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CONCEPTUAL MODELS OF GEOTHERMAL SYSTEMS – INTRODUCTION

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ABSTRACT

The key to the successful exploration, development (incl. drilling) and utilization of any type of geothermal system is a clear definition and understanding of the nature and characteristics of the system in question. This is best achieved through the development of a conceptual model of the system, which is a descriptive or qualitative model incorporating, and unifying, the essential physical features of the system. Conceptual models are mainly based on analysis of geological and geophysical information, temperature and pressure data, information on reservoir properties as well as information on the chemical content of reservoir fluids. Monitoring data reflecting reservoir changes during long-term exploitation, furthermore, aid in revising conceptual models once they become available. Conceptual models should explain the heat source for the reservoir in question and the location of recharge zones, the location of the main flow channels, the general flow patterns within the reservoir as well as reservoir temperature and pressure conditions. A comprehensive conceptual model should, furthermore, provide an estimate of the size of the reservoir involved. Cooperation of the different disciplines involved in geothermal research and development is of particular importance. Conceptual models are an important basis of field development plans, i.e. in selecting locations and targets of wells to be drilled and ultimately the foundation for all geothermal resource assessments, particularly volumetric assessments and geothermal reservoir modelling, used to assess the energy production capacity of a geothermal system. Initially a conceptual model depends mostly on surface exploration data, but once the first wells have been drilled into a system subsurface data come into play, increasing the knowledge on a geothermal system. Most important are feed-zone, temperature-logging and well-test data. Conceptual models should be revised, and improved, continuously throughout the exploration, development and utilization history of a geothermal system, as more data and information become available.

1. INTRODUCTION

Geothermal resources are distributed throughout the Earth's crust with the greatest energy concentration associated with hydrothermal systems in volcanic regions at crustal plate boundaries. Yet exploitable geothermal resources may be found in most countries, either as warm ground-water in sedimentary formations or in deep circulation systems in crystalline rocks. Shallow thermal energy suitable for ground-source heat-pump utilization is available world-wide and attempts are underway at developing enhanced geothermal systems (EGS) in places where limited permeability precludes natural hydrothermal activity. Geothermal systems and reservoirs are classified on the basis of different aspects, such as reservoir temperature or enthalpy, physical state, their nature and geological setting. Steingrímson et al. (2013) and Axelsson (2008a) review these classifications and the distribution of geothermal resources worldwide.

Geothermal springs have been used for bathing, washing and cooking for thousands of years in a number of countries world-wide, e.g. China, Japan and the remnants of the Roman Empire (Cataldi et al., 1999). Yet commercial utilisation of geothermal resources for energy production only started in the early 1900's. Electricity production was initiated in Larderello, Italy, in 1904 and operation of the largest geothermal district heating system in the world in Reykjavik, Iceland, started in 1930. Extensive geothermal heating of greenhouses also started in Hungary in the 1930's. Since this time, utilisation of geothermal resources has increased steadily.

The understanding of the nature of hydrothermal systems didn't really start advancing until their large-scale utilization started during the 20th century. Some studies and development of ideas had of course been on-going during the preceding centuries, but various misconceptions were prevailing (Cataldi et al., 1999). In Iceland, where highly variable geothermal resources are abundant and easily accessible, a breakthrough in the understanding of the nature of geothermal activity occurred during the middle of the 19th century, a breakthrough which was, however, beyond the scientific community at the time (Björnsson, 2005). Increased utilization and greatly improved understanding went hand in hand with geothermal wells becoming the main instrument for geothermal development. This is because geothermal wells enable a drastic increase in the production from any given geothermal system, compared to its natural out-flow, as well as providing access deep into the systems, not otherwise possible, which enables a multitude of direct measurements of conditions at depth.

The key to the successful exploration, development (incl. drilling) and utilization of any type of geothermal system is a clear definition and understanding of the nature and characteristics of the system in question, based on all available information and data. This is best achieved through the development of a ***conceptual model*** of a geothermal system, which is actually the focus of this short course. Conceptual models are descriptive or qualitative models incorporating, and unifying, the essential physical features of the systems in question (Grant and Bixley, 2011). The cooperation of the different disciplines involved in geothermal research and development is of particular importance here, rather than each discipline developing their own models or ideas independently. Conceptual models are an important basis of field development plans, i.e. in selecting locations and targets of wells to be drilled (Axelsson and Franzson, 2012) and ultimately the foundation for all geothermal resource assessments, particularly volumetric assessments and geothermal reservoir modelling (Axelsson, 2013a).

This paper presents an introduction to the development and utilization of conceptual models of geothermal systems, the subject of this short course. Other presentations go into comprehensive detail regarding the data that provide the basis for conceptual models, how they are developed and finally how they are used for siting the different types of wells and as the basis of resource assessments, including the development of models of geothermal systems.

2. WHAT ARE CONCEPTUAL MODELS?

The diverse information and data available on geothermal systems is increasingly being unified through the development of conceptual models of the respective systems. They play a key role in all phases of geothermal exploration and development, e.g. by providing a unified picture of the structure and nature of the system in question. Conceptual models are descriptive or qualitative models, not used for calculations. They are mainly based on geological information, both from surface mapping and analysis of subsurface data, remote sensing data, results of geophysical surveying, information on chemical and isotopic content of fluid in surface manifestations and reservoir fluid samples collected from wells, information on temperature- and pressure conditions based on analysis of available well-logging data as well as other reservoir engineering information. Comprehensive conceptual models of geothermal systems should incorporate the following as far as available information allows:

(1) Provide an estimate of the size of a system, more specifically information on areal extent, thickness and depth range as well as external boundaries (vertical)
(2) Explain the nature of the heat source(s) for a system
(3) Include information on the location and strength of the hot up-flow/recharge zones, including the likely origin of the fluid
(4) Describe the location and strength of colder recharge zones
(5) Define the general flow pattern in a system, both in the natural state and changes in the pattern induced by production
(6) Define the temperature and pressure conditions in a system (i.e. initial thermodynamic conditions through formation temperature and pressure models)
(7) Indicate locations of two-phase zones, as well as steam-dominated zones
(8) Describe locations of main permeable flow structures (faults, fractures, horizontal layers, etc.)
(9) Indicate the location of internal boundaries (vertical and/or horizontal) such as flow barriers
(10) Delineate the cap-rock of the system (horizontal boundaries)
(11) Describe division of system into subsystems, or separate reservoirs, if they exist

Not all geothermal conceptual models incorporate all of the items above, in fact only a few do so. How advanced a conceptual model is depends on the state of development of the system in question. In the early stages knowledge is limited and only information on a few of the items above will naturally be available. When development continues knowledge on the items above increases; first when substantial deep drilling has been conducted and later when large-scale utilization has been on-going for quite some time, with associated monitoring. Fairly comprehensive knowledge on all the items listed has only then become available.

Three examples of visualizations of geothermal conceptual models are presented in Figures 1 – 3. Other examples are available in the geothermal literature, such as a number of examples presented by Grant and Bixley (2011), the conceptual model for the Olkaria geothermal system in Kenya (Axelsson et al., 2013) and the conceptual model for the Hengill geothermal system presented by Franzson et al. (2010). It may also be mentioned that general conceptual models have also been proposed for different types of geothermal systems, capturing their main characteristics, without being as detailed as conceptual models for individual systems (Steingrímsson et al., 2013).

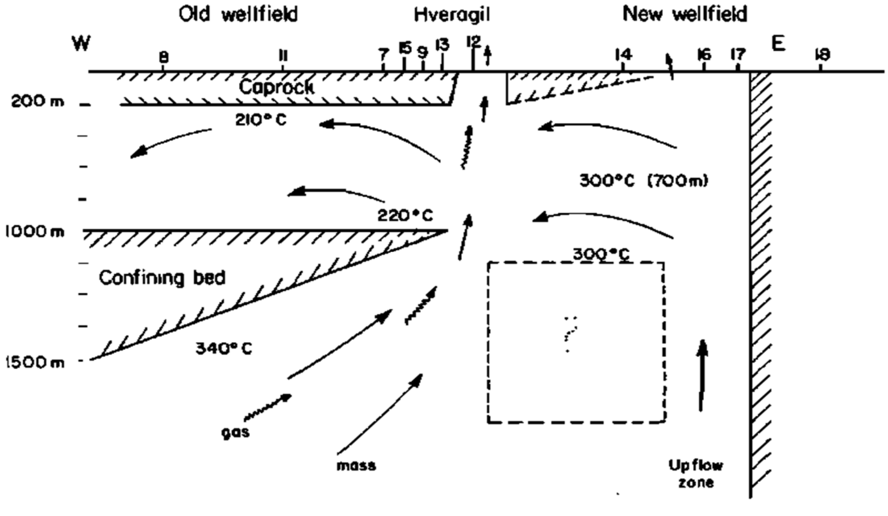

FIGURE 1: A simplified sketch of one of the first conceptual models of the Krafla volcanic geothermal system in N-Iceland (Bödvarsson et al., 1984)

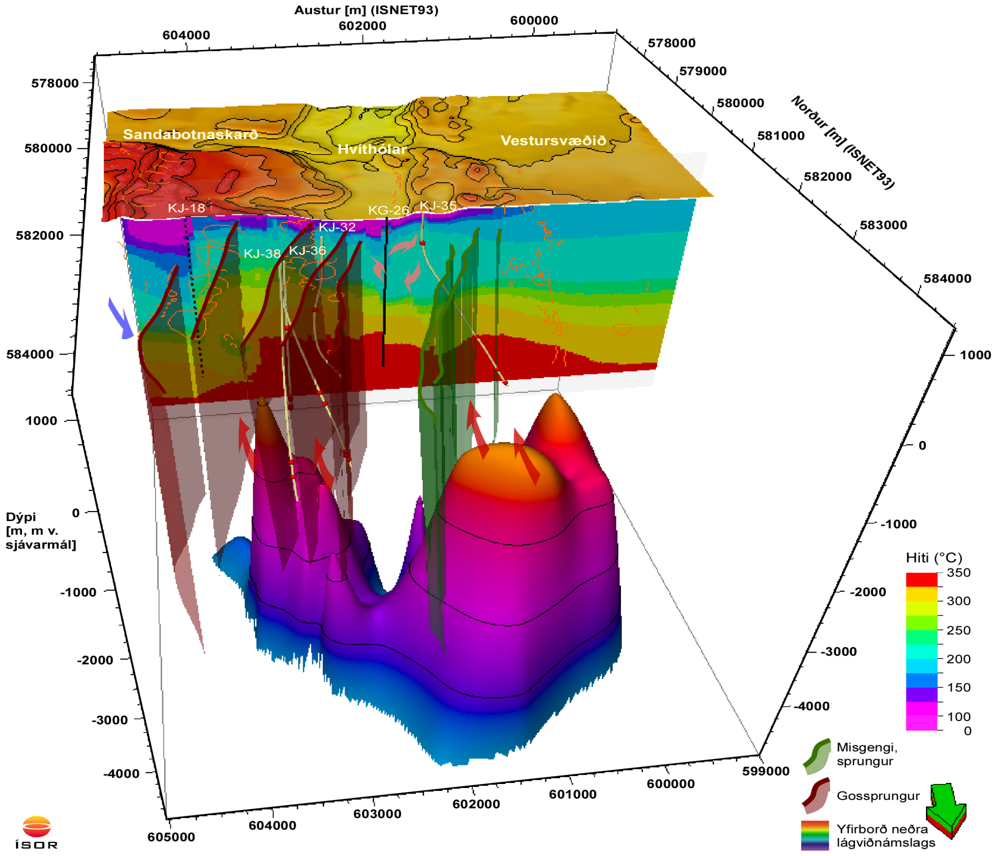

FIGURE 2: A 3-dimensional view of the current (25 years younger than the one in Figure 1) conceptual model of the Krafla geothermal system in N-Iceland (Mortensen et al., 2009) showing a deep-seated low-resistivity anomaly reflecting a magma chamber, faults and eruption fissures as well as temperature conditions and inferred flow directions

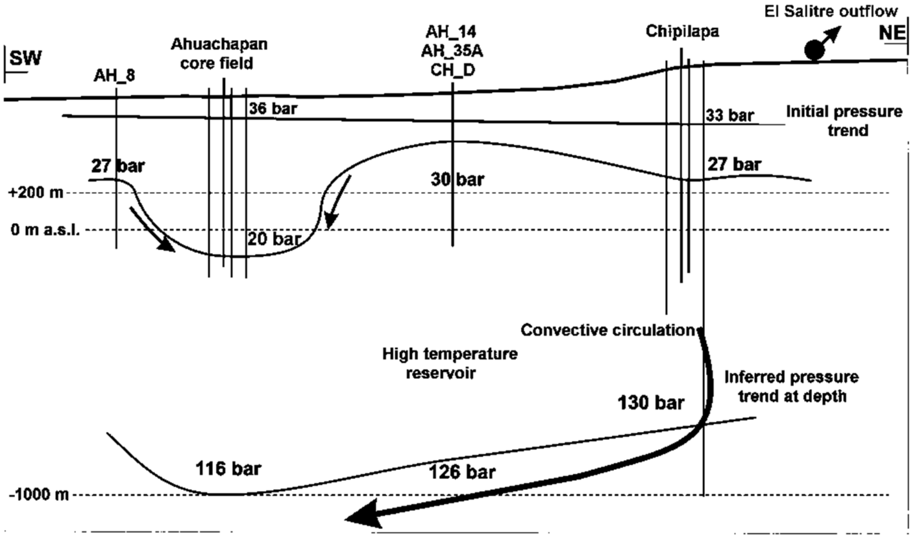

FIGURE 3: A simplified sketch of the Ahuachapan geothermal system in El Salvador (Monterrosa and Montalvo, 2010)

3. DEVELOPING CONCEPTUAL MODELS

Geothermal exploration and exploitation is a multidisciplinary science, starting with surface exploration followed by collection of drill-hole data and finally reservoir engineering modelling studies and utilization monitoring. Each discipline looks at the geothermal system from a certain viewpoint, having a tendency to define the geothermal system from that perspective. That is why developing a conceptual model is quite beneficial, as it unifies the different viewpoints. In order to create the most comprehensive geothermal conceptual model all the disciplines have to be incorporated, but essentially the focus is on geological structures, permeability, temperature and pressure conditions as well as fluid chemistry.

When developing conceptual models the focus should be placed on the following data / information:

- Surface geological and structural maps and other related information. Particular emphasis should be placed on information on fractures, faults and the general tectonic setting (including crustal stress conditions at the location in question). Aerial photos and other remote sensing data should also be considered, if available.
- Borehole information including location and design.
- Borehole geological data including geological cross sections and information on zones of circulation losses.
- Information on porosity of different formations, as far as available.
- Data on borehole alteration mineralogy.
- Surface geophysical data including gravity data, magnetic data and resistivity data. Emphasis should be placed on available interpretations of such data.
- Seismic data, including information on regional seismicity, micro-earthquake data and seismic survey data (seldom available), as well as relevant interpretations.
- Information on temperature and pressure conditions in the geothermal system from well-logging data. Also initial temperature- and pressure-models, if available.
- Information on feed-zone locations based on circulation losses, temperature and pressure logs, as well as spinner logs, if available.
- Pressure transient data, both from short-term well-tests and longer-term interference tests, along with available interpretation results.
- Available information on the chemical composition and gas content of reservoir fluid, including isotope data, e.g. based on samples from surface manifestations.
- Detailed well-by-well information on mass production history.
- Detailed well-by-well information on reinjection history.
- Monitoring data including information on reservoir pressure changes (preferably from monitoring wells) and reservoir temperature changes as well as changes in well-head pressure, well enthalpy, chemical content and gas content.
- Reinjection test data, tracer test data and reinjection monitoring data.
- Surface monitoring data such as geodetic measurements (e.g. surface subsidence data) and results of repeated micro-gravity surveying.
- Hydrogeological information on the whole geothermal region, including available hydrogeological models incorporating ideas on regional flow, recharge and boundaries.
- All relevant previous studies, in particular studies presenting conceptual models, resource assessments, modelling work and chemical studies.

The relevant data and corresponding interpretation results, for the different disciplines involved in geothermal research and development, are described in various presentations at the present short course as well as how these data and results are combined in a unified conceptual model (Mortensen and Axelsson (2013). Cumming (2009) discusses the development of conceptual models on basis of surface exploration data in particular. Specific examples of interpretation results incorporated into the relevant conceptual models are presented in Figures 4 – 6 below.

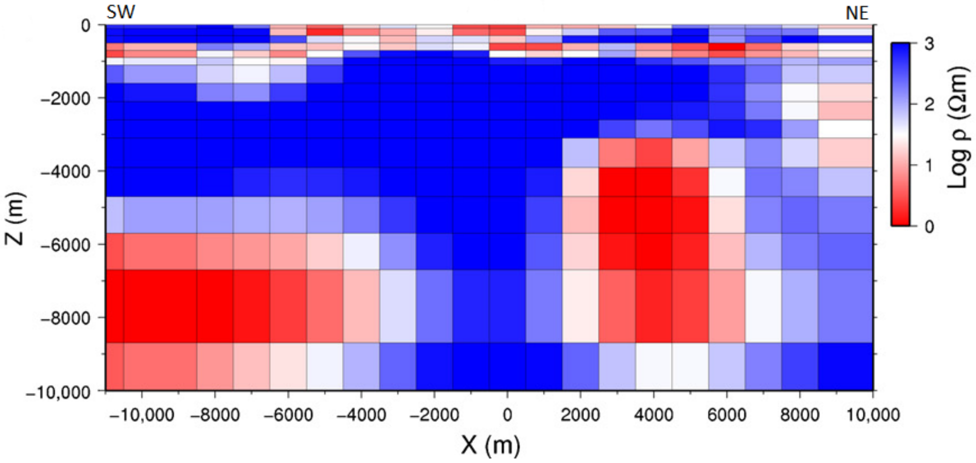

FIGURE 4: Resistivity distribution in a NE-SW cross-section through a 3-D resistivity model of the Hengill geothermal region in SW-Iceland, extending down to 10 km depth (from Árnason et al., 2010)

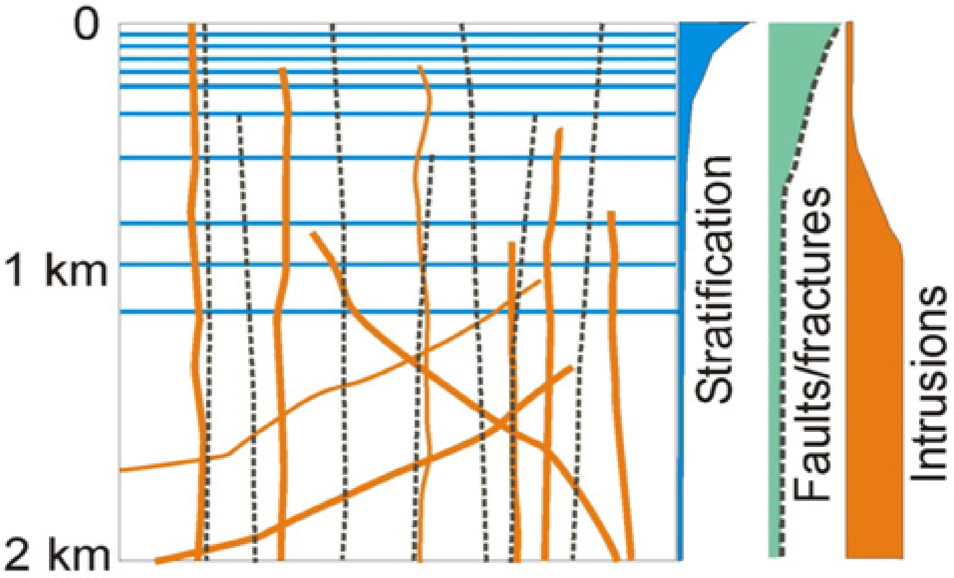

FIGURE 5: A schematic figure showing how the importance of permeability associated with different geological structures varies typically with depth in volcanic geothermal systems in Iceland (from Axelsson and Franzson, 2012). The best permeability is often found at the intersection of two such structures

It may be mentioned that three-dimensional visualization software is increasingly being used to visualize, merge and jointly interpret various types of geothermal research data, as great advances have been made recently in computer software intended for this purpose. The PETREL software package, developed by Schlumberger Ltd. (initially for the petroleum industry), is e.g. used to some extent by the geothermal business.

Initially conceptual models depend mostly on surface exploration data, with geological (e.g. faults /fractures) and geophysical (e.g. resistivity) data being most important. Formation temperature is e.g. unknown at such an early stage. The only indications of reservoir temperature at that stage come from chemical investigations. Once the first wells have been drilled, however, subsurface data come into play, increasing drastically the knowledge on, and understanding of, a geothermal system. Most important are lithological and feed-zone data, temperature-logging data and well-test data. Some of the logging and reservoir engineering data collection in geothermal wells is described in other presentations at this short course (see also Axelsson and Steingrímsson, 2012). Thus a conceptual model of a geothermal system relies more and more on subsurface data as development progresses.

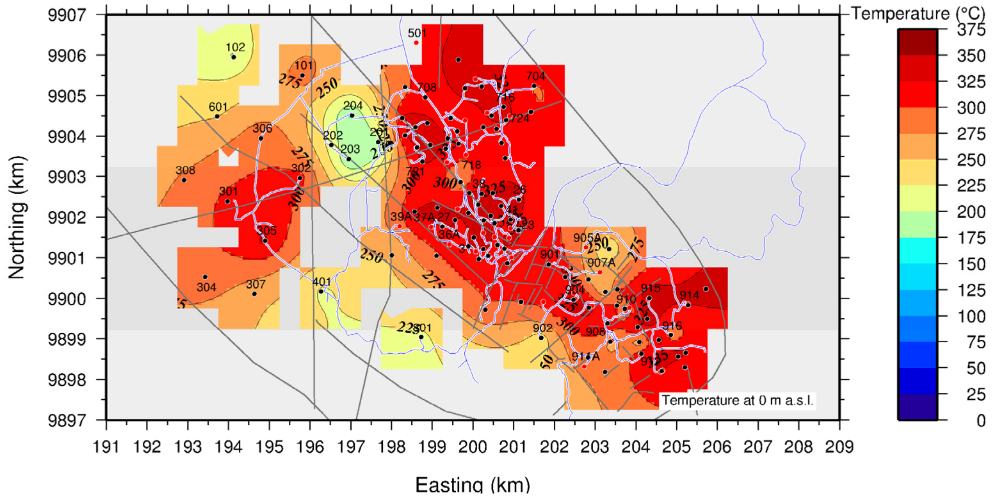

FIGURE 6: Horizontal view of the temperature distribution at 0 m a.s.l. (~2000 m depth) in a temperature model of the Olkaria geothermal system in Kenya (Axelsson et al., 2013)

Once the drilling of a geothermal well has been completed the results, or data collected from the well, should be compared with the interpretation of surface exploration data, i.e. with what was expected. Based on this comparison the conceptual model of the geothermal system should be updated, e.g. to ensure that the next well siting will be based on the most up-to-date information and understanding.

4. EMPLOYING CONCEPTUAL MODELS

Conceptual models of geothermal systems play two main roles in geothermal development and utilization management, as already stated; firstly as the basis of field development plans, in particular in terms of well siting, and secondly as the basis of resource assessments and modelling studies. These two roles will be reviewed briefly below. The importance of revising geothermal conceptual models on a regular basis is also discussed.

4.1 Field development / well siting

Geothermal field development plans are plans describing how a geothermal field should be developed for utilization; including the generation capacity to aim for, well drilling plans (drilling targets, well number and well locations) and reinjection strategies. These are based on conceptual models in two ways:

(1) Indirectly through energy production capacity estimates based on the results of the models used for capacity assessment, which are in turn based on available conceptual models. This also involves the number of wells as well as the appropriate distance between wells, both production and reinjection wells.

(2) Directly by using a conceptual model to delineate both general and specific well drilling targets. This applies to all type of geothermal wells, exploration, production, step-out, make-up, reinjection and monitoring wells. Conceptual models also provide the basis for reinjection strategies during long-term utilization and management.

Axelsson and Franzson (2012) discuss well siting in more detail, as well as reviewing the different types of geothermal wells.

The principal geothermal drilling targets (for production wells) are in fact structures, or volumes, of adequate permeability and sufficiently high temperature to yield adequately productive wells. The nature of the permeability depends on the type of geothermal system concerned, being controlled by the geology involved (formations, faults/fractures, etc.) and in-situ stress conditions reflected by the nature of local seismic activity. Temperature conditions may be indirectly inferred from resistivity surveying and concentration of chemical components or measured directly through wells. The permeability structure of a geothermal system is usually quite complex and usually not well defined until a certain number of wells has been drilled into a geothermal system. Once this structure becomes well known and clearly defined drilling success usually peaks. Figure 5 above shows e.g. a schematic figure of the geological structures most often controlling permeability in Icelandic geothermal systems as well as how their relative importance changes with depth. It should be pointed out that experience has shown that the best permeability is often found at the intersection of two or more such geological structures.

Targets for reinjection wells are not fully comparable to the targets of production wells. This applies in particular to temperature conditions as reinjection is not always applied directly in the hottest parts of a geothermal reservoir or system (Axelsson, 2012). In fact reinjection sectors selected are quite variable from one area to another with the reinjection targets therefore being quite different. Sufficient permeability is, of course, also a necessary requirement for successful reinjection wells. A research method particular to reinjection studies is tracer testing, which is used to study connections between reinjection and production wells and to estimate the danger of production well cooling because of reinjection (Axelsson, 2012 and 2013b).

4.2 Geothermal resource assessments / modelling

Conceptual models of geothermal systems also provide an essential basis for the development of all reliable models of geothermal systems (Axelsson, 2013a). This applies to a varying degree to the different kinds of models, ranging from static volumetric models to dynamic models such as simple analytical models, lumped parameter models and detailed numerical reservoir models. This was emphasised as early as by Bödvarsson et al. (1986) in their treatise on numerical modelling of geothermal systems. Axelsson (2013) and Sarmiento et al. (2013) review the different geothermal modelling, or assessment, methods in later presentations at this short course.

The volumetric assessment method involves estimating the total energy content (both that of the solid rock and energy content of water stored in pores and fractures) in a geothermal system and consequently estimating how much of that can be extracted (i.e. recovery factor) and used over a specific time-period. The principal input parameters for this are the size (i.e. surface area and thickness) of the system in question and temperature conditions in the system. These are clearly derived from a corresponding conceptual model. Other parameters, such as rock porosity, physical and thermal properties of the reservoir rocks and water at reservoir conditions, are only of secondary importance, however, regarding the outcome of a volumetric assessment. In addition the recovery factor depends on the nature of the system; permeability, porosity, significance of fractures and recharge, all of which hinges on the corresponding conceptual model. The recovery factor also depends on the mode of production, i.e. whether reinjection is applied as well as being to some extent dependent on time. Figure 7 shows an example of the outcome of a volumetric resource assessment for the Hengill geothermal region in SW-Iceland, in which the Monte Carlo method was used by assigning probability distributions to the different parameters involved and consequently estimate the system potential with probability, enabling incorporation of overall uncertainty in the results (see Sarmiento et al., 2013).

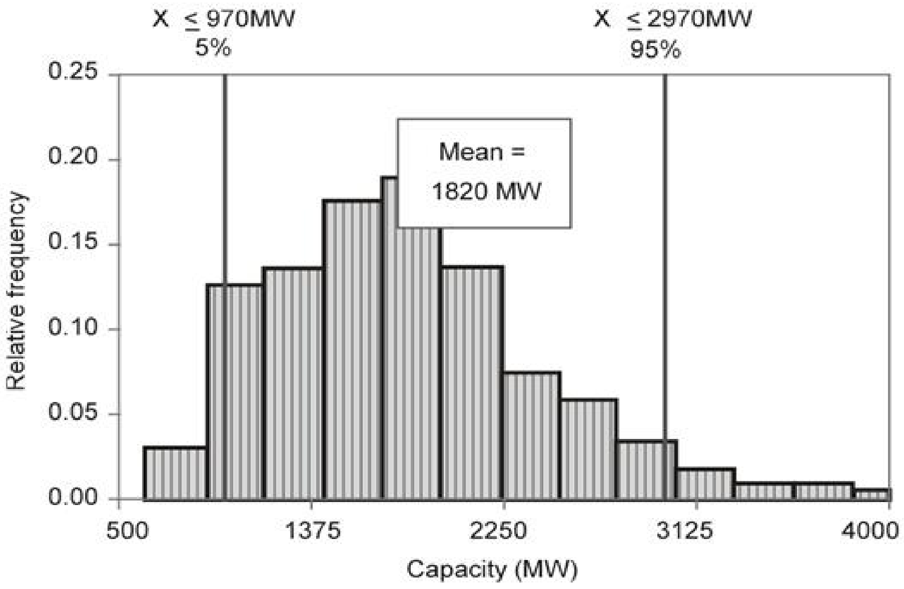

FIGURE 7: An example of the results of a volumetric resource assessment for the greater Hengill geothermal region in SW-Iceland. The Monte Carlo method was applied in the assessment (Sarmiento and Björnsson, 2007)

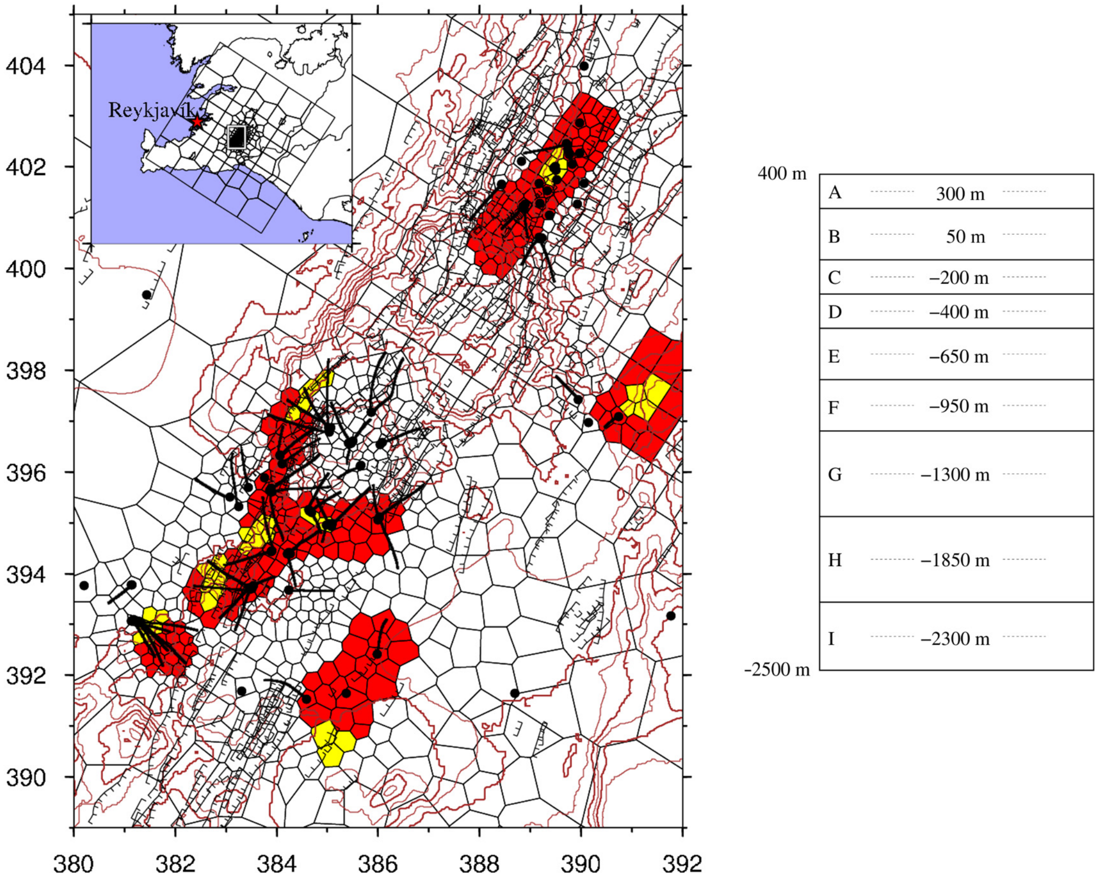

FIGURE 8: The numerical grid of detailed numerical model of the Hengill geothermal region in SW-Iceland (see insert top left), horizontal grid on the left and vertical stratification on the right in m a.s.l. (Gunnarsson et al., 2010). The coloured areas show the elements where heat is introduced into the bottom of the model, with the yellow ones indicating hot fluid recharge

Detailed numerical modelling of geothermal systems is the most comprehensive and accurate geothermal modelling method, provided comprehensive and correct data are available to calibrate the models. Such models rely heavily on corresponding conceptual models, principally in designing the numerical grid of a model, setting up the relative distribution of permeability, defining boundary conditions and setting up heat sources, all of which is incorporated before actual calibration of a numerical model is performed. The corresponding temperature and pressure model are also kept in mind when a numerical model is set up, while these data are also the principal data used to calibrate the numerical model (the natural state) along with well-test and physical monitoring data (production state). Figure 8 shows an example of the grid of a numerical model of the Hengill geothermal system in SW-Iceland, along with the distribution of heat sources.

Finally it should be mentioned that the conceptual models of geothermal systems should be kept in mind when selecting a simple analytical model of a geothermal system (Axelsson, 2013), even though such a model constitutes a drastically simplified version of the real system. The converse applies to lumped parameter models, which in fact ignore the geometry of a geothermal system. The results of lumped parameter modelling can be used, however, as supporting information for conceptual model development.

4.3 Revising conceptual models

Once a conceptual model of a geothermal system has been developed it isn't a stationary entity, as it should be revised and updated continuously as new, relevant information becomes available. This is essential so as to keep them up-to-date and to incorporate data which may lead to significant changes in the model. This applies e.g. to when new surface exploration data, new well data (even from a single well) or monitoring data become available. An example of such revisions over a long period (~3 decades) is presented by Axelsson et al. (2013) at the present workshop. The most important aspects / steps of conceptual model revision are:

a) Incorporation of new surface exploration data (geological, geophysical and / or chemical), not available for previous model developments. Such data and their interpretation are discussed in several presentations at this short course.
b) Incorporation of well data from newly drilled wells, e.g. on lithology, alteration and feed-zone locations; also discussed in other presentations.
c) Upgrading of temperature and pressure models on basis of formation temperature and pressure profiles estimated for new wells (see later presentations).
d) Incorporation of results of production response monitoring (Monterrosa and Axelsson, 2013); e.g. well-output data (mass-flow and enthalpy changes), reservoir pressure and temperature change data and data on changes in chemical content. These results, which usually don't become available until long-term utilization has started, may comprise essential information on boundary conditions, recharge characteristics, permeability structure, etc.
e) Indirect monitoring, such as repeated micro-gravity and surface deformation surveying as well as monitoring of micro-seismic activity, may also provide invaluable information on the nature of geothermal systems and their recharge.

The results of geothermal system modelling (see above) may, moreover, provide input into the development, or revision, of conceptual models of geothermal systems, or lead to changes therein, e.g. if the modelling indicates discrepancies between what appears to be physically acceptable and the conceptual model.

5. CONCLUSIONS AND RECOMMENDATIONS

This paper presents an introduction to the development and utilization of conceptual models of geothermal systems, the subject of this short course. A good conceptual model provides a clear understanding of the nature and characteristics of the system in question, and unifies the essential physical features of the system, which is the key to its successful exploration, development (incl. drilling) and utilization. The paper has reviewed the variable data and information conceptual models are based on, but it should be emphasised that monitoring data, reflecting reservoir changes during long-term exploitation, can be extremely useful in revising conceptual models once they become available (often overlooked). Cooperation of the different disciplines involved in geothermal research and development is of particular importance when conceptual models are developed, as well as being one of the benefits of their development.

Conceptual models are an important basis of field development plans, i.e. in selecting locations and targets of wells to be drilled and ultimately the foundation for all geothermal resource assessments, particularly volumetric assessments and geothermal reservoir modelling, used to assess the energy production capacity of a geothermal system. Initially a conceptual model depends mostly on surface exploration data, but once the first wells have been drilled into a system subsurface data come into play, increasing the knowledge on a geothermal system. Most important are feed-zone, temperature-logging and well-test data. Conceptual models should be revised, and improved, continuously throughout the exploration, development and utilization history of a geothermal system, as more data and information become available.

Conceptual models are qualitative and, hence, not used for calculations. But the results of geothermal system modelling may provide input into the development, or revision, of conceptual models of geothermal systems, or lead to changes therein, e.g. if the modelling indicates discrepancies between what appears to be physically acceptable during calibration of a numerical model and the conceptual model itself.

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