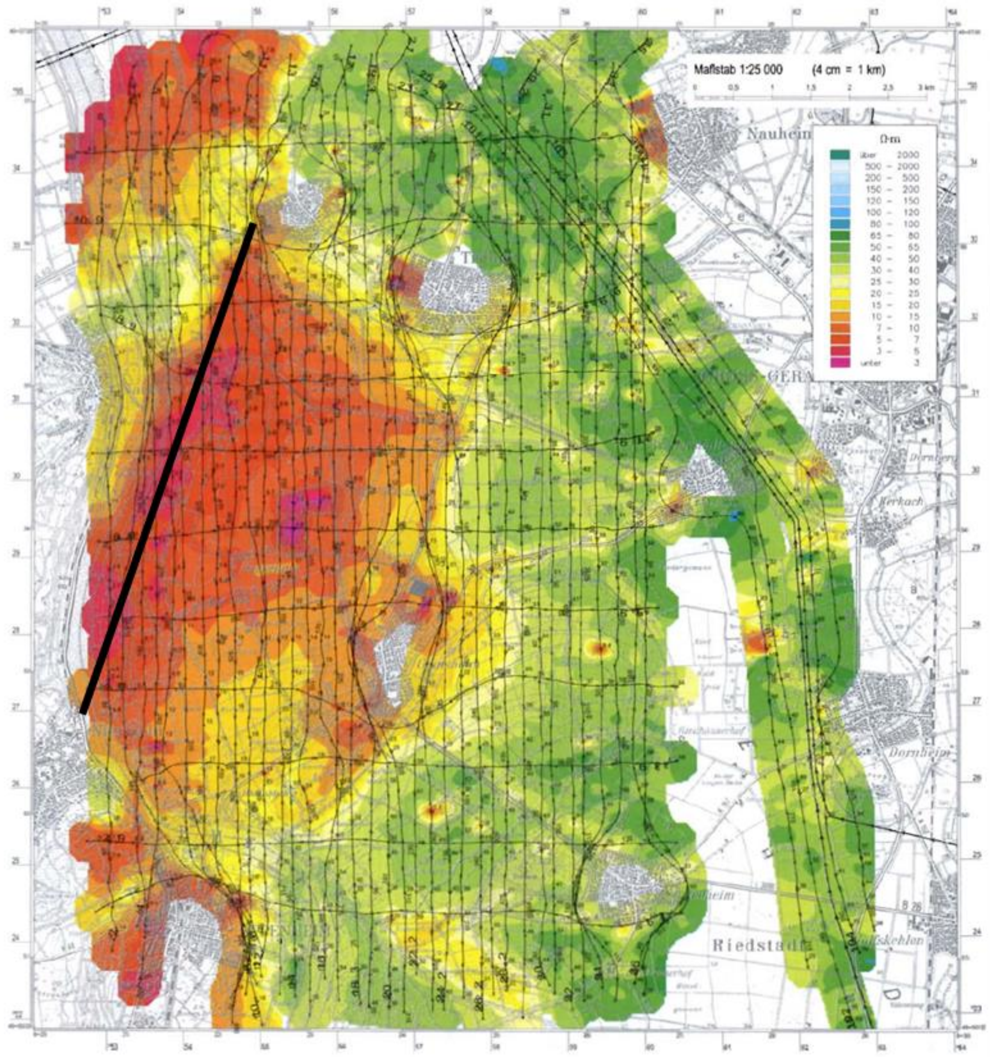




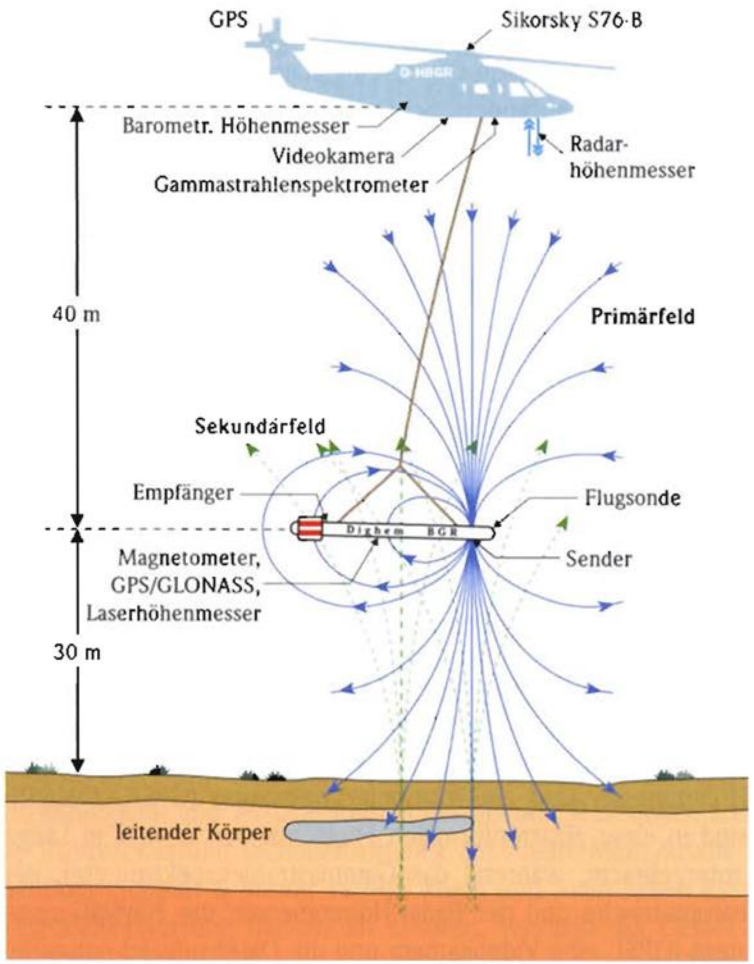
Exploration Methods – Isotope Geochemistry



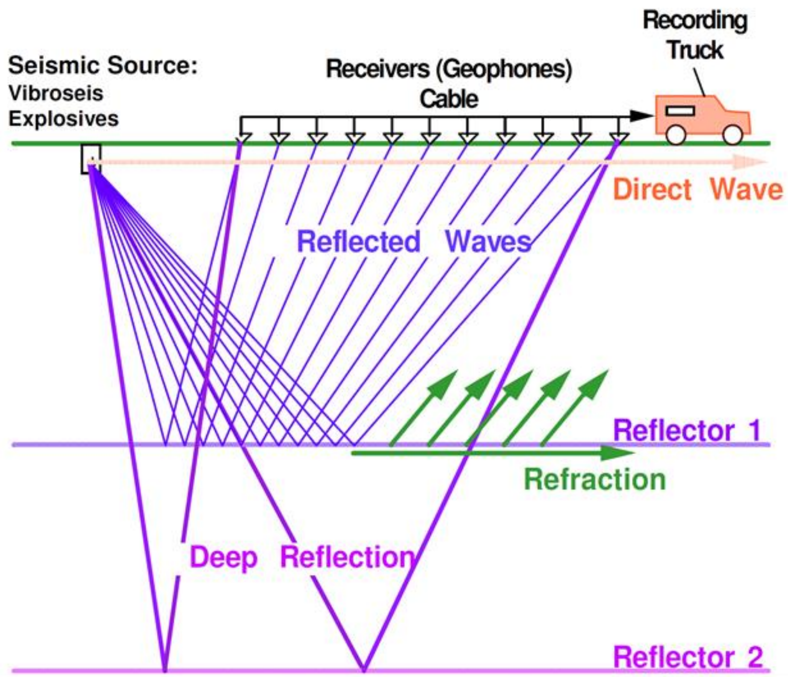
Freundt et al. (2013)



Siemon et al. (2001)



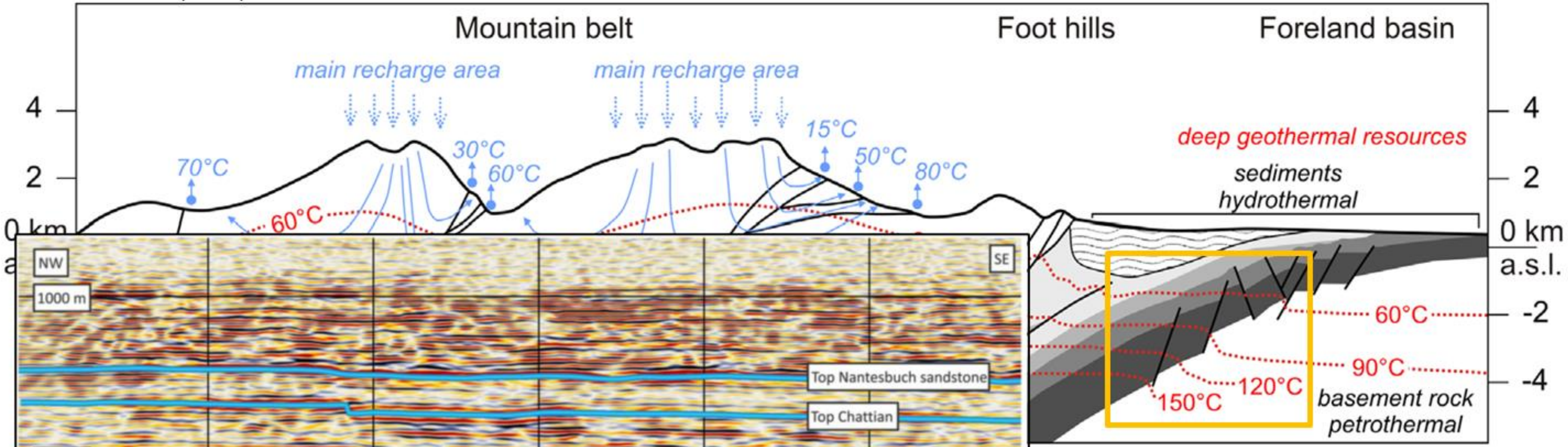
Exploration Methods – Seismics

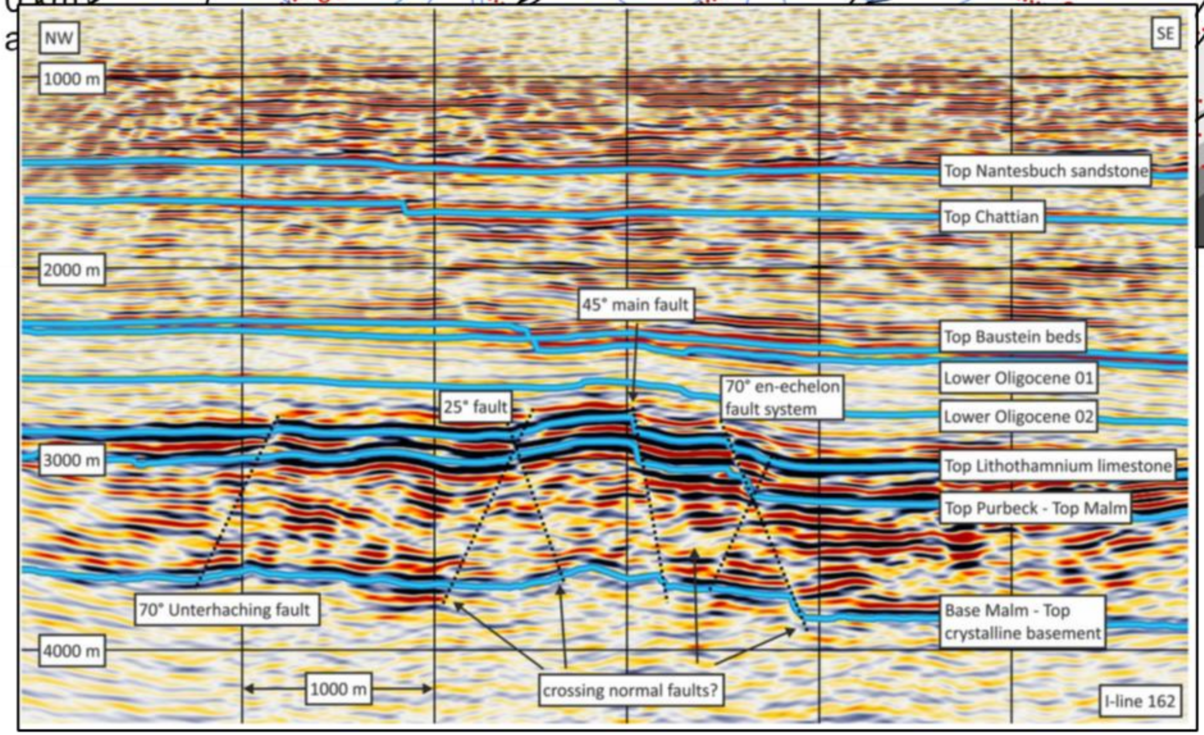


Graf (2013)

Exploration Methods – Seismics

Moeck (2014)





Budach et al (2018)

Exploration (setting up a geological underground model)

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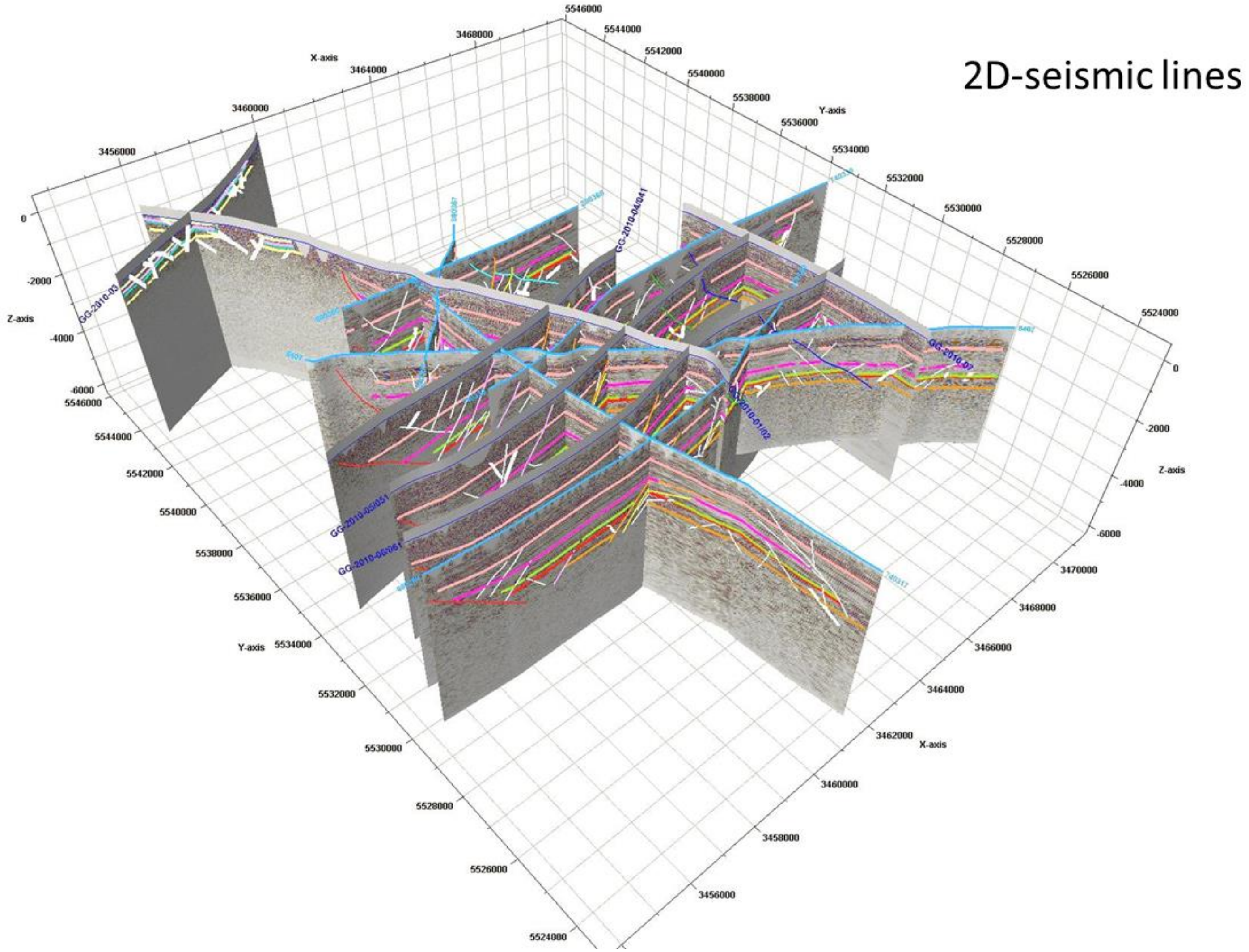
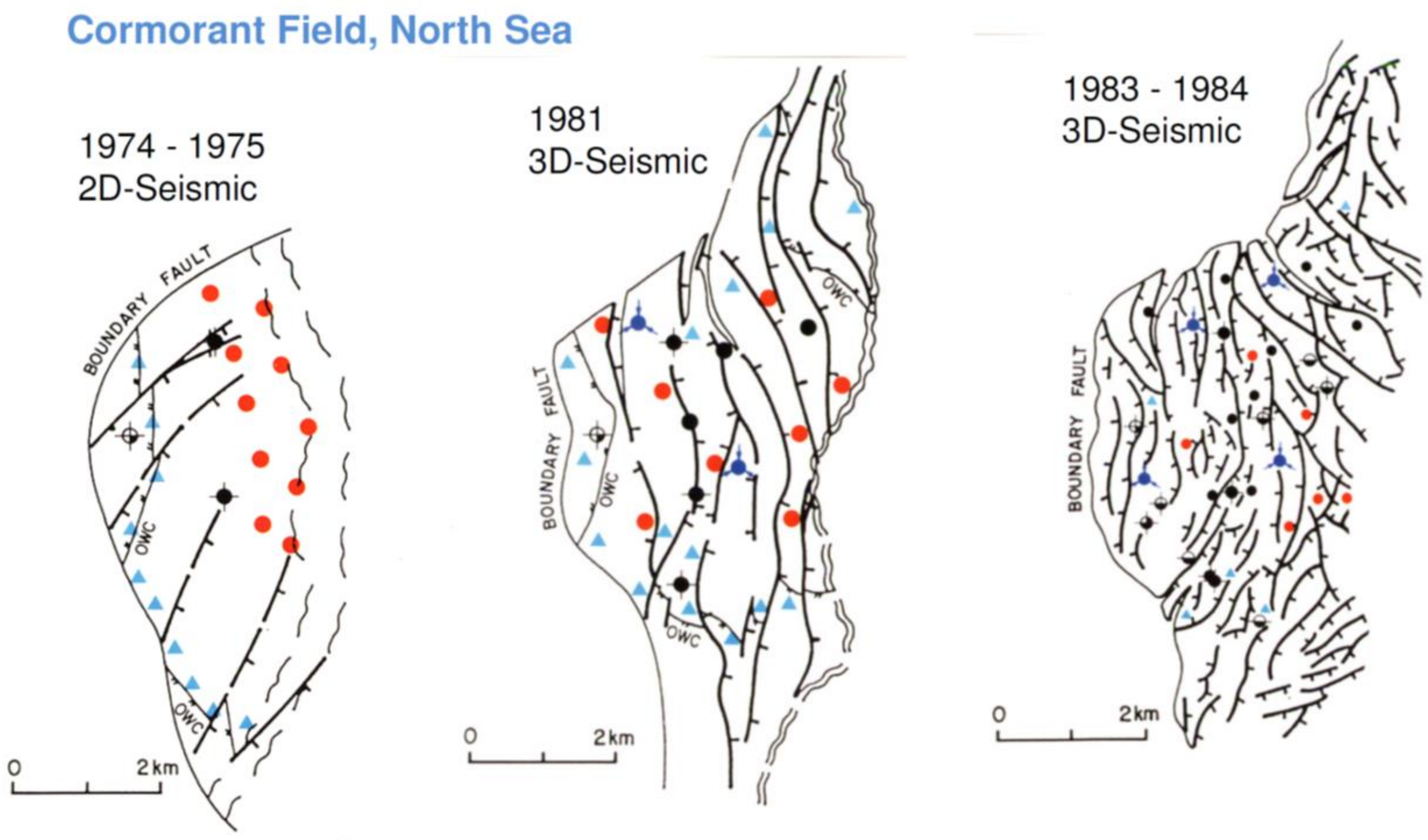


Exploration (setting up a geological underground model)



Graf (2013)

Exploration (setting up a geological underground model)

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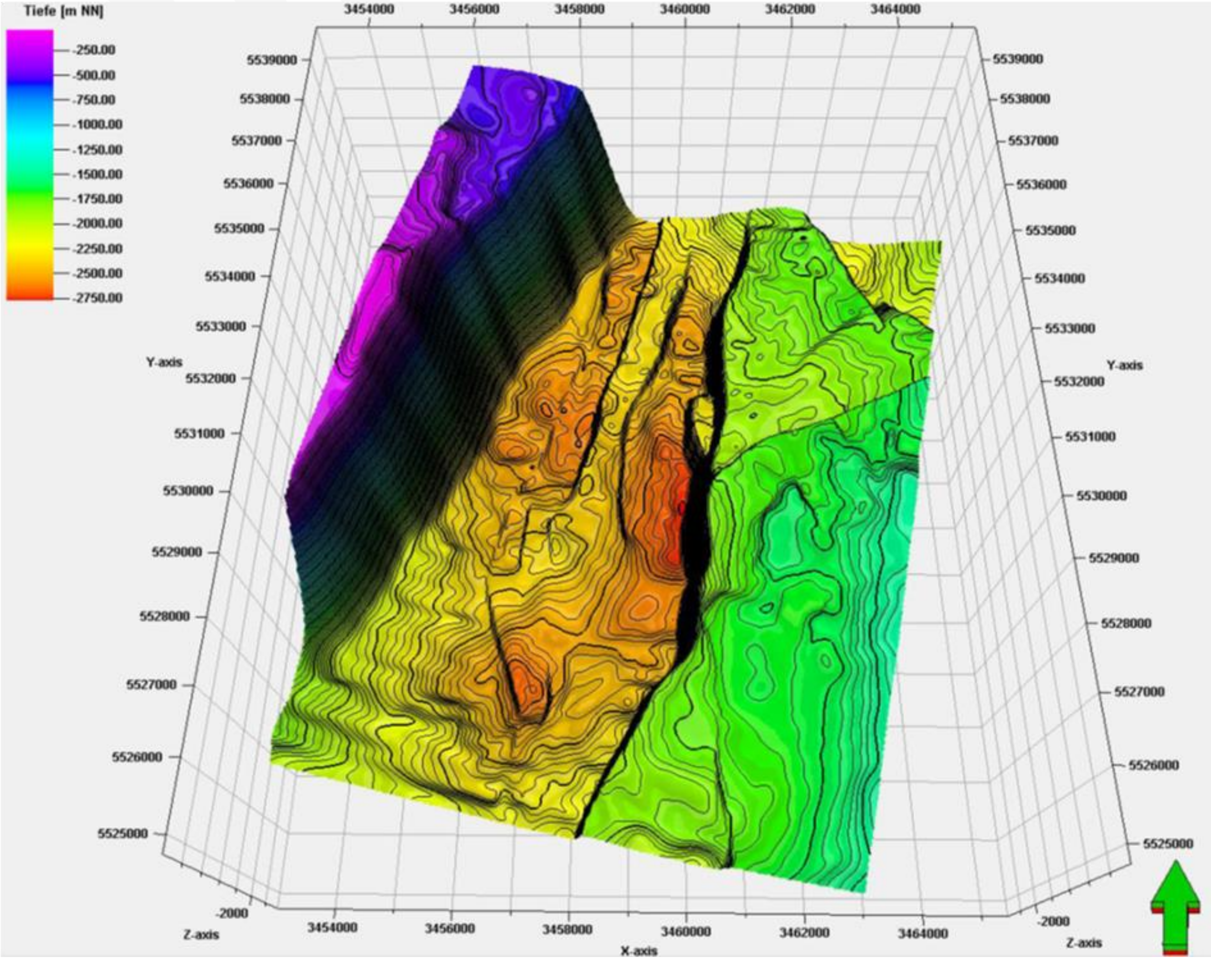
3D-seismic ⇒ improved image of the subsurface

- faults
- structures
- formation depths
- formation thickness



Exploration (facies analysis)

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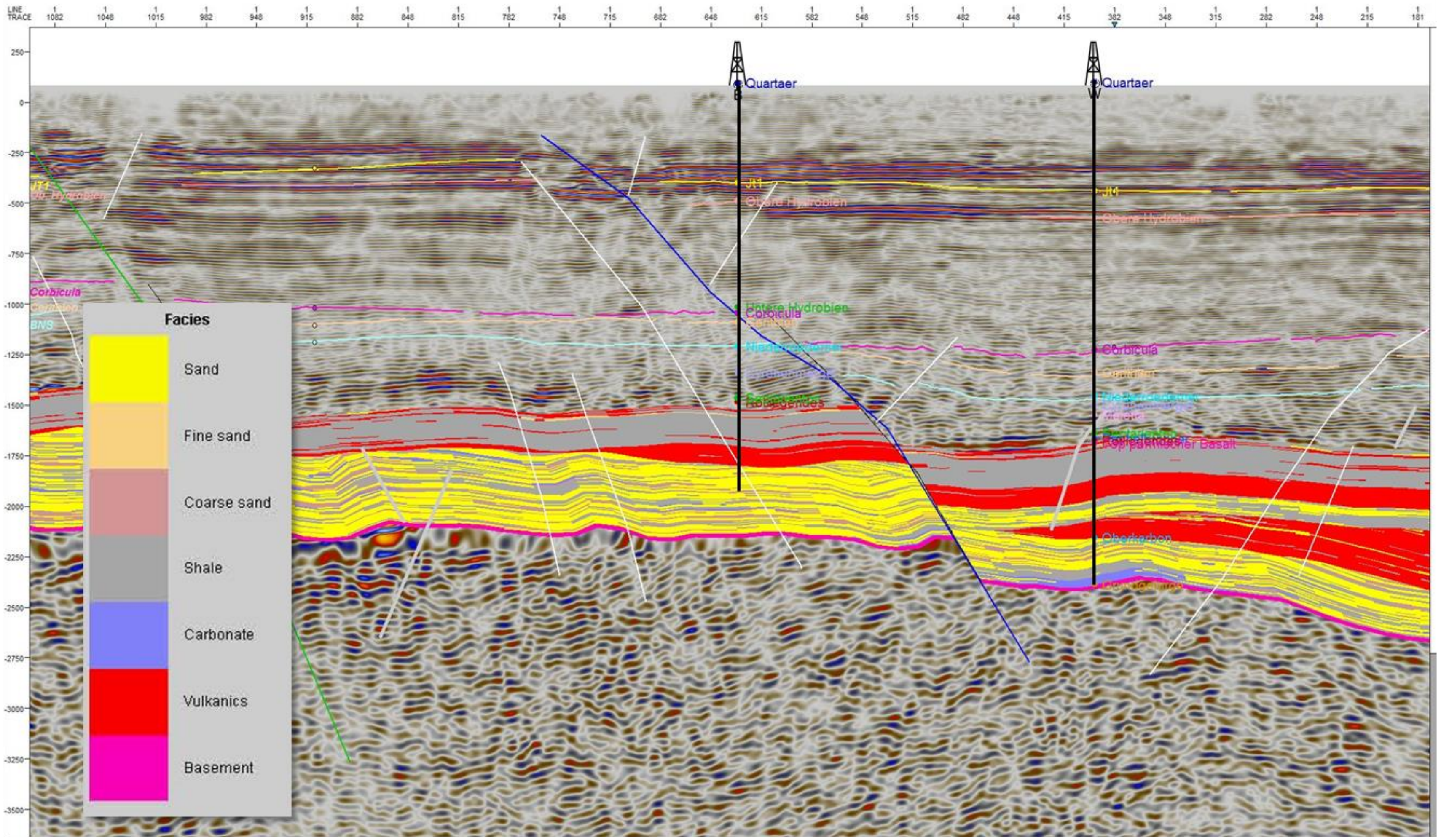
Seismic facies ⇒ sedimentary facies model (together with borehole informations)



Rohrer (2012)

Reservoir Characterisation

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

Permeability vs. Flow Rate

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No	Factor	Description	Impact
1	fault offset	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	+
2	fault activity	ability to re-open clogged fractures; seismicity	+
4	fault orientation in stress field	tendency for reactivation (slip) and dilation of sub-parallel fractures	++
3	thickness of reservoir formation	vertical extend of open fracture network enabling hydrothermal convection	++
5	juxtaposition of hanging and footwall	cross hydraulic link	++
6	hanging wall vs. footwall	intensity of facturing / density and width of fracture network	+
7	mineralization	clogging of fractures	o
8	well path	exploitation of fractures / fracture network	+
9	well design	area of effective cross section for fluid flow into well (length and diameter of open hole)	++
10	lateral well	enhancing fluid flow by enlarging effective cross section for fluid flow into well	++
11	well stimulation	enhancing fluid flow by opening near borehole fluid pathways	++

affect permeability / flow rate

++	very positively
+	positively
o	no positive impact

Geothermal Gradients within Hydraulic Active Fault Zones

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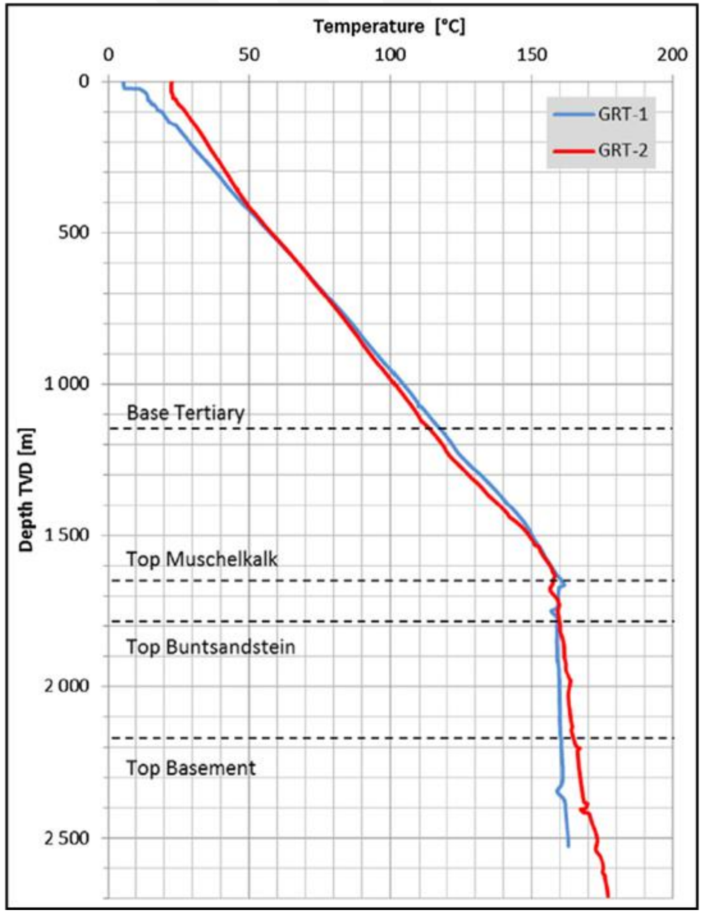
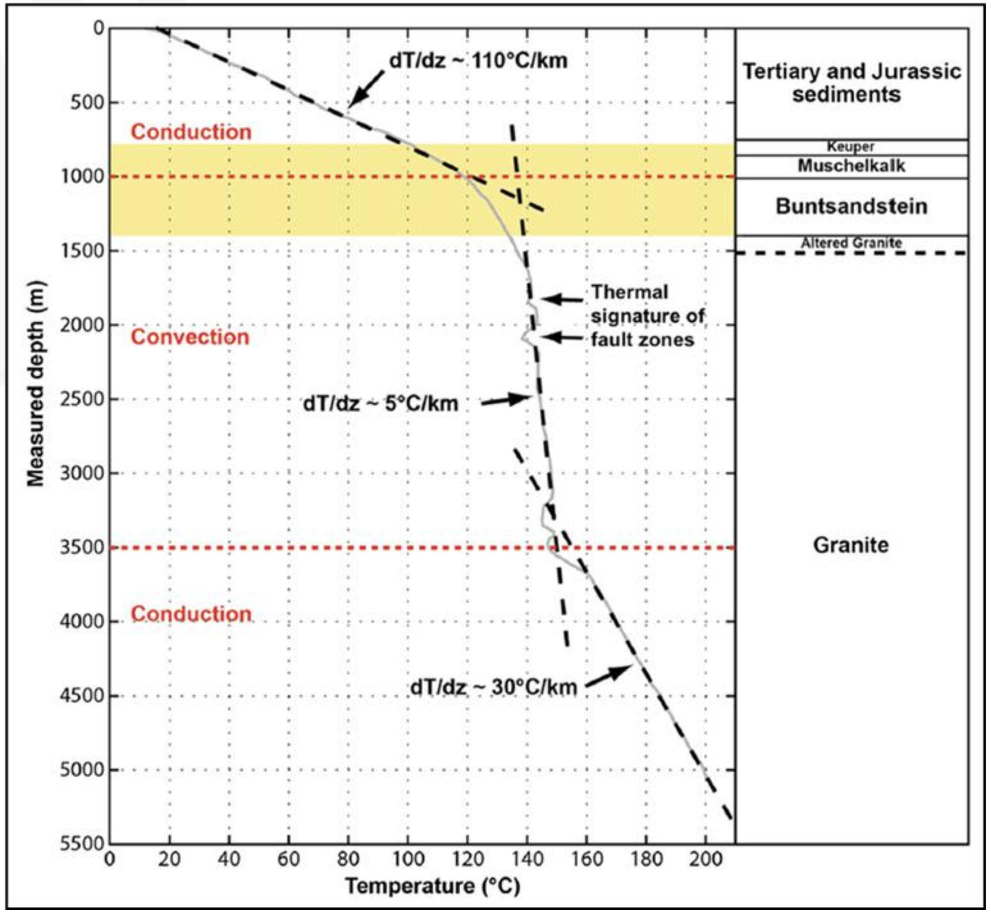
Rittershoffen (Baujard et al. 2017)



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

Exploration (steps 1–12)

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 you attention!

Questions?