Modelling of Geothermal reservoirs - an overview

Thomas Kohl, GEOWATT AG
Clément Baujard, GEOWATT AG
Günter Zimmermann, GFZ

Introduction

Activity in framework of WP3

- 3.1 recent progress concerning the European lithosphere
- 3.2 Mechanical behaviour of the upper crust
- 3.3 Exploring different types of geothermal reservoir
  - 3.3.1 High-energy geothermal fields
  - 3.3.2 High-temperature / low-permeability reservoirs
  - 3.3.3 New deep, and possibly supercritical, geothermal reservoirs
  - 3.3.4 Multipurpose geothermal reservoirs
- 3.4 Technological challenge of the investigation phase
  - 3.4.1 Improved exploration methods
  - 3.4.2 Combined imaging methods for potential heat exchanger
  - **3.4.3 3D modelling and imaging of permeable systems**

Deliverables of WP6

- 42. A chapter 1a of the Best Practice Handbook on the definition of innovative concepts for investigating geothermal energy
- **43. A chapter 1b of the Best Practice Handbook on generic studies for Unconventional Geothermal Resources and Enhanced Geothermal Systems in contrasting geo-environments in Europe**
- 44. A chapter 1 of the European Reference Manual for the development of Unconventional Geothermal Resources and Enhanced Geothermal Systems

Introduction

Literature source:

- GRC on-line Database
- IGA on-line Database, including :
  - World Geothermal Congresses
  - Stanford Geothermal Workshops
  - European Geothermal Conferences
  - And others…
- Geothermics papers

Important review on Modelling:

“State of the art in geothermal reservoir stimulation”

O‘Sullivan M.J., Pruess K. & Lippmann M.J., 2001, *Geothermics*, 30(4), p.395-430

Overview of talk:

- Physical processes for individual reservoir types
- Available simulators
- Examples
- Conclusion

Very Low Enthalpy Systems (Boreholes Heat Exchangers)

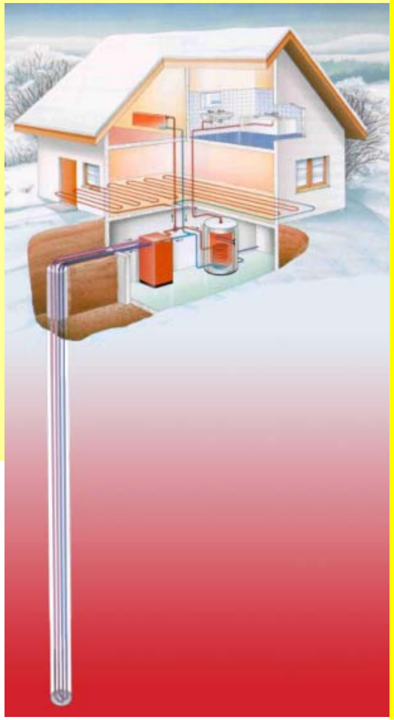
Closed loop systems

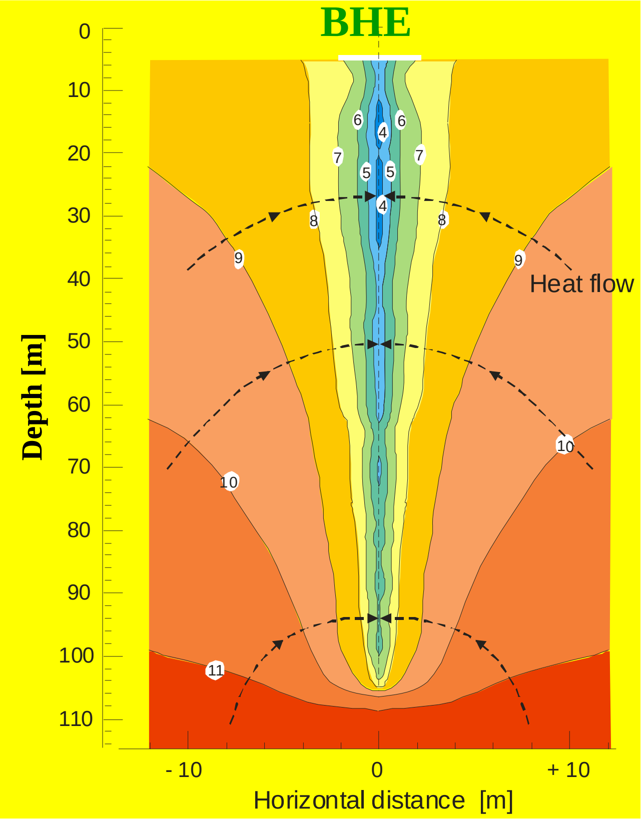
Use of numerical designing tools, based on ground thermal conductivity / heat supply:

- EWS
- EED
- And others…

Thermal diffusion only :

$$\rho c_p \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) - Q^T$$





Low to Medium Enthalpy Systems (Aquifer utilization)

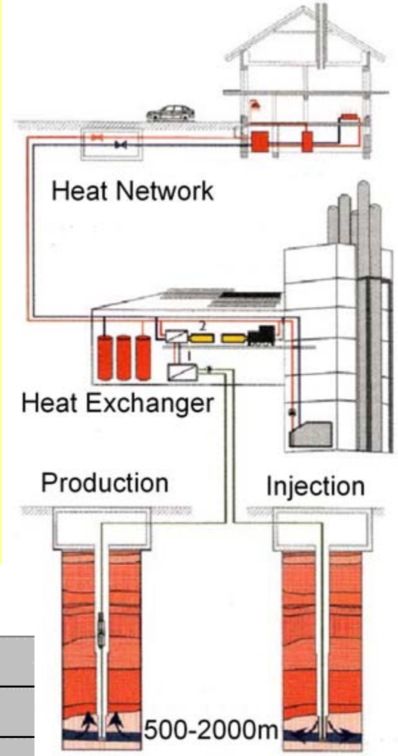
- Porous (continuous) medium Darcy flows, low fluid velocities in the aquifer

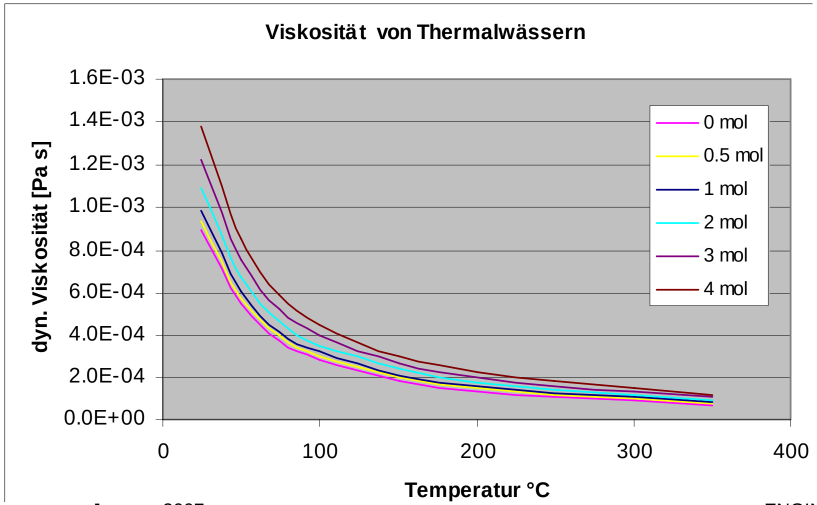
$$C_c \, {\partial h}/{\partial t} + \nabla \cdot v + Q^h = 0 \quad \text{with } v = K \cdot \nabla h$$

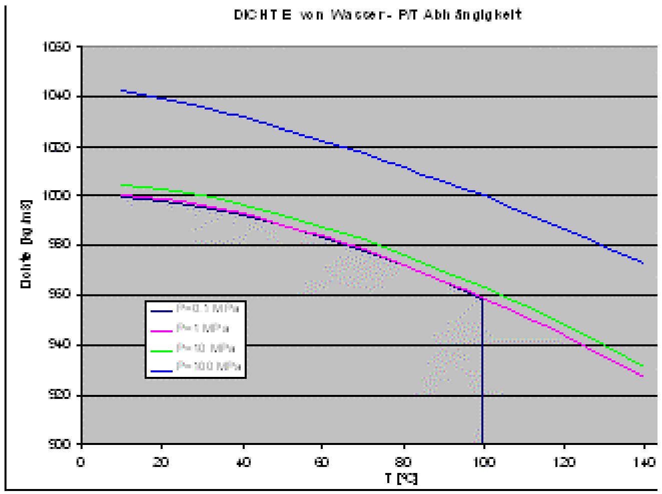
- Hydraulic coupling: advection

$$\rho c_p \, {\partial T}/{\partial t} = \nabla \cdot (\lambda \nabla T) - \rho c_p v \cdot \nabla T - Q^T$$

- Thermal coupling: buoyancy, density, viscosity
- Various transport codes (TOUGH2, FRACTure, FEFLOW, ROCKFLOW, SHEMAT…)





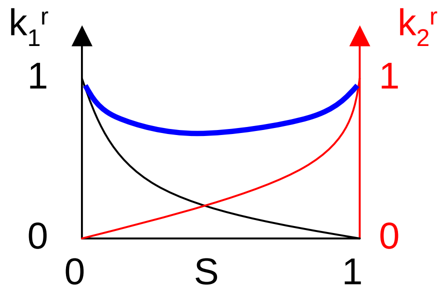


High Enthalpy Systems
(High Temperature Aquifers)

- Porous and fractured medium, Darcy and non-Darcy flows, high fluid velocities in the aquifer
- Hydraulic coupling: advection
- Thermal coupling: buoyancy, density, viscosity
- Often two phases systems, liquid+steam:

$$\frac{\partial(\Phi S_\beta \rho_\beta)}{\partial t} + \nabla \cdot (\rho_\beta v_\beta) + Q_\beta^h = 0$$

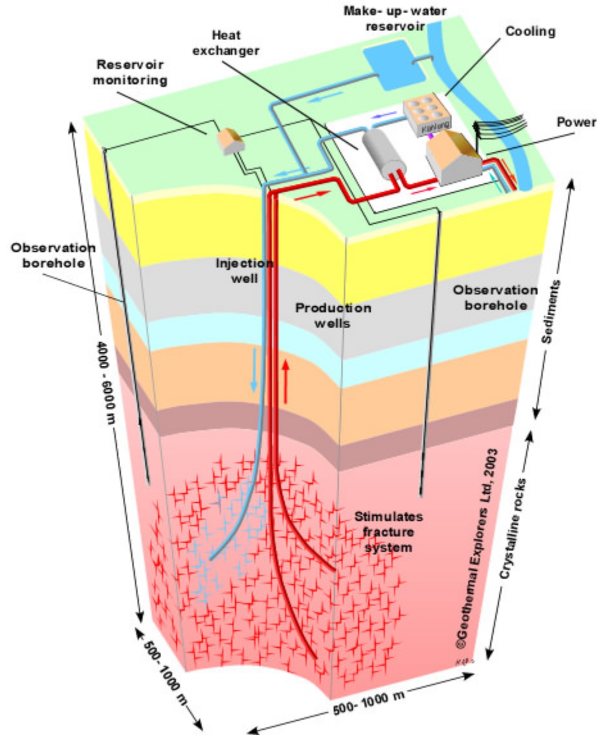
$$v_\beta = -\frac{k k_\beta^r}{\mu_\beta}\left(\nabla P_\beta - \rho_\beta g z\right)$$



Φ porosity, S_β saturation, $k_\beta{}^r$ relative permeability

EGS
(Enhanced Geothermal Systems)

- Essentially fractured medium, Darcy flow; non-Darcy flow at high fluid velocities in fractures
- Hydraulic coupling: advection
- Thermal coupling: buoyancy, density, viscosity
- Mechanical processes play an important role in reservoir development and assessment
  - Fracture mechanics
    - Shear fracturing $$\tau = c + \tan(\Phi) \cdot \sigma_n$$
    - Tensile fracturing $$P_f > S + \sigma_{\min}$$ $$P_f > S + \sigma_{\min} + \alpha \cdot P_p$$
  - Matrix elasticity
    - Poroelasticity
    - Thermoelasiticity
- Injected fluid and formation fluids are different; biphasic flow or multicomponent transport
- Geochemistry also play an important role in reservoir characteristics



EGS: Elastic Matrix Mechanisms

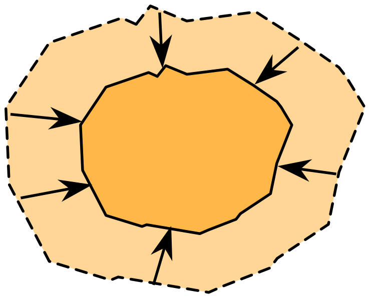
Injection of cold fluid in a hot rock matrix

Thermo-elastic matrix stresses

$$S_{ii}^{T} = 3 \cdot K \cdot \beta_T \cdot \Delta T$$

with K Bulk modulus

β_T coeff. linear expansion

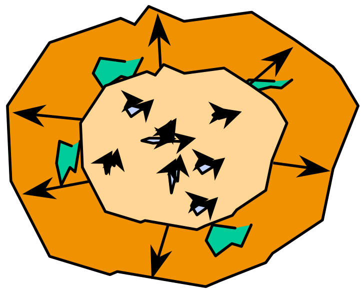


Injection of pressurised fluid in ambient matrix

Poro-elastic matrix stresses

$$S_{ii}^{P} = \alpha_B \cdot \Delta P$$

with α_B Biot coeff.



EGS:
Possible Coupling Schemes

Hydraulic — PRESSURE FIELD

- transient
- Darcy
- non-linear (fracture aperture, non-Darcian)
- ρ(T, P) buoyancy
- μ(T, P)

Thermal — TEMPERATURE FIELD

- transient
- diffusion
- advection
- λ(T, P), ρ(T, P)

Matrix Elasticity — STRESS FIELD

- Steady state
- linear
- Poro-Elasticity
- Thermo-Elasticity

Fracture Mechanics — FRACTURE APERTURE

- Shearing
- Compliance

Reservoir simulators : Global features classification

Different approaches to be distinguished :

- Continuum
  - **A.** Classical porous modelling
  - **B.** Dual porosity models (or MINC); fractures are high permeability zones and rock matrix is a high storage zone
  - **C.** Stochastic continuous media; properties of the media are heterogeneous and respond to stochastic distribution

- Discrete
  - **D.** Unique fracture model, often used in geochemical approaches
  - **E.** Complete stochastic discrete network approach; no rock matrix is in that case considered

Reservoir simulators : Numerical features

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- Spatial discretisation:
  - Analytic
  - Finite Differences
  - Finite Elements
  - Finite Volumes
  - Hybrid, mixed

- Time discretisation:
  - Implicit
  - Explicit
  - Semi Implicit

- Resolution algorithm:
  - Picard
  - Newton-Raphson

- Solver:
  - Matrix Preconditionning
  - Direct Solver
  - Conjugate Gradient
  - …

- In case of Multiphase flow:
  - Linearisation method, saturation variable treatment
  - Weighting scheme: upstream, centered…

Many reservoir simulation codes exist…

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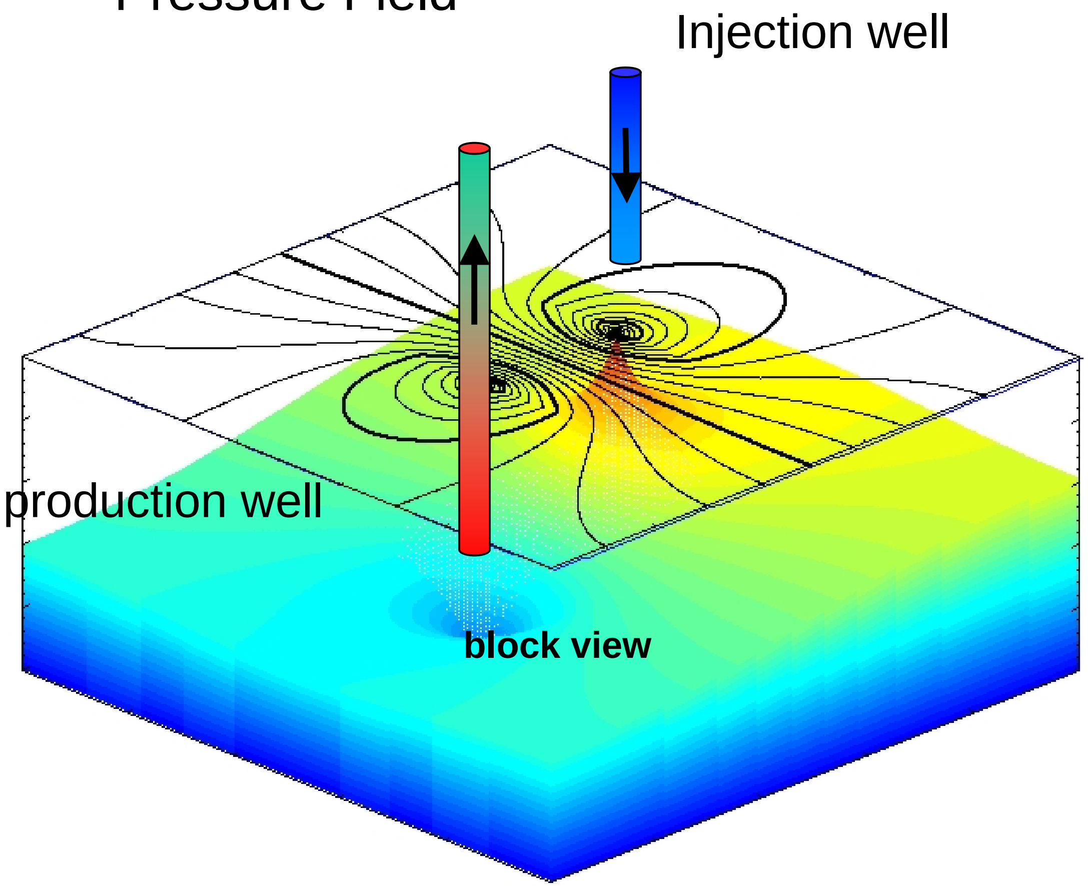
	Code	Discretisation	GUI	Flow processes	Transport	Mechanics	Global Feat.
1	**COMSOL Multiphys.**	FE unstructured	Yes	Any Physical Process			**A.**
2	**FEFLOW**	FE 2D/3D unstructured	Yes	Darcy laminar Faults (Darcy)	Heat Transport Multicomponent transport		**A., B., D.**
3	**FEHM**	FE 2D/3D unstructured FV 2D/3D Faultzones and Dual-Porosity	Yes	Darcy laminar Faults (Darcy)	Heat Transport Multicomponent transport Multiphase transport	Elasticity	**A., B., D.**
4	**Fracas**	FV Stochastic Fracture Network	No	Darcy laminar Faults (turbulent)	Heat Transport Multiphase transport	Deformation and Mohr Coulomb	**D., E.**
5	**FRACTure**	FE 2D/ 3D unstructured Faultzones and Stochastic fractures	Yes	Darcy laminar Darcy non linear Faults (Darcy)	Heat Transport Multicomponent transport	Deformation and Mohr Coulomb	**A., B., C., D.**
6	**GeoCrack 3D**	FE 2D/ 3D unstructured Faultzones and Dual-Porosity		Darcy laminar	Heat Transport Heat diffusion in porous media	Deformation	**A., B., C., D.**
7	**HST3D**	FD Regular	Yes	Darcy laminar	Heat Transport		**A.**
8	**ROCKFLOW**	FE 2D/ 3D unstructured Adaptive Mesh Faultzones	Yes	Darcy laminar Darcy non linear Faults (turbulent)	Heat Transport Multiphase transport Multicomponent transport	Deformation	**A., B., D.**
9	**SHEMAT**	FD Regular	Yes	Darcy laminar	Heat Transport Multicomponent transport		**A., B.**
10	**Sutra3D**	FE 2D/ 3D regular	Yes	Darcy laminar	Heat Transport Multicomponent transport		**A., B., D.**
11	**THOUGH2**	FV Regular Faultzones and Dual-Porosity	Yes	Darcy laminar	Heat Transport Multicomponent transport		**A., B., C., D.**

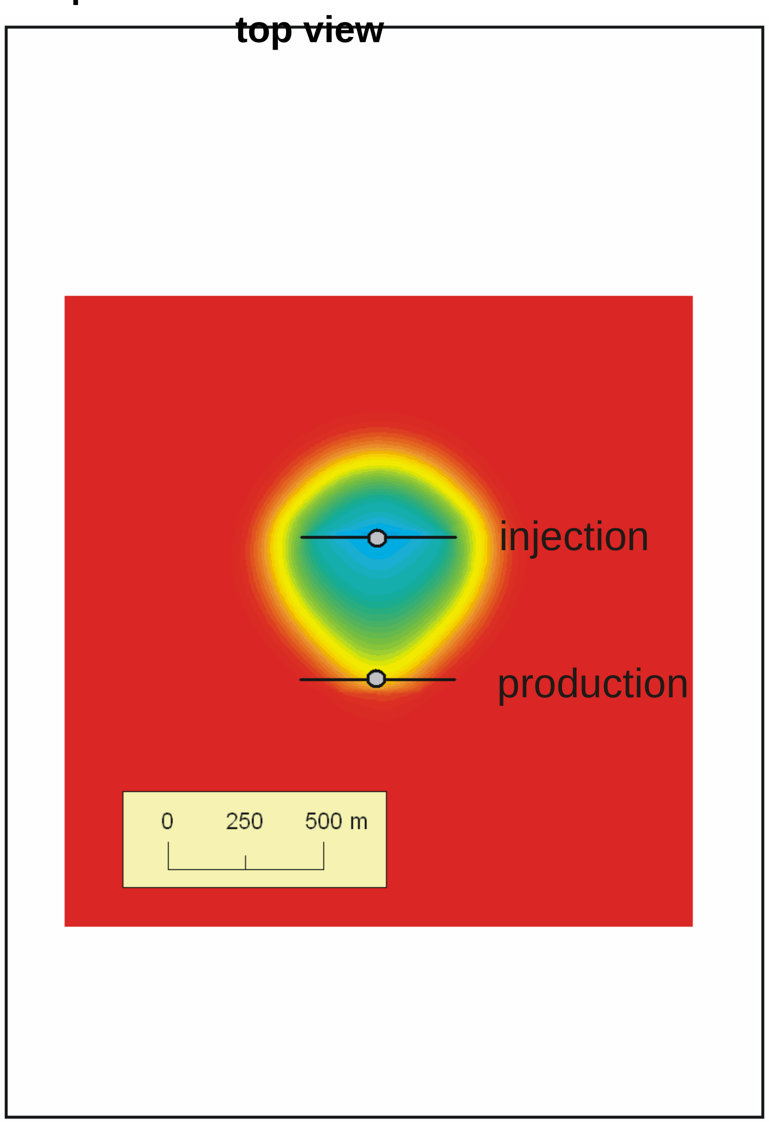
Example 1: Rockflow (Zimmermann)
HT Simulation Gr. Schönebeck

GFZ POTSDAM

Pressure Field

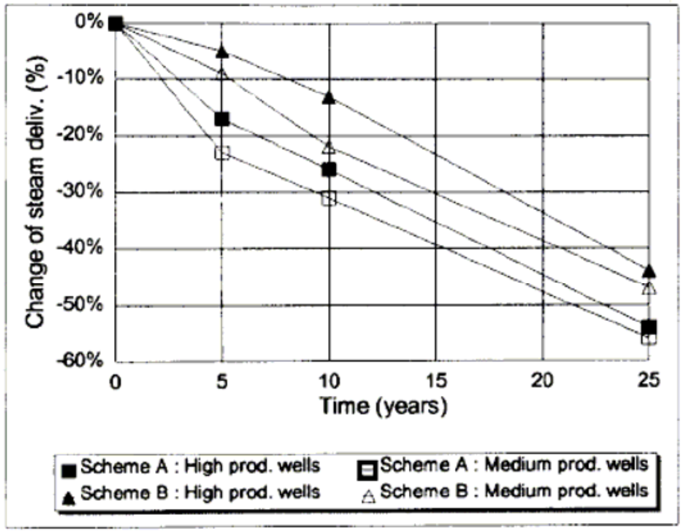


Temperature Field



Example 2: TOUGH2 (Parini, 1996)
Miravalles Reservoir reinjection scenarios

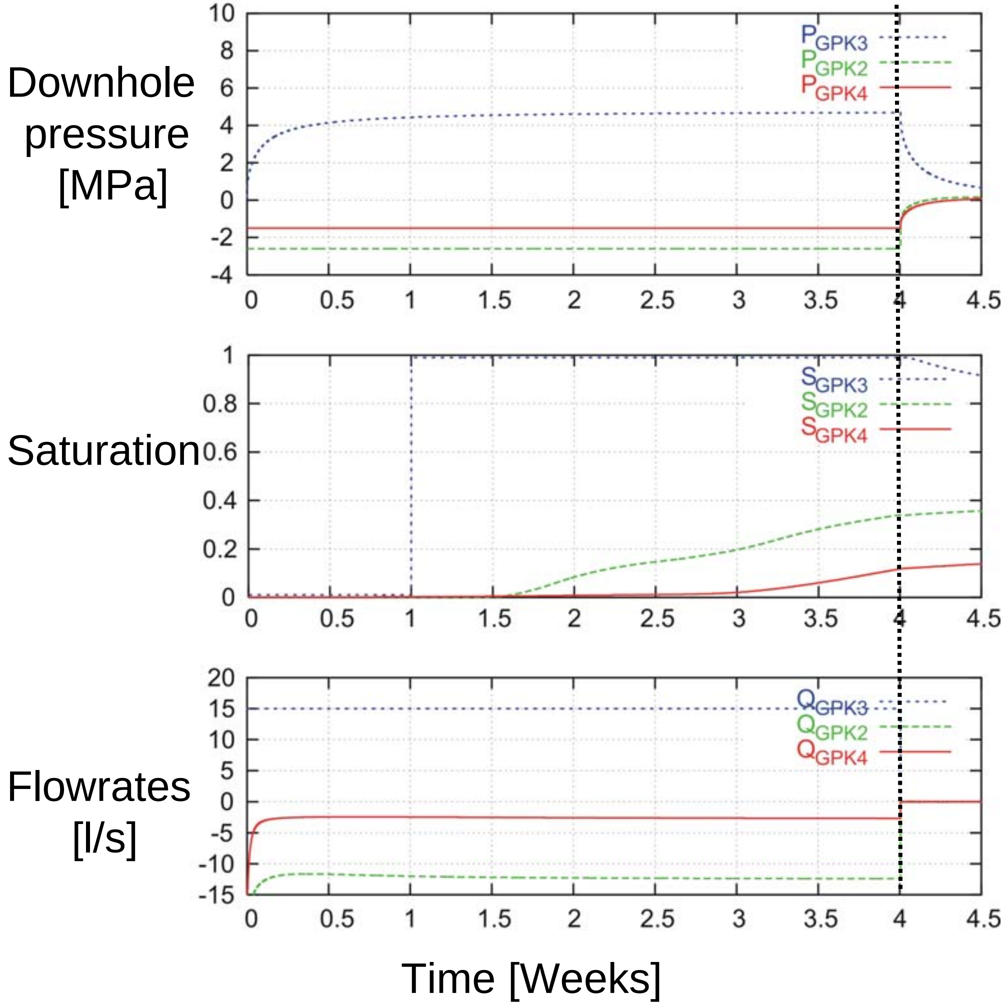
- 35 wells were drilled in the Miravalles Geothermal reservoir
- Short breakthrough time intervals between wells were observed; danger to lead to a fast steam production decrease
- Dual Porosity Model with TOUGH2
- Breakthrough times reproduced with model
- 2 reinjection scenarios were numerically tested



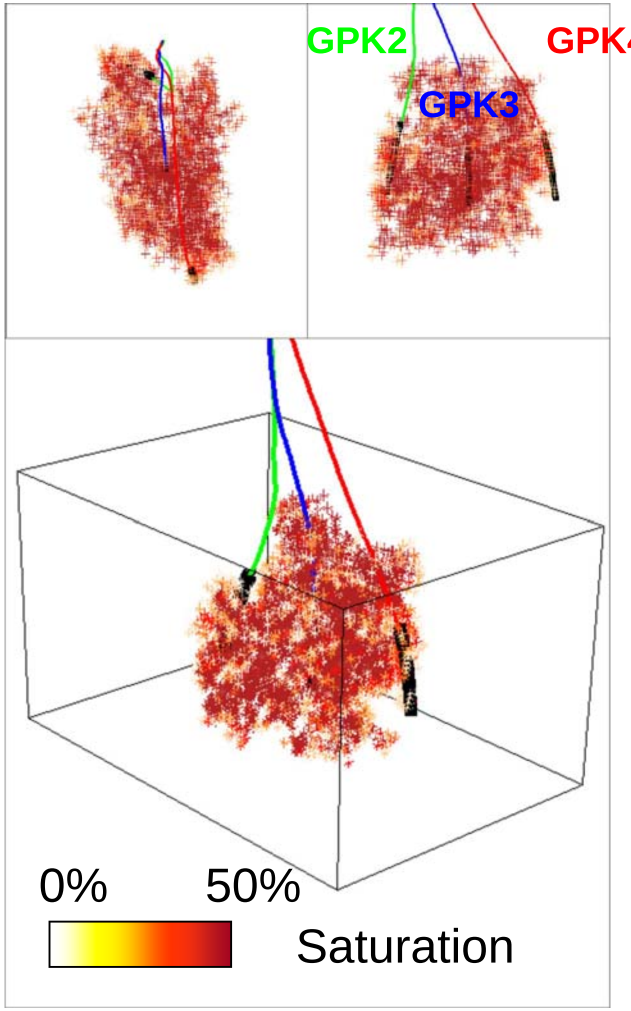
- Model results clearly pointed out a risk of cooling of important portions of the reservoir in the mid term with proposed reinjection scheme
- An alternative strategy seems to be more adequate

Example 3: Fracas (Baujard & Bruel, 2005)
Reservoir volume estimation at Soultz

Circulation test Summer 2005

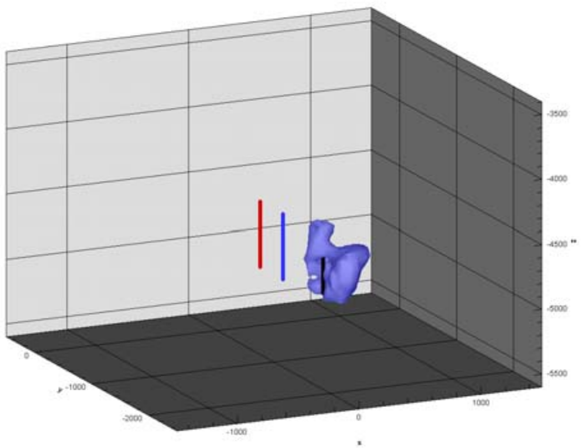


Each colored point corresponds to the center of a single fracture partially invaded by injected fluid after 4 weeks circulation

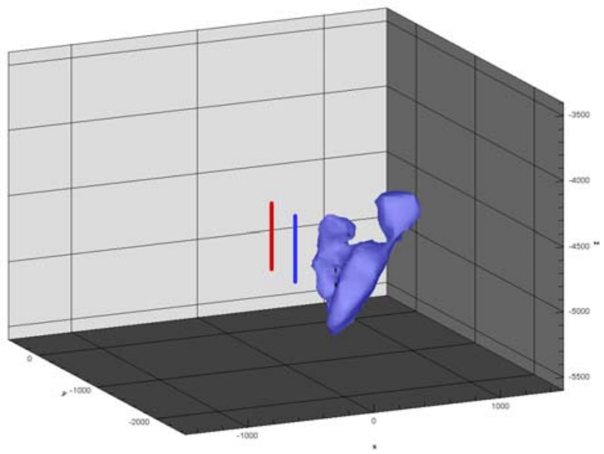


Example 4: HEX-S (Kohl & Mégel, 2007) EGS Stimulation – Perm. development

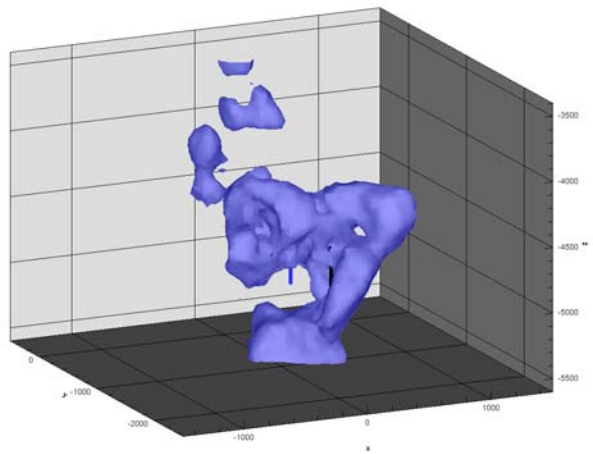
2.7 h



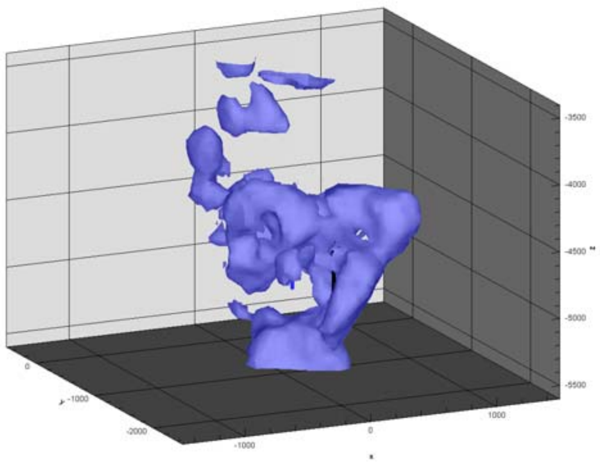
5 h



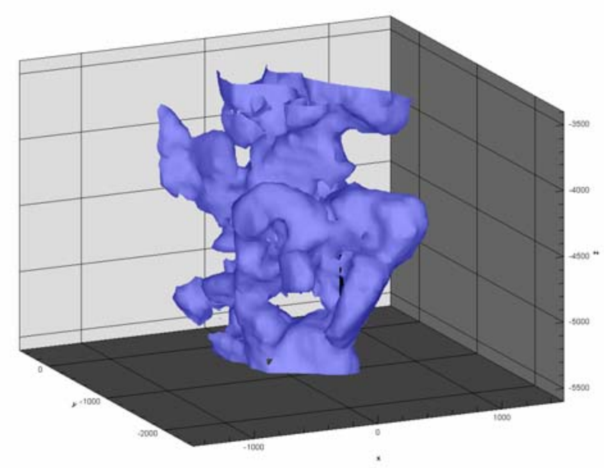
20 h



36 h



53 h



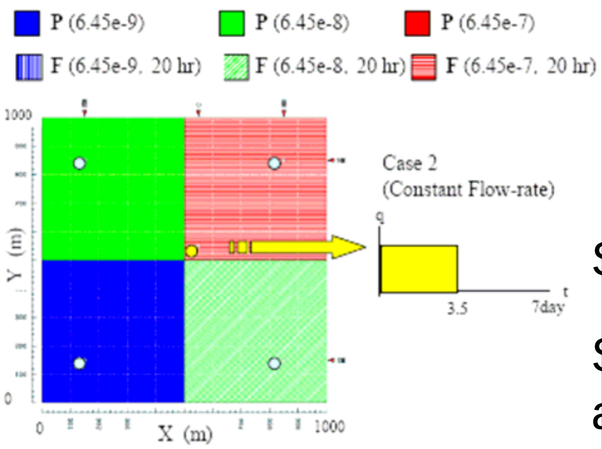
Iso-Surface = 0.0001 m

New trends: Inverse Modelling, Automatised calibration

- Inverse Modelling allows user to take in account various field measurements:
  - Pressure interference of wells (S. Nakao and al.)
  - Downhole electrical Monitoring (J. W. Pritchett and T. Ishido)
  - Microgravity changes (S. Nakanishi and al.), seismic profiles…
  - 3D Joint Bayesian Inversion (Rath et al.)

Example 4: Nakao & al.(2005)
Inverse modelling using Pressure interference

1. Definition of a conceptual MINC model :



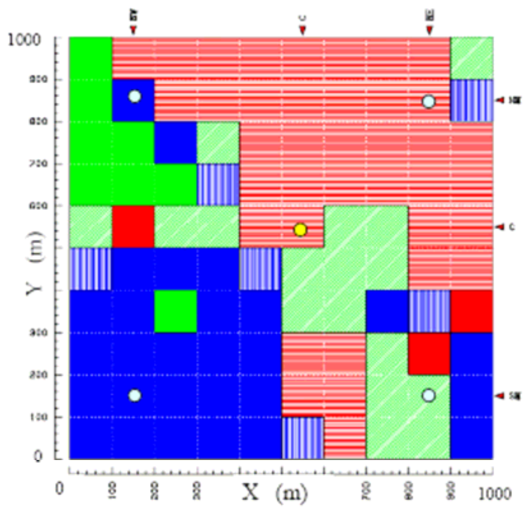
P= Porous media (Transmissivity)
F= Fractured Media (T, Drainage Time)

Simulation of an Injection step test

Simulated Observation at the well, adding random perturbations

2. Rebuild this conceptual model from observed well data, using the „Simulated Annealing“ optimizing method

Results:



Given data:

- Domain size
- Domain boundaries

New trends: Inverse Modelling, Automatised calibration

- Experiments successefully driven with MINC (dual porosity model) and STAR (geophysical postprocessors)

- Efforts were lead since 2002 to couple the TETRAD reservoir model with geophysical postprocessors at Idaho National Engineering and Environnemental Laboratory(G.M. Shook and L. Renner)

Simplifying and enhancing models

- Use of semi-analytical solutions:
  - Near Well-bore thermal effects can be estimated by trial functions (K. Pruess and Y. Zhang)

- For multiphase flow simulations, the problem of phase flow from one continua to an other (like from fracture to rock matrix) can be solved by using very simple appropriated relative permeabilities functions (Y.S. Wu and K. Pruess)

Conclusion

- Model complexity increase with physical behaviour of reservoir and with the number of physical mechanisms to consider
- Various data sets can be incorporated in models (flowrates, pressures, volumes, microgravity variations, electrical surveys, boreholes properties…) and lead to a better fit
- Numerical simulations can lead to physical understanding of processes in geothermal reservoir
- Optimization:
  - Different strategies can be tested
  - Design of utilization strategies