From Phenomenological Studies to Well Layout Optimization:

Innovative workflow to assess geothermal reservoir performances

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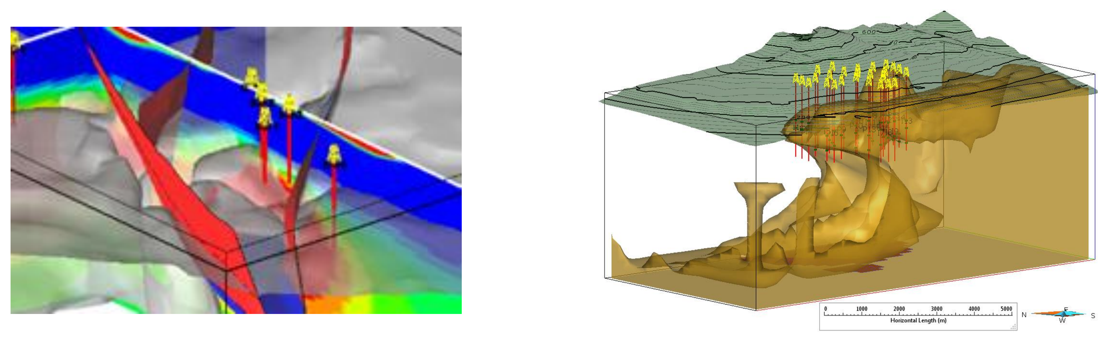
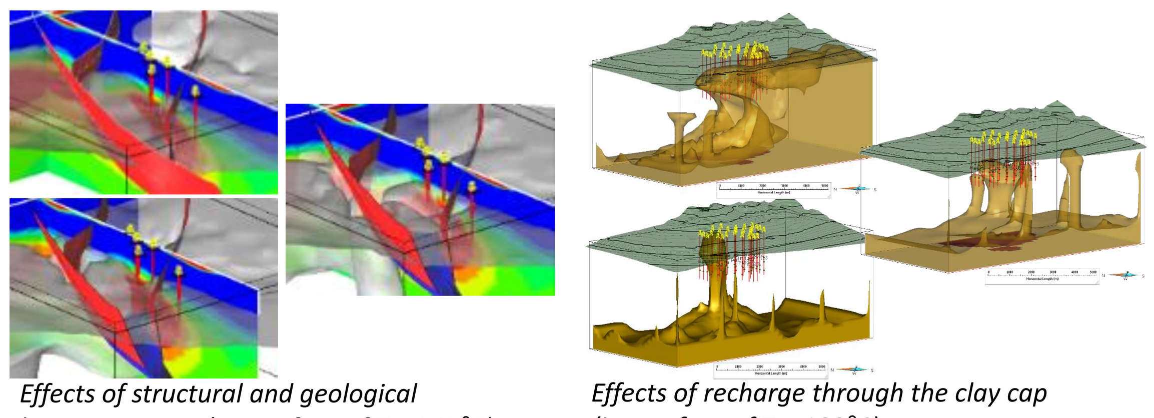
Geothermal resource assessment — Issues



Two-phase geothermal system showing compartments and convective cells (iso-surface of $T = 240°C$).

Single (liquid) phase geothermal system showing complex hot fluid flow paths (iso-surface of $T = 180°C$).

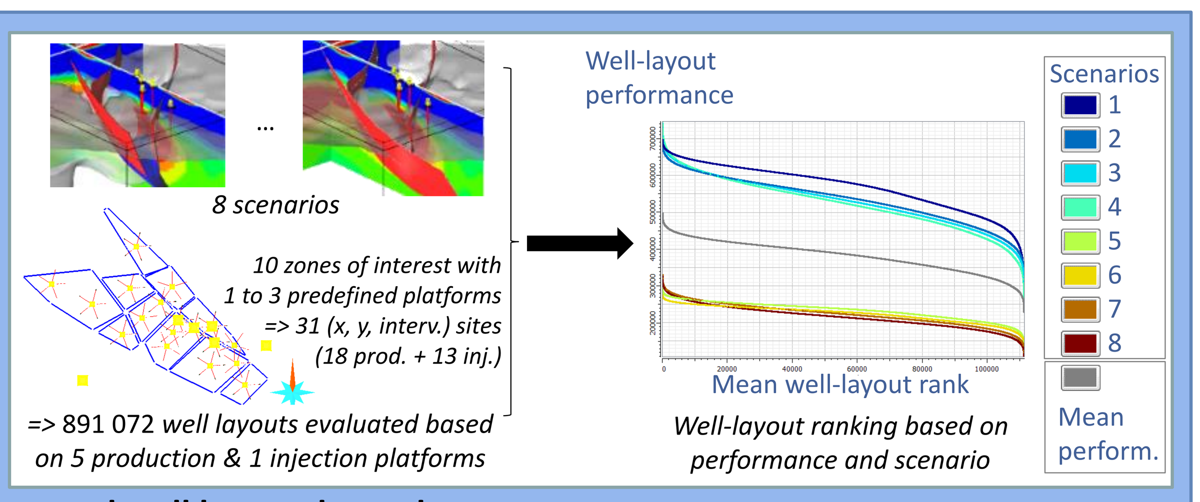
Geothermal systems are complex dynamic systems, …
- √ Convective cells
- √ Flow-path dependent temperature fields



Effects of structural and geological heterogeneities (iso-surface of $T = 240°C$).

Effects of recharge through the clay cap (iso-surface of $T = 180°C$).

… structurally, geologically and hydrogeologically controlled, …
- √ Conductive vs. non-conductive behavior of major structures
- √ Recharge-dependent temperature & pressure fields



=> 891 072 well layouts evaluated based on 5 production & 1 injection platforms

Well-layout ranking based on performance and scenario

… and well layout dependent.
- √ Search for highest sustainable electricity production zones
- √ Taking into account identified complexities and uncertainties.

Consequences on geothermal resource

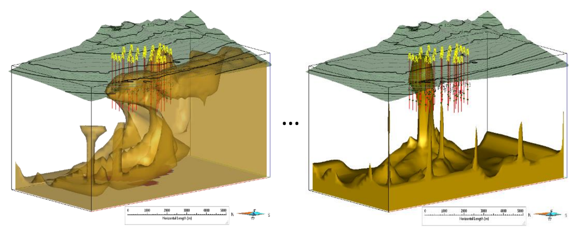
1. It cannot simply be summarized to estimate a stock of heat but it is **strongly initial / current condition dependent**.
2. It requires to **identify** and account for relevant reservoir **complexities and uncertainties**.
3. It requires first to **optimize** the well-layout based on **production objectives.**

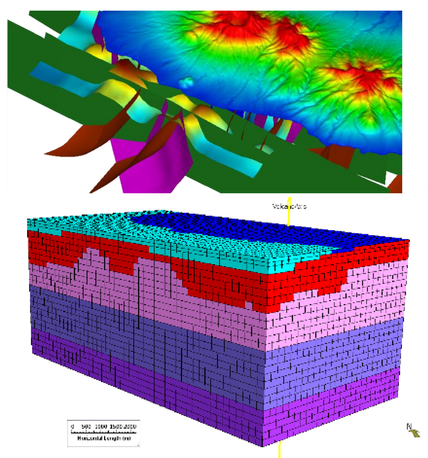
Geothermal resource assessment workflow

A four-step approach at prefeasibility study stage (before drilling)

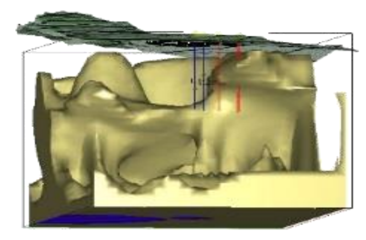
Numerical conceptual models: based on surface data and expert (structural, geological, geochemical, hydrogeological) interpretations & judgments

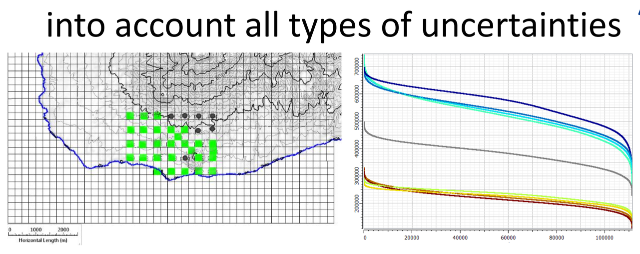
Phenomenological studies: sensitivity analysis of initial (current) conditions with structural, geological and hydrogeological uncertainties





Well layout optimization: based on production objectives, taking into account all types of uncertainties



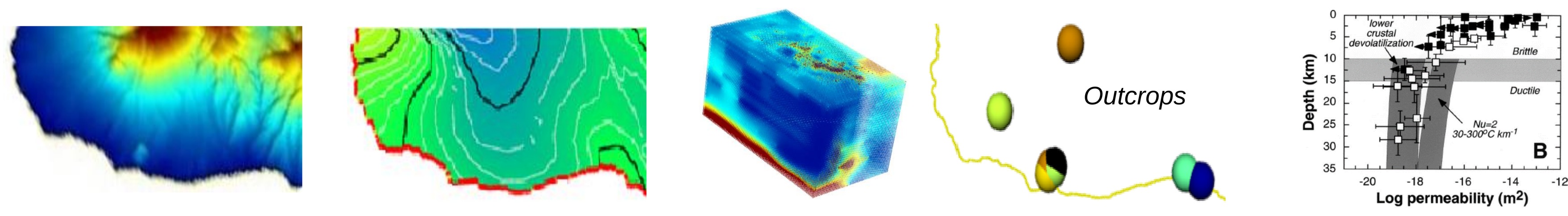


Reservoir performance assessment: based on the best well layout(s), taking into account all types of uncertainties

Presentation of the case study

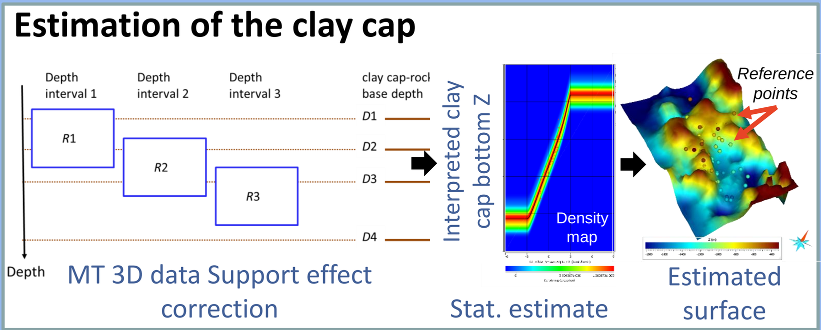
Main available data at the prefeasibility stage (before drilling)
- √ Digital terrain model
- √ Digitized structural objects
- √ Gravimetric map
- √ Resistivity cube from 3D inversion of MT data
- √ Geological map & geochemical data
- √ Petrophysical data from surface rock samples
- √ Hydrogeological data (shallow aquifer)

Key expert interpretations & assumptions
- √ Fault depth & inclination controlled by deep reservoir temperature
- √ Location, depth & extension of magmatic intrusions & heat sources
- √ Proportions of lava flow facies
- √ Geological map & geochemical data
- √ Resistivity of clay cap (cap-rock)
- √ Vertical permeability trend[3]



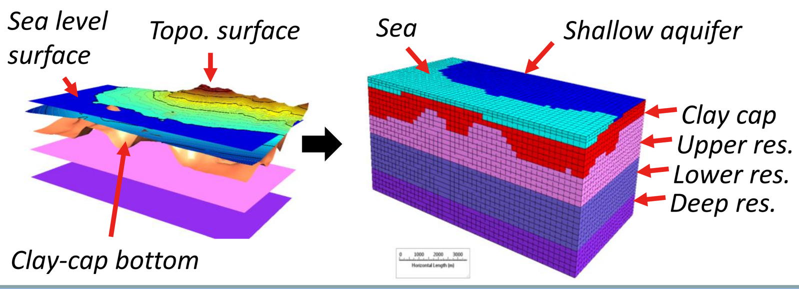
Numerical conceptual model — Step 1

Estimation of the clay cap

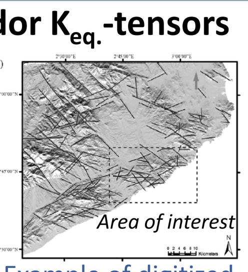


MT 3D data Support effect correction — Stat. estimate — Estimated surface

Thermo-mechanical-flow-units



Estimation of fault & fracture-corridor $K_{eq.}$-tensors
1. Densities estimated from digitized objects on a well characterized area
2. Transmissivities: from literature ⇨ Scenarios
3. Distinction by reservoir zones
4. Compute $K_{eq.}$-tensors assuming locally ∞ discontinuities (Oda's like method)
5. Apply in the clay cap with attenuation

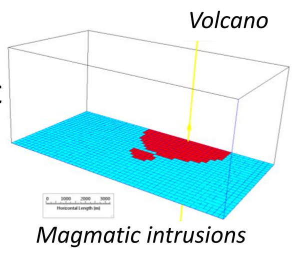


Example of digitized fault traces[2]

Flow and heat transport boundary conditions

Heat **Diriclet** conditions at Z = -5000 m
- **Magmatic intrusion:** T = 800°C
- **High geothermal gradient:** T = 500°C

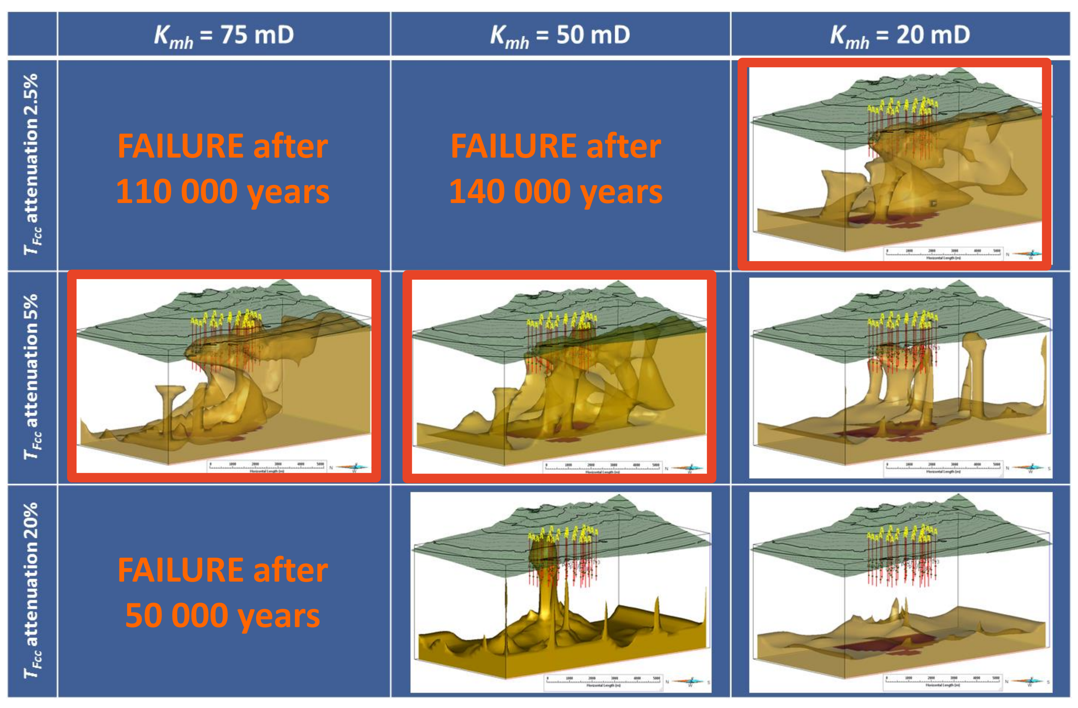
Surface **Diriclet** conditions
- **Temperature:** T_{Atm} = 27°C
- **Pressure:** P_{Atm} = 1.013 bars



Going beyond handmade conceptual model sketches and standard "heat in place" methods

Phenomenological studies — Step 2

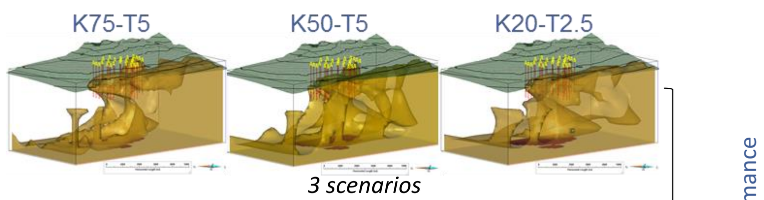
Uncertainties for phenomenological studies and sensitivity analysis
- √ Based on extremes and intermediate scenarios
- √ Main structural and geological uncertainties
  - Reservoir matrix properties
  - Attenuation of fault and fracture-corridor transmissivities through the clay cap
- √ Main hydrogeological uncertainties
- √ Geothermal reservoir simulator
  - HYDROTHERM 3D[1]

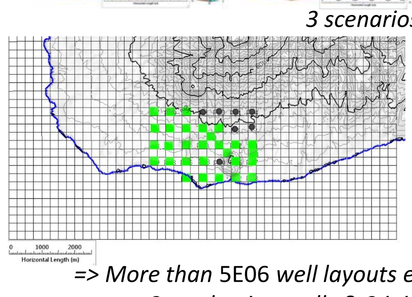


Iso-surfaces of T = 180°C — Good enough scenarios for resource assessment

Well layout optimization — Step 3

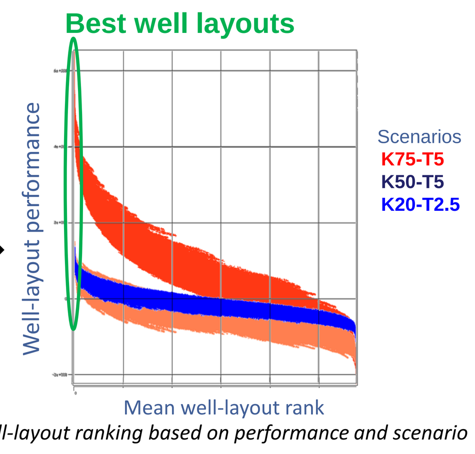
Proposed approach
- √ Production performance criterion
  - Overall production
  - Production sustainability
- √ Optimization parameters
  - Platform locations and perforation depths
- √ Sensitivity analysis parameters
  - Possible platform locations and perforation depths
  - Production mass rates & period
- √ Reservoir uncertainties
  - Based on scenarios
- √ Tools
  - Superposition principle used as a proxy to evaluate the performances of many well layouts from a few single platform simulations (injection/prod.)



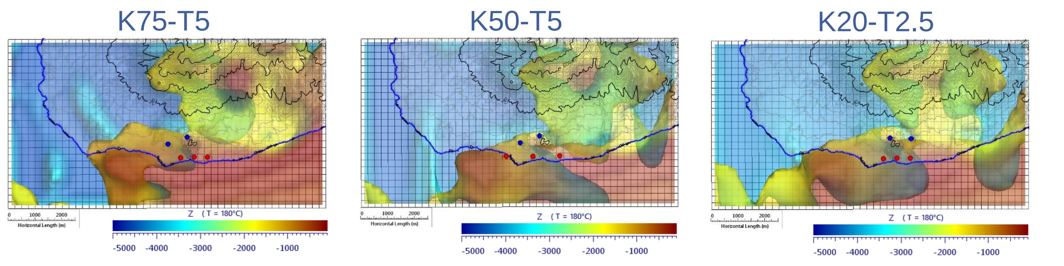


Predefined 1-sidetrack platform locations and perforated intervals => 74 (x, y, interv.) sites (44 prod. + 30 inj.)

=> More than 5E06 well layouts evaluated based on 3 production wells & 2 injection wells



Well-layout ranking based on performance and scenario



Performance assessment — Step 4

Available production performance criterions
- √ Production sustainability (Leftover resource)
  - Leftover geothermal production power in watts

$$L_\gamma = \sum_{\propto \in WL} H_\alpha Q_\alpha$$

H_α = geothermal fluid enthalpy in production well α
Q_α = potential production rate based on a targeted well-bottom pressure

- √ Overall production
  - Steam mass rate

$$L_\gamma = \sum_{\propto \in WL} Q_{s,\alpha}$$

  - "Exergy"[5]

$$L_\gamma = \sum_{\propto \in WL} Q_\alpha\left(H_\alpha - H_0 - T_0(s_\alpha - s_0)\right)$$

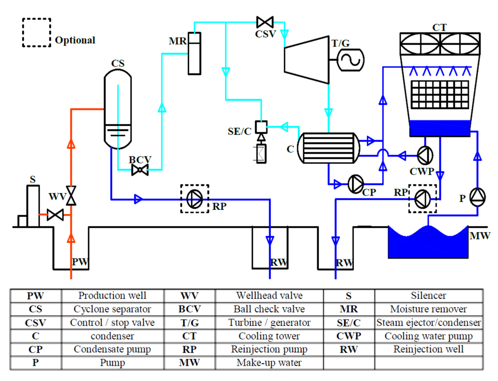
Q_α = mass rate of production well α
H_α = geothermal fluid enthalpy in production well α
s_α = fluid entropy in production well α
T_0 = reference temperature (e.g. 105°C)
H_0, s_0 = enthalpy & entropy at T_0

- √ Calculation of electrical power
  - Single-flash geothermal power plant [4]

$$W_f = \eta_t\, \eta_g\, Q_s\, \Delta H$$

W_f = flash plant electrical power
η_t = turbine efficiency fⁿ of steam mass fractions
η_g = generator efficiency
Q_s = total production steam mass rate
ΔH = enthalpy variation through the turbine

Scenario	Power production decrease	Scenario performance gain
K75-T5	6 %	+77%
K50-T5	0 %	+0 %
K20-T2.5	3 %	+54%

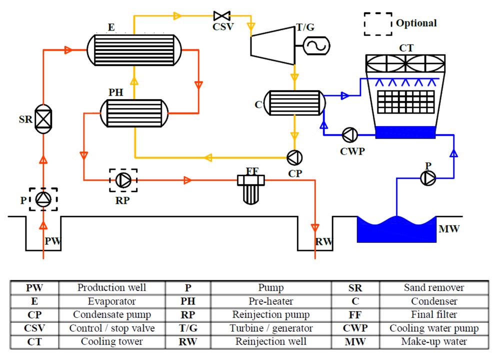


  - Basic binary geothermal power plant [4]

$$W_b = \frac{(0.18T_{in} - 10)}{218}\Delta H\, Q_l$$

W_b = net binary plant electrical power
T_{in} = fluid temperature at exchanger inlet
Q_l = total production liquid mass rate
ΔH = enthalpy variation through the exchanger

Scenario	Power production decrease	Scenario performance gain
K75-T5	6 %	+73%
K50-T5	2 %	+0 %
K20-T2.5	3 %	+38%



Ongoing r&d

- √ Automatic and assisted optimization of numerical simulation parameters
- √ Dual permeability and porosity model to better account for large scale objects
- √ Implementation of "reference" inversion methods for comparison and coupling purposes (Extended FAST, Ensemble Kalman Filter, I-TRACT)
- √ Automatic and assisted calibration of reservoir models against dynamic data workflow design

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