CONCEPTUAL AND QUANTITATIVE MODELS OF GEOTHERMAL SYSTEMS

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UNDERSTANDING GEOTHERMAL SYSTEMS

• Geothermal springs have been used for bathing, washing and cooking for thousands of years
  • Understanding limited and misconceptions prevailing

• Utilisation for energy production only started in the early part of the 20th century (Italy, Iceland, Hungary, etc.)

• Increased understanding went hand in hand with geothermal wells becoming main instruments of geothermal development, during the middle of the 20th century, as well as advancement of exploration methods

• Wells provide access deep into geothermal systems, enabling direct measurements of conditions at depth
  • Direct measurements at depth also yield better tools for exploration
CONCEPTUAL MODELS

• Understanding the nature and characteristics of a geothermal system is the key to **successful exploration and sustainable utilisation**

• Best achieved through the development of a **conceptual model** of the system in question, based on all available information and data from different disciplines

• Conceptual models are **descriptive or qualitative models** incorporating, and unifying, the essential physical features of the systems in question – **not used for calculations**

• Conceptual models are the **basis of field development plans**, i.e. in selecting locations and targets of wells to be drilled

• Also the **foundation for geothermal resource assessments**, particularly volumetric assessments and reservoir modelling
A CONCEPTUAL MODEL

Defines the natural properties of the geothermal system—in particular, interaction between temperature, pressure, permeability, and fluid flow in the system.
A CONCEPTUAL MODEL SHOULD INCORPORATE

• Size of system (area, depth range, boundaries)
• Nature of heat source(s)
• Location / strength of hot up-flow / recharge zones + origin
• Location / strength of colder recharge zones
• General flow pattern in a system (natural + production state)
• Initial thermodynamic conditions (T and P models)
• Location of two-phase and steam-dominated zones
• Location of main permeable flow structures (faults, layers, etc.)
• Location of internal boundaries, e.g. flow barriers
• Delineate cap-rock of system if present
• Division into subsystems, or separate reservoirs
A simplified sketch of one of the first conceptual models of the Krafla volcanic geothermal system in N-Iceland (Stefánsson, 1981)
A 3-D view of a 2009 conceptual model of the Krafla geothermal system, Iceland (Mortensen et al., 2009)
BUILDING A CONCEPTUAL MODEL

• Surface exploration
  • Geological mapping (structures, alteration, remote sensing)
  • Geophysical surface data (resistivity, gravity, seismic)
  • Geochemical surveys (fumaroles, hot springs, soil gas)
  • Hydrological data (regional flow, recharge, boundaries)
SURFACE EXPLORATION

Conceptual model
BUILDING A CONCEPTUAL MODEL

• Surface exploration
  • Geological mapping (structures, alteration, remote sensing)
  • Geophysical surface data (resistivity, gravity, seismic)
  • Geochemical surveys (fumaroles, hot springs, soil gas)
  • Hydrological data (regional flow, recharge, boundaries)

• Exploration drilling
  • Borehole geological data (lithology, alteration, circulation losses)
  • Well logging data (T, P, spinner, flow paths)
  • Well test data (pressure transient, porosity, enthalpy, chemistry)
EXPLORATION DRILLING
BUILDING A CONCEPTUAL MODEL

• Surface exploration
  • Geological mapping (structures, alteration, remote sensing)
  • Geophysical surface data (resistivity, gravity, seismic)
  • Geochemical surveys (fumaroles, hot springs, soil gas)
  • Hydrological data (regional flow, recharge, boundaries)

• Exploration drilling
  • Borehole geological data (lithology, alteration, circulation losses)
  • Well logging data (T, P, spinner, flow paths)
  • Well test data (pressure transient, porosity, enthalpy, chemistry)

• Production data
  • Production history (mass uptake, changes in T/P/h/chemistry)
  • Injection history (mass injected, interference tests, tracer tests)
PRODUCTION PHASE MONITORING

Conceptual model
MAINTAINING A CONCEPTUAL MODEL

• A geothermal conceptual model is **not a stationary entity**

• Should be **revised and updated continuously** as new, relevant information becomes available
  
  • Purpose to keep them up-to-date and to incorporate data which may lead to significant changes in the model
  
  • When new surface exploration (resistivity, micro-seismicity) and well data (logging or testing data) become available
  
  • Also production data which may comprise essential information on reservoir changes, boundary conditions, recharge characteristics, permeability structure, etc.

• Data **often compiled** in 3D visualisation software, e.g. RockWorks, Petrel, Leapfrog etc.
  
  • 3D modelling is an **aid to understanding**, not a goal
RENEWABILITY VS. SUSTAINABILITY

• A clear distinction necessary, some confusion in literature/discussions
• The term **renewable** refers to the nature of a resource
  • Geothermal resources generally classified officially as renewable
  • Don’t belong amongst the non-renewable resources
• The term **sustainable** refers to how a resource is utilized
  • Different definitions, different timescales
  • Need to assess how much energy can be extracted in a sustainable manner

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Resource assessment methods
PRODUCTION CAPACITY OR POTENTIAL

• Controlled by the response of a system to production, predominantly controlled by reservoir pressure decline

• Technical limit to how great pressure decline can be

• Also controlled by energy content, which is determined by temperature and reservoir size

• Pressure decline causes secondary changes; cooling due to recharge, increased boiling, chemical changes, etc.

• Appropriate reinjection management generally required to reduce pressure decline and maximise/maintain production capacity
PRESSURE DECLINE

Pressure decline is controlled by

- **Size** of geothermal reservoir
- Reservoir rock **permeability**
- Reservoir **storage capacity**
  - porosity
  - nature
- Water **recharge**
  - boundary conditions
- Geological **structure**
  - fractures
  - main permeable volumes
Production and pressure (water-level) response history of the Urban Area sedimentary system in Beijing, China
RESOURCE ASSESSMENT METHODS

- Used to assess **energy production capacity** of a resource
- Deep temperature estimates (based on chemical content)
- Surface thermal flux (conduction + discharge)
- Volumetric methods (adapted from mineral exploration and oil industry) – **static modelling**
- Decline curve analysis (adapted from oil/gas industry)
- Simple models (often analytical) – **dynamic modelling**
- Lumped parameter models – **dynamic modelling**
- Detailed numerical models of natural state and exploitation state (often called distributed parameter models) – **dynamic modelling**
VOLUMETRIC METHOD

• Estimates energy content in-place for a geothermal system based on **volume and temperature** conditions

• Then how much can be recovered during an assumed utilization period, based on a poorly defined **recovery factor**

• Parameters uncertain, hence **Monte Carlo method** is used

\[ E_{\text{res}} = E_{\text{rock}} + E_{\text{fluid}} \]

\[ E_{\text{rock}} = V (1 - \phi) \rho_{\text{rock}} \beta_{\text{rock}} (T_{\text{res}} - T_{\text{reference}}) \]

\[ E_{\text{fluid}} = V \phi \rho_{\text{fluid}} \beta_{\text{fluid}} (T_{\text{res}} - T_{\text{reference}}) \]

\[ E_{\text{recoverable}} = A \cdot R \cdot E_{\text{res}} \]

\[ E_e = \eta E_{\text{recoverable}} \quad P_e = \frac{E_e}{\Delta t} \]
An example of the results of a Monte Carlo volumetric resource assessment for the Olkaria geothermal system in Kenya for a 50-year generation period; note great uncertainty in results

(Arnaldsson et al., 2013)
DYNAMIC MODELLING

• More powerful than static modelling, **if based on sufficiently comprehensive data**

• Includes
  • simple analytical modelling
  • lumped parameter modelling
  • detailed numerical modelling

• Such models of geothermal systems are **calibrated** by reservoir physics data, e.g. temperature-, pressure-, well-test and monitoring data

• All reliable models of geothermal systems should be based on an accurate **conceptual model** of the corresponding system
In such models the complex structure and geometry of systems is **greatly simplified**, properties assumed constant, etc.

Thus mathematical (analytical) expressions can be derived that describe e.g. pressure- or temperature-changes.

E.g. Theis model and variants

(Böðvarsson and Witherspoon, 1989)
SIMPLE LUMPED PARAMETER MODELS
LUMPED PARAMETER MODELLING

• Lumped parameter models are composed of
  • **Tanks** that simulate storage capacity of a reservoir, and
  • **Resistors** that simulate permeability of reservoir

• May be used to **simulate pressure change data** very accurately, even very long datasets (several decades)

• An automatic method has been developed

• Has been used extensively to simulate and manage geothermal systems in Iceland (>25 systems), China, Philippines, Kenya, Turkey, Eastern Europe and Central America

• Ideal for **estimating sustainable production** capacity and for management purposes
Production and water level history of the Ytri-Tjarnir low-temperature geothermal system in central N-Iceland simulated by a lumped parameter model (squares = observed data, line = simulated data; Axelsson et al., 2005)
Predicted water level changes in the Urban sedimentary system in Beijing, China, for production scenarios with and without reinjection

(Axelsson et al., 2005)
DETAILED NUMERICAL MODELLING

• Numerical reservoir modelling has advanced through rapid development of high-capacity modern-day computers

• Numerical modelling is extremely powerful when based on comprehensive and detailed data; otherwise highly speculative
  • Temperature and pressure model (natural state)
  • Well-test and monitoring data (production state)

• Relies heavily on a good conceptual model

• Can accurately simulate a geothermal system’s structure, conditions and response

• Very good for sustainability assessments

• Yet, numerical modelling is time-consuming and costly
Geology (A) and grid of the numerical model (B) of the Larderello-Travale geothermal system in Italy on a W–E cross-section (Romagnoli et al., 2010)
Numerical grid of a numerical model of the Hengill geothermal region, SW-Iceland (Gunnarsson et al., 2010)
Pressure and temperature changes in different regions of the Hengill area, SW-Iceland, simulated by a numerical model for a 50-year production period followed by a recovery period

(Axelsson et al., 2010)
SIMPLE VS. NUMERICAL MODELLING

• Detailed numerical modelling is the most powerful modelling method available

• However, it is time-consuming and costly, requires powerful computers and comprehensive data

• Simple and lumped parameter modelling, in which structure and spatially variable properties are greatly simplified, is a time-saving and cost-effective alternative

• Purpose of a study, and available data, should determine modelling approach
ESTIMATING SUSTAINABLE CAPACITY

In the context of this short course the following is emphasized:

• **The volumetric method isn’t suitable** for the estimation of the sustainable production capacity of geothermal systems due to its inherent limitations

• **Lumped parameter modelling is ideal for predicting long-term reservoir pressure changes**; provides good accuracy and uncertainty bounds

• **Detailed numerical modelling is the most powerful modelling method for predicting long-term reservoir changes**, but must be based on very comprehensive data
CONCLUDING REMARKS

• Thorough understanding of the nature and properties of geothermal resources is an absolute prerequisite for their sustainable utilisation.

• Such understanding requires comprehensive interdisciplinary research, in particular an up-to-date conceptual model of the system.

• The production capacity is mainly controlled by the system’s response to utilisation, which primarily involves reservoir pressure decline.

• Reliable and accurate assessment of their production capacity is essential, which can be performed with the diverse dynamic modelling methods presented in this talk.

• Not all assessment methods are applicable to estimating sustainable production capacity.
Thank you!